LARGE DIAMETER TUBE FLOODING EXPERIMENTS AT ELEVATED PRESSURES

A Thesis

by

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ABSTRACT

A series of air/water and steam/water flooding experiments were conducted to study the effects of pressure and inlet water flow rate on flooding conditions in a large diameter vertical tube. Flooding is defined as the phenomena that occurs when an annular film flow reversal takes place due to the momentum of a countercurrent flowing gas. These experiments were performed to compare air/water and steam/water flooding data under various conditions and develop an empirical correlation that can be used to describe flooding in a large diameter vertical tube. For these experiments a vertical stainless steel tube was used to obtain well-characterized data in a simple geometry. Tests were conducted by establishing an annular liquid film into the test section followed by injecting gas into the test section to induce flooding. Flooding is considered to occur once some amount of the annular film reverses flow direction. Tests were performed at four different pressures ranging from atmospheric to 45 psig, at three different water inlet flow rates and with various tests, ranging from 0% to nearly 100% flow reversal.

The data used for this work is important due to it being the first of its kind in a well characterized large-diameter tube. The data suggest that there is little dependency on test section pressure and inlet water flow rate on flooding curves when plotted as non-dimensional Kutateladze parameters. The steam/water and air/water data trended very closely, and a correction factor was able to be used to translate the steam/water data to match with the air/water data. This data and corresponding empirical correlations developed can be used to modify and improve existing reactor safety codes.

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NOMENCLATURE

ABBREVIATIONS

CFM	Cubic feet per minute
DAQ	Data acquisition system
GPM	Gallons per minute
ID	Inner diameter
LOCA	Loss of Coolant Accident
NHTS	Nuclear Heat Transfer Systems
PSIA	Pounds per square inch absolute
PSIG	Pounds per square inch gauge
PWR	Pressurized Water Reactor
RCIC	Reactor Core Isolation Cooling

SYMBOLS

c	Constant in Wallis correlation
c_k	Constant in Kutateladze correlation
D	Diameter of test section
D^*	Bond number
f	Fraction of steam condensed
g	Acceleration due to gravity
h_i	Enthalpy of phase *i*
j_i	Superficial velocity of phase *i*
j_i^*	Wallis parameter for dimensionless superficial velocity of phase *i*

K_i	Kutateladze parameter of phase *i*
K_{ge}	Kutateladze effective gas flow rate
m	Constant in Wallis and Kutateladze correlations
$\dot{m}_i$	Mass flow rate of phase *i*
Q	Volumetric flow rate
T_s	Saturation temperature of the working fluid
T_{wall}	Temperature of the test section wall
ΔT_{sub}	Amount of subcooling present
V-xxx	Valve labeled with number xxx

GREEK SYMBOLS

ρ_i	Mass density of phase *i*
σ	Surface tension of liquid in test section

SUBSCRIPTS

f	Liquid
fd	Liquid down the test section
g	Gas
in	Inlet
out	Outlet
st	Steam

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1. INTRODUCTION

Flooding is a phenomenon that occurs when the downward flow of a liquid film is reversed by the increasing velocity of gas flowing in an opposite direction [1]. The reversal of the liquid film by increasing gas velocity can range from onset, partial or full flow reversal. This phenomenon has been studied extensively in the past in the area of many engineering applications including nuclear power plant reactor safety. Previous studies have noted the ability for flooding to occur in the pressurizer surge line of an AP 600 after a small break loss of coolant accident (LOCA) [2].

1.1 Project Motivation

This thesis covers the fifth installment of flooding research in the Nuclear Heat Transfer Systems (NHTS) laboratory at Texas A&M University. Flooding research was first conducted in the NHTS lab due to a growing interest in the effects of flooding in the pressurizer surge line of a Pressurized Water Reactor (PWR). The motivation in the current research follows the previous NHTS studies in being better able to understand the flooding phenomena as it occurs in the pressurizer surge line.

In a PWR the primary system, also referred to as Reactor Coolant System, is a combination of various components connected together with the goal of transferring heat from the reactor fuel. One of these components is the pressurizer which is in place to control the pressure of the Reactor Coolant System. One way that the pressurizer is designed to lower the pressure of the Reactor Coolant System is by allowing for the steam to vent out of the top of the pressurizer through the pressurizer relief valves. During an accident scenario such as a station blackout it has been found to be possible for a large amount of steam to generate in the core and vent out the top of the pressurizer relief valve. During this event the steam passes through the pressurizer surge line which is what connects the pressurizer with the rest of the Reactor Coolant System. The pressurizer surge line is composed of horizontal, vertical and elbow piping. It is in the vertical piping sections of the pressurizer surge line that Takeuchi et al have found flooding to occur as well as cause the largest adverse effects [2].

As flooding occurs in the surge line the wall temperature greatly increases due to the steam traveling along the wall piping. This is caused by the reversal, flooding, of the annular flow in the surge line which can be thought of as replacing the water flowing down with steam flowing up. The overall concern is that if the flooding took place over a long period of time it would be possible for the surge line piping to rupture at the location of flooding due to the high temperature creep.

1.2 Project Objectives

The purpose behind this project was to use an existing test facility to compare flooding data for steam/water and air/water flooding in a large diameter vertical tube at elevated pressures. Previous studies using this same test facility have been conducted however, these previous studies were performed with the goal of obtaining onset of flooding data. The current research differs from previous studies in that flooding data was obtained at various levels of flooding from onset to full flow reversal.

The data recorded from both the steam/water and air/water flooding tests were utilized to generate flooding curves. The flooding curves allow for the direct comparison of flooding data for the two fluid pairs at various pressures and water injection flow rates.

The flooding curves were used to generate flooding correlations specific to the large diameter vertical tube test section used for this research. The flooding correlations can be used to help predict how the flooding phenomena acts in a large diameter tube from onset of flooding to nearly full flow reversal. This data and correlations will be useful in attempting to predict flooding in reactor safety codes.

1.3 Technical Approach

In the fourth installment of flooding research at the NHTS laboratory Wynne heavily modified the existing facility that was first designed by Nicole Ritchey (née Williams) [3]. The modifications performed by Wynne allowed for the facility to be pressured up to 60 psia while allowing steam/water and air/water flooding tests to be ran. The current research was performed in the Wynne facility with the addition of a water heater just prior to the water entering the test section. The addition of the water heater allows for the experiment operator to keep the temperature of the water entering the test section much closer to saturation temperatures. Wynne designed the facility for the gas whether it be steam or air to travel into and out of the test section in the same manner [3]. The consistency in steam flow path along with the ability to control the inlet water temperature allows for the direct comparison of steam/water and air/water data with minimal affects to geometry and condensation.

1.4 Thesis Organization

This thesis is divided up into six sections to describe the problem, work performed and the results. Section 1 includes an introduction that describes the project motivations and objectives, a description of the technical approach and a general layout of the thesis.

Section 2 contains a literary review of flooding research that has occurred in the past. The literary review is broken into three subsections that cover preliminary flooding research, flooding research that has been performed at the NHTS Laboratory and flooding research that has involved a steam/water testing facility. Section 3 includes a description of the flooding facility with explanations of what facility designs were performed by which previous researcher. Section 4 consists of the test procedures that were used to run all flooding tests for the current research. The results and discussion section is located in Section 5. In this section a description of the raw data that was obtained along with the reduced data is given. The reduced data is plotted and a correlation is presented to represent air/water and steam/water tests. These correlations are then compared to previously generated correlations found in the literature. The conclusion and suggestions for future work are given in Section 6. Appendices are given that present the MATLAB scripts used along with reduced and raw data from each test.

2. LITERATURE SURVEY

2.1 Preliminary Flooding Research

In 1961 Wallis reported the findings from a series of air/water flooding experiments where he tries to find flooding velocities in a vertical tube with water falling down in annular flow [4]. Wallis gives a background of previous flooding work including the works of Lobo and Sherwood who studied flooding in chemical packing towers [4]. Through running flooding experiments with slightly different entrance and exit geometries Wallis was able to conclude that geometric specifics of a test section affect the overall flooding velocities [4]. Wallis was able to generate a correlation that matched well with his data along with previous data in the form of Equation (2.1) below.

$$j_g^{*\frac{1}{2}} + m j_f^{*\frac{1}{2}} = c \tag{2.1}$$

where

$$j_g^* = j_g \rho_g^{\frac{1}{2}} \left[gD\left(\rho_f - \rho_g\right)\right]^{-\frac{1}{2}} \tag{2.2}$$

$$j_f^* = j_f \rho_f^{\frac{1}{2}} \left[gD\left(\rho_f - \rho_g\right)\right]^{-\frac{1}{2}} \tag{2.3}$$

In Equation 2.1 *m* and *c* are constants that are dependent on the specific geometries of the test section j_i^* are the “Wallis” parameters for the dimensionless superficial velocity of phase i. Where in Equation 2.2 and 2.3 j_i is the superficial velocity of phase i, ρ_i represents the density of phase i, g represents the acceleration due to gravity and *D* represents the diameter of the test section. Wallis concluded that by setting the value for the superficial liquid velocity to zero it would be possible to find the velocity of gas required to stop water from falling down the test section or the full flow reversal gas velocity [4]. Figure 2.1 gives the results of Wallis plotting Equation 2.1 versus experimental data obtained in the past by Lobo and Sherwood [4]. The constants used to create the plot in Figure 2.1 were 1 and 0.775 for m and c respectively [4]. Figure 2.1 shows a trend that as the superficial gas velocity increases the superficial velocity of water falling down the test section decreases and vice versa. This trend is fundamental to flooding and will be expected in the results from the current research.

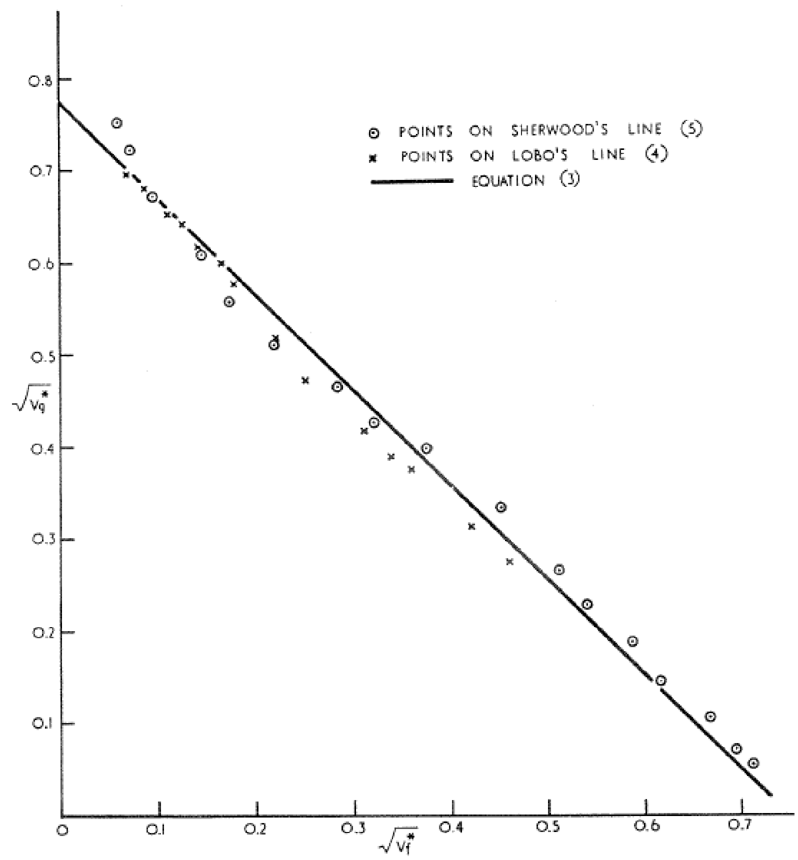


Figure 2.1: Comparison of Wallis correlation (Equation 2.1) to experimental data **[4]**.

Pushkina and Sorokin studied the Wallis correlation, Equation 2.1, against large amounts of collected flooding data with test section diameters ranging from 6 to 309 mm

[5]. The findings were that the test section diameter played very little effect on the overall data in the larger diameter tubes. This resulted in Equation 2.1 not being able to accurately predict flooding results at larger diameters. Pushkina and Sorokin found that using Kutateladze parameters in place of the superficial velocities, Equations 2.2 and 2.3, were better able to predict flooding velocities. The Kutateladze parameters for both gas and liquid flow are given in Equations 2.4 and 2.5 below.

$$K_g = j_g \rho_g^{\frac{1}{2}} \left[g\sigma\left(\rho_f - \rho_g\right) \right]^{-\frac{1}{4}} \tag{2.4}$$

$$K_f = j_f \rho_f^{\frac{1}{2}} \left[g\sigma\left(\rho_f - \rho_g\right) \right]^{-\frac{1}{4}} \tag{2.5}$$

where K_i is the Kutateladze parameter for phase i, and σ is the surface tension of the liquid in annular flow [6]. Wallis found that for tubes above a certain diameter using Kutateladze parameters was better at predicting flooding velocities then using his previous correlation [6]. Wallis states that similar to his parameters for superficial velocities the Kutateladze parameters are able to balance inertial, buoyancy and surface tension forces in the fluid/gas interaction [6]. Wallis recognized the need for a parameter to determine whether a tube is of a large diameter or a small diameter and finds that the bond number, Equation 2.6, above a certain value can result in a test section being deemed large [6].

$$D^* = D \left[\frac{g\left(\rho_f - \rho_g\right)}{\sigma} \right]^{\frac{1}{2}} \tag{2.6}$$

where D^* is the bond number. Much of the literature is in agreement that for $D^* > 30$ the tube can be considered to be a large diameter tube and the Wallis correlation, Equation 2.1, is not applicable [6]. As can be seen by analyzing Equation 2.6 the bond number is not just reliant on tube diameter but on fluid and gas parameters that would be specific to the test section. Vijayan conducted more experiments on the effects of tube diameter on flooding and concluded that two causes of flooding were observed and that they are dependent on the size of the test section diameter [7]. Vijayan found that in large diameter tubes flooding could be caused by the carryover of liquid [7]. However, in small diameter tubes flooding was found to be caused by the upward transport of waves [7]. These findings by Vijayan and previously mentioned literature all support that for large diameter tubes the Kutateladze is better at predicting flooding velocities. The knowledge gained from the preliminary flooding research with relation to tube diameter was used to determine for the current research, which uses a large diameter tube, Kutateladze parameters will be used to generate flooding curves rather than Wallis parameters.

2.2 Flooding Research at the NHTS Laboratory

The first installment of flooding research in the NHTS laboratory was conducted by running air/water tests in an acrylic test section [8]. In this work Solmos covers the work involved to be able to properly scale a 10-inch diameter pipe in the pressurizer surge line into a 3-inch diameter acrylic test section [8]. The work performed by Solmos with the scaling analysis was pivotal for Ritchey to design and build the stainless steel test section that is used in the current research [9].

Ritchey performed a scaling analysis similar to Solmos and determined based on literature similar to those presented above that a test section of 3 inches with the expected flow rates would classify as a large diameter test section [9]. The minimum water inlet flow rate for the test section to allow for continuous film of annular flow was found to be

3.5 GPM [9]. To match the flow conditions in the pressurizer surge line Reynolds numbers were calculated for both liquid and gas flow and both were found to be turbulent.

The test section Ritchey constructed is the same used in the current research with minor modifications made by Cullum and Wynne. The test section consists of a 3 inch (76.2 mm) diameter tube that is 72 inches in length [9]. The decision for test section length was made based on experiments conducted by Solmos with the conclusion that 72 inches is a large enough length for flooding to occur. Further information specific to the test section used for this research will be included in Section 3 for specific information on the design of the test section when used by Ritchey see [9].

Ritchey collected onset of flooding data for steam/water tests at atmospheric pressure and various inlet water flow rates [10]. This data was compared to data recorded by Solmos in an attempt to understand the effects of condensation on flooding data. When comparisons of the data were made it was found that trends in the steam/water data diverged from the air/water data when the water inlet flow rate was increased past 6 GPM. This was determined to be caused by sub cooling occurring in the test facility [9]. The data was transformed into both Wallis and Kutateladze type parameters and was found that the correlations were not able to predict the onset of flooding when comparing to Ritchey's data.

Although Ritchey was unable to match the recorded data with existing correlations a new correlation was developed to accurately predict the onset of flooding that uses an energy balance between the superheated steam and the subcooled water [10]. This is seen through an effective vapor Kutateladze parameter given in Equation 2.7 [10].

$$Ku_{ge} = K_g(1 - f) \tag{2.7}$$

where

$$f = \frac{\dot{m}_f c_p (T_s - T_{wall})}{\dot{m}_{st}(h_{st} - h_f)} \tag{2.8}$$

where f is the fraction of the steam that is condensed on the inner wall of the test section, T_s is the saturation temperature of the working fluid, T_{wall} is the temperature of the test section wall, $\dot{m}_{st}$ is the mass flow rate of steam going through the test section, $h_{st}$is the enthalpy of the steam and h_f is the enthalpy of the water [9]. These values were utilized to form a correlation similar to Equation 2.1 with Kutateladze parameters however in Equation 2.9 the Ku_f represents the water entering the test section where as the term in Equation 2.1 represents the water leaving the bottom of the test section.

$$K_{ge}^{\frac{1}{2}} + 0.56\, K_{f,in}^{\frac{1}{2}} = 1.6 \tag{2.9}$$

Cullum was responsible for the third installation of flooding research in the NHTS laboratory with a study of the effects of subcooling on the onset of flooding velocities in a large diameter tube [11]. This research was conducted by modifying the existing facility to allow for variable degrees of subcooling. Additional thermocouples were also attached onto the test section to allow for a better measurement of the change in test section wall temperature during a flooding test [11]. The flooding tests were performed from 65 °C subcooling to 3 °C subcooling. The results from the research were that when the water subcooling was kept small the results were able to follow closely with Wallis type correlation using Kutateladze parameters [11]. It was also noted that the onset of flooding velocity was higher when a large amount of subcooling was present. This was determined to be caused by the large fraction of steam that would condense on the annular water film [11]. It was also found across the various levels of subcooling that Equation 2.9 was accurately able to predict the onset of flooding across the range of subcooling [11]. From the knowledge gained on the effects of subcooling the current research aimed to keep subcooling to a maximum of 3 °C to allow for minimal amounts of phase change in the test section. This allowed for a better comparison of the air/water and steam/water data.

Wynne heavily modified the test facility to allow for flooding tests to be performed at elevated pressures [3]. The facility as produced by Wynne is the same facility used for this research with exception to the addition of the inlet water heater. The major modifications made by Wynne included hard piping stainless steel throughout the facility to allow for the test section to be pressurized up to 60 psia [3]. This included procuring new high temperature/pressure pumps to allow for the circulation of low subcooled water throughout the test facility [3]. A new air compressor was also procured for the facility to allow for air/water tests to be performed at elevated pressures in the same test section as the steam/water tests [3].

Wynne performed onset of flooding tests with steam/water up to 30 psia and air/water up to 60 psia [3]. It was concluded that when tests were performed at higher pressures flooding was achieved at a lower superficial gas velocity due to the increase in gas density [3]. Flooding curves that described the onset of flooding velocity were generated using Kutateladze parameters. When these values were adjusted to account for condensation using Equation 2.7 the steam/water and air/water data was found to closely agree.

2.3 Other Steam/Water Flooding Literature

Ritchey, Cullum and Wynne all performed Steam/Water flooding tests in the past. However, for the ability to describe the process of the facility changing over the years it was decided to include the Steam/Water research of the aforementioned in Section 2.2. A survey of the remainder of Steam/Water flooding research of interest will be given in the current section, Section 2.3.

Tien was one of the first researchers to study the effects of vapor condensation on flooding [12]. Tien also covers that when the bond number, Equation 2.6, is greater than 30 that a correlation using Kutateladze parameters that is analogous to the Wallis correlation is more applicable [12]. This correlation using Kutateladze parameters is given in Equation 2.10.

$$(K_g)^{\frac{1}{2}} + m(K_f)^{\frac{1}{2}} = c_k \tag{2.10}$$

where K_g is from Equation 2.4, K_f is from Equation 2.5, and m and c_k are empirically found constants. Tien continues to describe the gas effective Kutateladze parameter, K_{ge}, which can be used to substitute in for K_g in Equation 2.10 that can be used to account for the amount of vapor condensation taking place in the test section. Tien's definition for K_{ge} is given in Equation 2.11 [12].

$$K_{ge} = K_g - fK_f\left(\frac{c_p \Delta T_{sub}}{h_{fg}}\right)\left(\frac{\rho_f}{\rho_g}\right)^{\frac{1}{2}} \tag{2.11}$$

where h_{fg} is the latent heat of vaporization and ΔT_{sub} is the difference between the liquid temperature and the saturation temperature or the amount of subcooling present. As mentioned in Section 2.2, Ritchey attempted using Tien's definition for effective gas but was unable to properly characterize the steam Kutateladze data using Equation 2.11. The only conclusion that can be made is that geometrical concerns must be accounted for when attempting to characterize steam Kutateladze data using an effective gas parameter. Tien mentions this by discussing that the constants associated with Equation 2.10 are heavily dependent on the test section geometry and sizes [12].

Rothe and Crowley studied the effects of flooding in a scaled downcomer of a PWR across a pressure range of 15 to 65 psia [13]. Although the test section for the current work is largely different then that used by Rothe and Crowley it is hoped that the general trends observed when changing pressure and flowrates would be seen in the current work. Rothe and Crowley were able to show that the volumetric flow rate of water being sent to the test section had very little effect on flooding as seen in Figure 2.2. For Figure 2.2 the

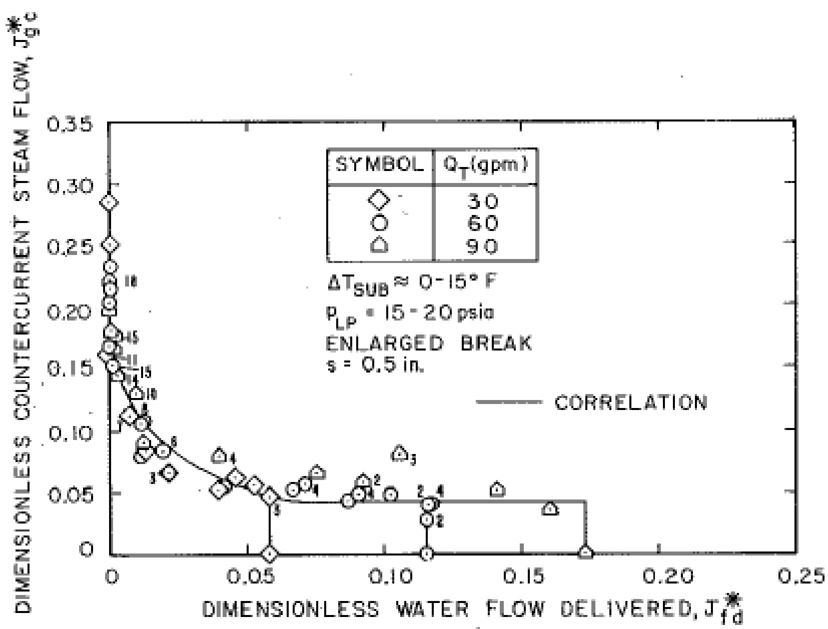


Figure 2.2: Rothe and Crowley showing the lack of a dependence on flow rate entering the test section with regards to flooding.

test section pressure was kept relatively constant at 15-20 psia and the inlet water flow rate was changed as flooding was studied from onset to full flow reversal [13]. What was observed is that the inlet water flow rate had relatively no effect on the flooding. Rothe and Crowley also show how flooding is affected by keeping the inlet water flow rate constant and changing the pressure. The results of these test are shown in Figure 2.3. It is seen that similar to the variable water inlet tests that there is little to no dependency on test section pressure. The reasoning behind this is that the Wallis parameters given in Equations 2.2 and 2.3 intrinsically account for pressure when the liquid is near saturation temperatures. Although the test section for the current work and the test section for the Roth and Crowley are vastly different it was hypothesized that the general trends and dependency relations would be similar. This paper leads the author to believe that the current work will produce data that has little to no dependency on inlet water flow rate and test section pressure when plotted as flooding curves.

3. FACILITY DESCRIPTION

As previously mentioned the test section was first designed by Ritchey, followed by slight modifications by Cullum and a large amount of facility modifications by Wynne [9] [11] [3]. The facility modifications performed by Wynne produced the facility used for the current research minus the addition of an inlet water heater. For this reasoning, only the portions of the facility necessary to recreate the data and the new inlet water heater will be covered in large detail. Supporting facility components will be slightly touched on but this work will not go over the details extensively as they are already presented in the Wynne thesis [3].Wynne has given an extensive description of all facility components and one should refer to the Wynne thesis if more information is desired [3].

The facility description is broken up based on the test section design specifics, gas flow path, water flow path and instrumentation. A facility piping and instrumentation diagram is given in Figure 3.1 to allow for graphical visualization of the flow paths and instrumentation locations.

3.1 Test Section

The test section is a 3-inch inner diameter tube, wall thickness of 0.25 inches, that is 72 inches in length made out of austenitic Type 304 stainless steel [9]. A rendering of the test section as given in Ritchey's thesis is provided in Figure 3.2 [9]. It should be noted that reason the legend of Figure 3.2 only mentions steam inlet or steam outlet is due to Ritchey originally designing this test section with only steam/water tests in mind [9]. For the current work items numbered 1 and 6, in Figure 3.2, can be considered the gas outlet and gas inlet respectively. The test section is designed for gas the be able to flow into

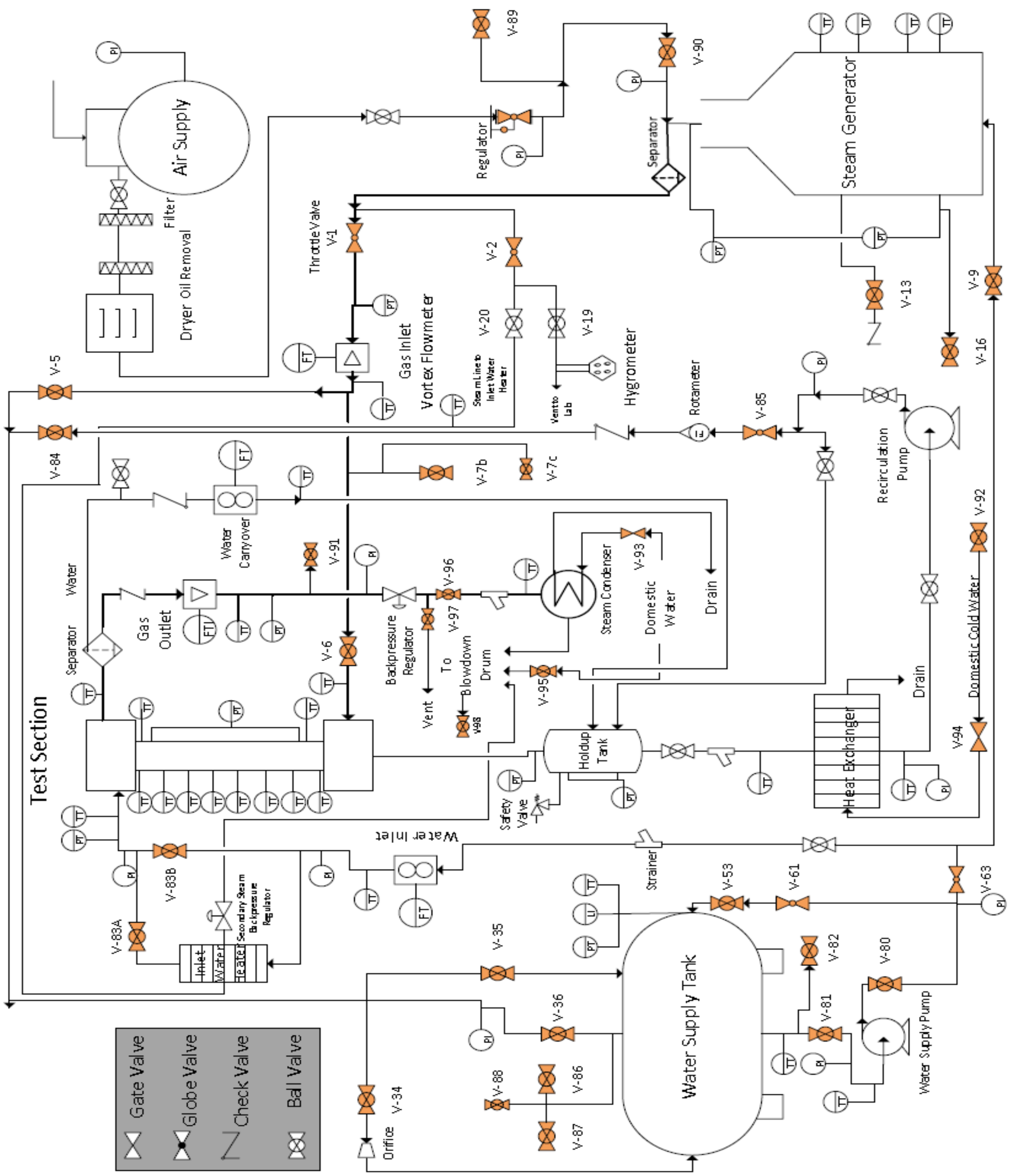
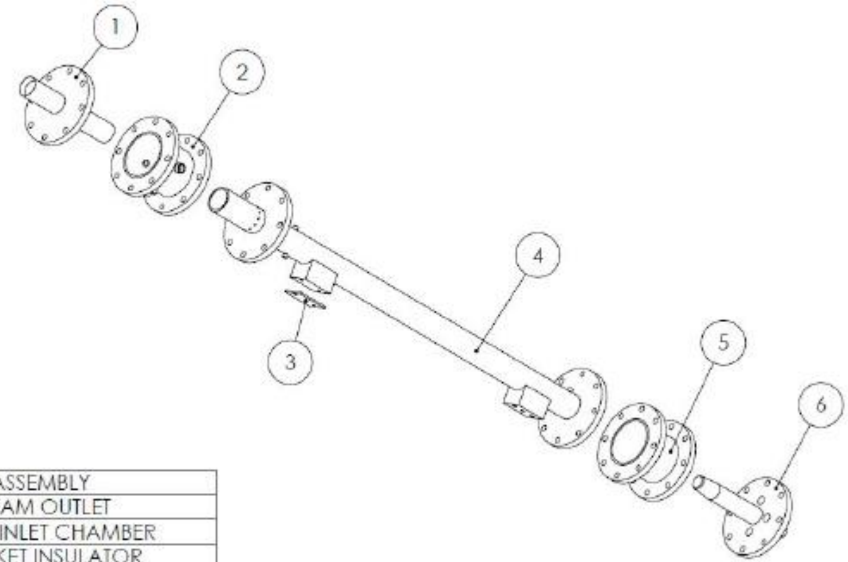


Figure 3.1: Facility piping and instrumentation diagram used for this work. Valves that are shaded in refer to high use valves.



ITEM NUMBER	ASSEMBLY
1	STEAM OUTLET
2	WATER INLET CHAMBER
3	BRACKET INSULATOR
4	TEST SECTION ASSEMBLY
5	WATER COLLECTION CHAMBER
6	STEAM INLET

Figure 3.2: Rendering of the test section as originally designed by Ritchey **[9]**.

item number 6, in Figure 3.2, and a gas/water two phase mixture to be able to flow out the top of item number 1 [9]. Water is directed into the top of the test section through two opposing 0.75 inch ports [9].

The top of the test section tube, item number 2 in Figure 3.2, contains a plenum with twelve 0.25 inch holes drilled equally around to allow for the inlet flow of water to form a thin annular film [9]. Ritchey based the design on findings by Solmos on requirements to recreate a thin annular film in the test section at the desired flow ranges. Ritchey was able consistently produce annular flow using this design with an inlet water flow range of 4.5 GPM to 12 GPM [9]. After water flows through the 12 holes it travels down the test section as a 0.125-inch-thick annular film [11]. The lower portion of the test section, item number 5 in Figure 3.2, is where the water collects at the bottom of the test section and is similar to the water inlet chamber. The difference in the water collection chamber is it has four 1 inch holes drilled in the bottom to allow water to flow out of the test section [9]. Included on the test section are five 0.125-inch instrumentation ports.

Wynne modified the test section gas outlet to allow for operation at higher pressures [3]. The gas outlet was modified by welding a 2-inch-long radius elbow with a centerline curvature of 12 inches to allow for the smooth flow of the entrained liquid and gas mixture out of the test section [3]. Other modifications to the test section by Wynne were made in order to ensure that the test section could be safely pressurized to twice the working pressure of the current research. This included replacing un-galvanized nuts with stainless steel hex head bolts and hex head nuts [3]. For the. current work no modifications have taken place and the test section is exactly as described in the Wynne thesis [3].

3.2 Gas Flow Path

For both steam/water and air/water tests the gas flow rate is controlled by a 1.5-inch stainless steel globe vale, referred to as the throttle valve or V-1 in Figure 3.1. The gas then flows to the test section where it is injected vertically upward to start the onset of flooding. Prior to entering the test section, the flow rate of the steam is recorded. After flooding has been established the gas is a two phase gas/water mixture that must be separated. A high efficiency multiple stage separator is used to remove the liquid from the gas/water mixture and allow the gas to continue moving to the backpressure regulator. The separator is an Anderson LCCR-200-RL-SC and is capable of separating the liquid droplets down to 1 micron in size. After the separator but before the gas flows through the backpressure regulator the flowrate is measured and recorded. The backpressure regulator is a Jordan Mark 50 valve that is controlled by the operator to regulate the amount of flow allowed through the valve and consequently the pressure level of the system. The only difference between steam flow and air flow for the facility is prior to the throttle valve and after the backpressure regulator. Those specific differences will be described below.

3.2.1 Steam Flow Specifics

Steam is generated inside the steam generator by boiling deionized water. The steam generator is a Schedule 10 Type 304 stainless steel pressure vessel with a maximum allowable pressure of 135 psig at 350 °F. The steam generator is equipped with six electric immersion heaters produced by Watlow Process Systems. The maximum power of all of the heaters is 157 kW and the heaters are wired such to allow for fine increment control of the specific power level. This is important as it aids the operator in controlling the level of superheated steam entering the test section. After the steam is generated it passes through a separator to remove entrained water droplets. This ensures that the steam entering the test section is dry and the measured steam flow rate is accurate. The separator is an Anderson Type TL high efficiency centrifugal type separator. After the steam passes through the separator it passes through a tee valve and then the throttle valve and completes the gas flow path as described above.

Once the steam passes through the back pressure regulator it is sent through a plate type heat exchanger, referred to as the steam condenser. The steam is condensed in the steam condenser by running domestic water through the cold side. The condensed water then gravity drains into a blowdown drum before being drained to the city sewage drain. The steam condenser is an AlfaNova 27-34H heat exchanger [3].

New to the facility from the research performed by Wynne was the addition of an inlet water heater. Wynne used a AlfaNova 27-30H heat exchanger to cool water prior to it entering the recirculation pump [3]. For the current work this heat exchanger was moved to a position just prior to the test section. Another plate type heat exchanger was purchased and installed to prior to the recirculation water pump to be able to still prevent cavitation. As mentioned above after the steam is generated in the steam generator and passes through a separator it flows through a tee to either flow through the throttle valve or the secondary throttle valve. This secondary throttle valve is referred to as V-2 in Figure 3.1 and is used to control the flow of steam that enters the inlet water heater. The purpose of the inlet water heater is to be able to precisely set the inlet water temperature right before the water enters the test section. This allows for the operator to keep the amounts of subcooling in tests to a minimum of less than 3 °C. After the steam passes through the inlet water heater it may either still be in the gas phase or have condensed into liquid water. The steam or condensed water flows through the secondary side backpressure regulator. The secondary side backpressure regulator is a Jordon Mark 60 regulating valve and is used to regulate the pressure of the steam line all the way back to the secondary throttle valve. This was necessary to be allow for temperature control in the inlet water heater. After passing through the secondary side backpressure regulator the gas or liquid drains to the blowdown drum before being sent to the city drain.

3.2.2 Air Flow Specifics

Air is supplied via a 15HP reciprocating Quincy air compressor that was installed by Wynne [3]. The compressor tank has a volume of 120 gallons and is capable of outputting 51 ACFM at 175 psig. Leaving the air compressor tank the air is filtered through a particulate and oil filter before passing through a refrigerated drier to partially remove any moister in the air. The pressure of the air leaving the drier can be regulated and then the air flows to the steam generator vessel. The steam generator is almost completely emptied for air tests to allow for a larger amount of pressurized air for the flooding tests. After air goes through the backpressure regulator the air is vented to the outside via a nylon braided hose.

A small amount of air is also passed through the secondary side throttle valve and diverted off before going into the inlet water heater. The relative humidity of the air is then measured using a hygrometer. The hygrometer is a Dwyer HHT humidity/temperature transmitter with an accuracy of ±2%.

3.3 Water Flow Path

Water is stored in a 1400-gallon pressure vessel made of Type 304 stainless steel referred to as the water supply tank. The water supply tank is capable of being pressurized to 88 psi at 400 °F. Below the water supply tank lies two pumps. The pump that will mainly be used for this work is referred to as the water supply pump. The water supply pump is a 1.5HP Liquidflo centrifugal pump that can operate at 500 °F at 300 psig. Upon leaving the pump the water passes through a 1-inch stainless steel globe valve that is used to regulate the water flow rate. For steam/water tests the water travels through the inlet water heater where the inlet water temperature is adjusted. For air/water tests the water flow bypasses the inlet water heater and is injected directly into the top of the test section.

After the leaves the test section it drains into a pressure vessel referred to as the holdup tank. If flooding is occurring some of the water will be sent through the top of the test section and form a gas/liquid mixture that goes through the separator. After being separated the liquid flow rate is measured and recorded, referred to as the carryover flowrate, and the liquid flows to the holdup tank.

The holdup tank is an 80-gallon stainless steel Type 316L vessel with a maximum pressurization of 150 psig at 400 °F. The holdup tank stores the water that drains from the test section or the liquid carryover as result of flooding. From the holdup tank water is passed through a plate type heat exchanger and pumped back to the water supply tank via the recirculation pump. The flowrate of the water being sent back to the water supply tank is controlled by a 0.75-inch globe valve. The purpose of the heat exchanger is to be able to cool the water enough to not allow for cavitation to occur in the recirculation pump. The recirculation pump is a 1 HP Liquidflo centrifugal pump that can operate at 500 °F at 300 psig.

3.4 Instrumentation

Type T copper-constantan thermocouples by Omega Engineering are used throughout the facility to measure and record temperatures. Eight thermocouples are cemented to the outside of the test section to allow for an axial temperature measurement during flooding tests. This was performed by Cullum as a part of his facility modifications [11]. Other pertinent temperature measurement locations include liquid inlet water just prior to water entering the test section but after passing through the inlet water heater, the temperature of the gas entering and leaving the test section. The remainder of the thermocouple locations are noted in Figure 3.1 “TT”.

Pressure measurements are taken throughout the lab to determine fluid parameters in post processing and to safely operate the facility. A Honeywell ST3000 STA940 pressure transmitter is used to measure the absolute pressure at the gas inlet flow meter, the gas outlet flow meter, and inside the steam generator. The absolute pressure of the test section is measured using a Keller Valueline High Accuracy pressure transmitter. This transmitter has a range of up to 150 psia with an accuracy of ±0.1 % [3]. Three Honeywell ST3000STD924 differential pressure transmitters are used in the facility. One is located in the test section to determine when the onset of flooding has occurred [3]. The other two are used to measure the water holdup tank level and the steam generator water level [3].

Flow meters are used throughout the facility to measure the flow rate of both gas and liquid fluids. The inlet gas flow rate is measured with an analog Foxboro Model 83W flowmeter. A Foxboro Model 84F flowmeter is installed prior to the backpressure regulator and is used to measure the outlet gas flow rate [3]. The gas flow meters have bore sizes of 1.5 inches [3]. The water flow rate entering the test section and the flow rate of the water carried over by flooding are both measured by two identical Azbil MagneW 3000 magnetic flowmeters with a 0.5 inch bore size [3].

All of the data recorded is output to a National Instruments SCXI 1000 Chassis to be displayed and recorded via LabView. LabView records 20 samples at a rate of 200 Hz which results in data being recorded to file at a rate of 10 Hz. The displayed LabView program is used during flooding tests to help the operator monitor the experiment and keep test parameters within the desired ranges. Recorded data was saved to ".dat" file types and used with MatLab scripts for post processing. Appendix F contains a copy of a table of the instrumentation used for this facility with operating ranges and levels of accuracy, as provided by Wynne [3].

4. OPERATIONAL PROCEDURES

Wynne developed operational procedures that cover the necessary steps to safely operate the facility [3]. Much of the procedures that were followed for this work were taken directly from the Wynne thesis with slight modification aspects involving the different stages of flooding or the use of the inlet water heater. Valve numbers given in this section refer to the valve tags in the facility along with the valve labels in the Facility P&ID given in Figure 3.1. For a more detailed description of the location of the valves and facility components referenced in the following section refer to Appendix G.

4.1 Data Acquisition System

The data acquisition system is used to safely monitor facility conditions from startup to cooldown. The data acquisition system is also the means to record the data during a test. To safely operate the facility, the data acquisition system should be the first piece of equipment started at the beginning of operation.

1. Startup and/or login to data acquisition computer.*
2. Power ON the remote computer monitor near the throttle valve.*
3. Open *D:\M_Garza\SteamFlooding_Version5.vi* for steam/water tests.*

   Open *D:\M_Garza\AirFlooding_Version3.vi* for air/water tests.*
4. Turn ON the DC power supply. The output should be set to 24.0 V.*

* Taken directly from Wynne Thesis [3].

5. Turn ON the National Instruments SCXI chassis.* Acquire data by selecting the “Run” button in LabVIEW.*
6. Verify that the instruments are reporting expected values. If irregular values are being reported the instruments should be corrected.*
    a. The test section differential pressure transmitter should output 55.75 inH2O ±5% during no flow of gas or water. If the output is beyond this range refer to Section 4.2 to obtain correct output values.*
    b. The outlet gas vortex flow meter needs to be set for the appropriate gas, steam or air. If the meter is not set for the appropriate gas the gas density, temperature, and viscosity must be changed directly on the flow meter panel. The appropriate fluid parameters should be input and the user manual should be referred to for details in how to set the fluid parameters.*
7. Fill in the filename for the appropriate date and test number for the data to be recorded. *
    a. The naming scheme for this work is “*YYYY_MM_DD_TestXX.dat*”. *
8. Turn the Write Data toggle switch on the LabVIEW front panel to “YES”.*
9. Select the “START” button on the LabVIEW front panel to begin writing data to file.*
10. Select the “End Execution” button on the front panel to end data recording.*
11. Repeat steps 4-22 for each individual test.*
12. Power OFF the remote computer monitor near the throttle valve after facility shutdown.*

13. Depending on time till next testing day consider turning off data acquisition computer. *

4.2 Purging Differential Pressure Transmitters

The following procedures are used to purge the tubing of the differential pressure transmitters. The tubing must constantly be filled with water to allow for accurate readings. The day after steam/water testing is when it is most likely necessary to purge the tubing. This is due to the water in the tubes evaporating from high temperature steam tests. Figure 4.1 should be referred to for a visualization of the valve names and alignment.

1. Fill the "pump-up" sprayer with deionized water.*
    a. The fill valve show in Figure 4.1 is connected to the sprayer hose. Close the fill valve. Detach the want at the compression fitting after the fill valve.*
    b. Attach the compression fitting to the impulse tubing near the isolation valve.*
2. Close the high side valve.*
3. Verify the equalization valve is closed.*
4. Verify the low side valve is open.*
5. Open the isolation valve. *
6. Open the fill valve. This will allow water to purge any air out of the low side tubing. Water flowing through the low side measuring port should be audible.*
7. Open the low side drain. Take caution to avoid the transmitter electronics getting wet. *
8. Close the low side drain when all the air bubbles have evacuated the drain. *

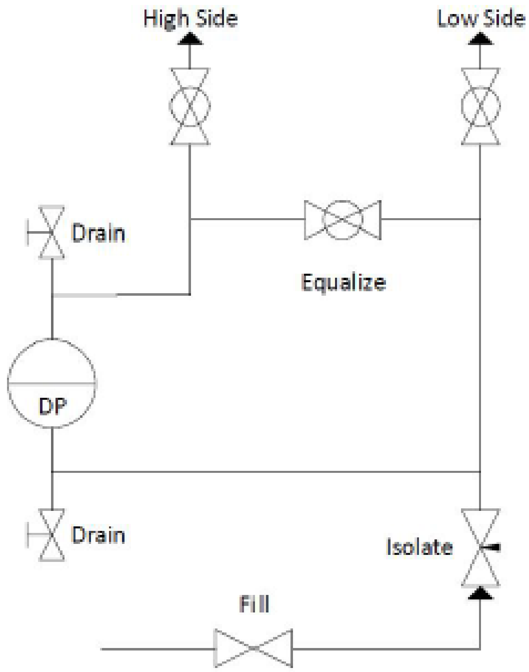


Figure 4.1: General impulse tubing and valve alignment for the differential pressure transmitters **[3]**.

9. Close the fill valve.*
10. Close the low side valve. *
11. Open the high side valve. *
12. Open the equalizing valve. *
13. Open the fill valve. This will allow water to purge any air out of the high side tubing. Water traveling through the high side port should be audible. *
14. Open the high side drain. *
15. Once a continuous stream of water exits the drain close the high side drain. *
16. Close the fill valve. *
17. Close the equalizing valve. *

18. Open the low side valve. *

19. Close the isolation valve. *

20. Verify the transmitter output is reading correctly. If not, repeat steps 1-19. *

21. Disconnect the compression fitting from the transmitter impulse tubing. *

4.3 Operating the Air Supply for Air/Water Flooding Tests

The air compressor is used as the air supply for air/water flooding tests. As large as possible volume of air is required to run air/water flooding tests. This means that it is necessary to drain the steam generator of as much water as possible to fill the steam generator volume with compressed air. Section 4.4.2 covers the instructions to properly drain the steam generator of water. For the safety of the steam generator instrumentation the steam generator and air compressor tank should be allowed to pressurize together. Double all maintenance frequency for periods of heavy use. The air compressor is loud and ear protection should be worn during extended operation. *

1. Turn on the refrigerated power dryer switch 5 minutes before air compressor startup. *
    a. Inspect and/or clean the condensate filter once a month. *
    b. Inspect and/or clean the condenser fins once every two months. *
    c. For other maintenance procedures refer to dryer user manual.
2. Inspect the air compressor to verify it is in good working order and all rotating components are free from obstructions. Complete regular scheduled maintenance, as given in the user manual [14]. *
3. Check the lubricant level in the crankcase.

a. If lubricant is low or contaminated, drain and replace. Refer to user manual for lubricant replacement procedures [14].
b. Replace lubricant after first 100 hours of operation and every 500 subsequent hours of operation [14]. *

4. Inspect the drive belt. Confirm no cracks, frays, or tears are present on the belt. *
    a. Check the belt tension every 160 hours of operation using the belt tension gauge. *
5. Plug in the electronic drain valve to allow for the condensate to drain from the air compressor tank. *
6. Align valves to pressurize only the steam generator. *
    a. Close air hose valve (V-89). *
    b. Close throttle valve (V-1). *
    c. Close steam generator vent valve (V-16). *
    d. Open the steam generator air isolation valve (V-90). *
    e. Close the steam generator vacuum breaker (V-13). *
7. Power on air compressor by flipping the 30A breaker in the 480 VAC electrical panel to "ON". *
8. Set the air supply regulator to the desired steam generator pressure level. For most air/water tests this level is 100 psig. The max allowable pressure for the steam generator is 135 psig. *
9. **Common** occurrences when operating the air compressor. *

a. The air compressor turns off when the air compressor pressure reaches 175 psig and turns back on when the pressure falls below this value. *

b. The electronic drain valve vent condensate to outside the lab every 45 minutes. *

4.4 Steam Generator Procedures

The steam generator is used to provide steam flow to the test section during tests, provide steam flow to the inlet water heater during tests, and provide steam flow to the water supply tank during heat up. Due to the multiple uses of the steam generator the steam generator procedures section is broken up into filling the steam generator, Section 4.4.1, draining the steam generator, Section 4.4.2, and operating the steam generator, Section 4.4.3.

4.4.1 Filling the Steam Generator

The steam generator must be filled with enough deionized water to allow for all of the steam generator heaters to be completely covered with water. This section covers the instructions to fill the steam generator. These instructions are followed for when the steam generator is below 40 cm on the visual level indicator. Tests should not be performed if the steam generator level is below 44 cm on the indicator. If the water level decreases below 35 cm the heaters will automatically shut off. *

1. The max pressure that the steam generator can be filled at is 90 psia. If the pressure is larger than this value, the steam generator pressure must be

depressurized using the steam generator vent (V-16). For the safety of lab personnel ensure that no one is near the vent when the steam generator is vented.*

2. Ensure the supply pump discharge valve (V-80) is closed. *
3. Open the RCIC pump suction valve (V-82). *
4. Confirm V-53 on the side of the water supply tank is open. *
5. Open the bypass valve (V-61). *
6. Open the flow control valve (V-63). It is most desirable to have the valve barely open enough to have a positive flow of water into the steam generator. This varies based on the water supply tank pressure and the steam generator pressure. *
7. Turn on the RCIC pump. *
    a. Ensure the RCIC pump fan is on the highest setting and pointing towards the pump. *
8. Open the steam generator fill valve (V-9) to allow for water to flow into the steam generator. *
    a. Quickly after opening V-9 walk to the water injection monitor and ensure that the water is flowing into the steam generator. Adjust V-61 and V-63 to control the water velocity entering the steam generator. *
9. Fill the steam generator till approximately 63 cm on the liquid level indicator.*
10. Close the steam generator fill valve (V-9). *
11. Turn off the RCIC pump and RCIC pump fan. *

The following procedural steps are for a special case that the water entering the RCIC pump exceed the thermal limits of the pump. This occurs when excessive “whining” comes from the pump. When filling the steam generator with the water supply pump the steam generator cannot be powered on or allowed to pressure up by a large amount.

12. When the pump begins to “whine” close valve V-9 and shutoff the RCIC pump.
13. If the steam generator needs to be filled more it must be filled using the water supply pump.
    a. Depressurize the steam generator, using V-16, to a point where the water supply tank pressure and the steam generator pressure are approximately equal.
14. Switch the pump alignment opening the supply pump discharge valve (V-80) and close the RCIC pump suction valve (V-82).
15. Turn on the water supply pump.
16. Open V-9 and make sure the water level is rising, if it is not the steam generator needs to be depressurized further.
17. Fill the steam generator to the desired level and close V-9.
18. Turn off the water supply pump.

4.4.2 Draining the Steam Generator

1. Ensure the pump supply and discharge valves are closed. *
    a. Close V-80 and V-82. *
2. Open V-63 completely. *
3. Open the bypass valve V-61 completely. *

4. Open V-51. *
5. Complete the air supply operating procedures in Section 4.3 and pressurize the steam generator to approximately 20 psig.
6. Slowly open V-9 to allow for water to reverse flow into the water supply tank.*
7. Observe the water flow on the LabVIEW VI and close V-9 when the water level is observed to fall below 24 inches.
8. Shutdown the air compressor and vent the steam generator to depressurize. *

4.4.3 Steam Generator Operations

1. Ensure at least one other person is present in the laboratory. At least two people must be present in the lab to operate the steam generator. *
2. Observe the steam generator water level and ensure it is above 44 cm. If less than this value, follow the "Filling the Steam Generator" instructions in Section 4.4.1. *
3. Isolate the steam generator. *
    a. Ensure V-1, V-2, V-9, V-13, V-16 and V-90 closed. *
4. Turn the steam generator breaker to on in the 480 VAC electrical panel. *
5. Unlock the steam generator control padlock and power the steam generator on by flipping the power control switch to on. *
6. Turn on the appropriate amount of heaters depending on the operation being performed. *
7. Monitor the steam generator temperatures in the LabVIEW VI. If a large temperature gradient is present and the steam generator is above 30 psia vent

the noncondensable gases from the steam generator using V-16 for approximately 30 seconds. *

a. This step will most likely need to be performed at the beginning of the operational day and occasionally will be necessary when refilling the steam generator with “cold” water. *
b. This step may need to be repeated multiple times until the temperature gradient is no longer present.

8. Monitor the steam generator heat up. *
    a. Shut off the steam generator when the desired pressure level is reached. *
    b. Do not let the steam generator pressurize above 130 psia. *

4.5 Water Supply Heatup

If performing air/water flooding tests skip to Section 4.6 for setting the system pressure. For saturation steam/water flooding tests to occur the water in the water supply tank needs to be heated using steam from the steam generator. These procedures cover the necessary steps to heat up the water supply to saturation temperatures.

4.5.1 Purging of Water from the Common Pipeline

1. Close the throttle valve (V-1). *
2. Ensure V-5 is closed. *
3. Close the RCIC sparger valve (V-34). *
4. Verify the SRV sparger valve (V-36) is closed. *
5. Open the air space sparger valve (V-35). *

6. Drain any condensate from steam trap #1. *
    a. Close the test section gas inlet valve (V-6). *
    b. Open V7b to drain condensate. *
    c. Close V7b when finished. *
7. Connect the 0.25-inch air hose from the quick connect air taps to the air purge coupling. *
8. Slowly open the air purge valve (V-7c) to 50 % at 50 psig of compressed air. *
9. Slowly open V-5 to purge water from the common pipeline. *
10. Close the air purge valve (V-7c) when the water supply tank pressure increases by 0.5 psi. *
11. Close the recirculation valve (V-84). *

4.5.2 Water Supply Heatup

1. Do not perform these steps unless the common pipeline has been purged and is free of water, Section 4.5.1. *
2. Follow Section 4.4.3 to startup the steam generator. *
3. Confirm that V-5 and V-6 are closed. *
4. Confirm the air space sparger valve (V-35) is open. *
5. Open the SRV sparger valve (V-36). *
6. If the water supply tank is in ambient conditions, such as being in the first cycle heatup of the day open the water supply tank vent (V-86). *
    a. If the heatup being performed is a reheat then do not open the vent.*

7. Open the throttle valve for steam to flow from the steam generator to the water supply tank. *
    a. For this portion limit the steam flow to 7-10 g/s. *
8. Check steam trap #1 for any condensate and drain if necessary by opening V-7b. *
9. Close the air space sparger valve (V-35) when:
    a. Water supply tank pressure increases. *
    b. Water supply tank air space temperatures increase. *
    c. Audible popping coming from the water supply tank blowdown drum.
10. Using the throttle valve (V-1) increase the steam flow being sent to the water supply tank to allow for a constant pressure in the steam generator and approximately 65 g/s of steam being sent to the water supply tank. Refill the steam generator using the steps from Section 4.4.1 when necessary. *
11. Close the suppression pool vent (V-86) when the average water supply temperature reaches 94 °C. This has been found to allow for the water supply tank to pressure up to approximately 5 psig above saturation pressures and allows for proper operation of the water supply pump. *
12. Heat the water to saturation temperatures then close the throttle valve (V-1). *
13. Shutoff the steam generator power. *

4.5.3 Purging of Steam from the Common Pipeline

1. Ensure the following valves are closed:
   a. V-1, V-5, V-34, V-36, V-6. *
2. Open the air space sparger valve (V-35). *
3. Open V-7b to drain any condensate. Once drained close V-7b. *
4. Open the air purge valve (V-7c) by cracking to 50% with 50 psig of compressed air. *
5. Slowly open V-5 to purge steam from the common pipeline to the water supply tank until the water supply tank pressure increases by 0.5 psi or more. Close V-5 after the pressure has increased. *
6. Close the air purge valve (V-7c). *
7. Open V-7b to vent the remaining air in the steam line. Take caution when venting as the air/steam mixture in the steam line is highly pressurized. Close V-7b when the venting is finished. *

4.6 Setting System Pressure

The back pressure regulator operates by setting a certain pressure for a certain gas flow rate. In order for the test section to be at the accurate pressure it needs to have the gas flow rate passing through it at approximately the same magnitude as during the tests. When no gas is flowing through the backpressure regulator the test section pressure falls below where the target pressure was at. This results in the water supply tank being largely over pressurized when compared to the test section. The following set of procedures cover the necessary steps to reach an approximate backpressure regulator setting for the expected gas flow. *

4.6.1 Setting the Test Section Pressure for Air/Water Flooding Tests

1. Set the air flow paths.
   a. Verify the following are closed:
      i. V-5, V-7b, V-7c, V-91, V-96. *
      ii. If the water supply tank is not pressurized isolate the water recirculation line to not allow the water holdup tank from emptying. This can be done by closing V-85.
   b. Open V-6 and V-97. *
   c. Point the air vent hose towards the outside. *
2. Inject air into the test section at a flow rate close to where flooding should occur using V-1 to increase or decrease the air flow rate. *
3. Adjust the back pressure regulator until the test section pressure is approximately at the desired pressure level. *
   a. If the desired pressure is atmospheric unscrew the backpressure regulator until completely removed. *
   b. Attach an addition vent hose to Steam Trap #2 and open V-91. *
4. Close the throttle valve (V-1). *

4.6.2 Setting the Test Section Pressure for Steam/Water Flooding Tests

1. Set the steam inlet and outlet flow paths
   a. Close V-5. *

    b. Open V-6. *
    c. Open Steam Trap #1 (V-7b). *
    d. Close the air purge valve (V-7c). *
    e. Open Steam Trap #2 (V-91). *
    f. Close the steam condenser isolation valve (V-96). *
    g. Close the air vent (V-97). *

2. Heatup the primary flow path piping.
    a. Open V-1 to allow for 10-15 g/s of steam flow to travel to the test section.*
    b. When steam exits Steam Trap #1 close V-7b. *
    c. When steam exits the Steam Trap #2 open V-96 and close V-91. *
3. Inject steam into the test section close to a steam flow rate at which flooding tests will be conducted using the throttle valve (V-1). *
4. Adjust the backpressure regulator until the pressure reaches the approximate desired test pressures. *
5. Close the throttle valve (V-1). *
6. Confirm that V-19 is closed and V-20 is open. *
7. Open V-2 to an appropriate level to send steam to the inlet water heater. *
8. Adjust the secondary side backpressure regulator until the pressure gauge reads approximately the correct value. *
    a. While adjusting the secondary side pressure it is normal for a large audible noise to be generated from the secondary side backpressure regulator. This is condensate traveling through the valve. *

4.6.3 Setting the Water Supply Tank Pressure

The steps in this section cover how to set the water supply tank pressure. This is important due to the water supply tank needing to be pressurized at least 5 psi above the test section pressure to prevent the water supply pump from cavitation. The other reason this is important is due to the operational procedures of setting a precise water flow rate. The water supply pressure is constantly changing in between tests and it is required to reset the pressure to be able to recreate water flow rates with a certain level of precision. These steps should be omitted for atmospheric air/water tests.

1. Ensure both water inlet valves are closed (V-83A and V-83B). *
2. Connect the 0.75-inch red air hose from the quick connect air tap to the water supply tank quick connect. *
3. Ensure the air hose vent valve (V-88) is closed. *
4. If the water supply tank vent (V-86) is open, then close it. *
5. Crack the air hose fill valve (V-89) and ensure the pressure of the compressor regulator is greater than the pressure in the water supply tank. *
6. Crack the water supply tank air space fill valve (V-87). *
7. Close water supply tank air space fill valve (V-87) once the water supply tank reaches the desired pressure. Usually 5 psi above the test section pressure. *
8. Close the air hose fill valve (V-89) and vent the air hose by slowly opening V-88.*

4.7 Water Supply Pump Operation

The water supply pump is used to send water from the water supply tank to the test section. The water supply flow rate is controlled via the water flow control valve (V-63), the bypass valve (V-61) and the water supply tank pressure level. It is recommended when performing tests that will be recorded to set the water supply tank to the same pressure and only adjust the control valves (V-63 & V-61) when slight adjustments are needed. This allows for a consistency when setting the water supply flow rate. To set the water supply tank pressure refer to Section 4.6.3.

1. Open the water supply pump suction valve (V-81). *
2. Close the RCIC pump suction valve (V-82). *
3. Open the water supply pump discharge valve (V-80). *
4. Ensure that V-53 is open. *
5. Turn on the water supply pump. *
6. Slowly open the water inlet valve:
   a. For Steam/Water tests open V-83A.
   b. For Air/Water tests open V-83B.
7. If the desire water flow rate is present skip to next section otherwise:
   a. Follow Section 4.6.3 to ensure the test section is at an appropriate pressure. *
   b. Follow Section 4.6.1 or 4.6.2 to set the appropriate test pressure. This requires sending gas flow through the test section. *
   c. Adjust the inlet water control valves (V-63 & V-61) until the inlet water flow rate is at the correct value. *

4.8 Recirculation Pump Operation

The recirculation pump sends water from the test section back to the water supply tank. While operating the recirculation pump during steam/water tests it is often necessary to have a second operator help to ensure the water level in the holdup tank stays at an appropriate level and to ensure that the pump does not cavitate by cooling the water being passed through the pump via the heat exchanger. The following section covers the operation of the recirculation pump.

1. If steam has been recently sent through the common piping, verify that Section 4.5.3 has been followed and the common piping is purged of steam.*
2. Open the recirculation valve (V-84). *
3. Align the necessary valves:
   a. Close: V-5, V-35, V-36. *
   b. Open V-34. *
4. Turn on the recirculation pump. *
5. Monitor the recirculation water flow rate using the rotameter. If adjustments need to be made the recirculation throttle valve (V-85) can be used to regulate flow. *
   a. If no flow is visible through the rotameter the pressure difference between the holdup tank and the water supply tank is too great and the test section should be pressurized to the testing pressure levels to adjust the flow rate. Refer to Section 4.6.1 or 4.6.2.
6. For steam/water tests if cavitation is present begin the heat exchanger operation. *
7. To operate the heat exchanger:
   a. During flooding tests send the secondary side water evacuation hose to outside the lab. Otherwise if in the cooldown phase send the water evacuation hose to the domestic drain.

b. Ensure that domestic water is able to flow into the blowdown drum. *

   i. Connect the domestic water fill line to the blowdown drum. *

   ii. Open the auxiliary domestic water valve (V-95). *

   iii. Open the domestic water supply valve (V-92). *

   iv. Close the auxiliary domestic water valve (V-95) when water is observed to enter the blowdown drum. *

   v. Open the heat exchanger domestic water supply valve (V-94) to send water to the heat exchanger. Adjust V-94 to cool the water entering the recirculation pump to an appropriate level. *

8. Monitor the recirculation of water back to the water supply tank. Keep the water level between 20% and 80% for standard operations. *

4.9 Flooding Procedures for Data Collection

1. Follow Section 4.1 on proper operating instructions of the data acquisition system.*
2. Determine the desired level of flooding for data to be acquired at. *
   a. It is common for the first test to be an onset of flooding test and subsequent tests to be increasing levels of flooding by going to larger gas flow rates.
3. If air/water tests are to be performed close valve V-20 and open valve V-19 then purge the hygrometer by opening V-2 to measure the humidity in the air. *
4. For steam/water tests ensure that the steam condenser is operating.
   a. Follow the domestic water supply instructions in Section 4.8.
   b. Open V-93 to send domestic water through the steam condenser using the rotameter to set the appropriate water flow rate through the steam condenser. *

5. Ensure the steam generator is at an appropriate test starting pressure.
    a. For Steam/Water tests follow steam generator procedures, Section 4.4.3, to power on the appropriate amount of heaters to ensure the steam generator is at an appropriate pressure.
    b. For Air/Water tests follow the air compressor procedures, Section 4.3, and adjust the air regulator valve to ensure the steam generator is at an appropriate pressure.
6. Ensure Section 4.6 has been performed so that an appropriate test section pressure will be achieved when gas flow begins. *
7. Confirm that the water supply tank is at the correct pressure as this is the means of ensuring a precise inlet water flow rate.
8. Follow Section 4.7 to begin water inlet flow. *
9. Follow Section 4.8 to begin water recirculation. *
10. Begin data collection.
11. For Steam/Water tests power on the appropriate amount of heaters.
12. For Steam/Water tests ensure that the inlet water temperature is at or near 3 °C of saturation temperature.
    a. Increase the inlet water temperature by opening V-2 to send steam to the inlet water heater.
13. Open V-1 to begin sending gas to the test section.
    a. For onset of flooding tests monitor the “Test Section DP” plot on the LabVIEW VI and use this as a visual representation of when flooding has occurred.

b. For other flooding tests past the onset of flooding set the gas flow rate to the previously decided level.

14. Once flooding has occurred attempt to keep the following parameters as steady as possible.
    a. Inlet gas flow rate by adjusting V-1.
    b. For steam/water tests. Inlet water temperature by adjusting V-2.
    c. Test section pressure by adjusting the backpressure regulator.
15. After the system is no longer able to be kept steady or steady flooding has been sustained for approximately 1-minute close V-1 to stop the test. If steam/water test also close V-2.
16. For steam/water tests power off all steam generator heaters.
17. Shutoff the water supply pump and close the appropriate V-83 valve.
18. Shutoff the water recirculation pump.
19. Stop data collection and prepare the facility for the next desired test.

4.10 Facility Shutdown

For the safety of lab personnel and equipment it is important to completely shut down the facility at the end of the day. This includes unplugging all extension cords and ensuring nothing is pressurized or above saturation temperature. Follow these procedures as applicable depending on what equipment is still in operation.

1. Shutoff the air compressor from the electrical panel controls. *
2. Vent the air in the air compressor by sending the air through the steam generator and out the steam generator vent (V-16). *

3. Once the air compressor is vented for at least 5 minutes turn off the refrigerated dryer and unplug the electronic drain valve. *
4. Shutdown the steam generator.
    a. Turn off all heaters.
    b. Turn the heater power switch off and lock the switch closed with the padlock.
    c. Turn of the steam generator breaker from the electronic panel.
    d. Vent the steam generator via the vent valve (V-16) or by sending the remaining steam to the water supply tank by following Section 4.5 appropriately.
    e. When steam generator is fully vented close V-16 and open V-13.
5. Blowdown the test section to the blowdown drum by completely unscrewing the backpressure regulator as well as the secondary side backpressure regulator.
6. Close V-34. *
7. Open V-35. *
8. Operate the water supply pump, recirculation pump and the heat exchanger to cool the water in the water supply tank to below saturation temperatures.
9. Open the water supply tank vent slowly to lower the pressure of the water supply tank.
10. Ensure the test section is completely depressurized by opening the steam trap valves (V-7b and V-91).
11. Shutoff the heat exchanger water flow and the steam condenser water flow.

12. Follow Section 4.1 for procedures on how to properly shut off the data acquisition system. *

5. RESULTS AND DISCUSSION

This section covers the collected data and a description of the analysis performed on the data along with explanations for the observed phenomena. The test ranges and target parameters are given along with explanations on why certain target values were chosen. An example of the raw data from a typical steam test showing key measurements including a description of the trends observed in the raw data plots. The data reduction techniques are described and plots of reduced steam/water and air/water tests are given as Kutateladze flooding curves. The air/water and steam/water data are compared with a steam/water correction correlation is given to translate steam/water data to air/water data. Finally, an error analysis is given explain the validity of the error bars included in the reduced data plots.

5.1 Test Ranges and Target Parameters

The test ranges for this work were motivated by the abilities of the equipment and the end goals of what was desired to be studied and compared. The goals of this work were to compare steam/water and air/water flooding tests at elevated pressures for different stages of flooding. The areas of interest to be studied for this work was across four pressures with three water inlet flow rates per pressure and 4 different stages of flooding per water inlet flow rate. This would result in a minimum desired number 48 Steam/Water tests and 48 Air/Water tests. Explanations for the specific values of the pressure, water inlet flow rates and gas inlet flow rates is given below.

As previously mentioned Wynne designed the facility to have a max working pressure of 45 PSIG [3]. A large majority of previous flooding work has been performed at atmospheric pressure conditions. For this reasoning it was decided to have the pressure for the tests range from 0 PSIG to 45 PSIG with two pressures in between to be able to study the effects on flooding across four different pressures. The pressure range directly impacted the range of water inlet temperature for the steam tests. This lead to the inlet water temperature ranged from approximately 100 °C for atmospheric tests up to approximately 144 °C for 45 PSIG tests. When possible it was attempted to keep the superheat of the tests to a minimum and for this reasoning the target steam temperature was for 10 °C above saturation temperature. This lead to a target steam temperature of 110 °C to 154 °C.

In past studies in the NHTS laboratory a wide range of water inlet flow rates was important to complete the onset of flooding curves. Due to the flooding curves of this work focused on the different stages of flooding rather than onset a smaller range of water inlet flow rates was chosen. Threw studying the literature it was determined that three different water inlet flow rates would be sufficient to study the effects of variable water flow rate [13]. Another factor that lead to water inlet flow rate ranges was the max water flow rate capable of passing through the separator as carryover. With the intention of this work being to get as closed to full flow reversal as possible it was determined that a max inlet flow rate of 7 GPM would be appropriate. This would be below the maximum water flow rate of the separator of 7.5 GPM if full flow reversal were to be achieved.

The range of inlet gas mass flow rate was dependent on the mass flow rate necessary to achieve flooding and the maximum desired mass flow rate to achieve close to full flow reversal. The typical onset of flooding mass flow rates was covered in the

Wynne thesis and were used to build the ranges [3]. It was decided to have a minimum of four inlet gas mass flow rates for each inlet water flow rate. This meant that the onset mass flow rate and three others that were typically spread 5 to 10 g/s apart depending on equipment abilities. For the atmospheric and 15 PSIG tests the gas inlet flow rate was limited by the regulator valve only being able to pass a maximum of 65 g/s before beginning to pressure up past the desired values. At higher pressures the onset of flooding was at a higher flow rate then at the lower pressure tests. This would mean a much higher gas flow rate was required to get to the close to full flow reversal stages of flooding. The gas supply was unable to sustain continuous flow for the necessary amount of time at these higher gas flow rates which lead to some limitations on the max inlet gas flow rate for higher pressure tests. A table summarizing the test ranges for this work is given in Table 5.1.

Table 5.1: Test ranges summary for the data presented in this work.

Parameter	Steam/Water Range	Air/Water Range
Test Section Pressure	0 - 45 PSIG	0 - 45 PSIG
Gas Inlet Flow Rate	26 - 66 g/s	38-99
Gas Inlet Temperature	103 - 149 °C	15 °C
Water Inlet Temperature	100 - 144 °C	25 °C
Water Inlet Flow Rate	5 - 7 GPM	5 - 7 GPM

5.2 Raw Data and Observations

Air/Water raw data is very similar to Steam/Water data with the exception of no need to observe the temperatures or temperature dependencies. For this reason, the raw data can be fully explained through an example of a Steam/Water test. For examples of the Air/Water raw data for all tests see Appendix A. As mentioned in the operational procedures section the goal of each test was to first initiate with a set water inlet flow rate. Set the gas inlet mass flow rate to the predetermined value and determine flooding was occurring. Modify the pressure so it is at the correct level. If a Steam/Water test, make sure that the inlet water temperature was close to saturation temperature. The focus of the raw test data was the parameters that the operator was monitoring during the test to achieve these listed goals.

No matter which type of test was being run it was necessary to confirm that flooding was occurring. Due to the test section being opaque and the facility being loud the visual and audible confirmations of flooding during testing were not available. Instead the operator observed a plot of the "test section differential pressure" in the LabView VI to watch for a large drop that signified flooding was occurring. If the test was an onset of flooding test, then the inlet gas flow rate was increased until the test section differential pressure was signified flooding had occurred. A plot of the test section differential pressure for a typical onset of flooding test is given in Figure 5.1. When the test begins the differential pressure is approximately 55.75 inH2O which corresponds to the height difference between the high and low pressure port. From the start of the test until flooding occurs the gas flow rate is increased until a predefined inlet gas flow rate is reached. As can be seen the differential pressure stays relatively constant during this period of time until a large drop on the order of 2 to 3 inH2O. This large drop signifies the start of flooding. In previous studies it was determined that the cause for the large differential

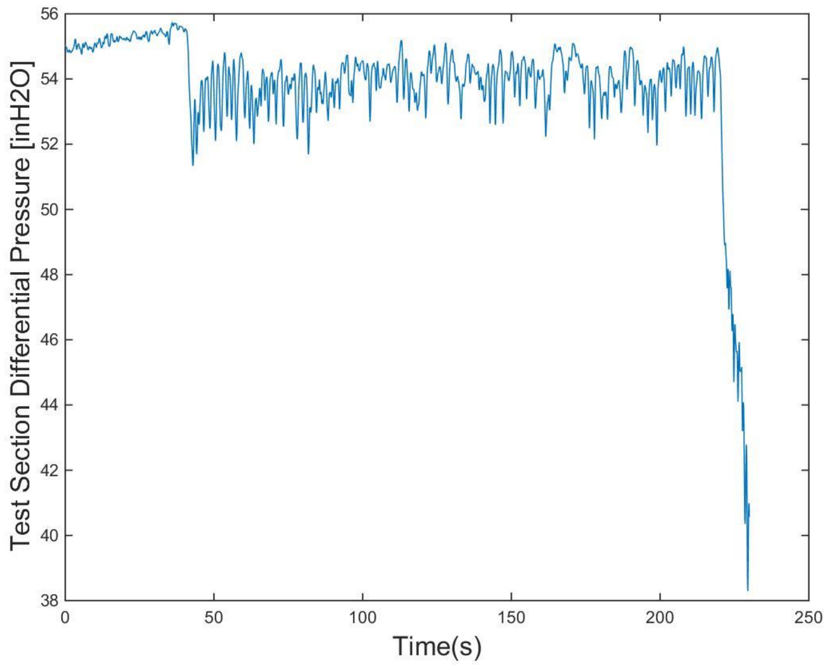


Figure 5.1: Test section differential pressure for a typical flooding test. This plot corresponds to 2015_12_13_test01 in Appendix B.

pressure drop is due to a pressure wave traveling up the test section at the moment flooding occurs [3]. This pressure wave causes positive pressure to enter the low side pressure port as it is below the vertical location in the tube that flooding occurs. The positive pressure entering the low side port causes the drop in differential pressure as the pressure in the low side port is now larger than what it was previously, on the order of 2 – 4 inH2O. Towards the end of the test a much larger differential pressure drop is observed. This is an effect of the remaining gas from the holdup tank and gas inlet line venting out of the regulating valve. This causes a much larger wave of positive pressure to enter the low side port and cause the differential pressure to drop greatly.

As the gas flow rate increases so does the system pressure. This relationship between the test section pressure and the gas flow rate makes it obvious to have these to parameters on the same plot. Figure 5.2 gives the inlet and outlet gas flow rate on the right y-axis and the test section pressure on the left y-axis. At the beginning of the test it seen that both the inlet and outlet gas flow rates are at 0 g/s and the pressure is just below 20 PSIG. This is due to manner at which the regulator valve operates and this is seen as the pre gas flow pressure. As the gas flow rate is increased to the point that flooding is achieved the pressure increases and gets to approximately 30 PSIG which was the working pressure for this specific test. The operator keeps the gas flow as steady as possible for as much time as possible at the mass flow rate at which flooding occurred. Typically, during

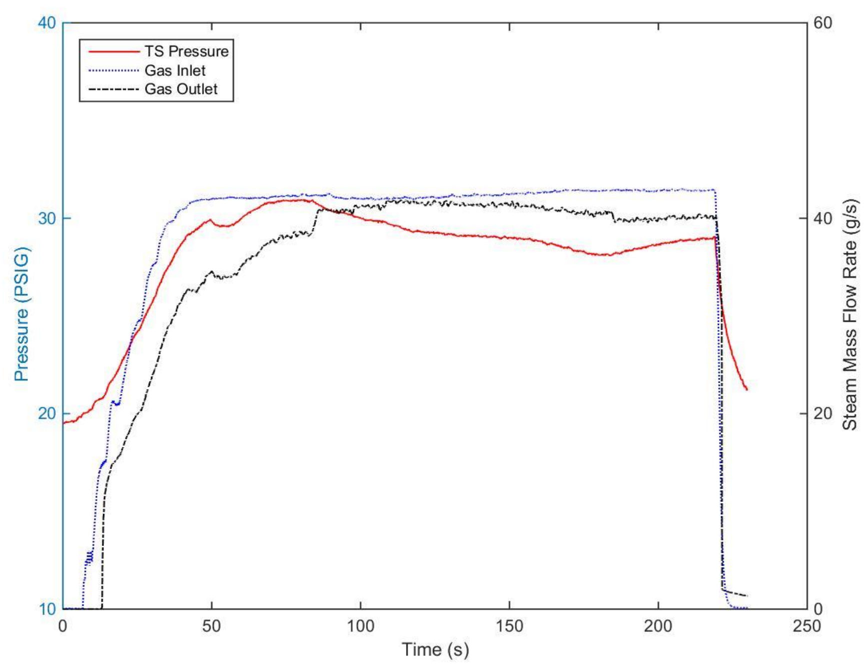


Figure 5.2: Test section pressure and inlet/outlet gas mass flow rate for a typical steam/water test. This plot corresponds to 2015_12_13_test01 in Appendix B.

a test the pressure is adjusted after getting to the appropriate inlet gas flow rate as to be as close as possible to the target pressure. As can be seen the pressure in the system drops some amount throughout the test, the amount that the pressure drops were attempted to be kept to a minimum of ± 2 PSIG during the test by adjusting the regulating valve. Towards the beginning of the test the outlet gas flow rate is seen to be much lower than the inlet gas flow rate. The difference in inlet and outlet gas flow rates can be attributed to the steam condensing in the test section. As the test continues the inlet and outlet gas flow rates are seen to converge. This was caused by the operator increasing the inlet water temperature to near saturation via the inlet water heater. As can be seen the end of the test is signified by the inlet and outlet gas flow rates going back to 0 g/s. It was after this point that the operator would typically stop recording the data for that particular test.

The saturation temperature of the test section was monitored via the LabView VI and it was attempted to keep the temperature of the inlet gas and liquid as close to the saturation temperature as possible. The inlet gas temperature was controlled by attempting to keep the steam generator pressure at just large enough of a value to achieve choked flow. For certain tests it was difficult to keep the steam generator from pressuring to high and some amount of superheat was unavoidable, it was attempted to be kept to a minimum. As mentioned previously the liquid inlet temperature was required to be within 3 °C of saturation temperature. The typical temperatures observed for a steam/water test are given in Figure 5.3. It is noted that at the beginning of the test the saturation temperature is much

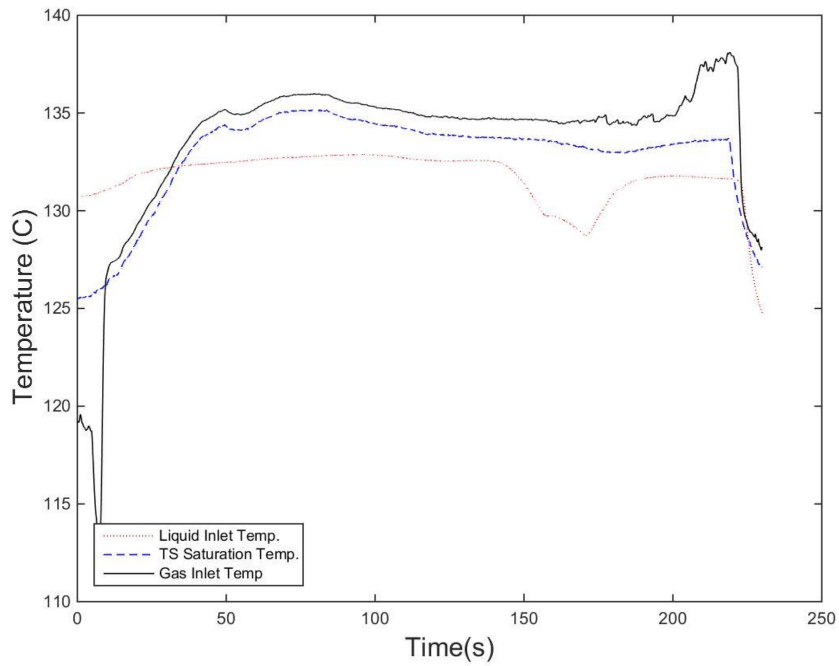


Figure 5.3: Liquid inlet temperature, gas inlet temperature and saturation temperature for a steam/water test. This plot corresponds to 2015_12_13_test01 in Appendix B.

lower then as the middle portion. This corresponds to the starting pressure of the test section, as seen in Figure 5.2. As the test section pressure increased so does the saturation temperature. Also at the beginning of the test the gas inlet temperature is much lower, this is due to the piping leading up to the test section cooling between tests and heat up. The liquid inlet temperature at the start of the test is from the source of water in the water supply tank being preheated. As the test continues the water temperature stays as closed to constant as possible by being heated from the inlet water heater.

The water flow rates of interest are plotted on Figure 5.4. The inlet water flow rate was set before the test began to drop to approximately 7 GPM when the test section was

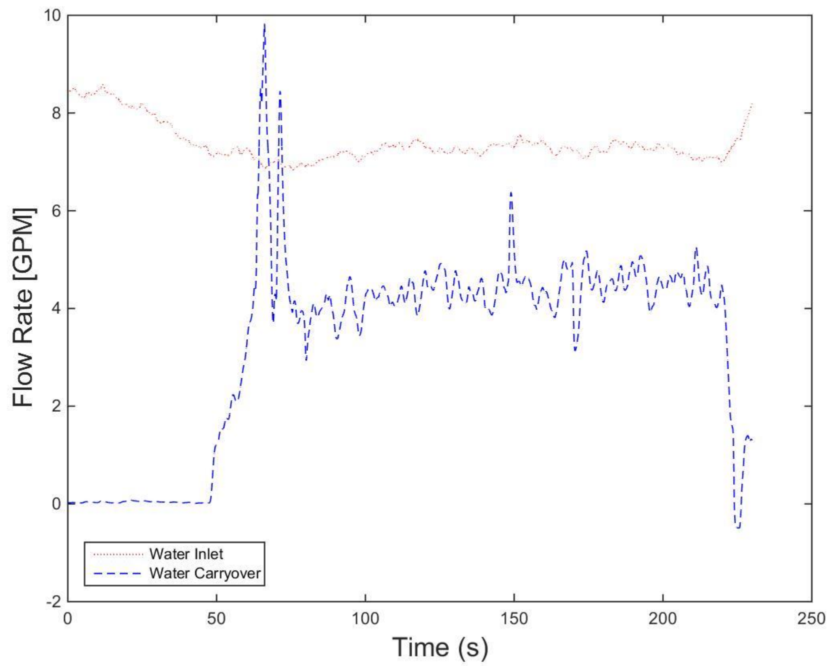


Figure 5.4: Water inlet and water carryover flow rates for a steam/water test. This plot corresponds to 2015_12_13_test01 in Appendix B.

at the target pressure. At the beginning of each test the water supply tank is at a much higher pressure than the test section causing the need to preset the water flow rate to be at the target value when the test section is at the target pressure. The water carryover flow rate represents the amount of water that flows through the carryover flow meter. This is the flow rate of water leaving the test section through the top after flooding has been initialized. After flooding has been established a large spike in the carryover is observed which can be seen as an instrumentation error or not representative of what is possible. After flooding has been established for a long enough amount of time the water carryover is seen to be quasi steady state. This is unique data in that it shows the characteristics of the flow rate during flooding across multiple levels of flooding. The water down pipe flowrate represents the inlet water flow rate minus the carryover flow rate and represents the amount of water that is able to still travel to the bottom of the pipe after flooding occurs. It should be noted that this is assuming the effects of subcooling are low enough to not cause a large enough difference in the mass balance of the water entering and leaving the test section. Due to how the water down the pipe is calculated it is seen to be relatively inverse of the water carryover flow rate, however this value for water down pipe flow rate will be used in the Kutateladze flooding curves and that is why it is included in the raw data plots. Tabulated results of the reduced data are given in Appendix D.

5.3 Reduced Data

5.3.1 Data Reduction Technique

The raw data from each test was saved in files with the extension ".dat". A MATLAB script, entitled "Get Range of Interest" included in Appendix C, was used to find what is defined as the "range of interest". The "range of interest" is a section of each test that the began when the operator was capable of reaching all test parameters and was able to keep all the test parameters as consistent as possible for a minimum of 30 sec. The script was used to load and plot the "Inlet Gas Flow Rate" and "Test Section Pressure" parameters for each individual test. Once the test's plots were up the author manipulated the plots to find the region of the tests that were start and end of the range of interest. The start and stop points were found by searching for the positions on a plot that corresponded to the closest to steady state for the inlet gas flow rate and the test section pressure. The reason why this was performed manually rather than automatically through a script is because each test is different not allowing for a way to properly automate the process.

These starting and ending points were recorded in an excel file and the next test's plots were examined. This action was done for every test performed. The point behind this was to be able to find a region in the test that would be considered "quasi-steady state" and allow for the mean of the test parameters to be taken over a minimum of a 30 sec period. As seen in Figure 5.4 the water carryover flow rate can be described as unpredictable. This was the reason why it was determined necessary to average the test parameters in this "range of interest". The averaging of test parameters of this range allowed for a reliable set of data that correspond to approximate test conditions.

As previously mentioned the point of the "range of interest" was to acquire a mean value across a range of data points that were determined to be quasi-steady state. The mean values across the range were acquired using a separate MATLAB file, entitled "autocalc". The script used a loop to individually load the data from each test in a directory. After the data was loaded the parameters of interest were assigned to variables and averaged over the range of interest. For steam/water tests an adjustment was made to calculate the water entering the test section due to the inlet water heater being further down the line then the mag meter that measured the inlet water flow. This was necessary as the water entering the test section could be at a different flow rate due to the density changing as the water traveled through the inlet water heater. Steam, air and water flow parameters necessary to calculate the superficial velocities or Kutateladze parameters were looked up using a MATLAB steam table function titled "XSteam". Equation 5.1 was used to calculate the values for superficial velocity for the following parameters: gas inlet, gas outlet, water inlet, water carryover and water down pipe.

$$j_k = \frac{Q_k}{A} = \frac{\dot{m}_k}{\rho_k * A} \tag{5.1}$$

where Q is the volumetric flow rate, A is the test section area, $\dot{m}$ is the mass flow rate and the subscript k denotes which flow rate parameter of the five listed above is being calculated. Equation 2.4 and Equation 2.5 were used to calculate the Kutateladze parameters for the five flow rate variables given above. A generic version of the "autocalc" script is included in Appendix C, two separate MATLAB scripts were used depending on if the calculations being performed were for a steam/water or air/water test.

5.3.2 Reduced Data Results

A flooding curve for the steam/water tests performed for this work is given in Figure 5.5. The x-axis represents the square root of the Kutateladze parameter for the water falling down the pipe and the y-axis represents the square root of the Kutateladze parameter for the gas entering the bottom of the test section. The plot can be interpreted as the further right from the origin, on the x-axis, represents more water flowing down the pipe. Similarly, the further up from the origin, on the y-axis, represents more gas flowing into the bottom of the test section. Each point on the plot represents one flooding test. Groups of tests are designated by the differing symbols on the plot. These groups were based on what the test target pressure and what the inlet water flow rate was for the test groups. The idea behind this was to attempt to find some correlation between test section pressure or inlet water flow rate on where a point lies in the Kutateladze flooding curve.

Similar to what has been observed in the literature the general trend of the data is for the greater the value for the gas Kutateladze parameter, $K_g^{1/2}$, the less the value is for

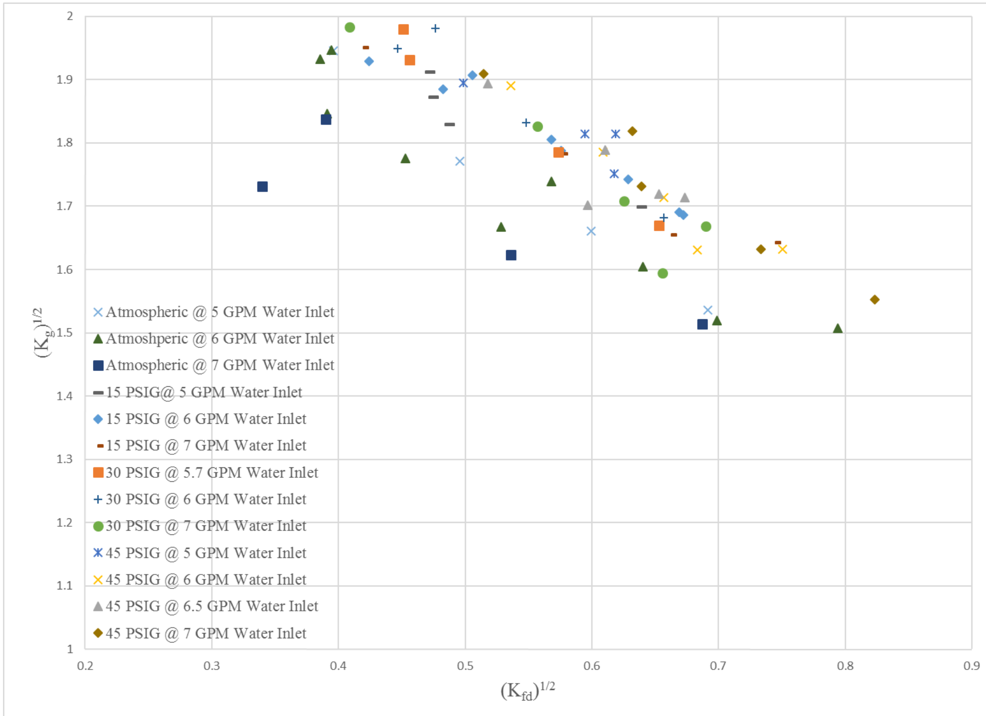


Figure 5.5: Kutateladze flooding curve for the steam/water flooding tests. Test points are differentiated based on the test section pressure and the inlet water flow rate.

the water down Kutateladze parameter, $K_{fd}^{1/2}$. This makes sense on the fundamental level that the higher gas flow rate entering the test section would result in less water flow rate flowing down the bottom of the test section pipe. When analyzing the curve in Figure 5.5 it is hard to pinpoint a definitive trend for flooding curves based on test section pressure or inlet water flow rate. The inlet water flow rate appears to have no effect on where a data point lies on the flooding curve. This is easily seen by observing the 45 psig tests with four different inlet water flow rates given in Figure 5.6. By having multiple inlet water flow rate tests per pressure value one is able to see that no obvious changes occur in the

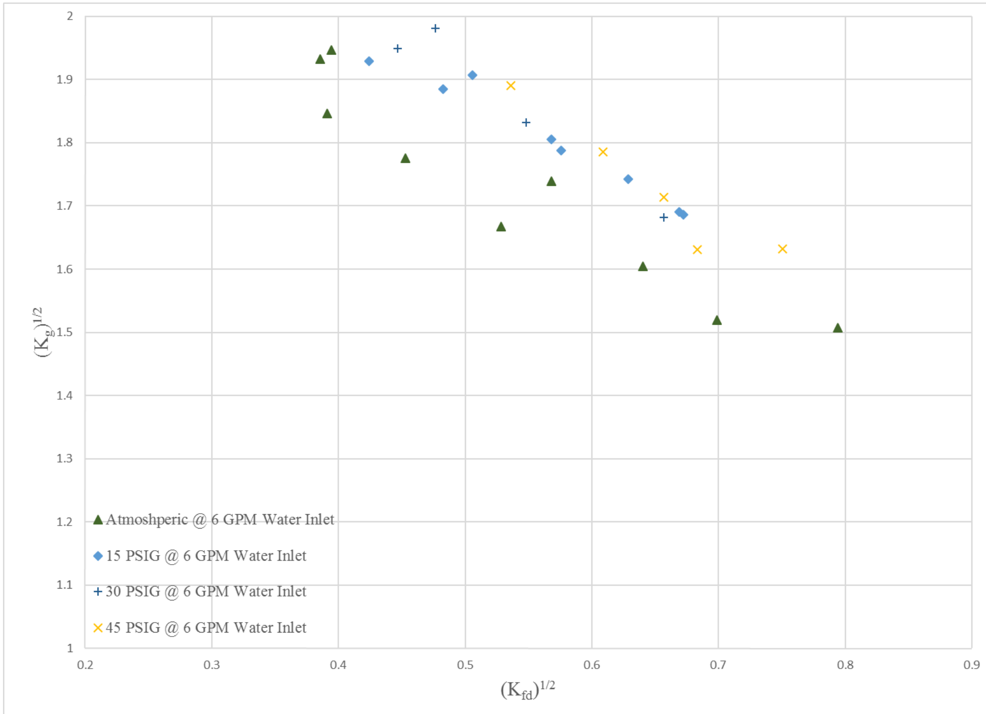


Figure 5.6: Kutateladze flooding curve for the 45 psig steam/water flooding tests across four different water inlet flow rates.

flooding curve when changing the inlet water flow rate. This same result was observed by Roth and Crowley when multiple inlet water flow rates were used at the same pressure to generate flooding curves [13]. Wynne observed that as the inlet water flow rate was increased so did the carryover rate with no increase on the water down flow rate [3]. This same phenomenon is present in that the amount of water falling down the test section is relatively independent of the amount of water flowing into the test section but rather is entirely dependent on the amount of gas flow entering the bottom of the test section.

Figure 5.7 can be used to analyze the effects of test section pressure on flooding curves. For Figure 5.7 the inlet water flow rate is kept constant and the pressure is changed from atmospheric conditions up to 45 psig. The general trend of each data set is consistent with what appears to be the same slope however it is seen that the atmospheric data set appears to trend slightly lower than the pressurized data sets. The amount of difference between the atmospheric tests and the pressurized tests is small and can be contributed to the various error present in the system. It is seen that the data sets for 15, 30 and 45 psig all trend very closely. This allows one to make the conclusion that Kutateladze parameters are relatively independent of test section pressure. This makes sense when considering the test section pressure is inherently accounted for in the Kutateladze parameter calculations. The reason behind this is that both the liquid and gas densities are used to calculate the Kutateladze parameters, Equation 2.4 and Equation 2.5. The liquid and gas densities are

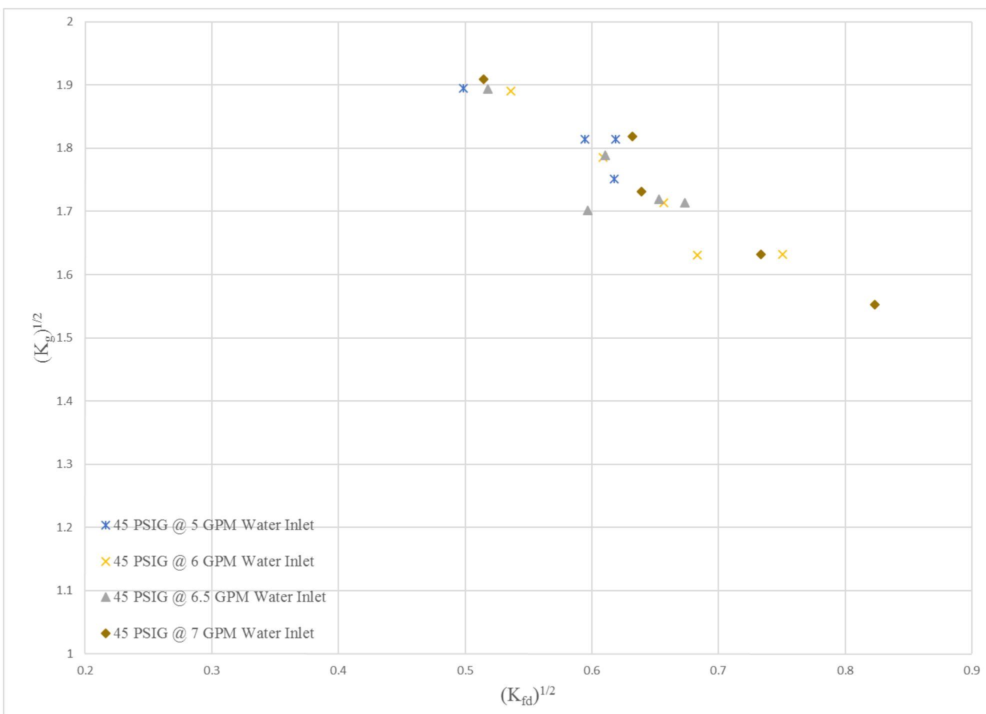


Figure 5.7: Kutateladze flooding curve for 6 GPM water inlet steam/water flooding tests across four different test section pressures.

dependent on test section pressure. This allows for one to conclude that when generating flooding curves using Kutateladze parameters test section pressure is relatively unimportant due to the densities of the liquid and gas being included in the Kutateladze parameter calculations. Individual plots of the Kutateladze curves keeping pressure or inlet water flow rate constant are given in Appendix E.

Similar to the steam/water tests the air/water tests were also plotted as the square root of Kutateladze parameters to form a flooding curve as seen in Figure 5.8. The trends observed in the steam/water tests, were also seen in the air/water tests as seen in Figure 5.8. Similarly, there is no perceivable dependency on test section pressure or inlet water flow rate on the flooding curve.

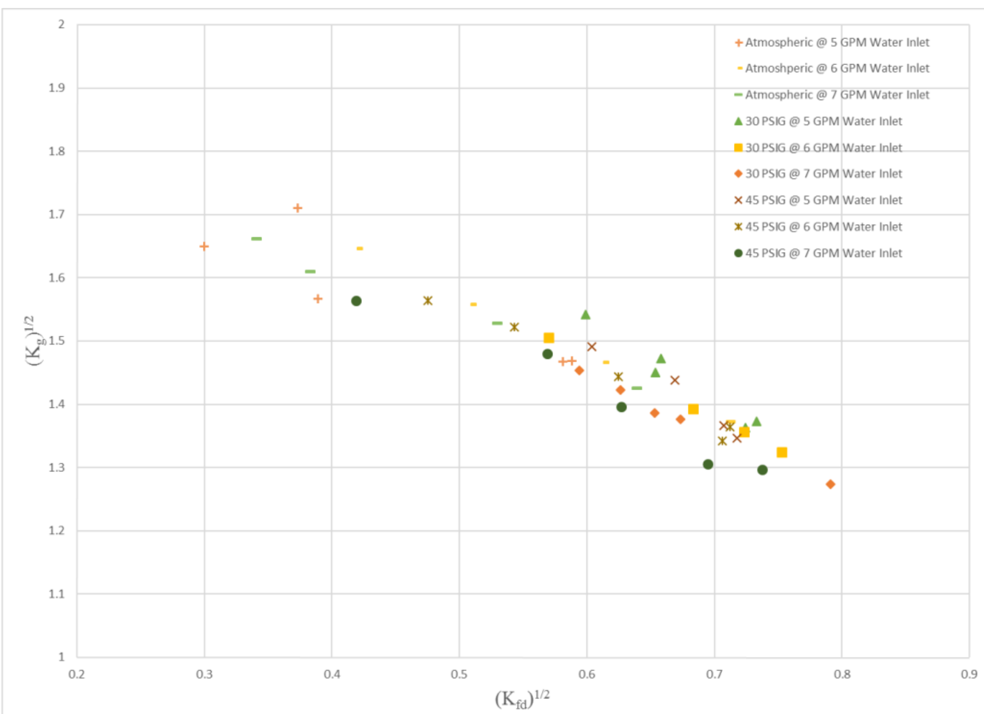


Figure 5.8: Kutateladze flooding curve for the air/water flooding tests. Test points are differentiated based on the test section pressure and the inlet water flow rate.

As previously mentioned the main purpose of this work is to be able to compare steam/water and air/water flooding curves. Figure 5.9 does this by plotting the steam/water and the air/water flooding data on the same plot. Included in Figure 5.9 are trend lines that can be used to describes the steam/water and air/water data sets. The equations of the trend lines are also included and show that the slopes of the trend lines are generally equal. Contrary to this the y intercept of the two trend lines are seen to differ with the steam/water data trending further upward then the air/water data. This was observed by Wynne and it was concluded that the steam/water data trends further upward due to some amount of condensation occurring when the steam comes in contact with the water [3]. The equations

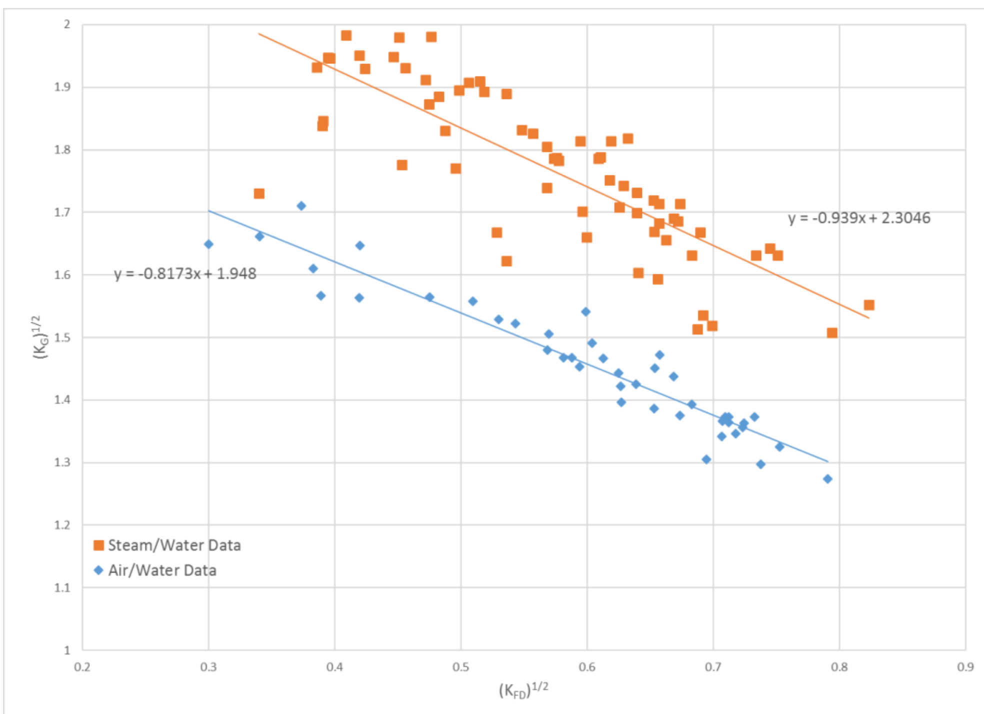


Figure 5.9: Comparison of steam/water and air/water flooding curves using Kutateladze parameters.

of the trend lines can be used to achieve a correlation similar to the Wallis correlation, Equation 2.1, using Kutateladze parameters that can be used to describe flooding in this test section. These correlations are given in Equations 5.2 and 5.3 for steam/water and air/water respectively.

$$K_g^{\frac{1}{2}} + 0.939 * K_{fd}^{\frac{1}{2}} = 2.3046 \tag{5.2}$$

$$K_g^{\frac{1}{2}} + 0.817 * K_{fd}^{\frac{1}{2}} = 1.9480 \tag{5.3}$$

As mentioned the flooding curves above are generally linear, this is easily seen in Figure 5.9. This is the result of taking the square root of the Kutateladze parameter. It can be seen that at some point the water flowing down will be zero for some specific value of gas entering the test section. This point at which no water is flowing down the test section is referred to as full flow reversal. Using Equations 5.2 and 5.3 you can solve for this point at which full flow reversal occurs by setting $K_{fd}^{1/2}$to 0. This allows one to see that the y-intercept in Figure 5.9 also represents the point of full flow reversal. Although full flow reversal was not directly observed, the amount of data present allows for the accurate prediction of at what gas inlet Kutateladze parameter full flow reversal would occur.

5.3.3 Reduced Data Condensed Steam Correction

With the available steam/water and air/water data it became evident that a vertical shift downward of the steam/water data would allow for it to be transformed into the air/water data. The reasoning behind this is the amount of condensation that takes place causes a need for a higher gas Kutateladze number for steam as compared to air. As mentioned in the literary review Tien proposed a correlation adjustment that takes into account the amount of condensation that takes place in the test section [12]. However, this was found to not adequately transform the steam/water data into a proper representation of the air/water data for the data presented in this work. Similarly, Ritchey developed a value for the effective gas Kutateladze parameter and this was also found to not match well with the data from this work. Ritchey's correlation seemed the most promising because of the form it was given in, Equation 2.7. With the correct value for *f* it is easily seen that the steam/water data will be translated down to fit the air/water data. It was attempted to develop a different definition for *f* rather than the one presented in Equation 2.8. However, no combination of flow parameters was accurately able to reproduce the steam/water data as air/water data. It was then decided that it would be necessary to find an empirically driven value for *f*. This value was found to be *f=0.3*, and the result of plotting the Equation 2.7 with this particular value for *f* is given in Figure 5.10. As can be seen a trend line that represents the transformed steam/water data lies almost exactly over the air/water data. Equation 5.4 represents the trend line of the corrected steam water data and can be compared to the air/water Kutateladze correlation, Equation 5.3.

$$K_g^{\frac{1}{2}} + 0.786 * K_{fd}^{\frac{1}{2}} = 1.928 \qquad (5.4)$$

As can be seen by observing the closeness of Equations 5.4 and 5.3 along with observing the corrected steam/water data lying on top of the air water data it is concluded by using Equation 2.8 with a correction factor of *f=0.3* the steam/water data is transformed into an accurate representation of the air/water data.

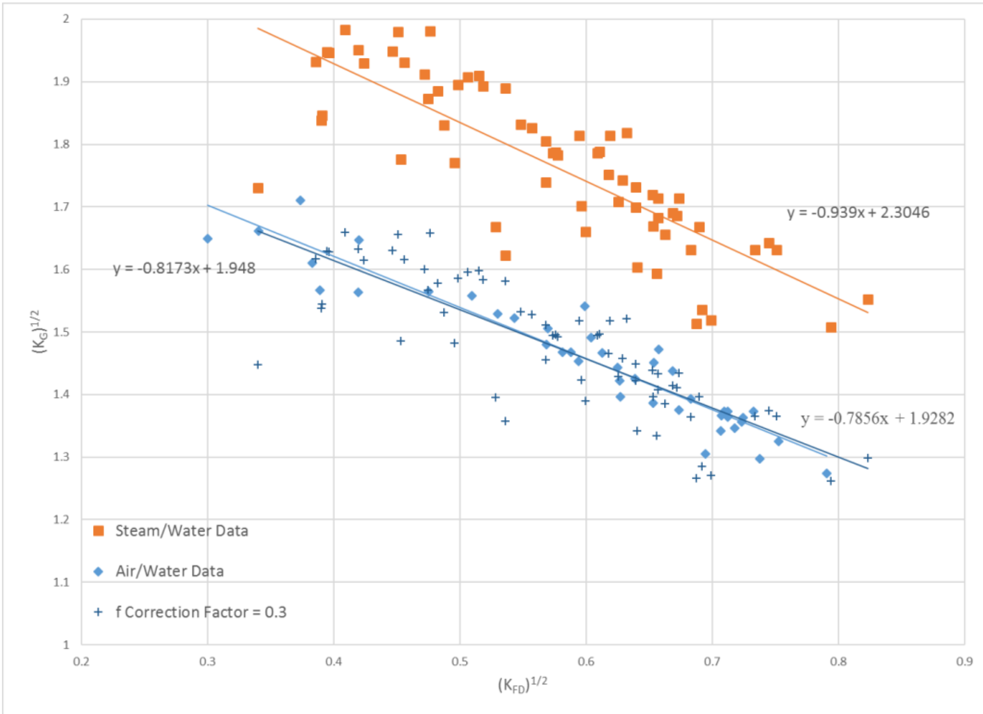


Figure 5.10: Plot comparing the original steam/water Kutateladze curve and the translated curve using a correction factor of *f*=0.3. The air/water Kutateladze curve is also presented for comparison purposes.

5.4 Error and Uncertainty Analysis

For the work there were three possible sources of error. The first possible source of error is the error associated with measuring the system parameters. This was found to be only 1% of the measured values. This value was found through the vortex flow meters' instruction manuals. This 1% value was ignored as it is assumed that the repeatability tests performed account for any error in measured values. The second possible source of error comes from converting the analog measured signal into a digital value. This associated error percentage is so small that it is considered negligible and will not be considered. The third source of error comes from the randomness involved with running the experiments.

For both steam/water and air/water tests repeatability tests were performed to measure the amount of random error involved with the experiments. These repeatability test conditions along with the results are given in Table 5.1. In the past these tests involved the random error that was associated with onset of flooding. However, since the purpose of this work was to study the quasi steady state region that flooding occurred at. Random water inlet flow rates along with random inlet gas flow rates were chosen and ten repeatability tests were performed. The standard deviation for the Kutateladze parameters were found and divided by the average value for the Kutateladze parameters for a given set of repeatability tests. This gives a percentage of error for each of the test types that repeatability tests were performed on. To be conservative the largest steam/water error found was the error associated for all steam/water tests and the largest air/water error found was the error for all air/water tests. These error values were used to attach error bars to the flooding curve given in Figure 5.9 as seen in Figure 5.11.

Table 5.2: Tabulated results of uncertainty analysis through repeatability testing**.**

Fluid Pair	Test Parameters			Error Percentages	
	Target Pressure [psig]	Inlet Water Flow Rate [GPM]	Inlet Gas Flow Rate [g/s]	$K_g^{1/2}$	$K_{fd}^{1/2}$
Steam/Water	15	7	45	0.83957	3.61087
Steam/Water	30	6.3	55	0.314674	2.026342
Steam/Water	Atmospheric	6	32	0.138351	1.770643
Air/Water	30	6	45	0.126823	0.554785
Air/Water	Atmospheric	7	70	0.101013	1.976251

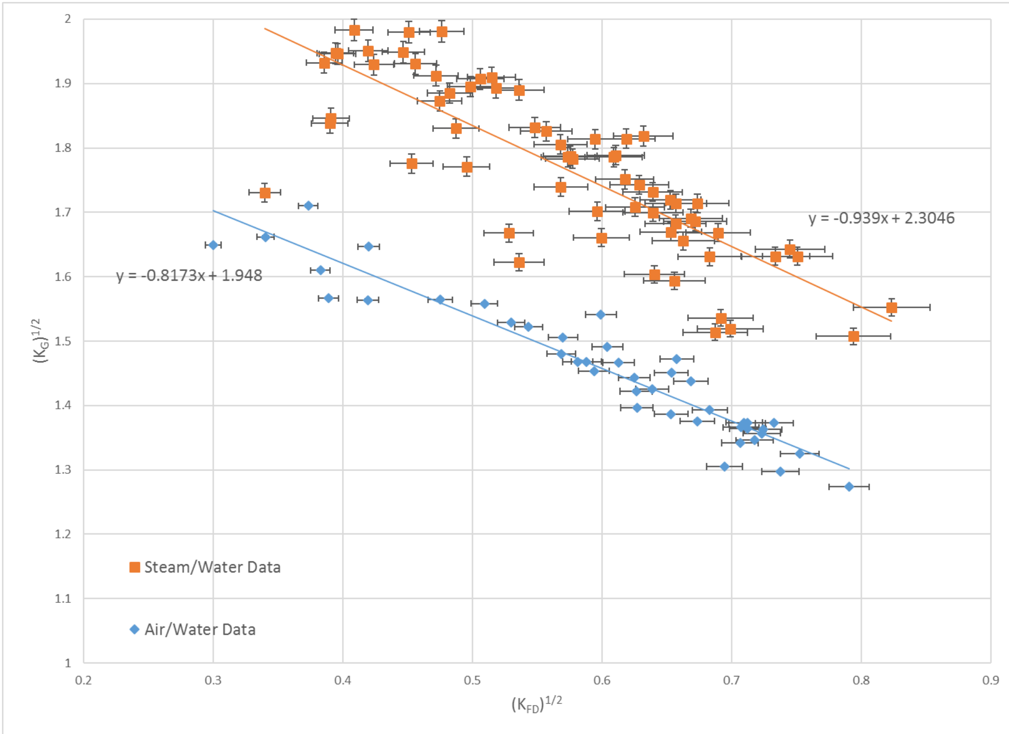


Figure 5.11: Steam/water and air/water Kutateladze curves with associated error bars.

6. CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

Flooding experiments were performed at elevated pressures and varying inlet water flow rates from the onset of flooding to near full flow reversal in a large diameter vertical tube. The purpose behind this work was to gain a better understanding of how elevated pressure and variable inlet water flow rate would affect flooding in the pressurizer surge line of a PWR. Another goal of the current research was to find an empirical method that was capable of translating steam/water data to air/water data at various pressures and inlet water flow rates. A better understanding of this phenomena and how it relates to these parameters can be used to modify existing reactor safety codes and be used to better predict flooding behavior in an accident scenario.

To perform the flooding tests, an existing facility in the NHTS laboratory was slightly modified to allow for flooding tests at near saturation temperature of the water. This was done by installing a heat exchanger that used the existing source of steam to pre/heat the water entering the test section to within 3 °C of saturation temperature. The importance of near saturation inlet water is to be able to study the flooding phenomena with as minimal amount of mass transfer, due to condensation, as possible.

Steam/water flooding tests were performed at atmospheric pressure, 15 psig, 30 psig, and 45 psig. Air/water flooding tests were performed at atmospheric, 30 psig, and 45 psig. At each of these pressures, flooding tests were performed with an inlet water flow rate of 5 GPM, 6 GPM and 7 GPM. At each inlet water flow rate, flooding was achieved at some previously decided inlet gas flow rate and test conditions were stabilized for at least 30 seconds producing a quasi-steady state system. In post processing calculations were performed on the recorded data to produce flooding curves using the non-dimensional Kutateladze parameters.

The Kutateladze flooding curves were studied to attempt to find dependencies on either variable, pressure or variable inlet water flow rate. There were no large dependencies observed for elevated pressures or the inlet water flow rate. Some small pressure effect was present for atmospheric tests. These results match with what was found in work performed by Rothe and Crowley [13].

It was attempted to find a correlation that took fluid parameters and translated the steam/water flooding test data into air/water flooding data however no such correlation was found. Rather an empirical multiplying factor of $f=0.3$ was used to shift the steam/water data vertically down the flooding curve to match with the air/water data. This reveals that the steam/water flooding curve and air/water flooding curves trend very closely with respect to slope but are off by some factor, when comparing magnitudes. This work can be used to improve reactor safety codes as mentioned in the project motivations.

6.2 Future Work

As previously mentioned this is considered the fifth installment of flooding research at the NHTS laboratory. With each installment, the analytical model for flooding in a large diameter vertical tube has been improved. Much of the issue with previous models was an inability to confirm assumptions about the effect of test section pressure on affect flooding curves. With the current research performed, a new list of research topics pertaining to flooding in the current facility can be performed.

The actual location in the test section where flooding occurs has been hypothesized to be in the lower third of the tube. This is based on the findings of Solmos, performing flooding research in a clear test section [8]. However, it has not been confirmed that this location holds true for the current test section due to it being opaque. If it were possible to study the location that flooding occurs with a degree of confidence it would also be useful to existing codes to study how the location of flooding changes with variable pressure, variable inlet water flow rate and even the flow rate of the gas being sent to the tube. Solmos was also only able to locate where in the test section flooding occurs using air/water flooding tests, it would be important to be able to test whether the location of flooding differs when steam/water tests are being performed.

For the current work air/water flooding tests were performed with an inlet water temperature of 25 °C. This was done because there were no concerns of mass transfer as there are with steam and subcooled water tests. To further be able to accurately convert steam/water flooding curves to air/water flooding curves it would be useful to study the effects of air/water flooding tests with the water near saturation temperatures. The belief is that some differences should be present, even though no mass transfer is present. This is due to the much different fluid parameters of the water in the test section when near saturation temperatures. These parameters are the water density, viscosity and possible the surface tension.

Although the current work approached full flow reversal it never quite achieved it. To confirm that the current flooding correlations are accurate it would be important to obtain flooding data at full flow reversal for elevated pressures. Since the current results closely match what was presented by Rothe and Crowley it is believed these results will also match, but it is important to check [13].

Tien reported on a hysteresis effect that occurred when performing subcooled steam/water flooding tests in smaller diameter tubes. It would be important to confirm the existence of the same effect by performing subcooled steam/water flooding tests and variable pressures. If the hysteresis effect is present it would allow for data currently unavailable on the current flooding curves presented in this work. The hysteresis effect is also important because if it exists that means that a system may not stop flooding at the exact gas flow rate that it started flooding and flooding may exist at lower gas flow rates.

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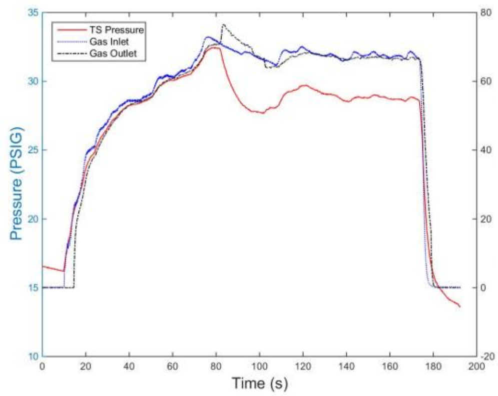
APPENDIX A: AIR/WATER RAW DATA

This section contains the plots of the raw data from the air/water tests. The name of the tests is included on the figure caption and the names correspond with the names given in the reduced data tables given in Appendix D.



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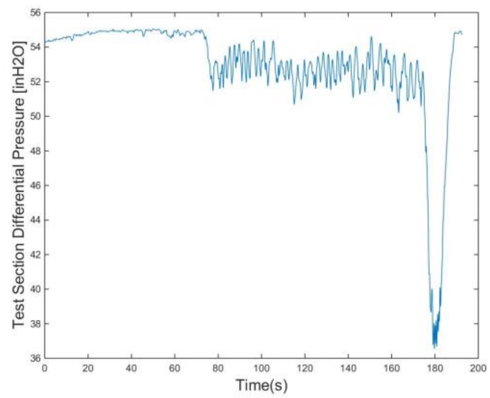

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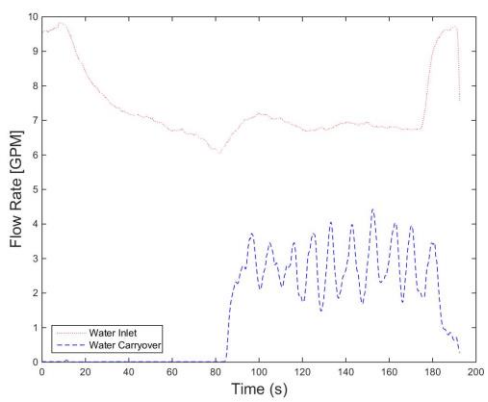

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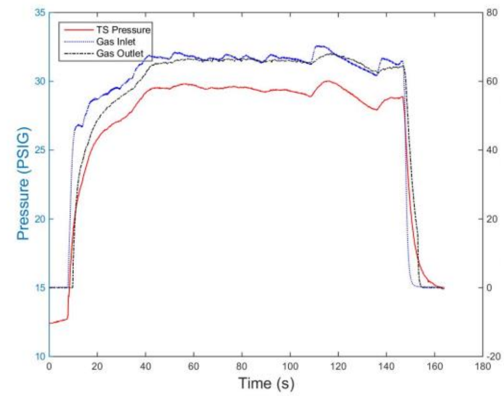
Figure A1: Raw data for air/water test “2015_12_30_test01”. The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the test section differential pressure and (c) the water inlet and water carryover flow rates.



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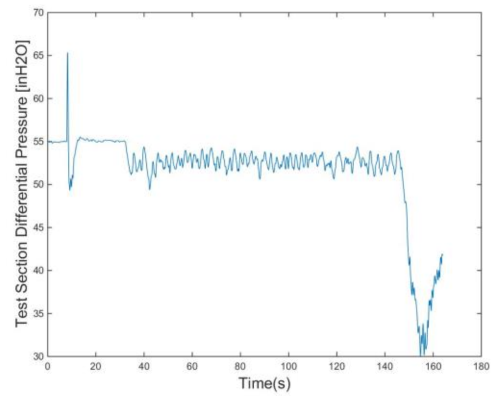

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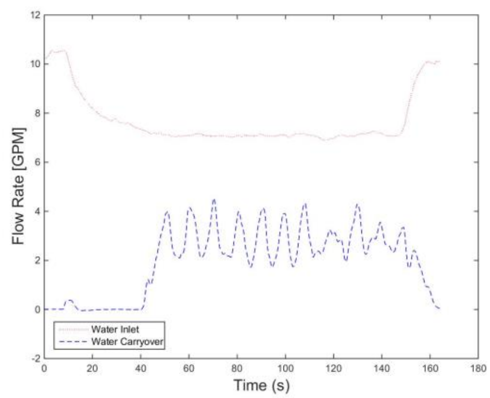

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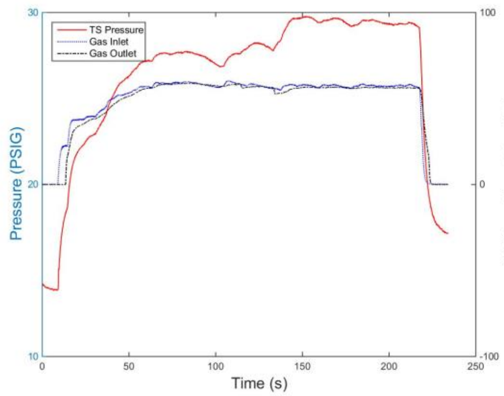
Figure A2: Raw data for air/water test “2015_12_30_test02”. The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the test section differential pressure and (c) the water inlet and water carryover flow rates.



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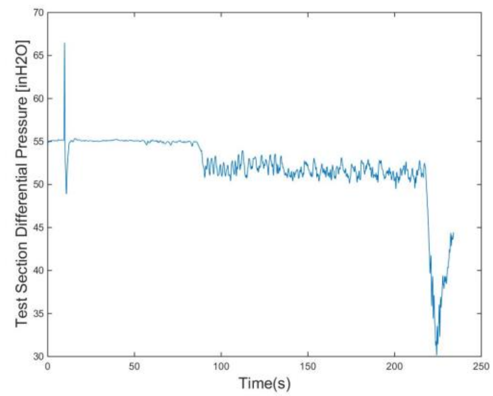

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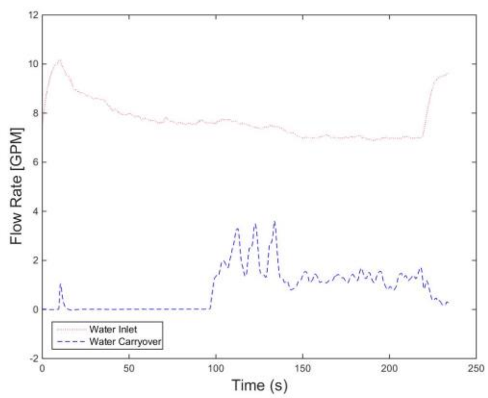

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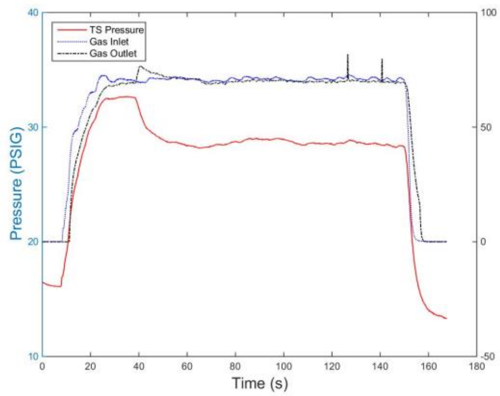
Figure A3: Raw data for air/water test “2015_12_30_test03”. The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the test section differential pressure and (c) the water inlet and water carryover flow rates.



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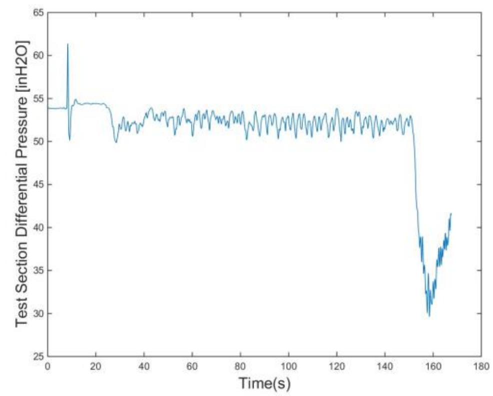

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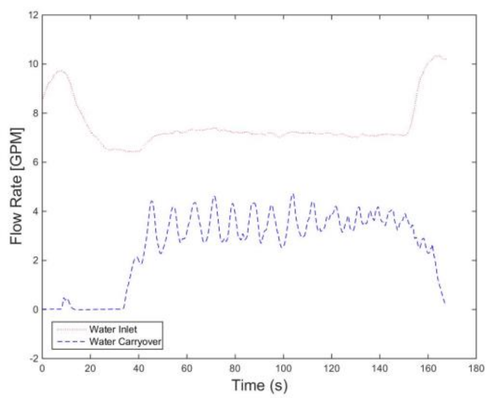

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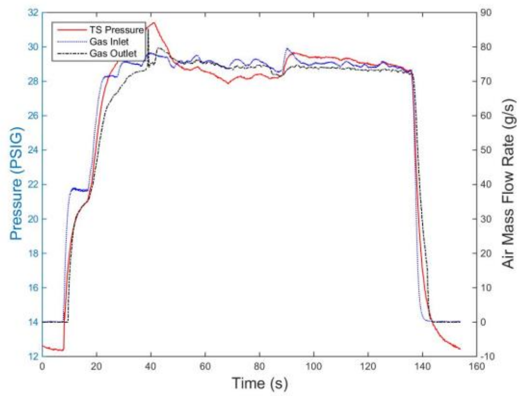
Figure A4: Raw data for air/water test “2015_12_30_test04”. The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the test section differential pressure and (c) the water inlet and water carryover flow rates.



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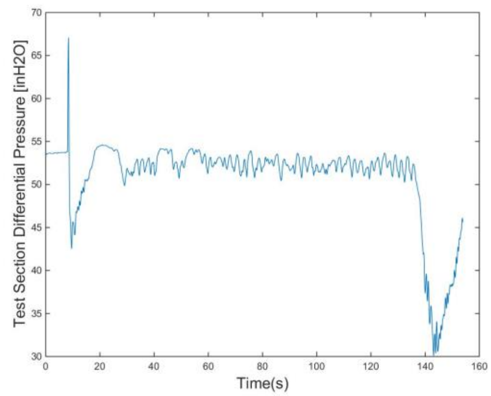

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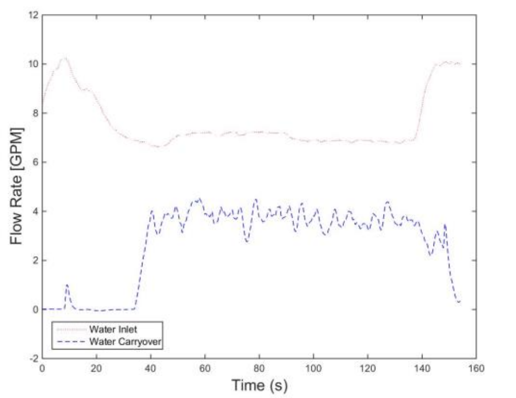

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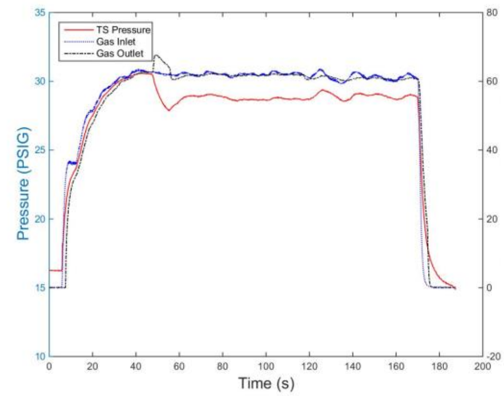
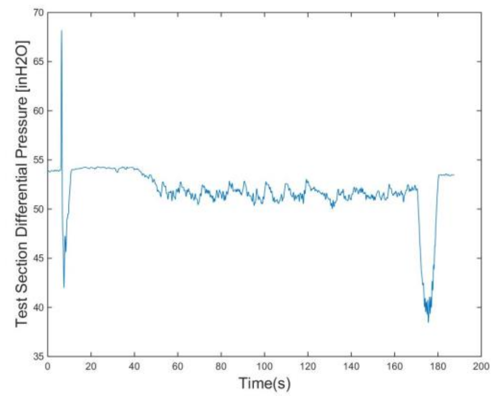
Figure A5: Raw data for air/water test “2015_12_30_test05”. The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the test section differential pressure and (c) the water inlet and water carryover flow rates.





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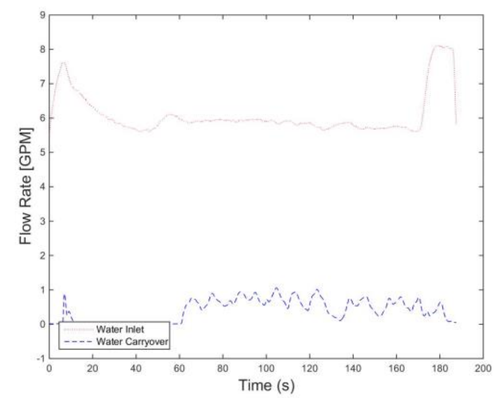

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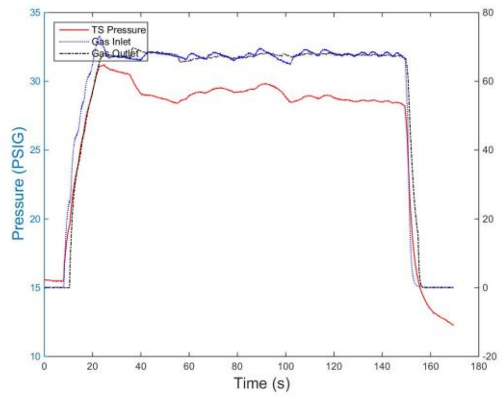
Figure A6: Raw data for air/water test "2015_12_30_test07". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the test section differential pressure and (c) the water inlet and water carryover flow rates.



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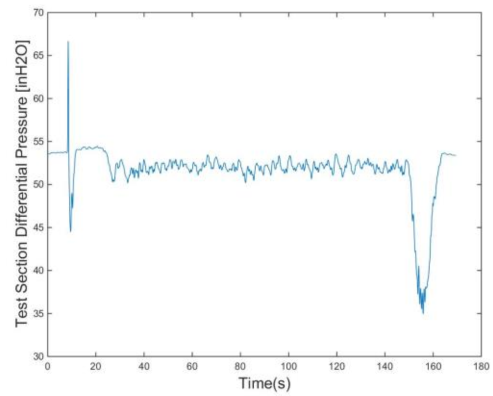

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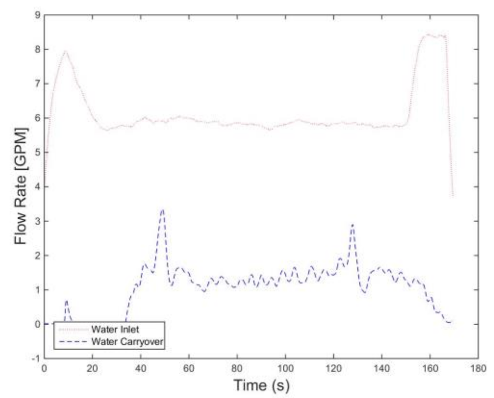

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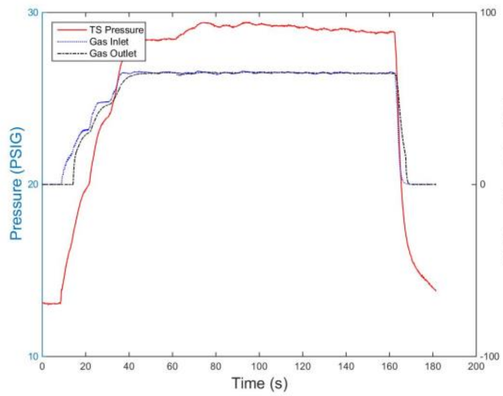
Figure A7: Raw data for air/water test "2015_12_30_test08". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the test section differential pressure and (c) the water inlet and water carryover flow rates.



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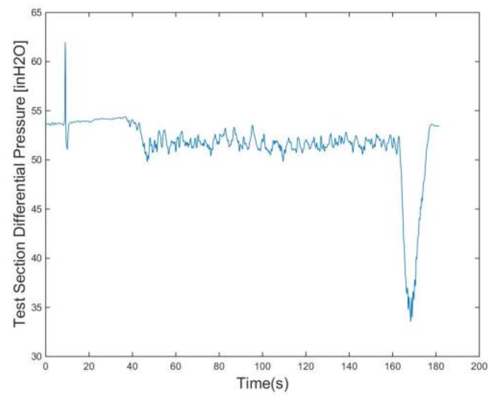

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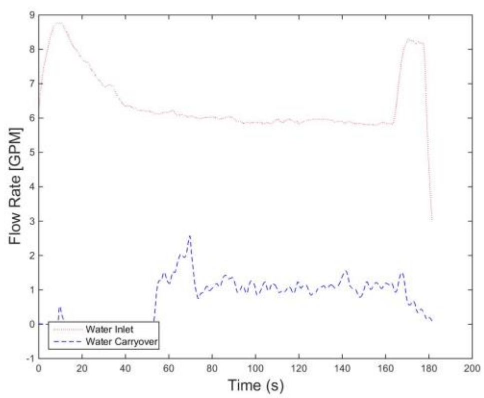

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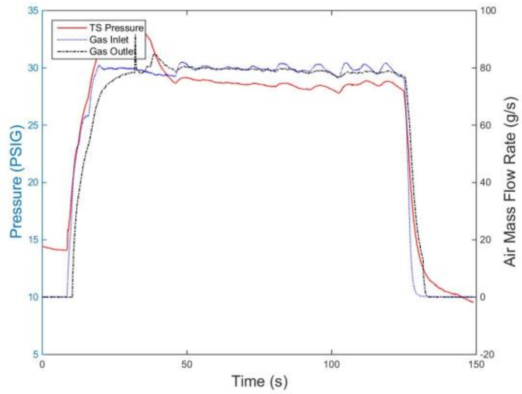
Figure A8: Raw data for air/water test "2015_12_30_test09". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the test section differential pressure and (c) the water inlet and water carryover flow rates.



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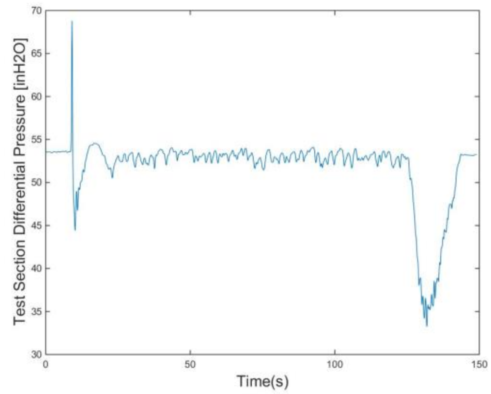

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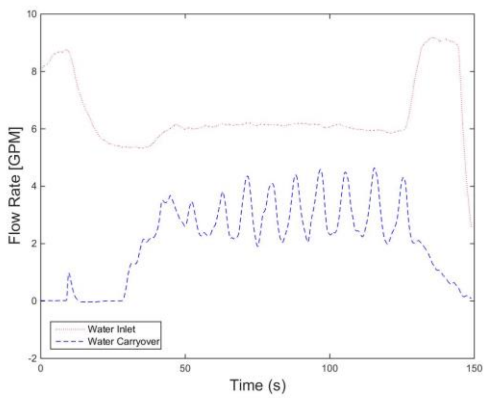
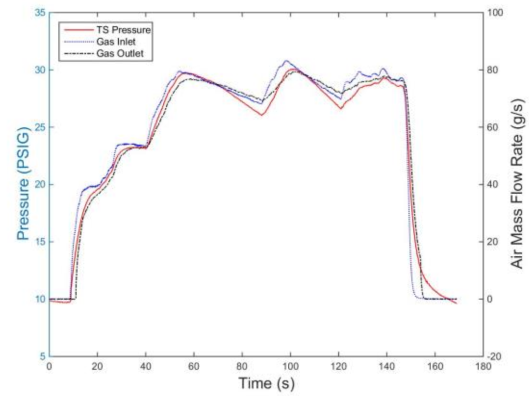


(c)

Figure A9: Raw data for air/water test "2015_12_30_test10". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the test section differential pressure and (c) the water inlet and water carryover flow rates.



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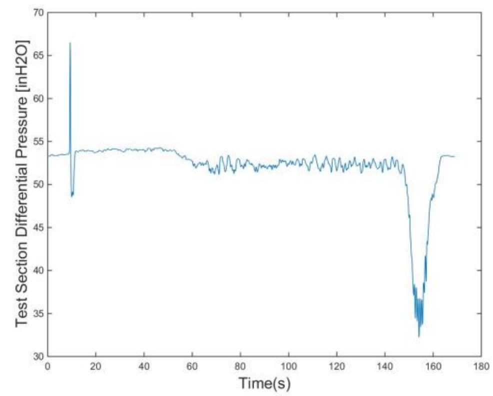

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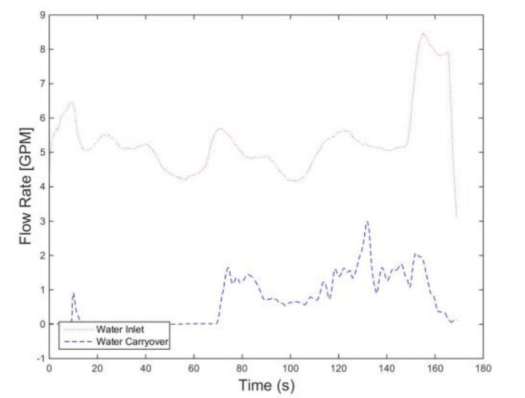

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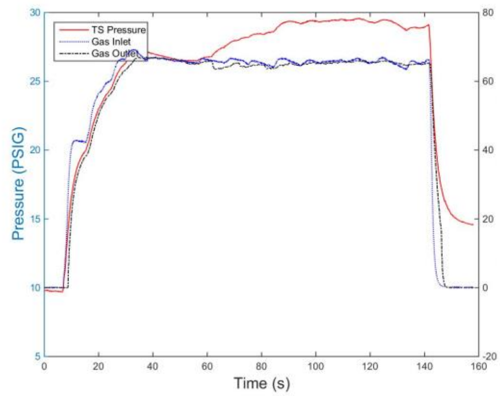
Figure A10: Raw data for air/water test “2015_12_30_test11”. The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the test section differential pressure and (c) the water inlet and water carryover flow rates.



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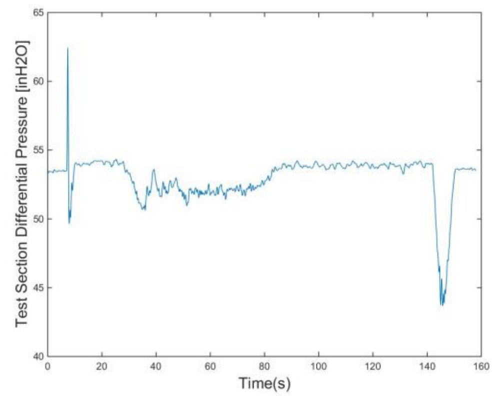

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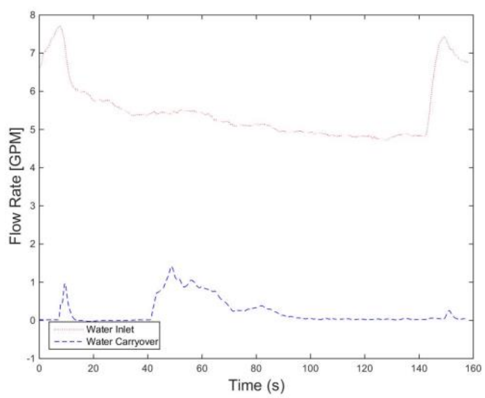

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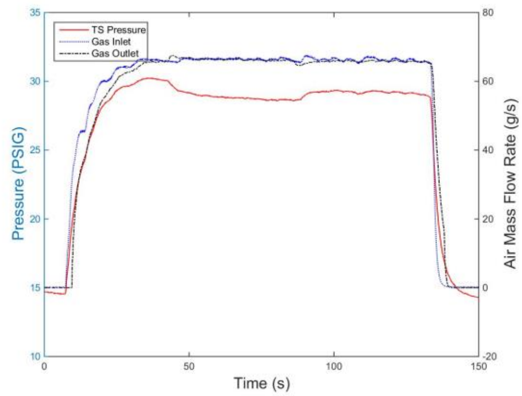
Figure A11: Raw data for air/water test "2015_12_30_test12". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the test section differential pressure and (c) the water inlet and water carryover flow rates.



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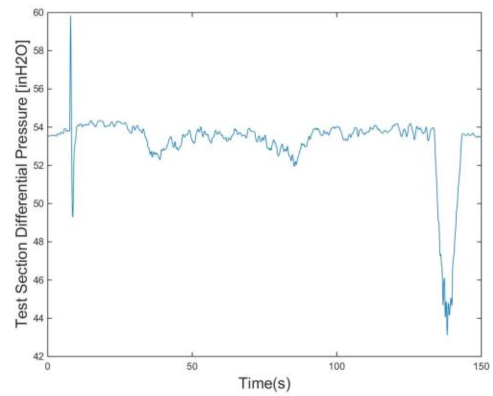

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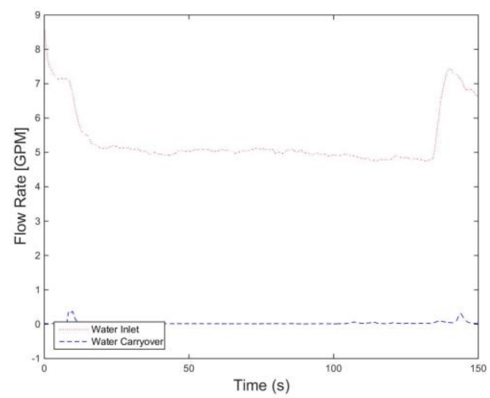

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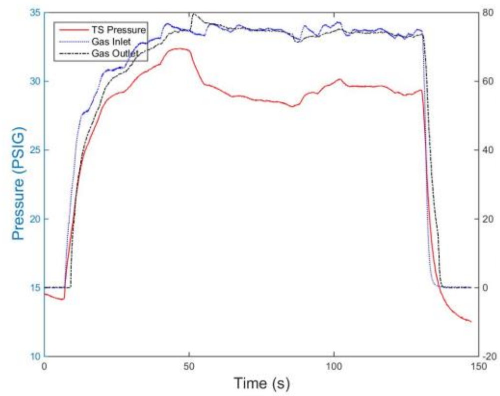
Figure A12: Raw data for air/water test "2015_12_30_test13". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the test section differential pressure and (c) the water inlet and water carryover flow rates.



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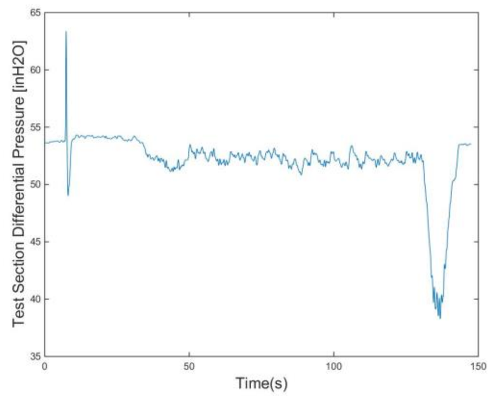

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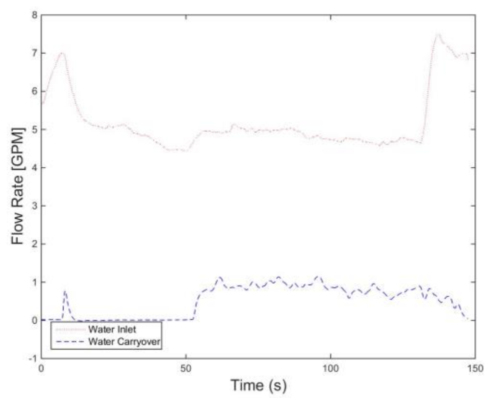

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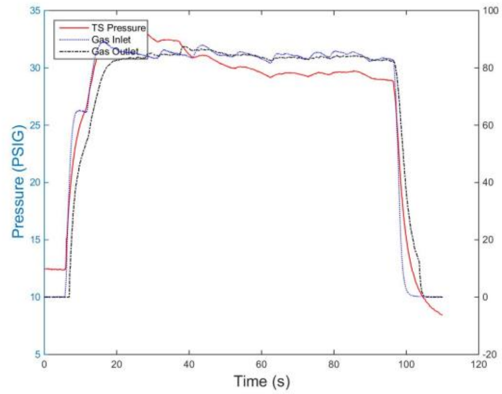
Figure A13: Raw data for air/water test "2015_12_30_test14". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the test section differential pressure and (c) the water inlet and water carryover flow rates.



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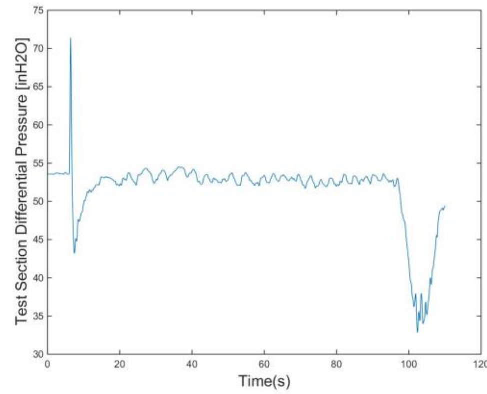

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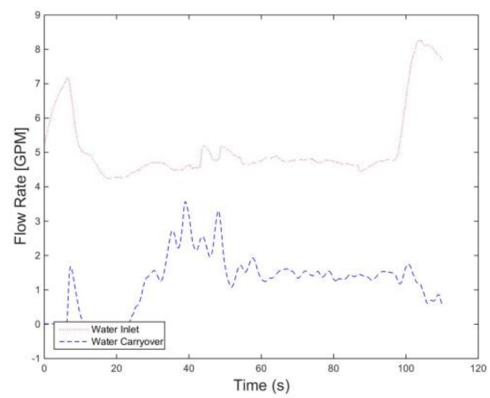
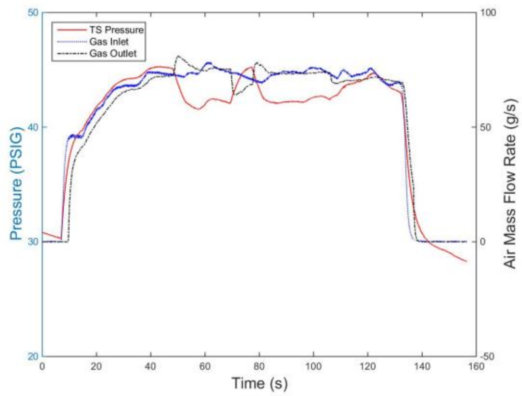
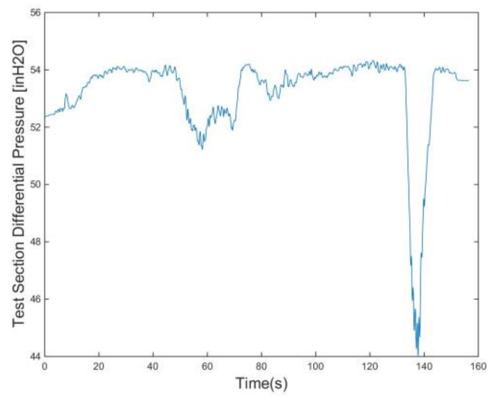


(c)

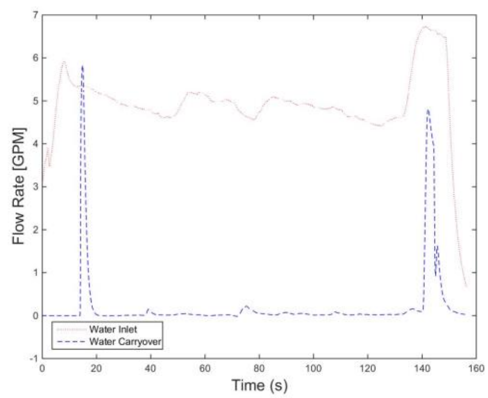
Figure A14: Raw data for air/water test “2015_12_30_test15”. The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the test section differential pressure and (c) the water inlet and water carryover flow rates.



(a)

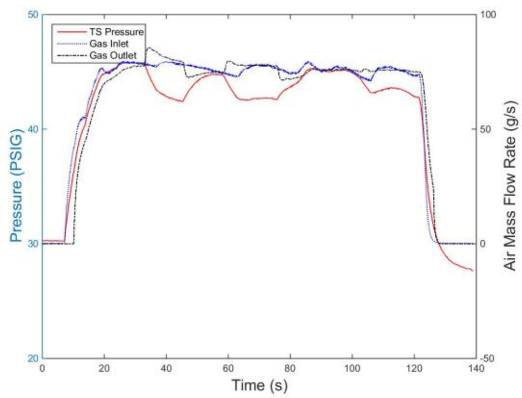


(b)

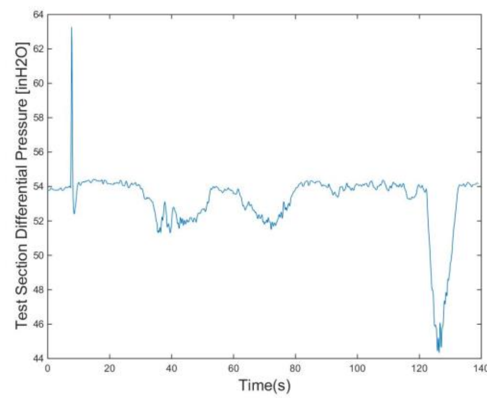


(c)

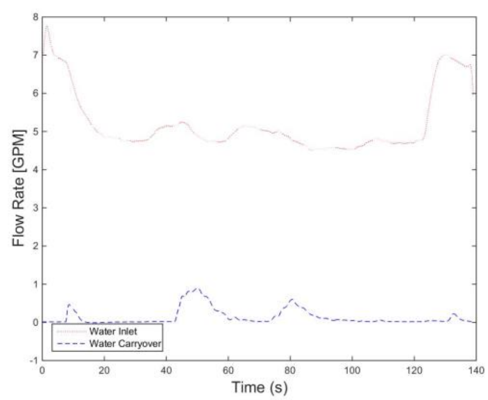
Figure A15: Raw data for air/water test “2015_12_30_test16”. The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the test section differential pressure and (c) the water inlet and water carryover flow rates.



(a)

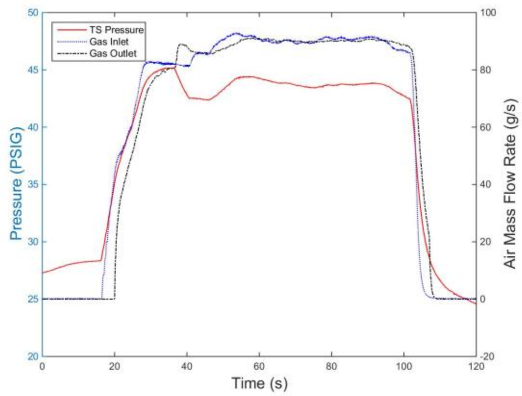


(b)

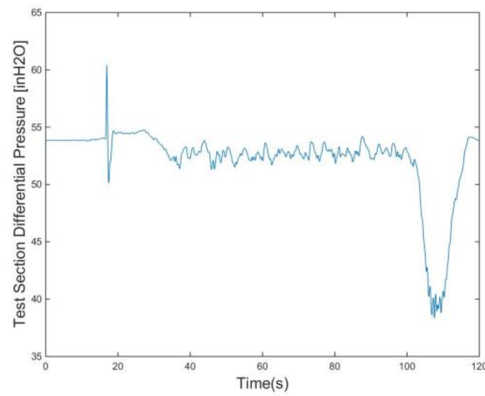


(c)

Figure A16: Raw data for air/water test "2015_12_30_test17". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the test section differential pressure and (c) the water inlet and water carryover flow rates.



(a)



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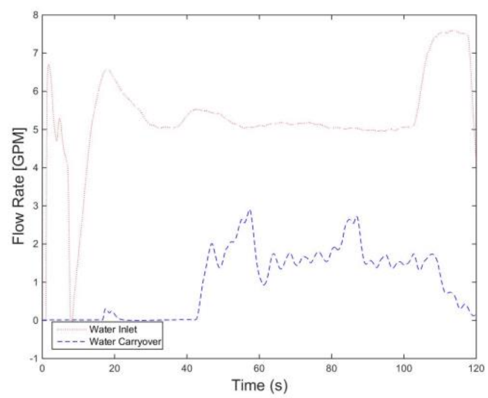
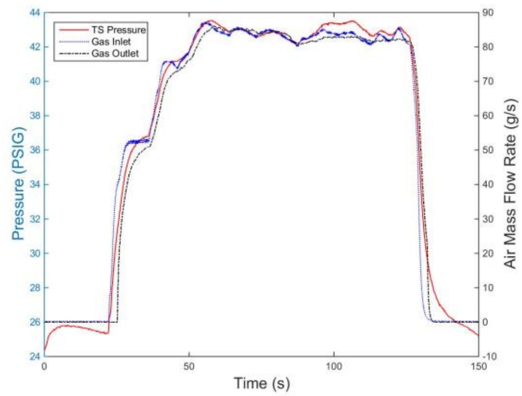
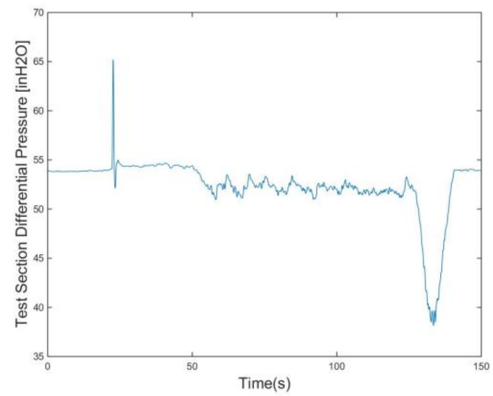


(c)

Figure A17: Raw data for air/water test "2015_12_30_test18". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the test section differential pressure and (c) the water inlet and water carryover flow rates.



(a)



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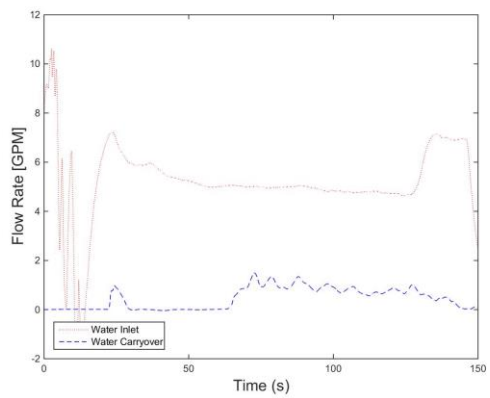
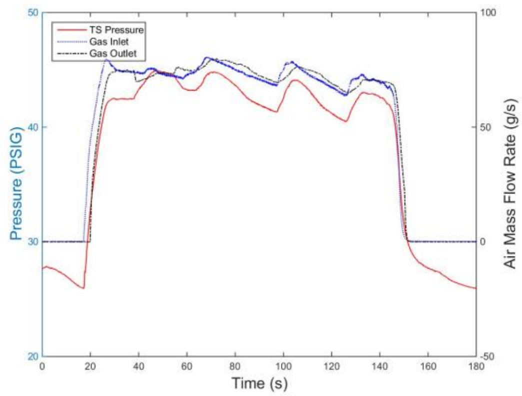
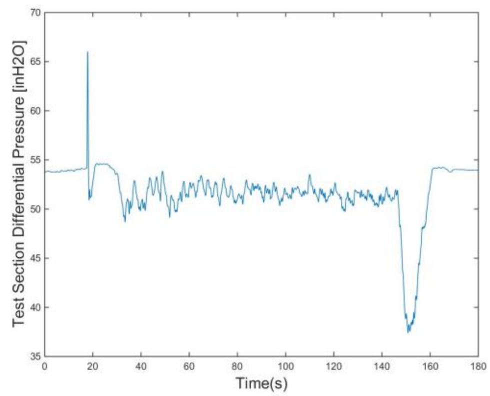


(c)

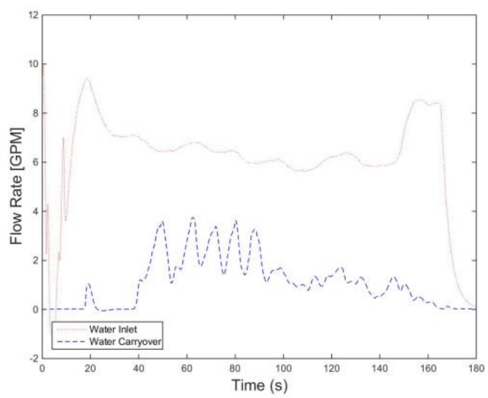
Figure A18: Raw data for air/water test “2015_12_30_test19”. The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the test section differential pressure and (c) the water inlet and water carryover flow rates.



(a)

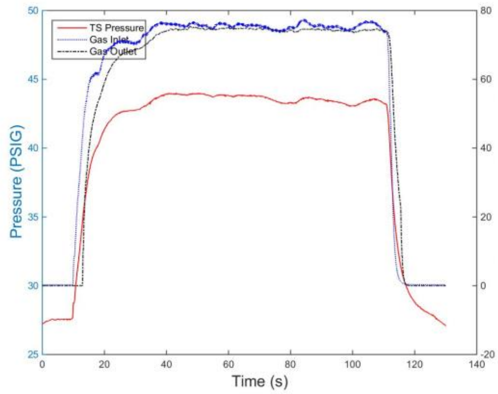


(b)

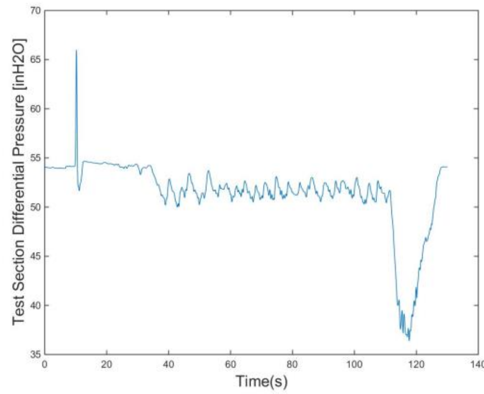


(c)

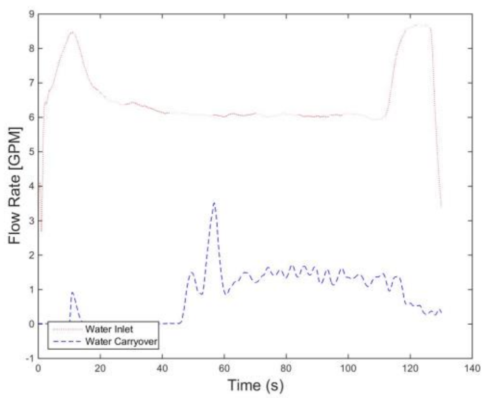
Figure A19: Raw data for air/water test "2015_12_30_test21". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the test section differential pressure and (c) the water inlet and water carryover flow rates.



(a)

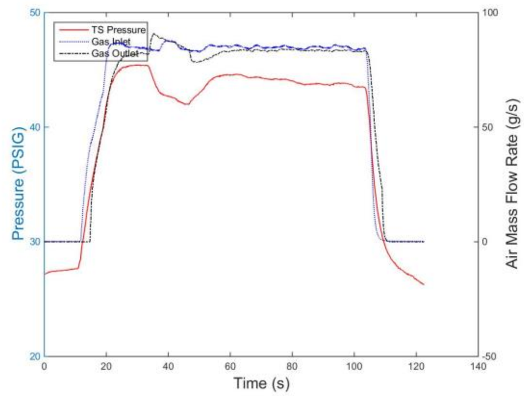


(b)

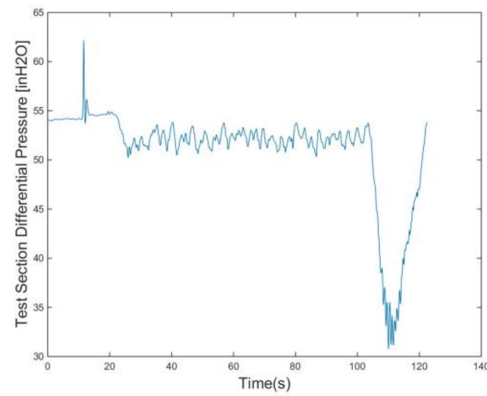


(c)

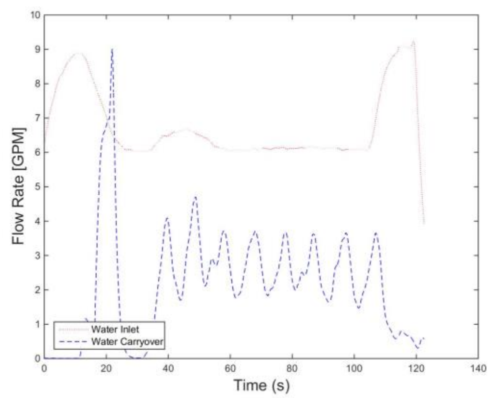
Figure A20: Raw data for air/water test “2015_12_30_test22”. The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the test section differential pressure and (c) the water inlet and water carryover flow rates.



(a)

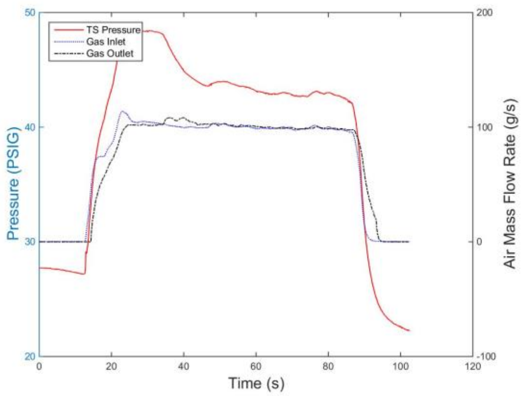


(b)

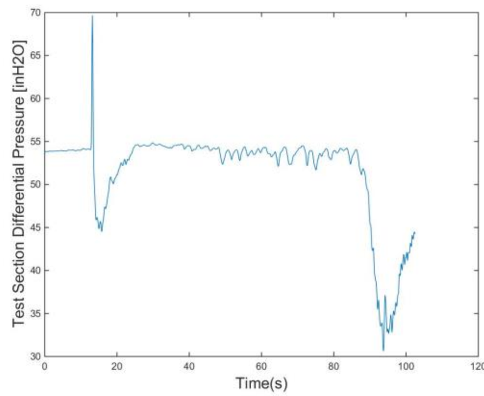


(c)

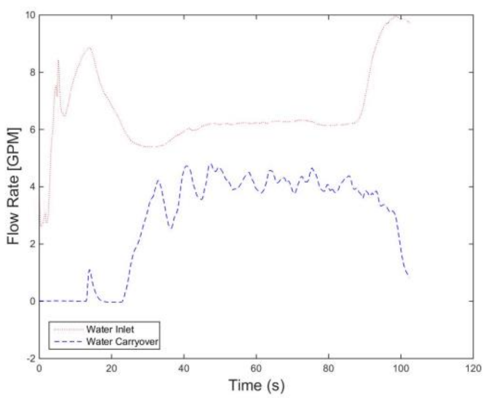
Figure A21: Raw data for air/water test “2015_12_30_test23”. The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the test section differential pressure and (c) the water inlet and water carryover flow rates.



(a)

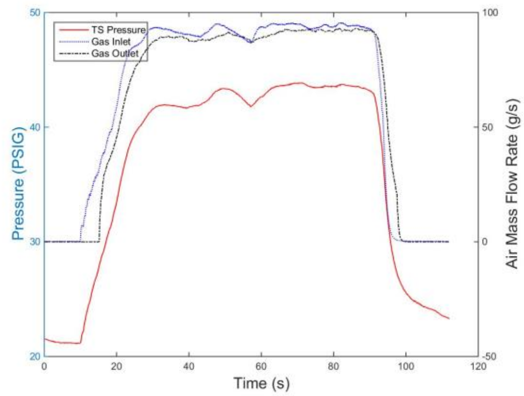


(b)

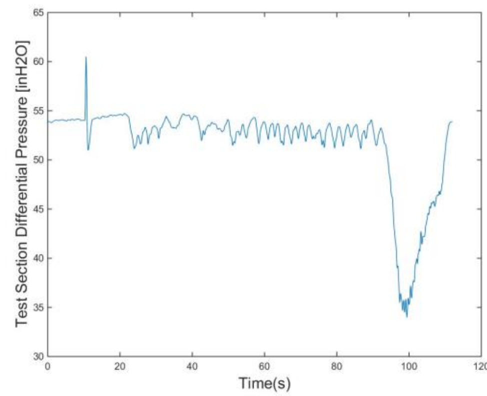


(c)

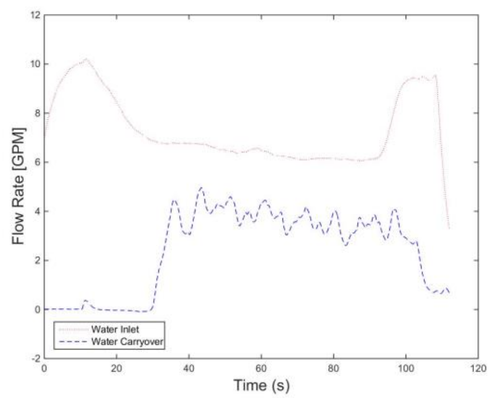
Figure A22: Raw data for air/water test "2015_12_30_test24". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the test section differential pressure and (c) the water inlet and water carryover flow rates.



(a)

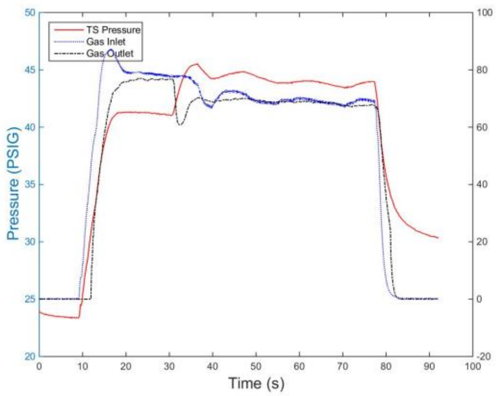


(b)

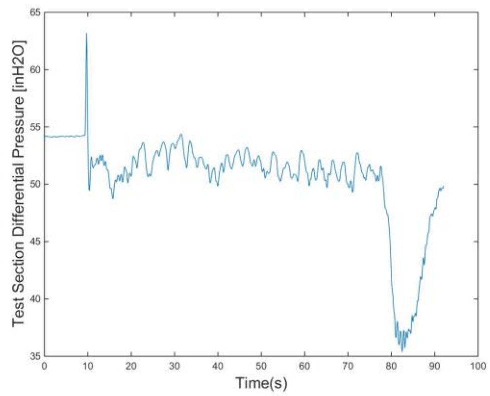


(c)

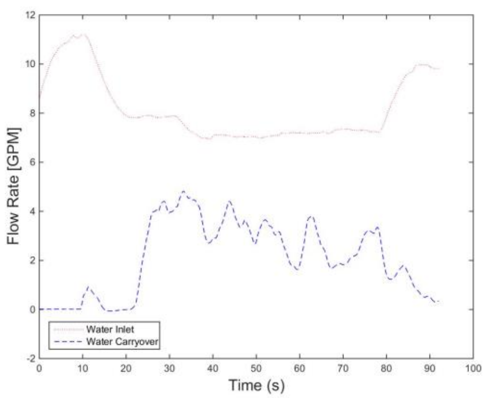
Figure A23: Raw data for air/water test "2015_12_30_test25". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the test section differential pressure and (c) the water inlet and water carryover flow rates.



(a)

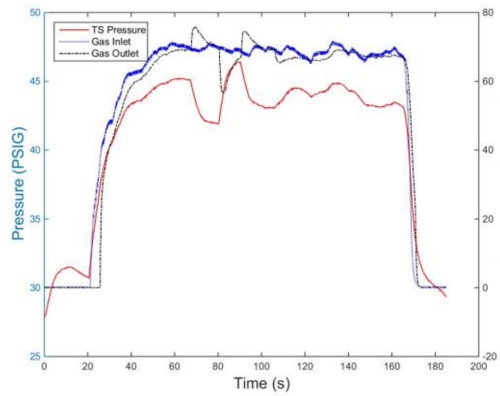


(b)

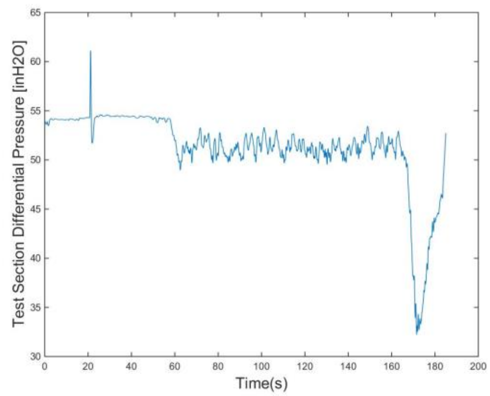


(c)

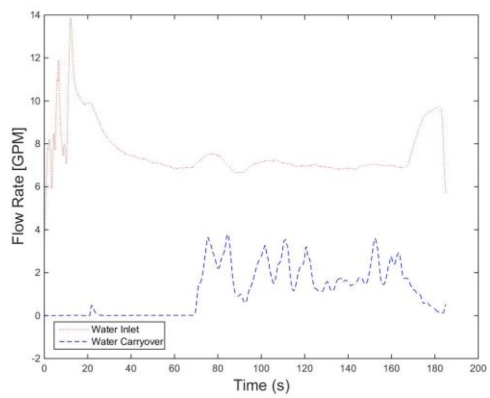
Figure A24: Raw data for air/water test "2015_12_30_test26". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the test section differential pressure and (c) the water inlet and water carryover flow rates.



(a)

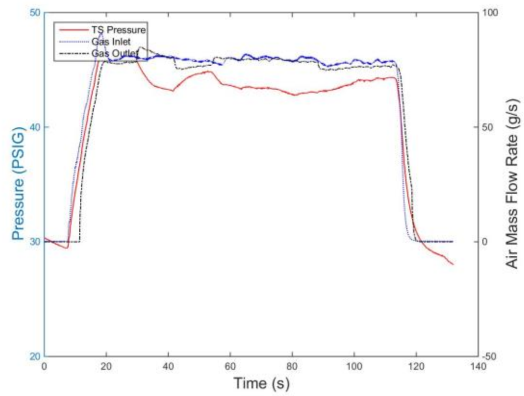


(b)

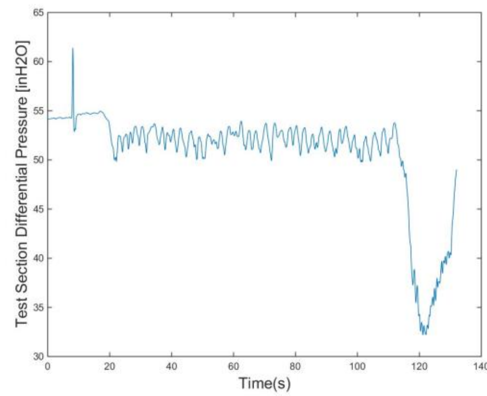


(c)

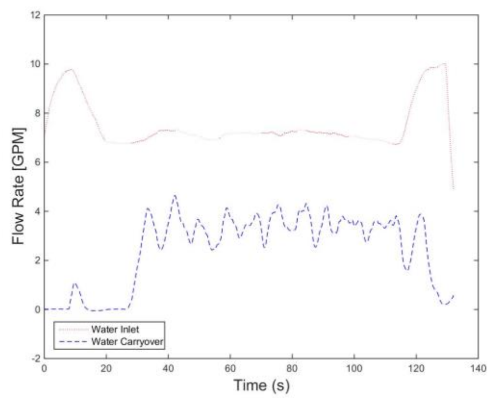
Figure A25: Raw data for air/water test "2015_12_30_test27". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the test section differential pressure and (c) the water inlet and water carryover flow rates.



(a)

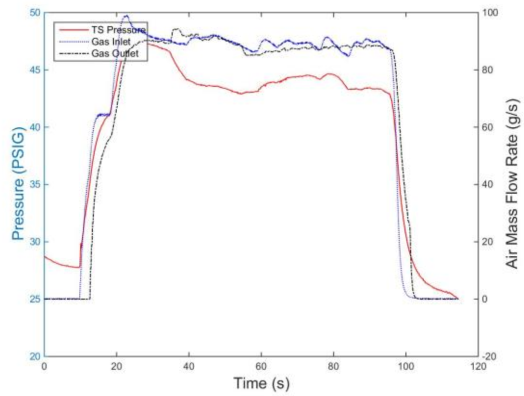


(b)

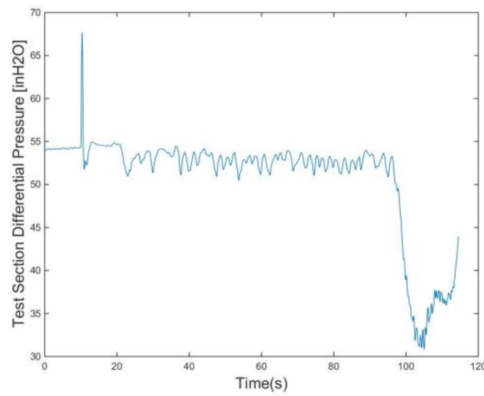


(c)

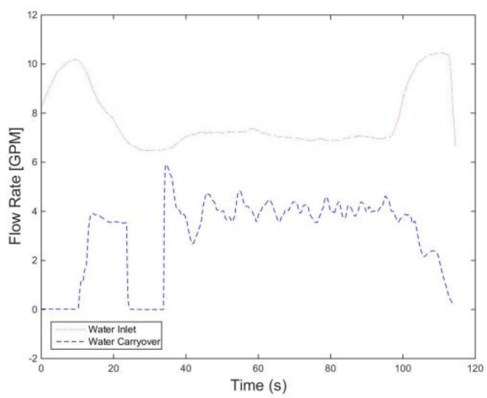
Figure A26: Raw data for air/water test "2015_12_30_test28". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the test section differential pressure and (c) the water inlet and water carryover flow rates.



(a)

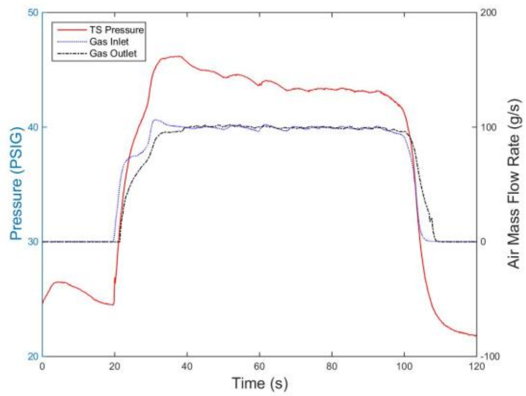


(b)

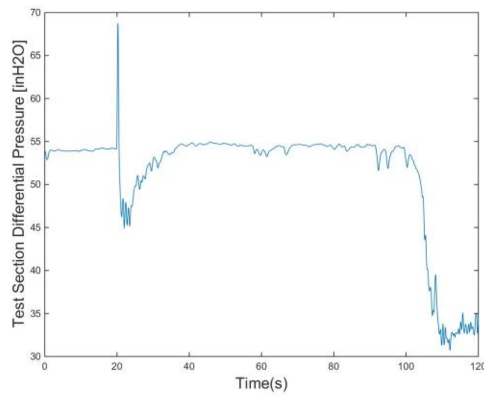


(c)

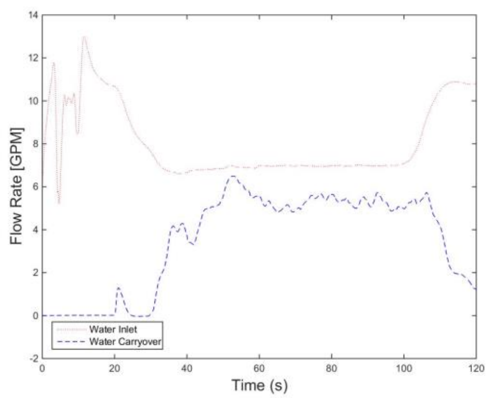
Figure A27: Raw data for air/water test "2015_12_30_test29". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the test section differential pressure and (c) the water inlet and water carryover flow rates.



(a)

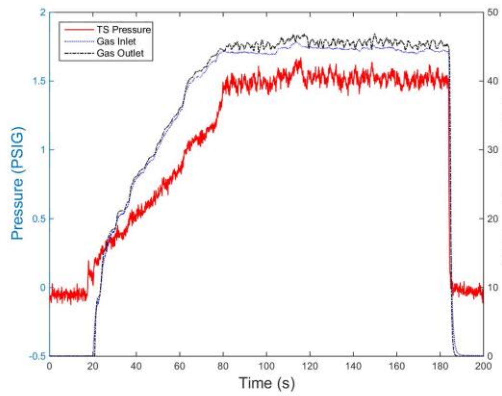


(b)

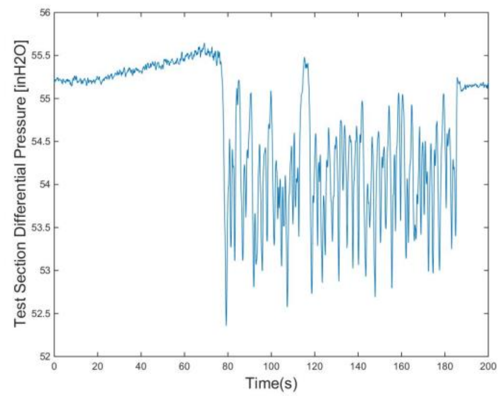


(c)

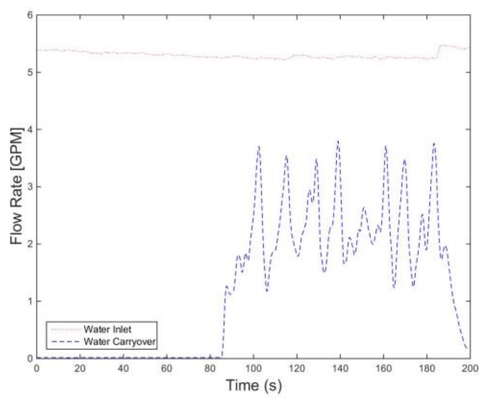
Figure A28: Raw data for air/water test "2015_12_30_test30". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the test section differential pressure and (c) the water inlet and water carryover flow rates.



(a)

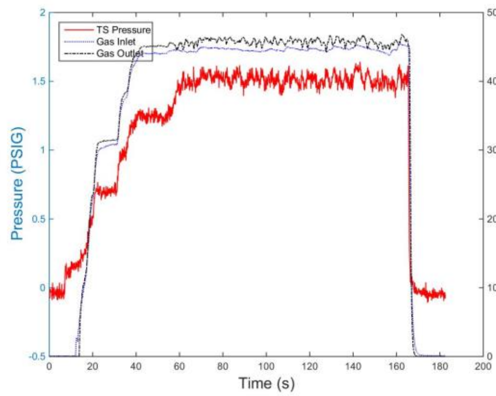


(b)

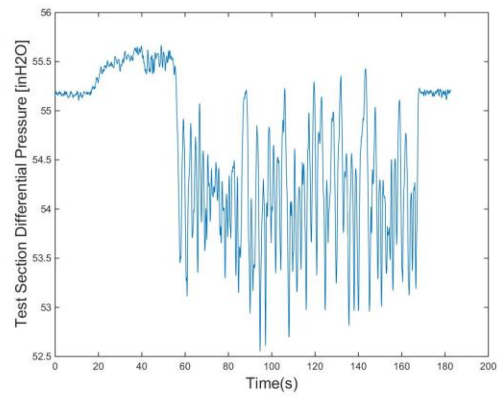


(c)

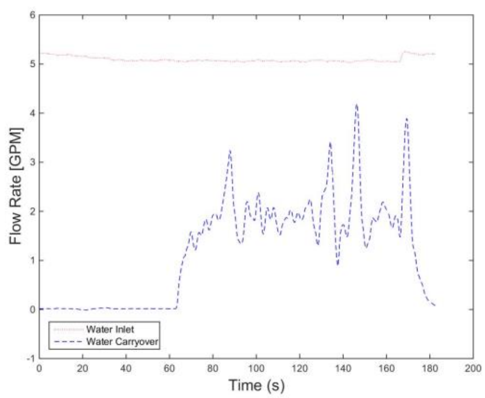
Figure A29: Raw data for air/water test “2016_01_21_test01”. The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the test section differential pressure and (c) the water inlet and water carryover flow rates.



(a)

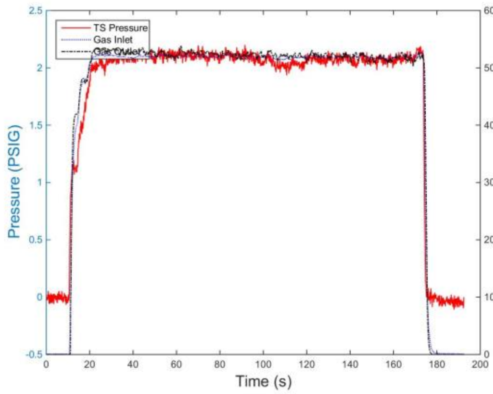


(b)

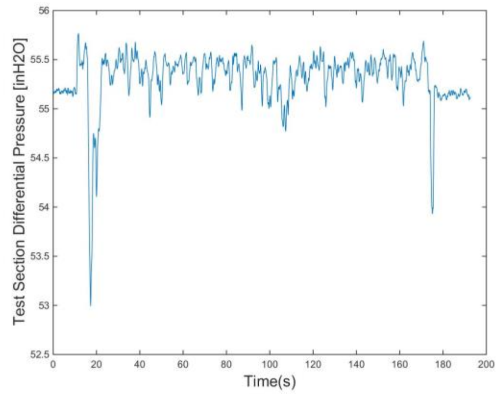


(c)

Figure A30: Raw data for air/water test “2016_01_21_test02”. The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the test section differential pressure and (c) the water inlet and water carryover flow rates.



(a)



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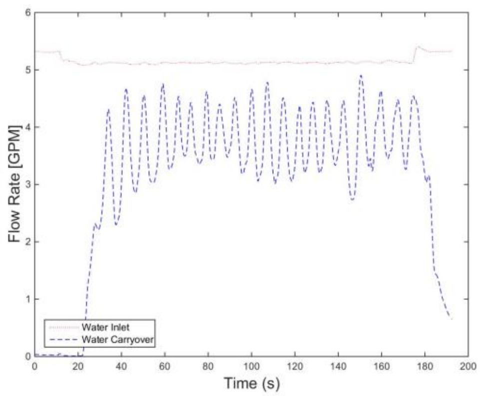
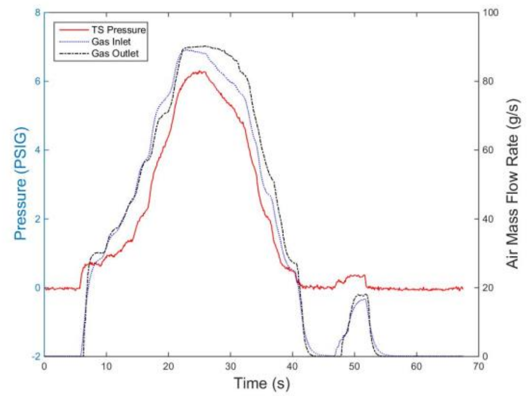
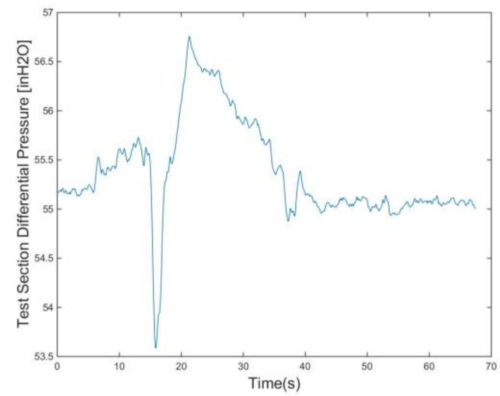


(c)

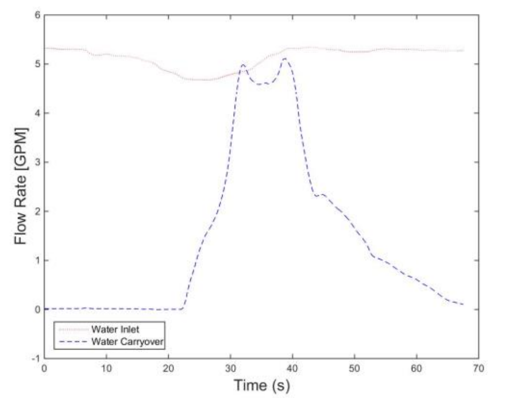
Figure A31: Raw data for air/water test “2016_01_21_test03”. The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the test section differential pressure and (c) the water inlet and water carryover flow rates.



(a)

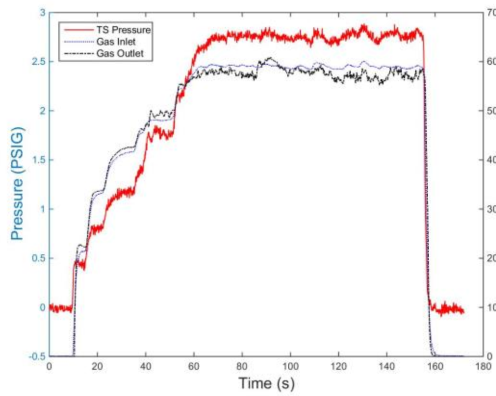


(b)

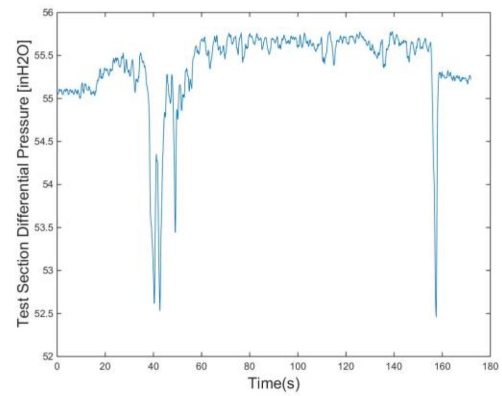


(c)

Figure A32: Raw data for air/water test “2016_01_21_test04”. The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the test section differential pressure and (c) the water inlet and water carryover flow rates.



(a)



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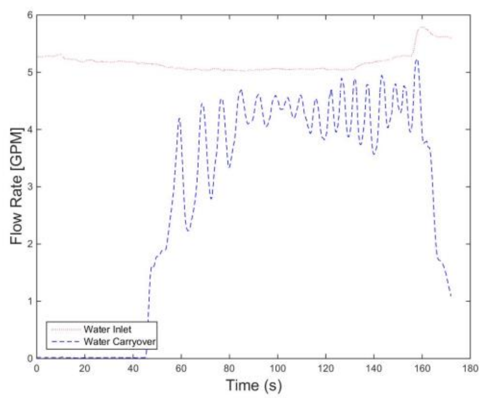
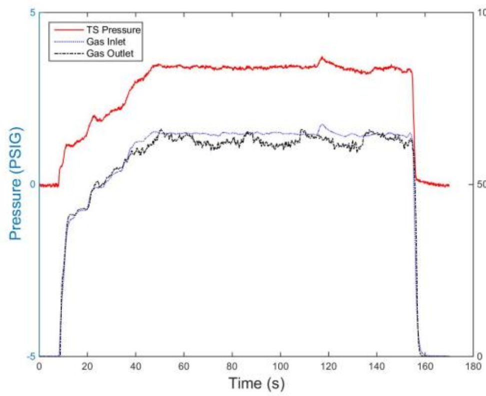
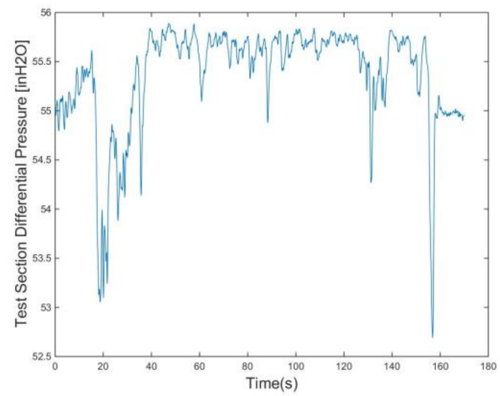


(c)

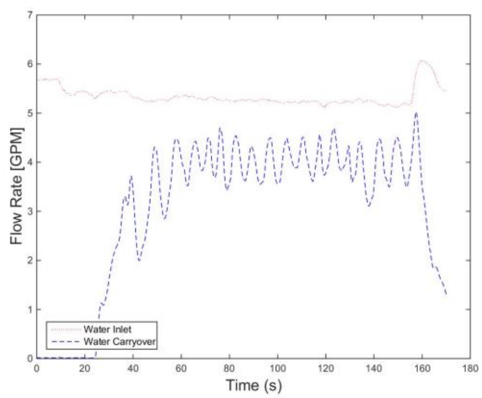
Figure A33: Raw data for air/water test "2016_01_21_test05". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the test section differential pressure and (c) the water inlet and water carryover flow rates.



(a)

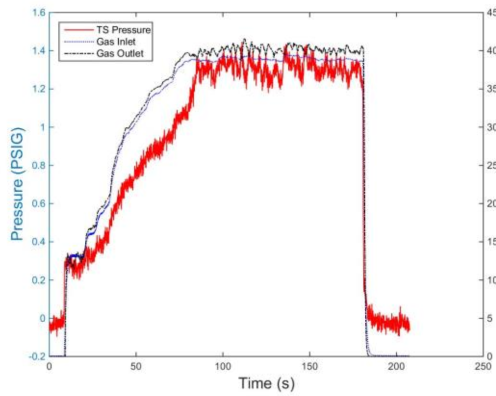


(b)

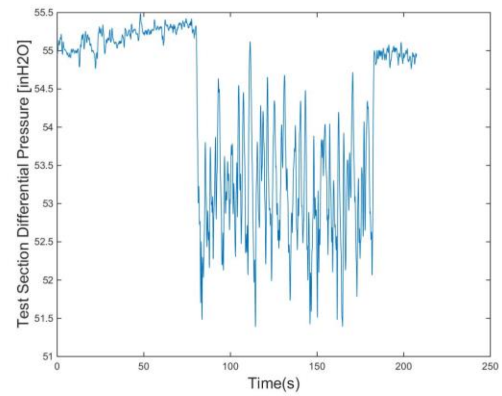


(c)

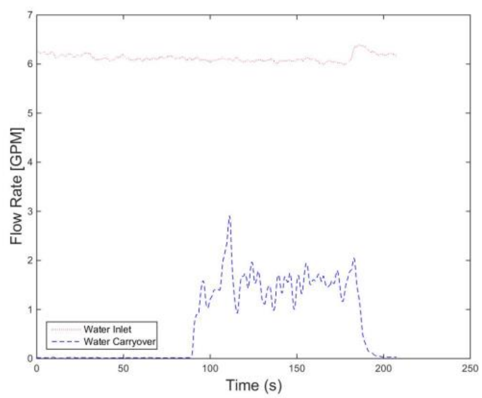
Figure A34: Raw data for air/water test “2016_01_21_test06”. The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the test section differential pressure and (c) the water inlet and water carryover flow rates.



(a)

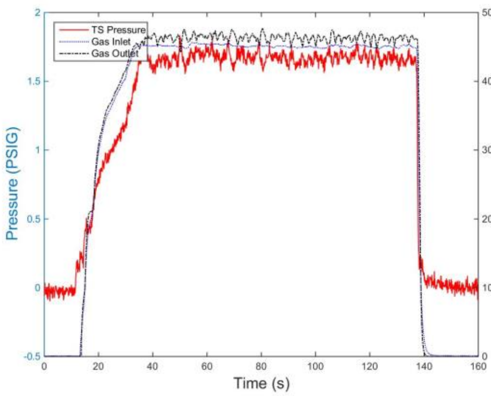


(b)

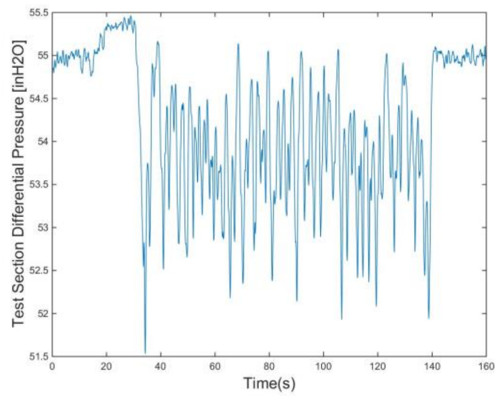


(c)

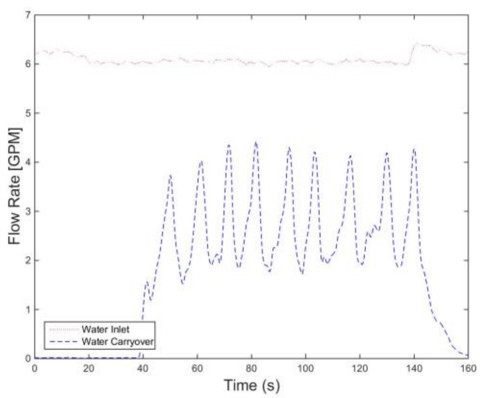
Figure A35: Raw data for air/water test “2016_01_21_test07”. The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the test section differential pressure and (c) the water inlet and water carryover flow rates.



(a)

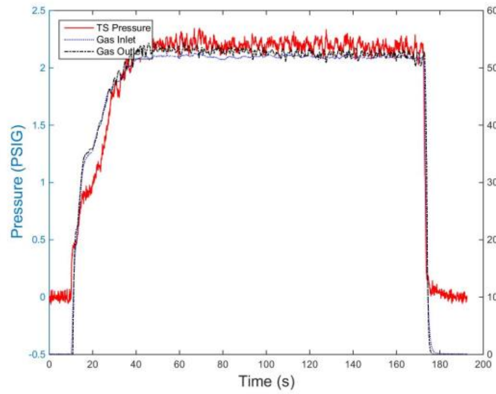


(b)

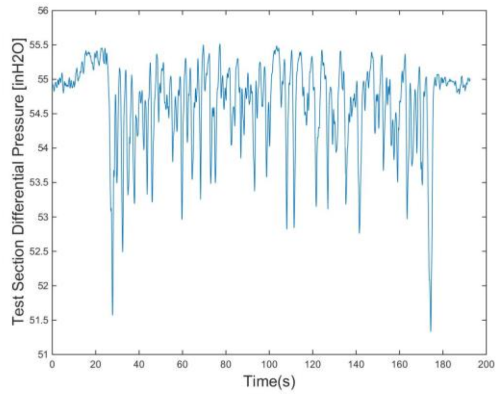


(c)

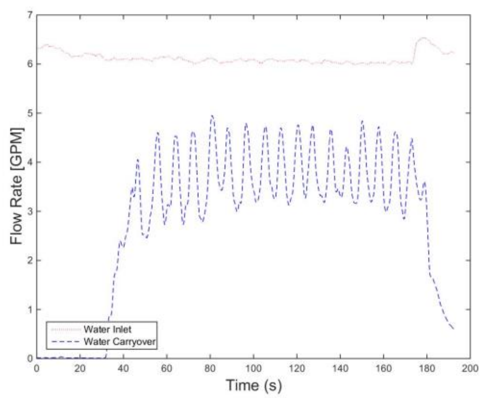
Figure A36: Raw data for air/water test "2016_01_21_test08". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the test section differential pressure and (c) the water inlet and water carryover flow rates.



(a)

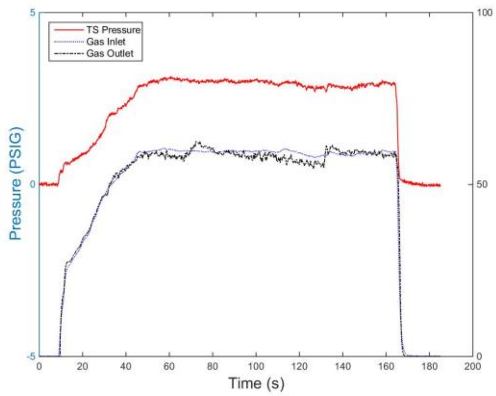


(b)

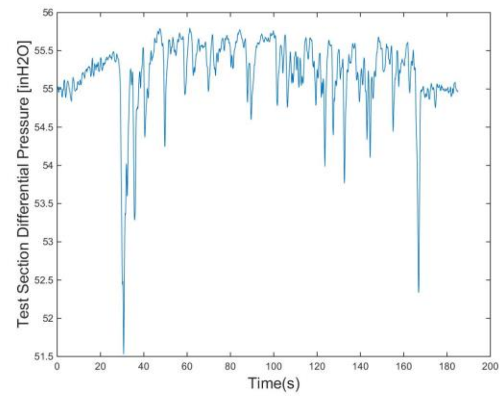


(c)

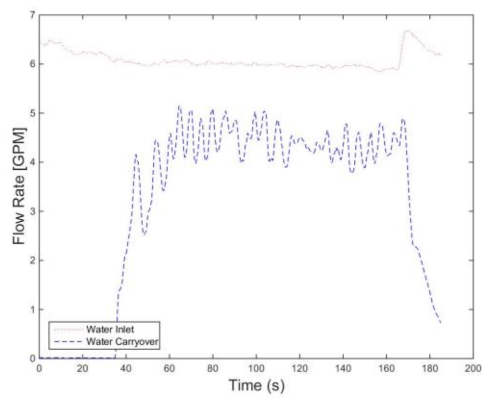
Figure A37: Raw data for air/water test "2016_01_21_test09". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the test section differential pressure and (c) the water inlet and water carryover flow rates.



(a)

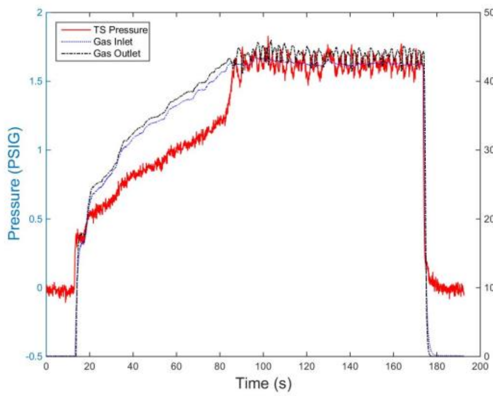


(b)

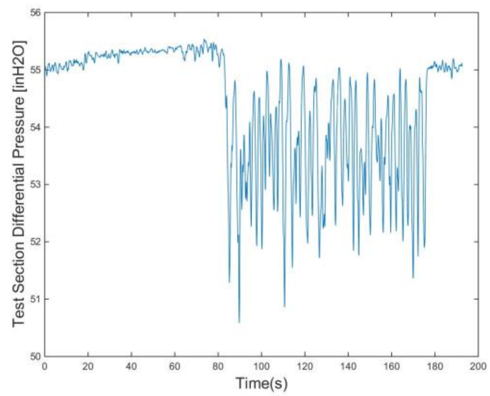


(c)

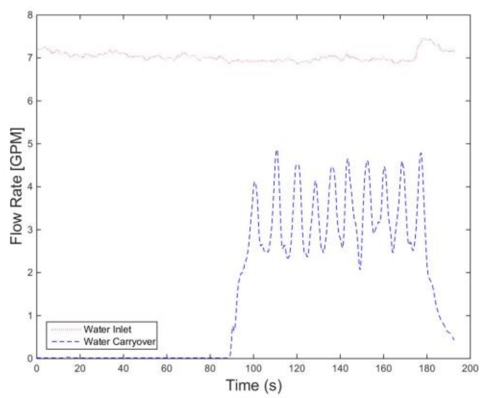
Figure A38: Raw data for air/water test “2016_01_21_test10”. The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the test section differential pressure and (c) the water inlet and water carryover flow rates.



(a)

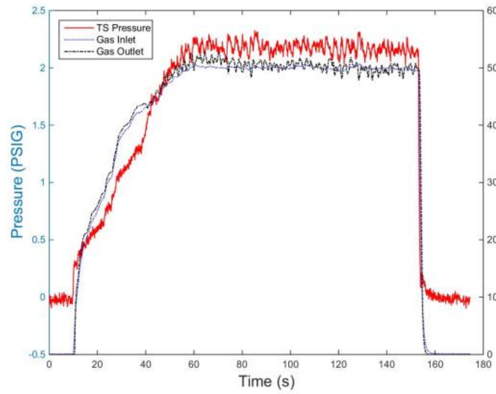


(b)

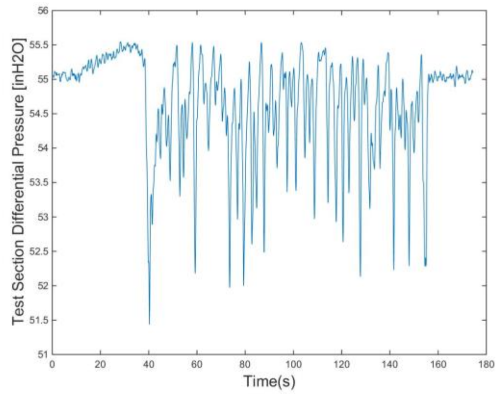


(c)

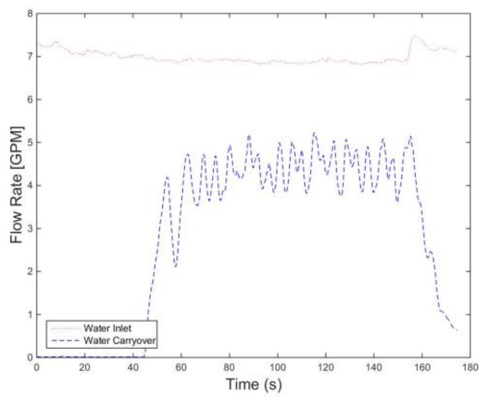
Figure A39: Raw data for air/water test "2016_01_21_test11". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the test section differential pressure and (c) the water inlet and water carryover flow rates.



(a)

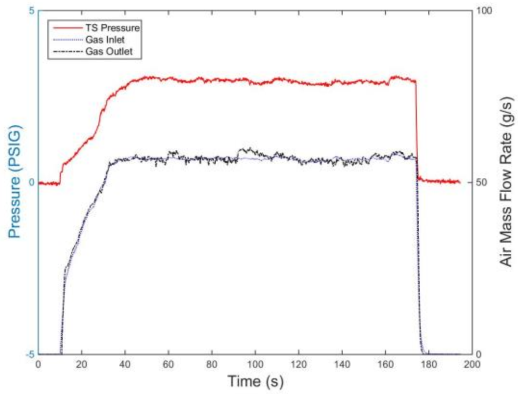


(b)

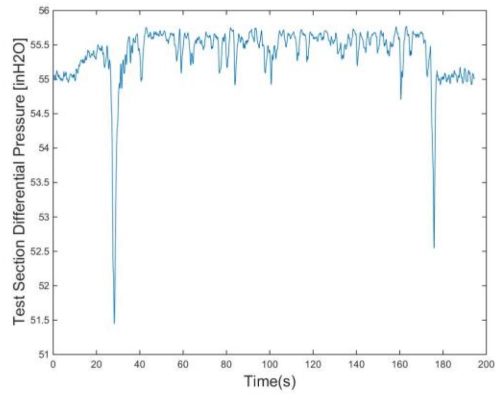


(c)

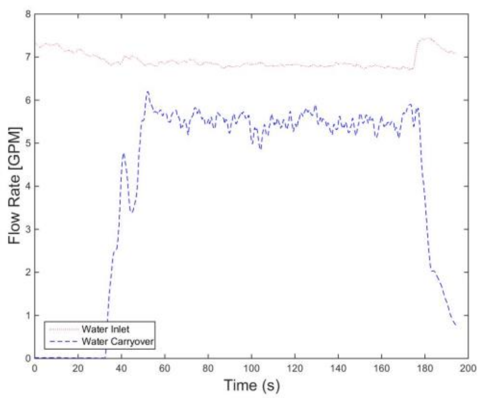
Figure A40: Raw data for air/water test “2016_01_21_test12”. The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the test section differential pressure and (c) the water inlet and water carryover flow rates.



(a)

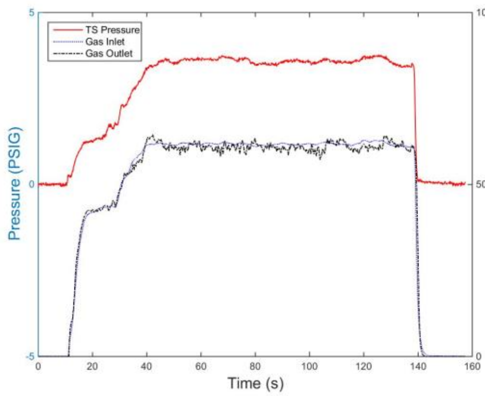


(b)

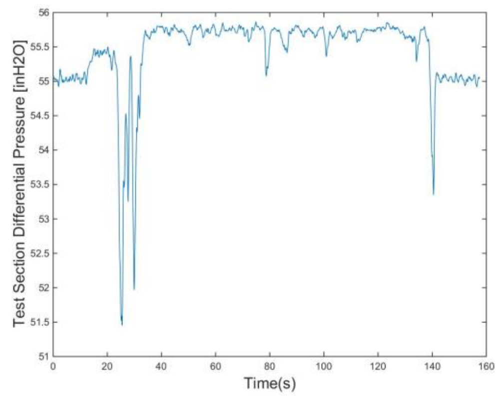


(c)

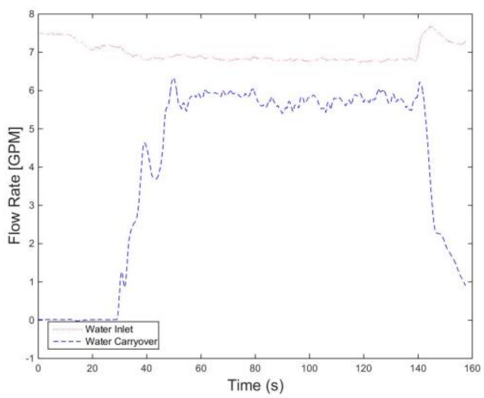
Figure A41: Raw data for air/water test "2016_01_21_test13". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the test section differential pressure and (c) the water inlet and water carryover flow rates.



(a)

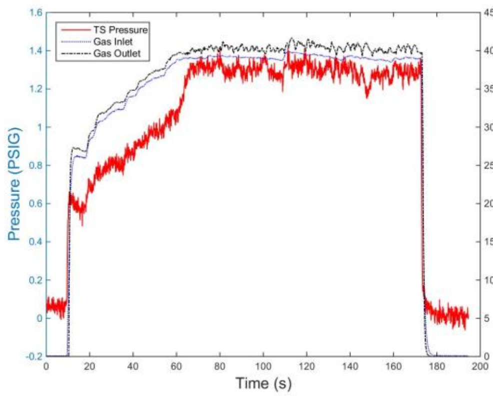


(b)

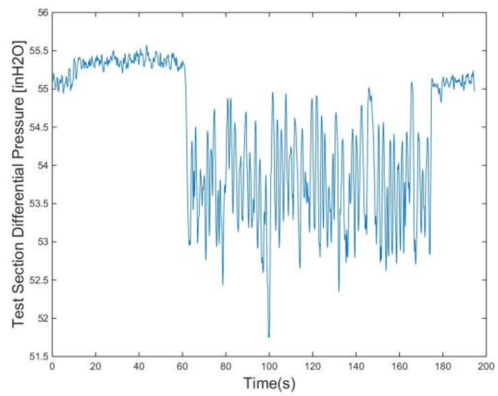


(c)

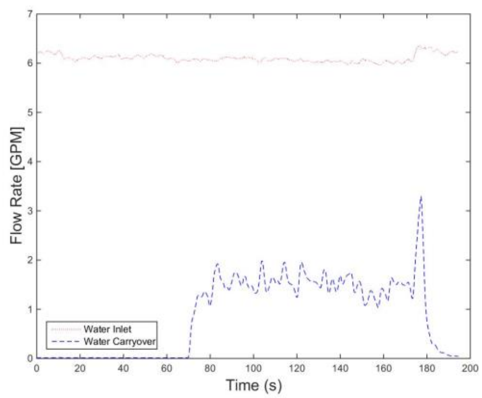
Figure A42: Raw data for air/water test "2016_01_21_test14". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the test section differential pressure and (c) the water inlet and water carryover flow rates.



(a)



(b)

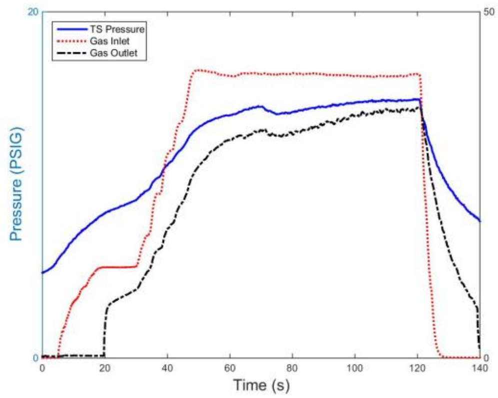


(c)

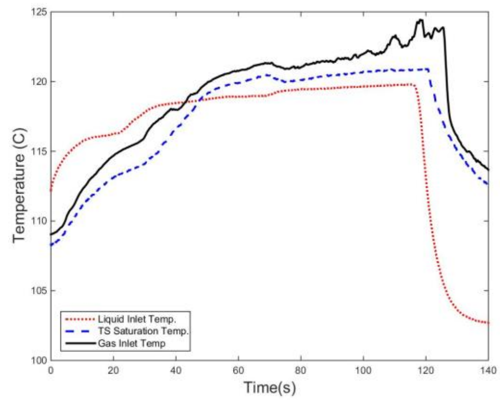
Figure A43: Raw data for air/water test "2016_01_21_test15". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the test section differential pressure and (c) the water inlet and water carryover flow rates.

APPENDIX B: STEAM/WATER RAW DATA

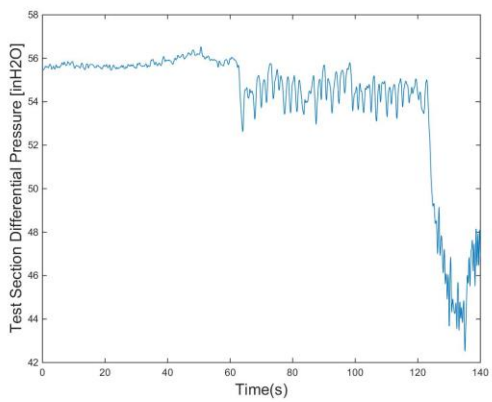
This section contains the plots of the raw data from the steam/water tests. The name of the tests is included on the figure caption and the names correspond with the names given in the reduced data tables given in Appendix D.



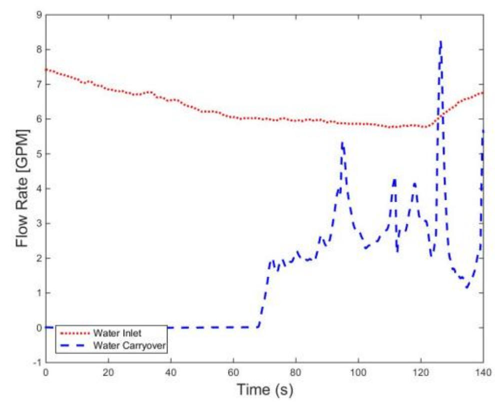
(a)



(b)



(c)



(d)

Figure B1: Raw data for steam/water test “2015_12_01_test01”. The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.

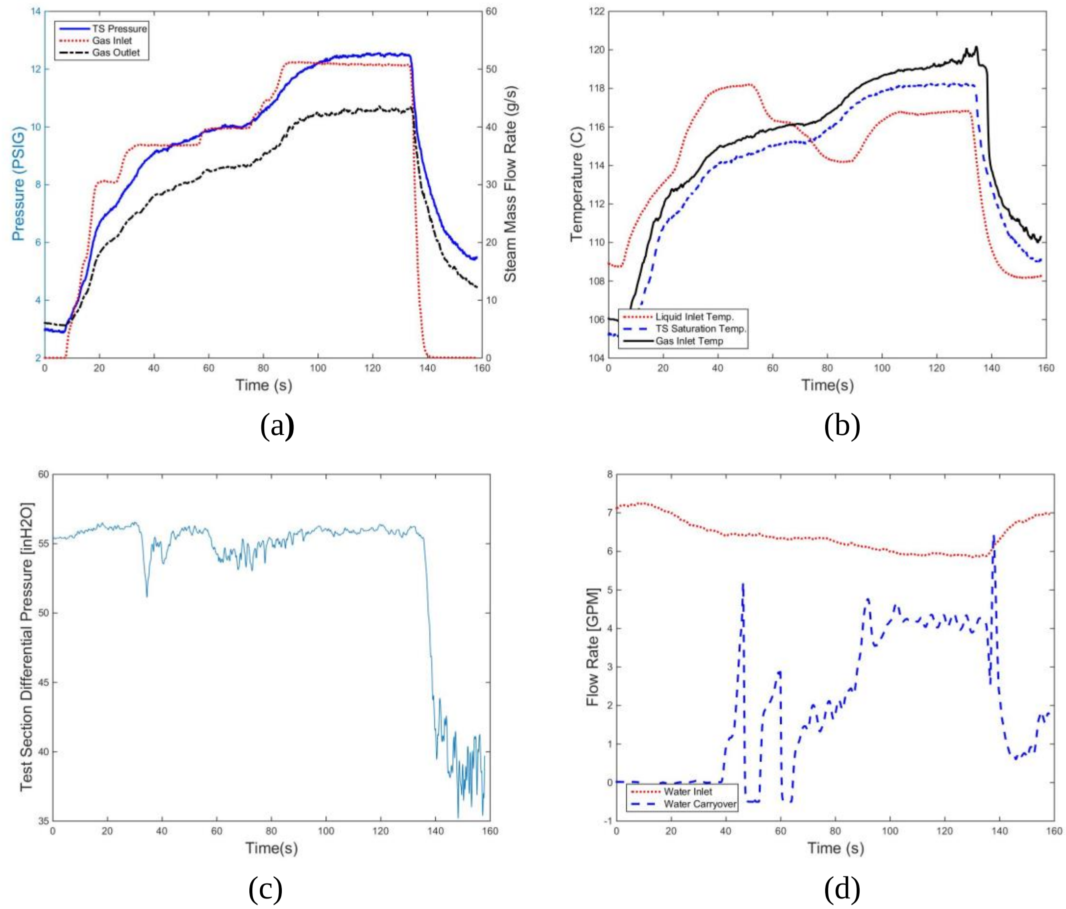


Figure B2: Raw data for steam/water test "2015_12_01_test02". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.

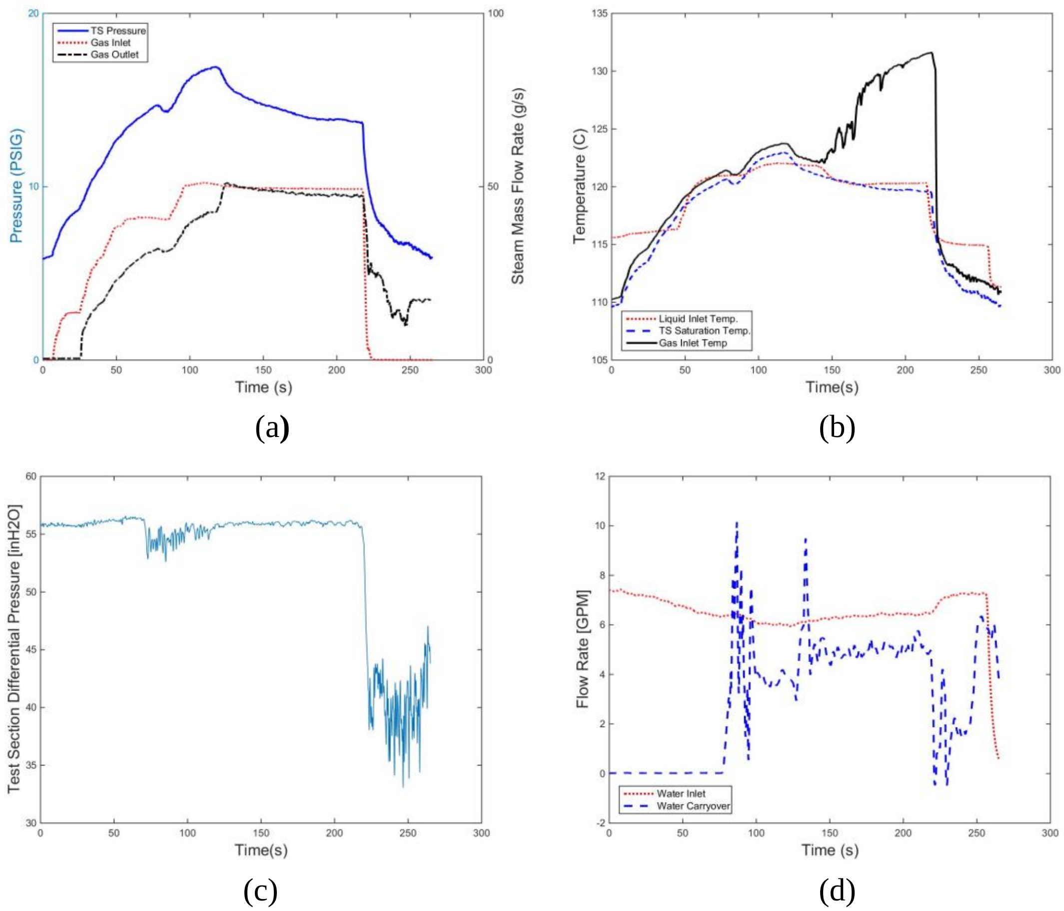
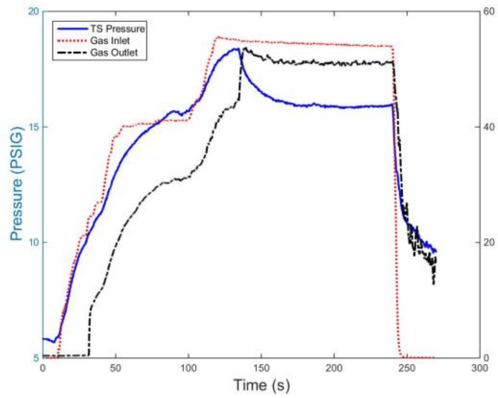
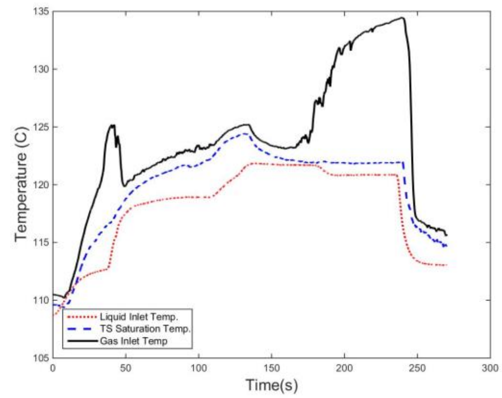


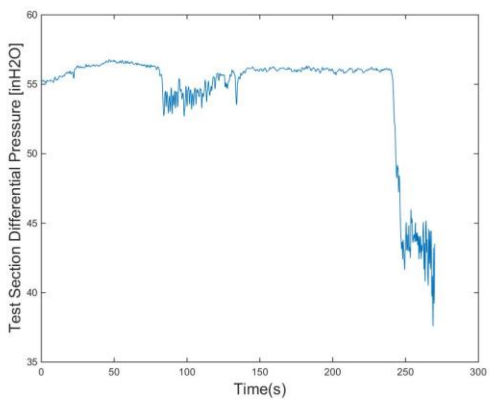
Figure B3: Raw data for steam/water test “2015_12_01_test03”. The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



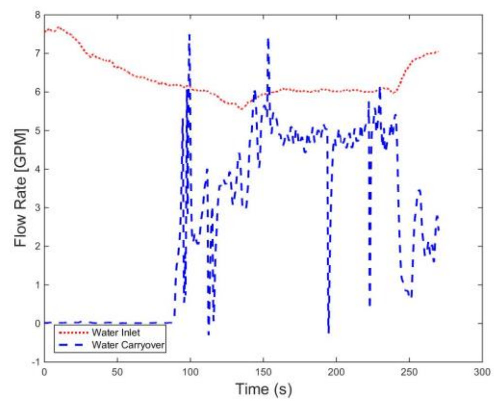
(a)



(b)

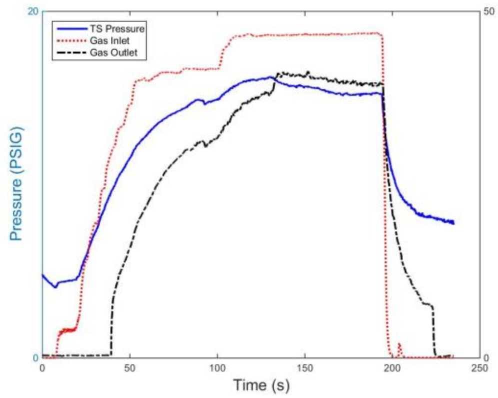


(c)

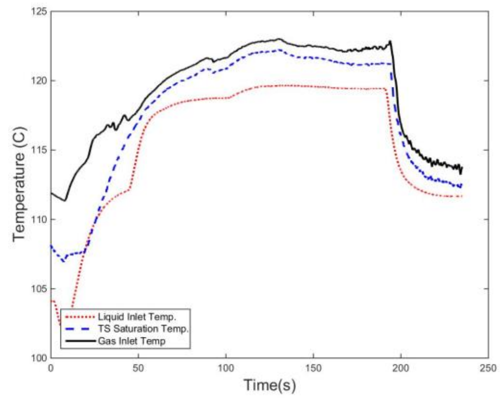


(d)

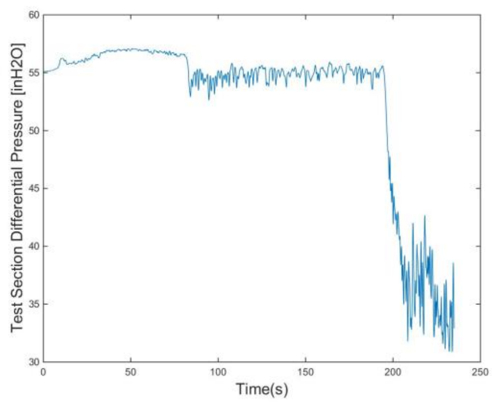
Figure B4: Raw data for steam/water test "2015_12_01_test04". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



(a)



(b)



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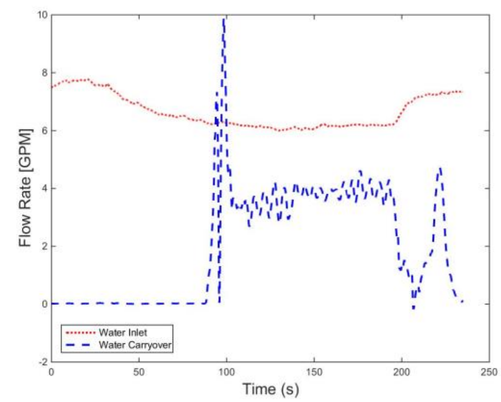
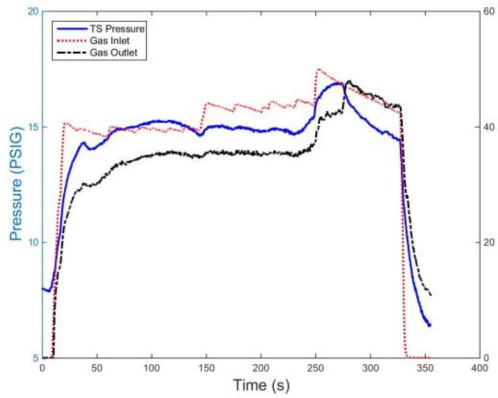
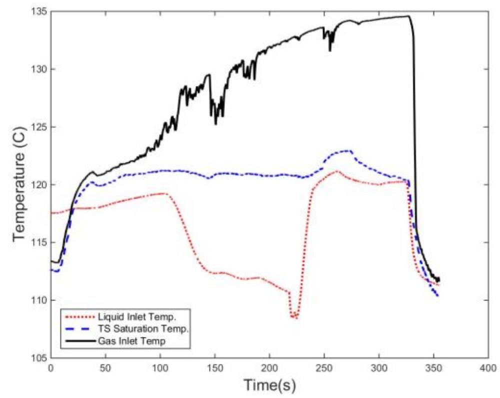


(d)

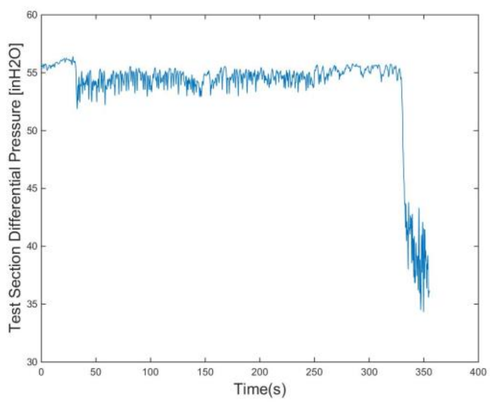
Figure B5: Raw data for steam/water test "2015_12_01_test05". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



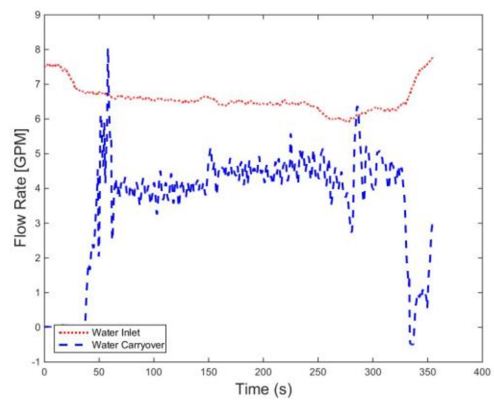
(a)



(b)

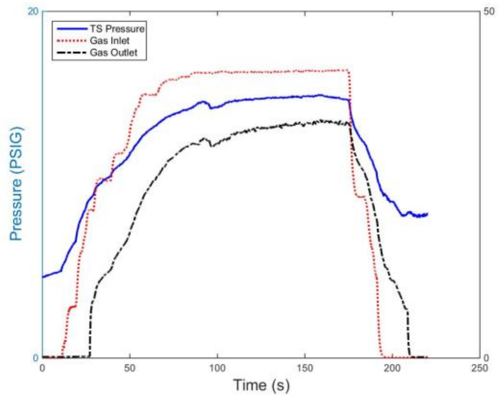


(c)

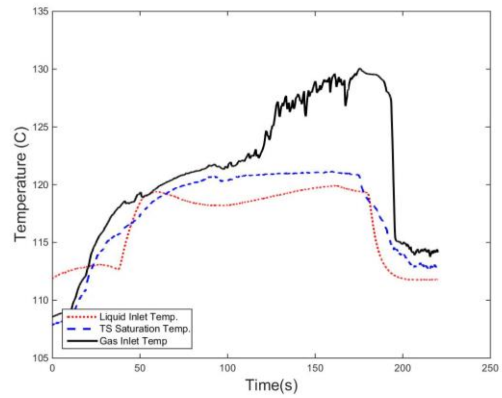


(d)

Figure B6: Raw data for steam/water test "*2015_12_02_test01*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



(a)



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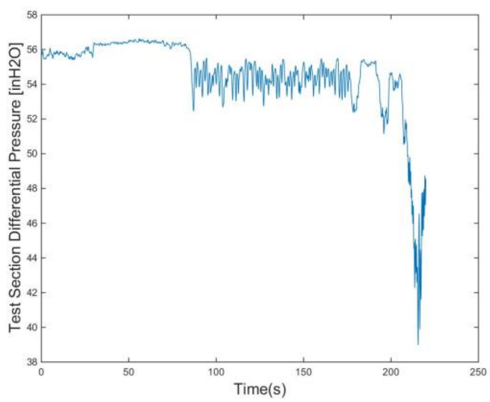
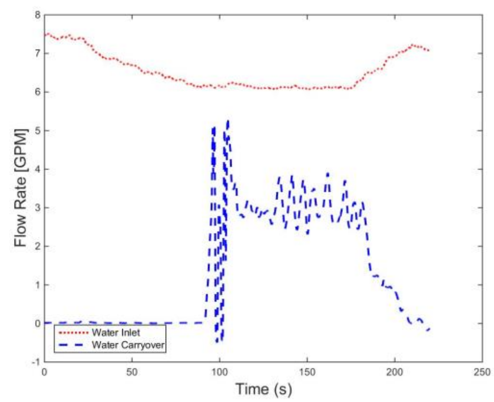
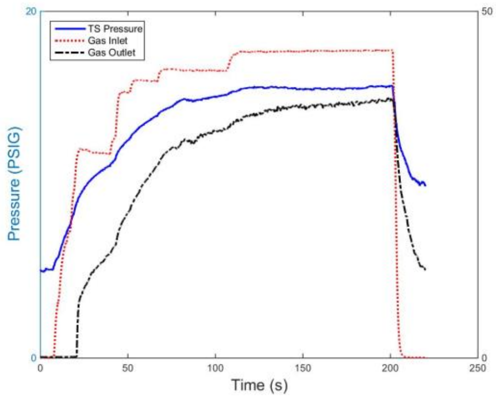


(c)

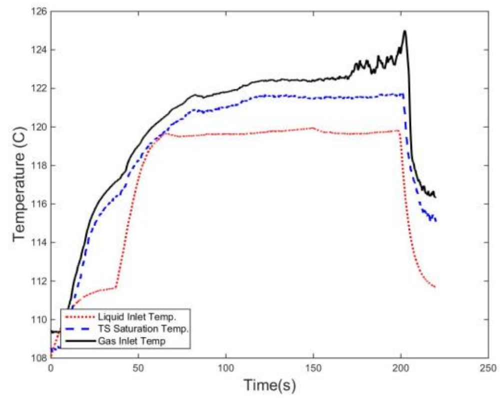


(d)

Figure B7: Raw data for steam/water test "*2015_12_02_test02*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



(a)



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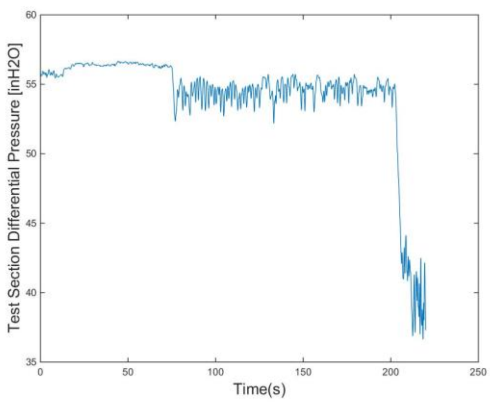

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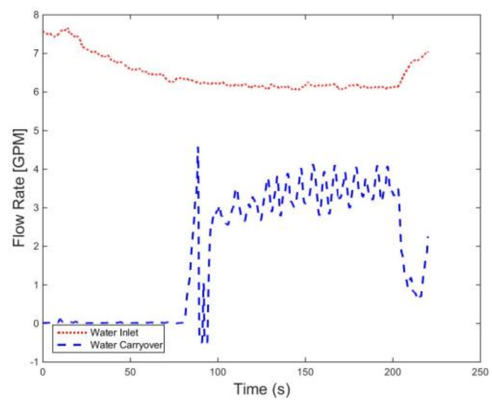
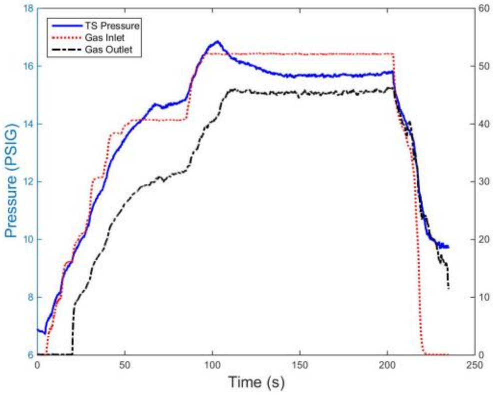
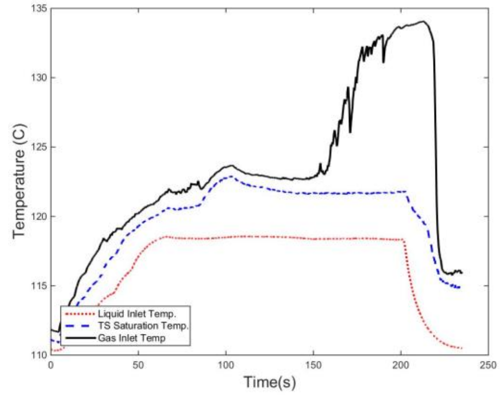


(d)

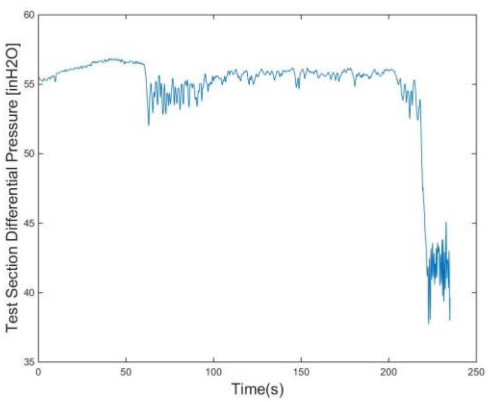
Figure B8: Raw data for steam/water test "*2015_12_02_test03*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



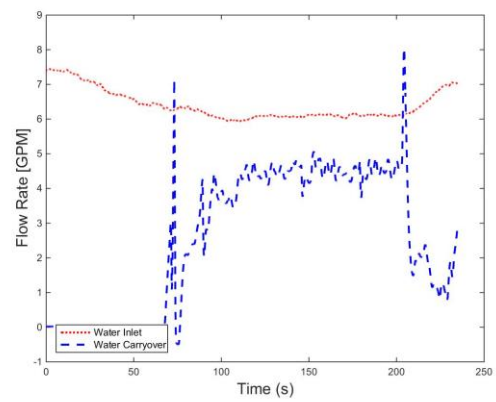
(a)



(b)

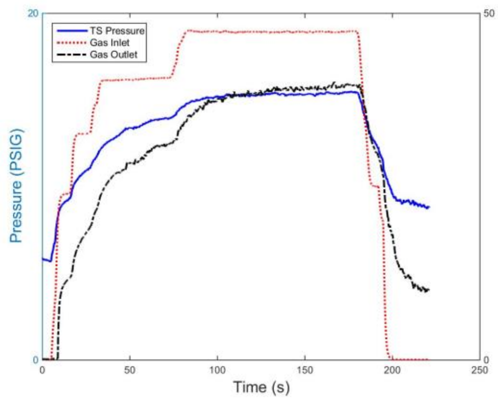


(c)

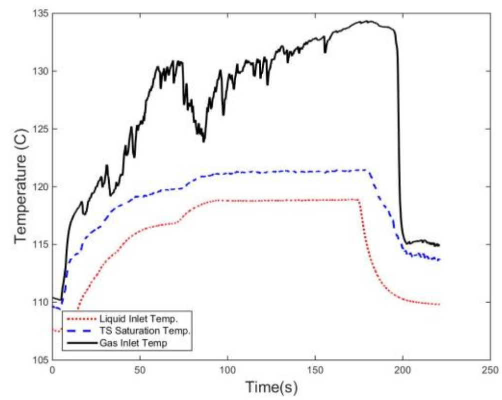


(d)

Figure B9: Raw data for steam/water test "*2015_12_02_test04*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



(a)



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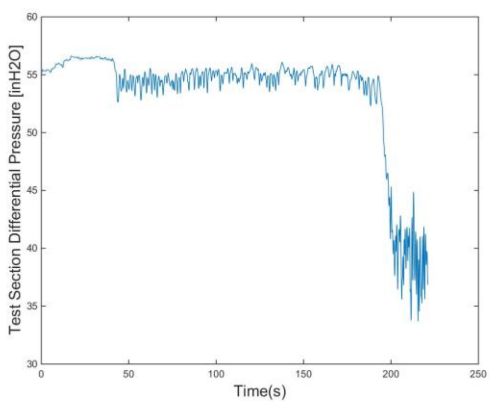
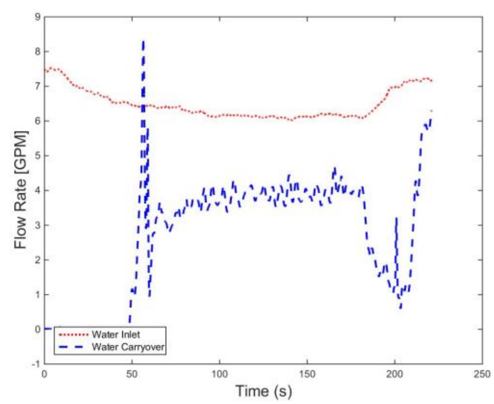
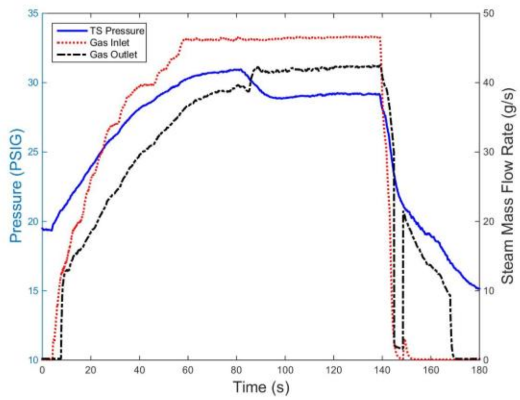


(c)

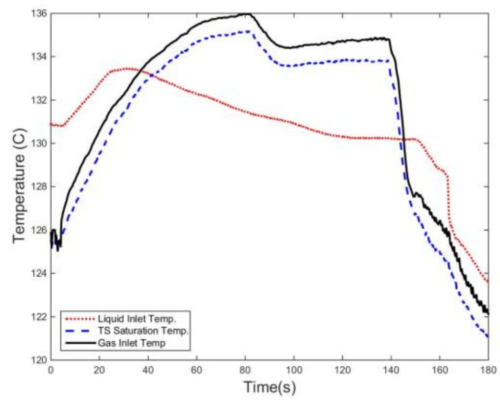


(d)

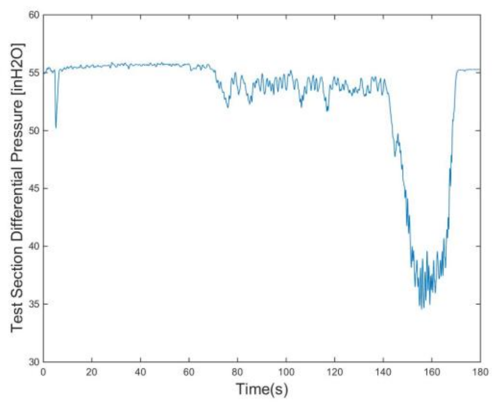
Figure B10: Raw data for steam/water test "*2015_12_02_test05*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



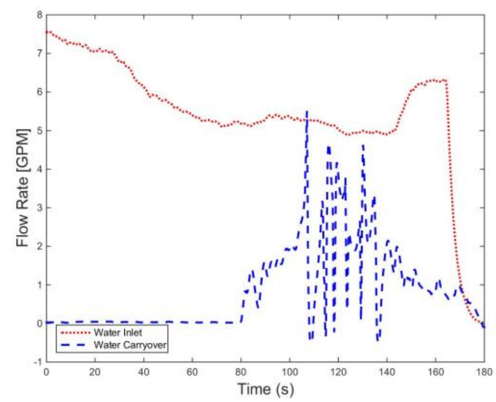
(a)



(b)

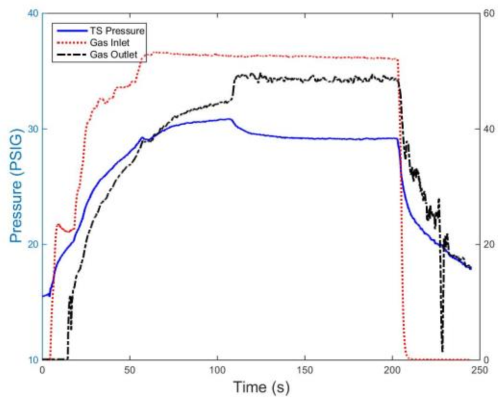


(c)

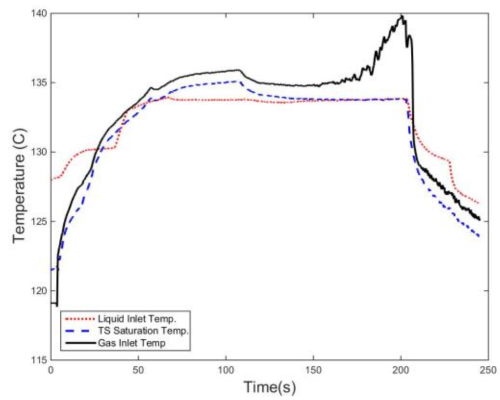


(d)

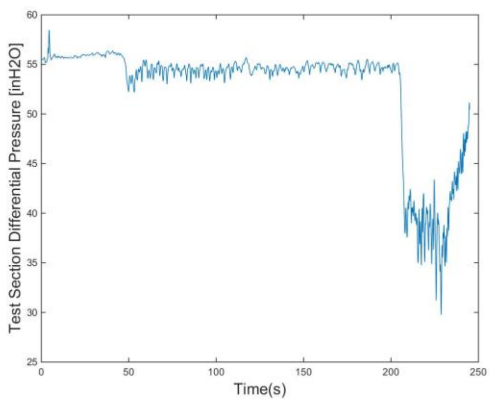
Figure B11: Raw data for steam/water test "*2015_12_11_test01*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



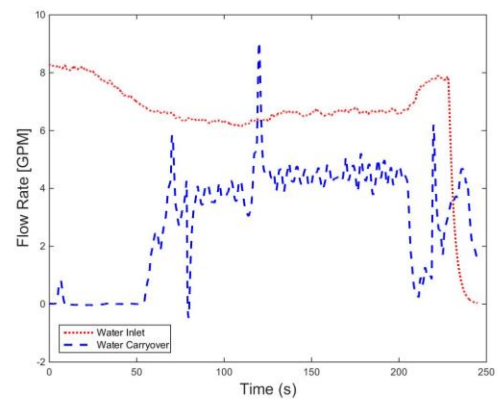
(a)



(b)

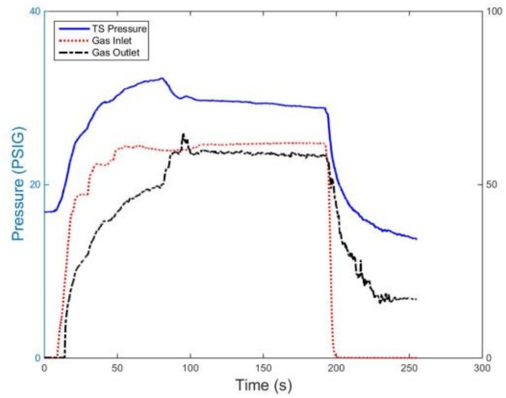


(c)

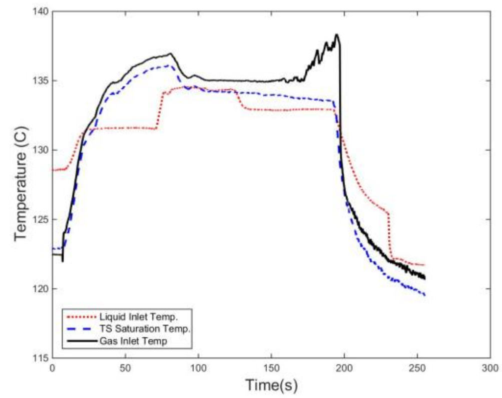


(d)

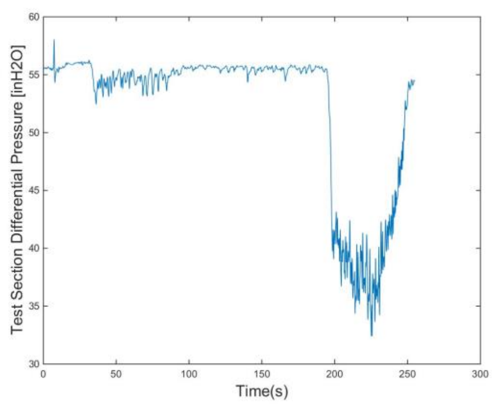
Figure B12: Raw data for steam/water test "*2015_12_11_test02*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



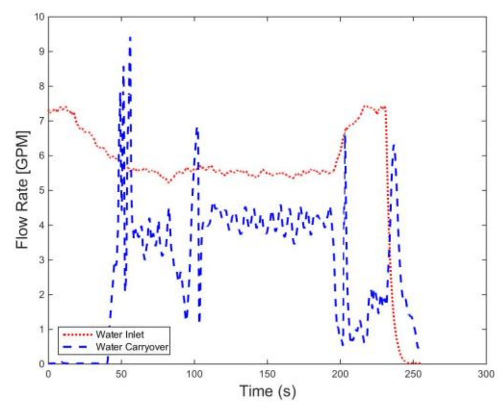
(a)



(b)

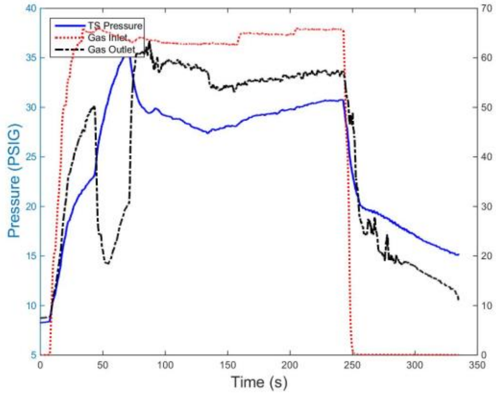


(c)

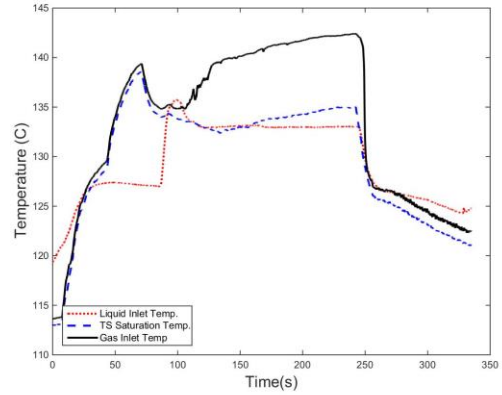


(d)

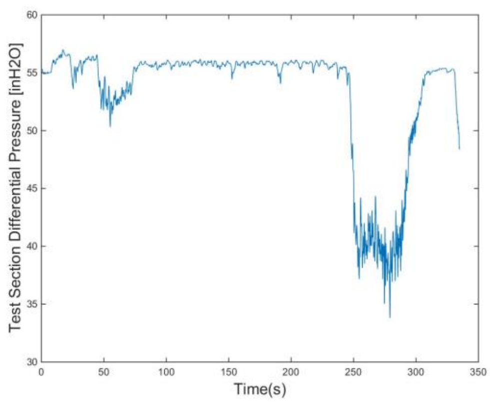
Figure B13: Raw data for steam/water test "*2015_12_11_test03*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



(a)



(b)



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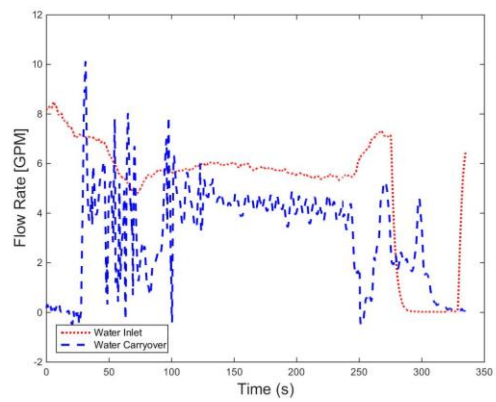
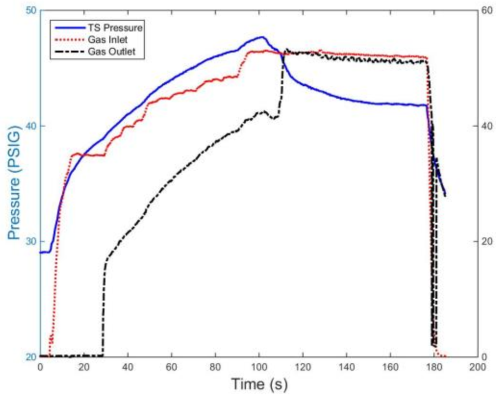
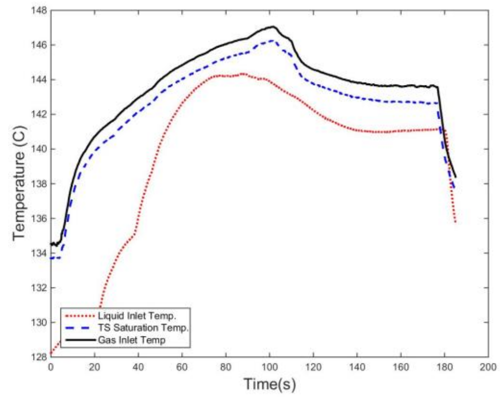


(d)

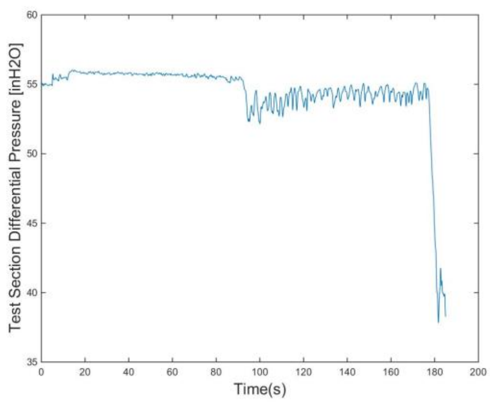
Figure B14: Raw data for steam/water test "*2015_12_11_test04*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



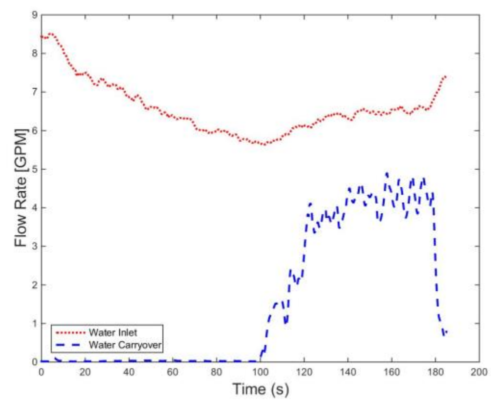
(a)



(b)

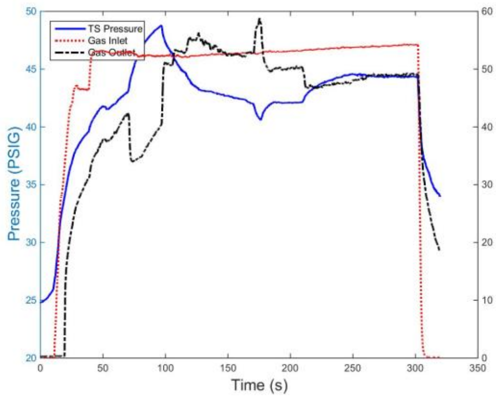


(c)

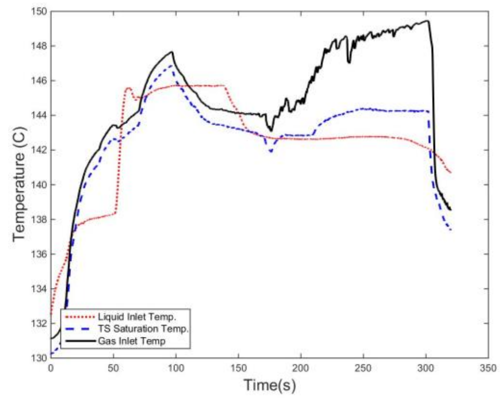


(d)

Figure B15: Raw data for steam/water test "*2015_12_12_test01*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



(a)



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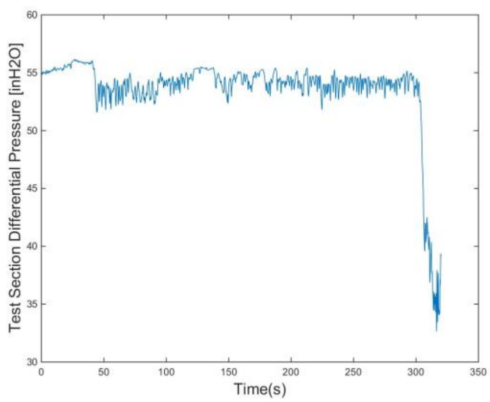
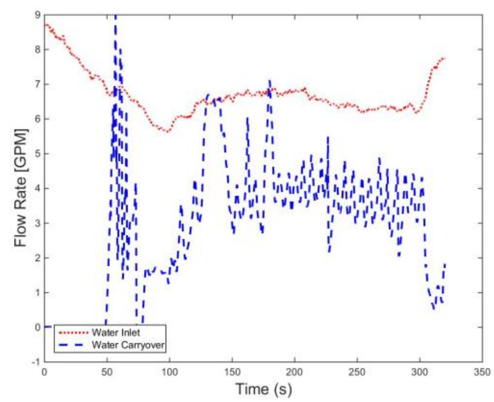
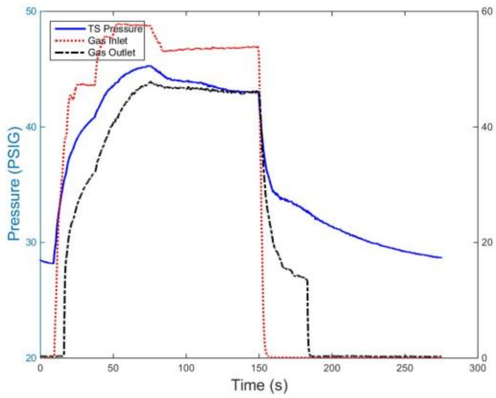


(c)

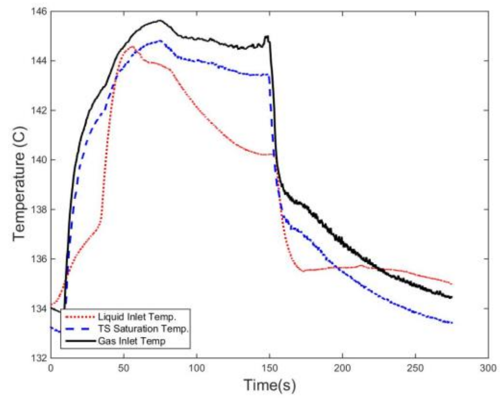


(d)

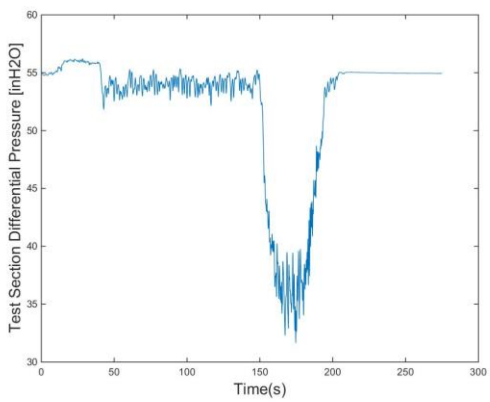
Figure B16: Raw data for steam/water test "*2015_12_12_test02*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



(a)



(b)



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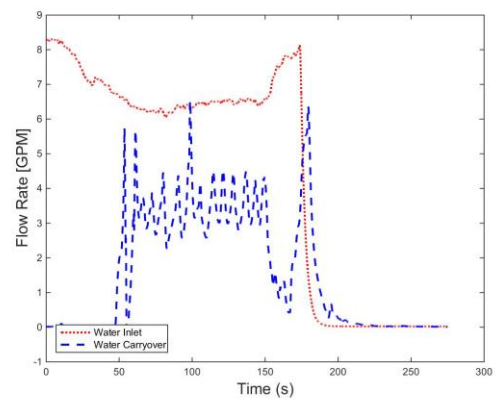
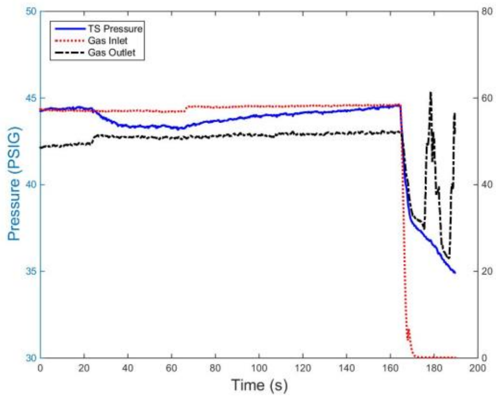
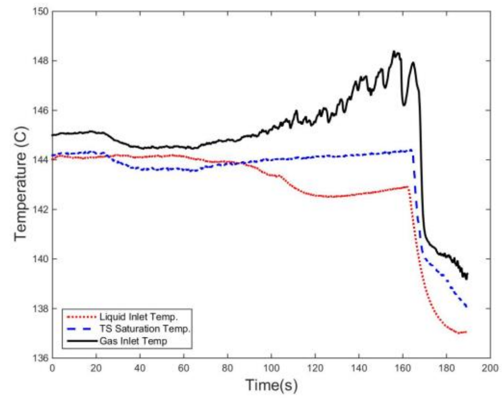


(d)

Figure B17: Raw data for steam/water test "*2015_12_12_test03*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



(a)



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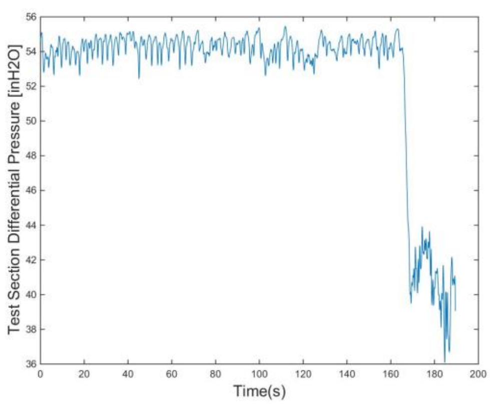

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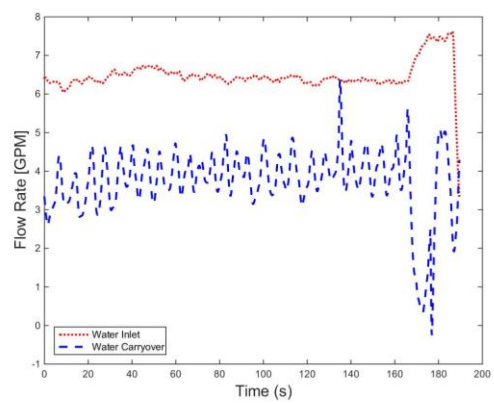
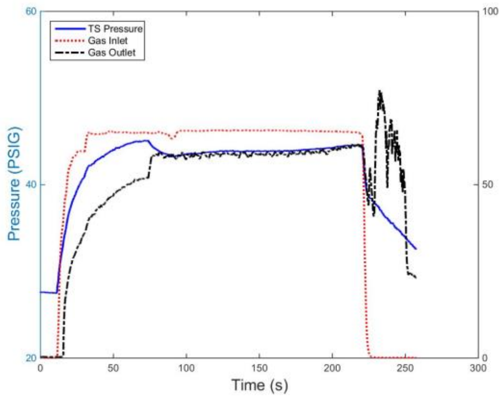
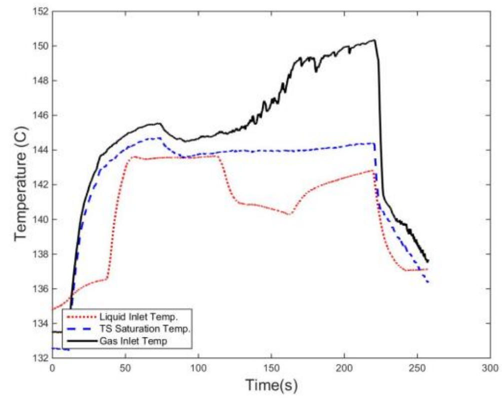


(d)

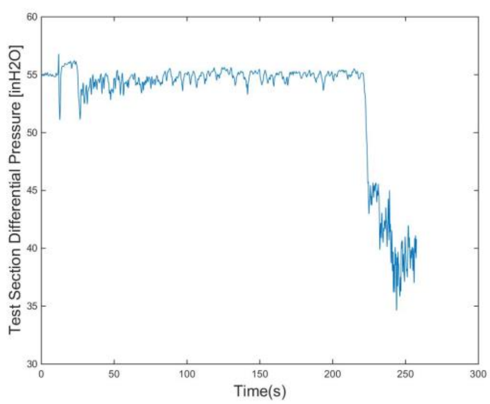
Figure B18: Raw data for steam/water test "*2015_12_12_test04*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



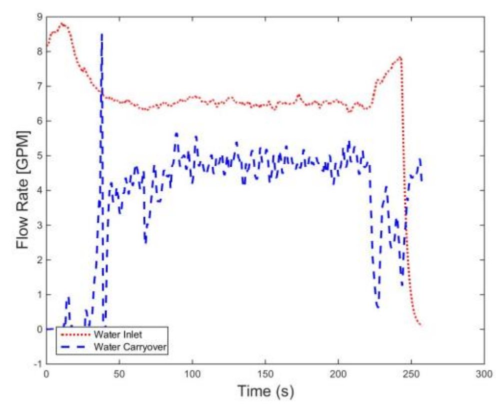
(a)



(b)

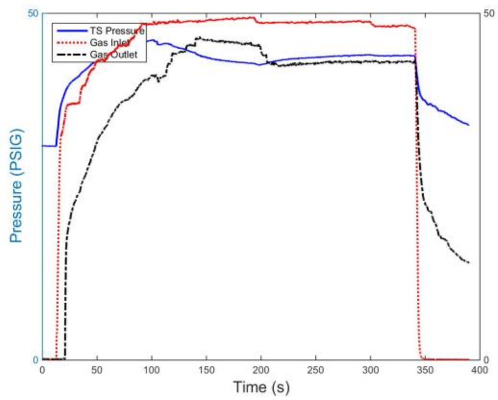


(c)

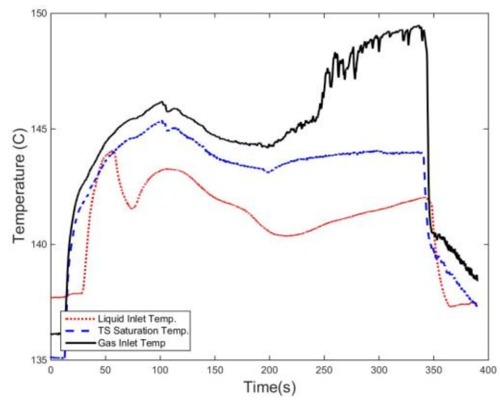


(d)

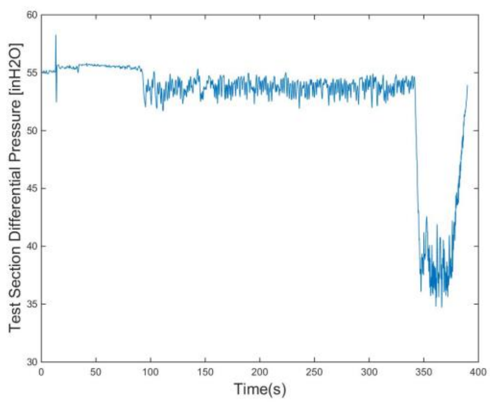
Figure B19: Raw data for steam/water test "*2015_12_12_test05*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



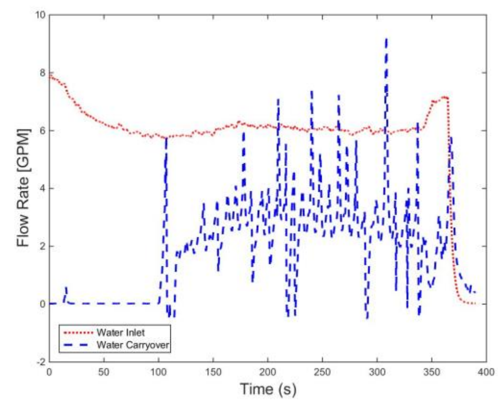
(a)



(b)

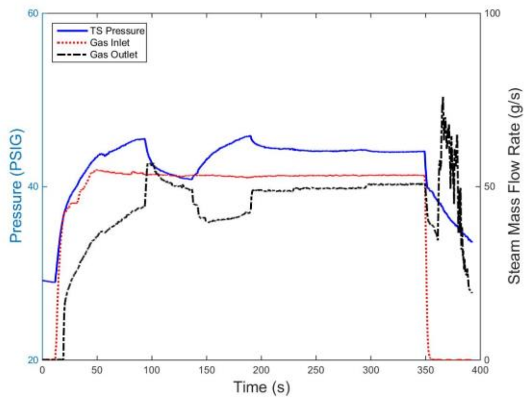


(c)

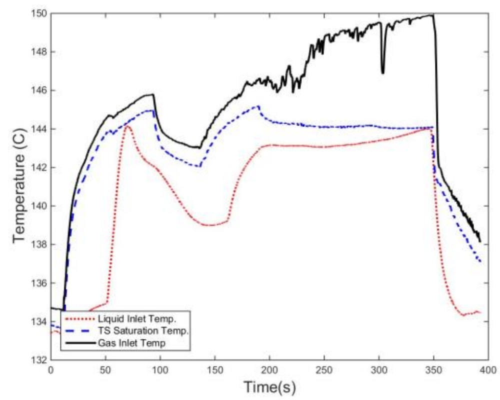


(d)

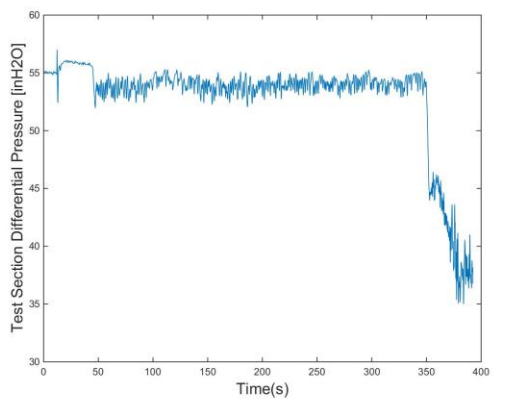
Figure B20: Raw data for steam/water test "*2015_12_12_test06*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



(a)



(b)



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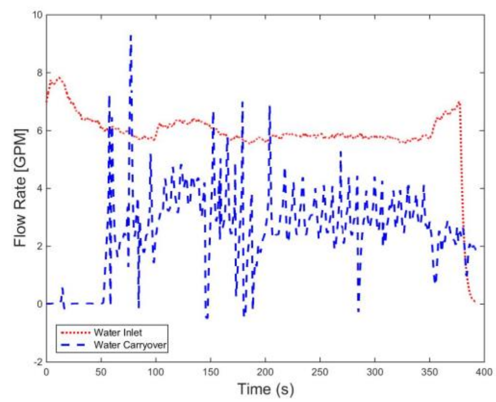
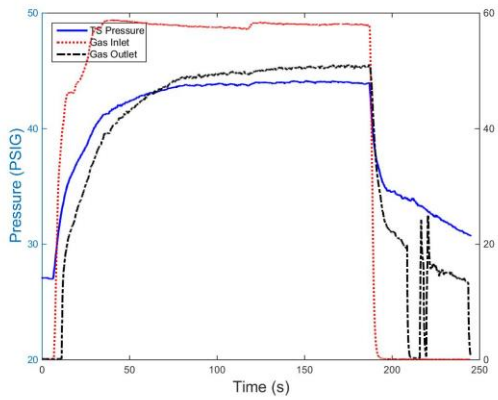
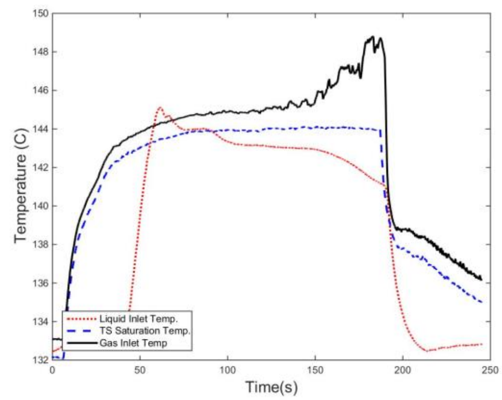


(d)

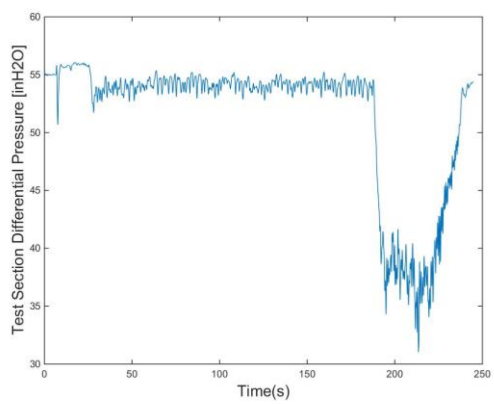
Figure B21: Raw data for steam/water test "*2015_12_12_test07*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



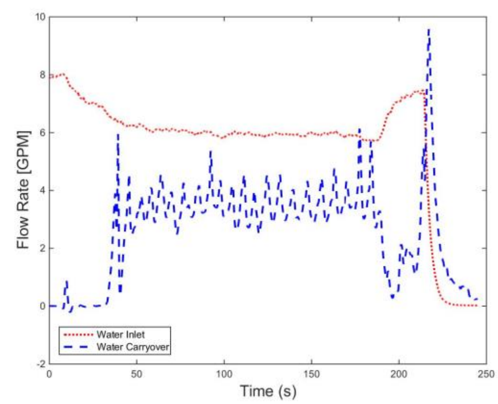
(a**)**



(b)

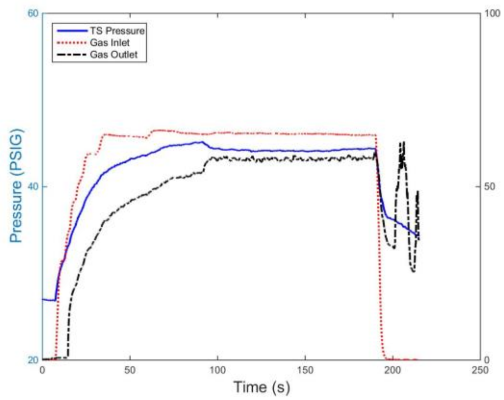


(c)

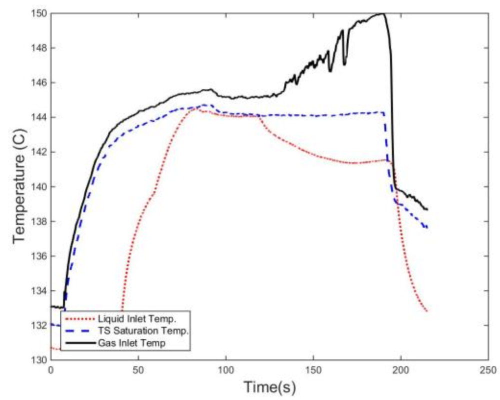


(d)

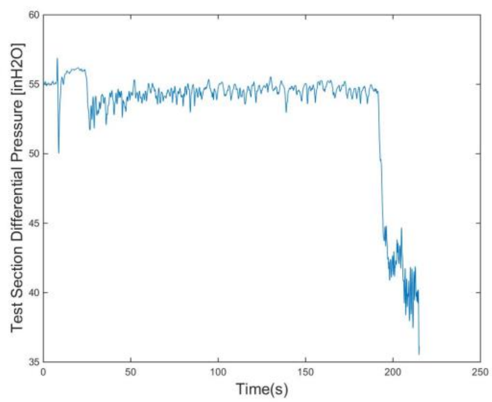
Figure B22: Raw data for steam/water test "*2015_12_12_test08*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



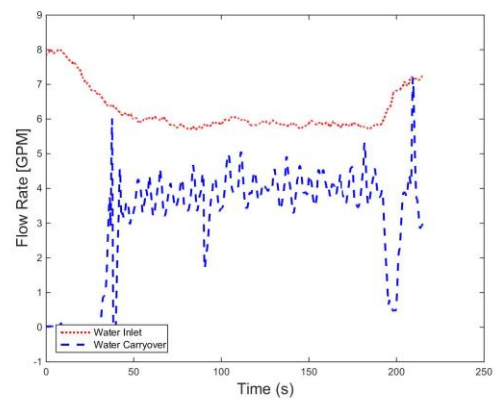
(a**)**



(b)

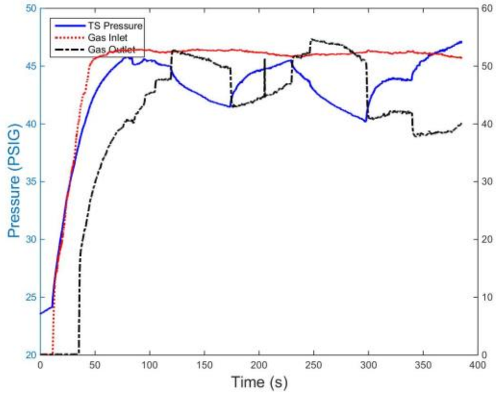


(c)

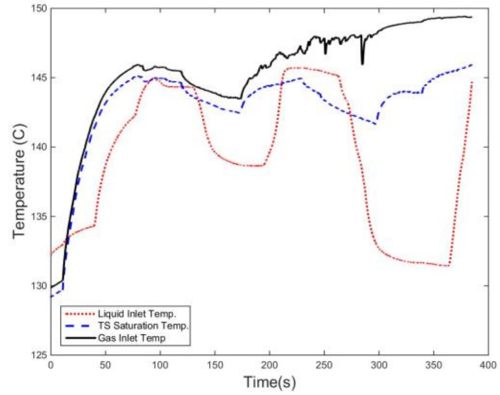


(d)

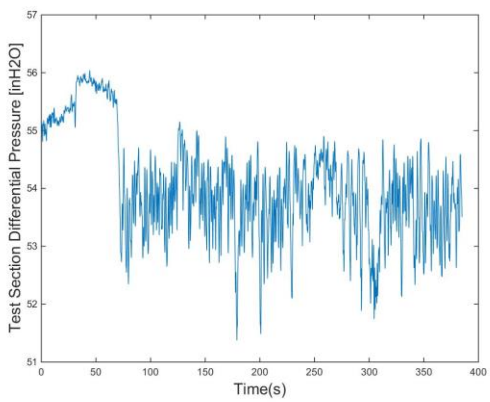
Figure B23: Raw data for steam/water test "*2015_12_12_test09*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



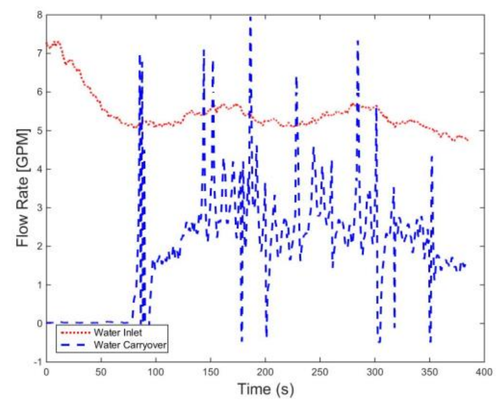
(a)



(b)



(c)



(d)

Figure B24: Raw data for steam/water test "*2015_12_12_test10*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.

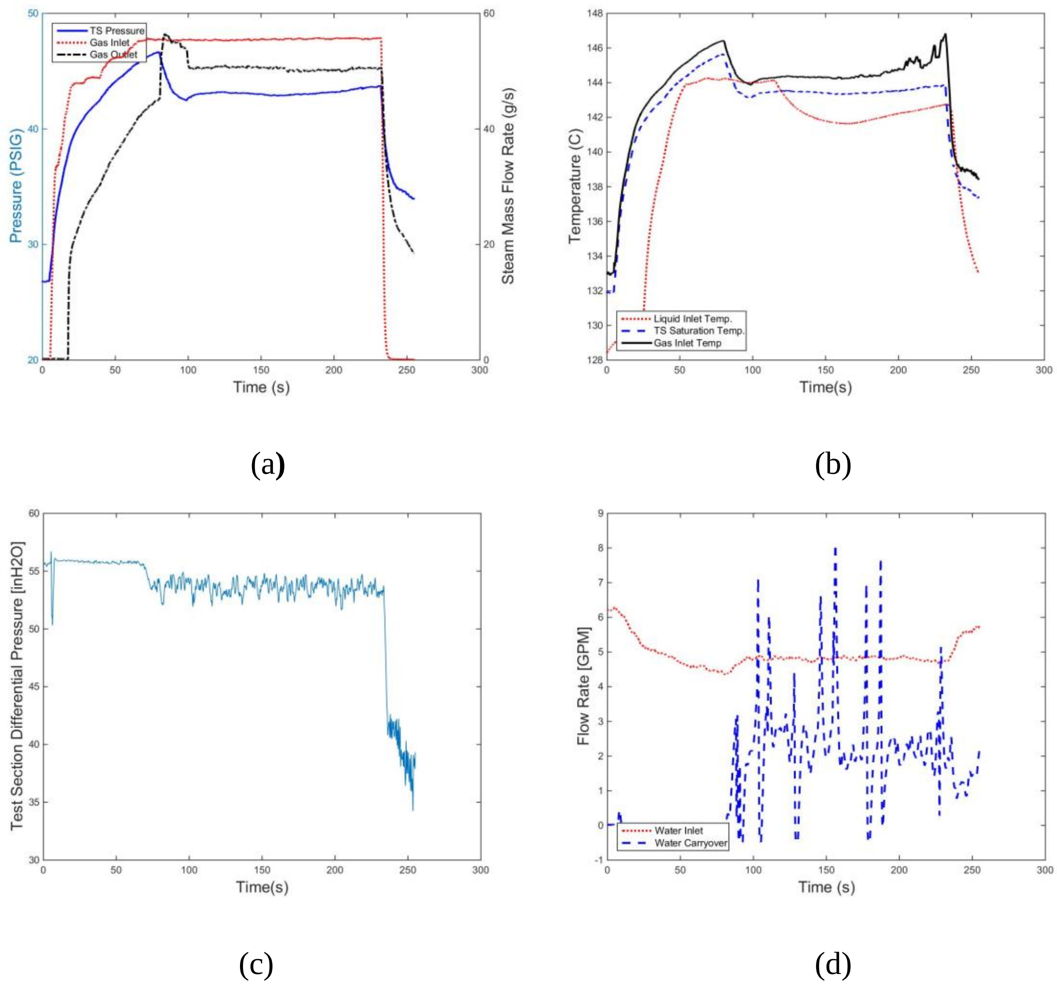
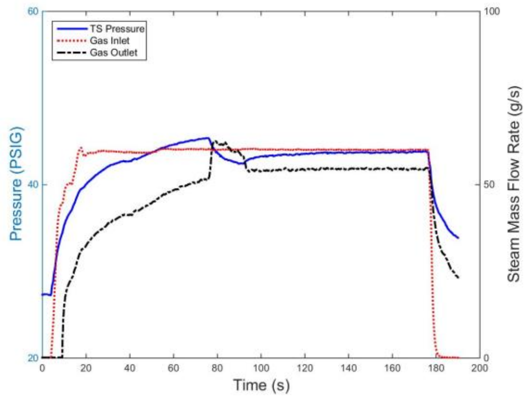
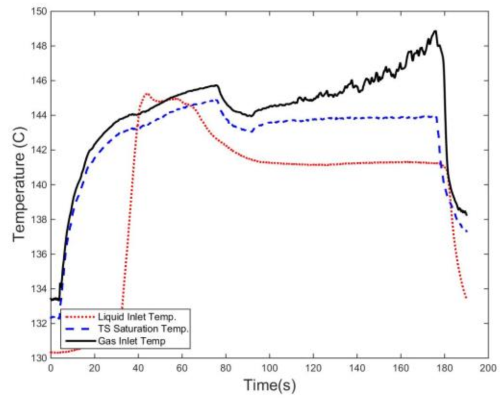


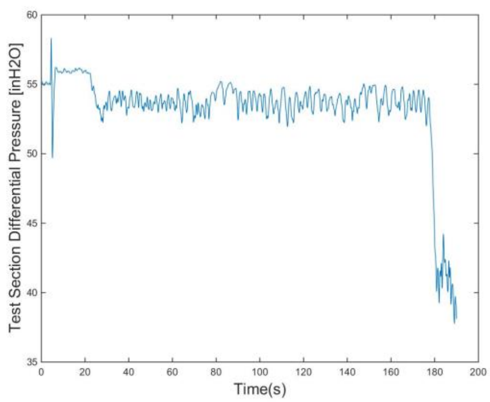
Figure B25: Raw data for steam/water test "*2015_12_12_test11*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



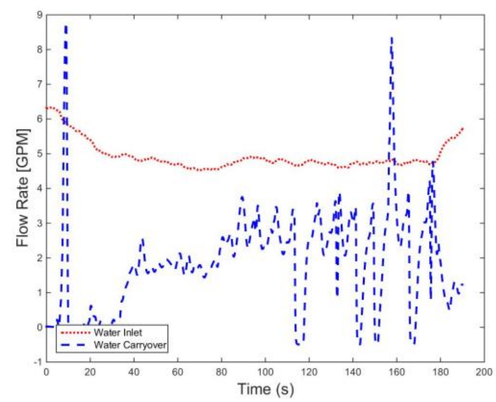
(a)



(b)

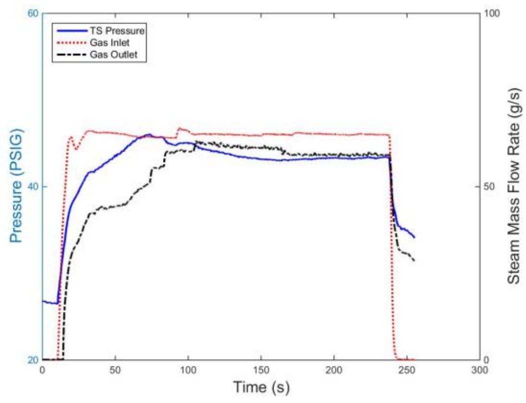


(c)

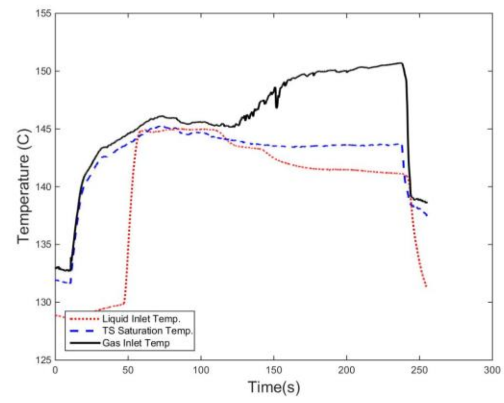


(d)

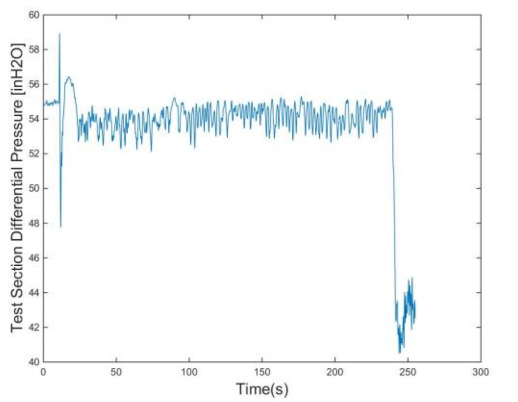
Figure B26: Raw data for steam/water test "*2015_12_12_test12*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



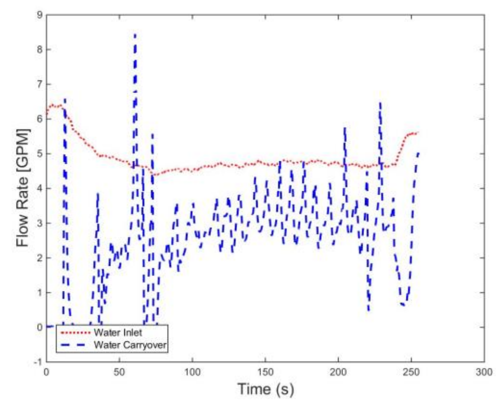
(a)



(b)



(c)



(d)

Figure B27: Raw data for steam/water test "*2015_12_12_test13*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.

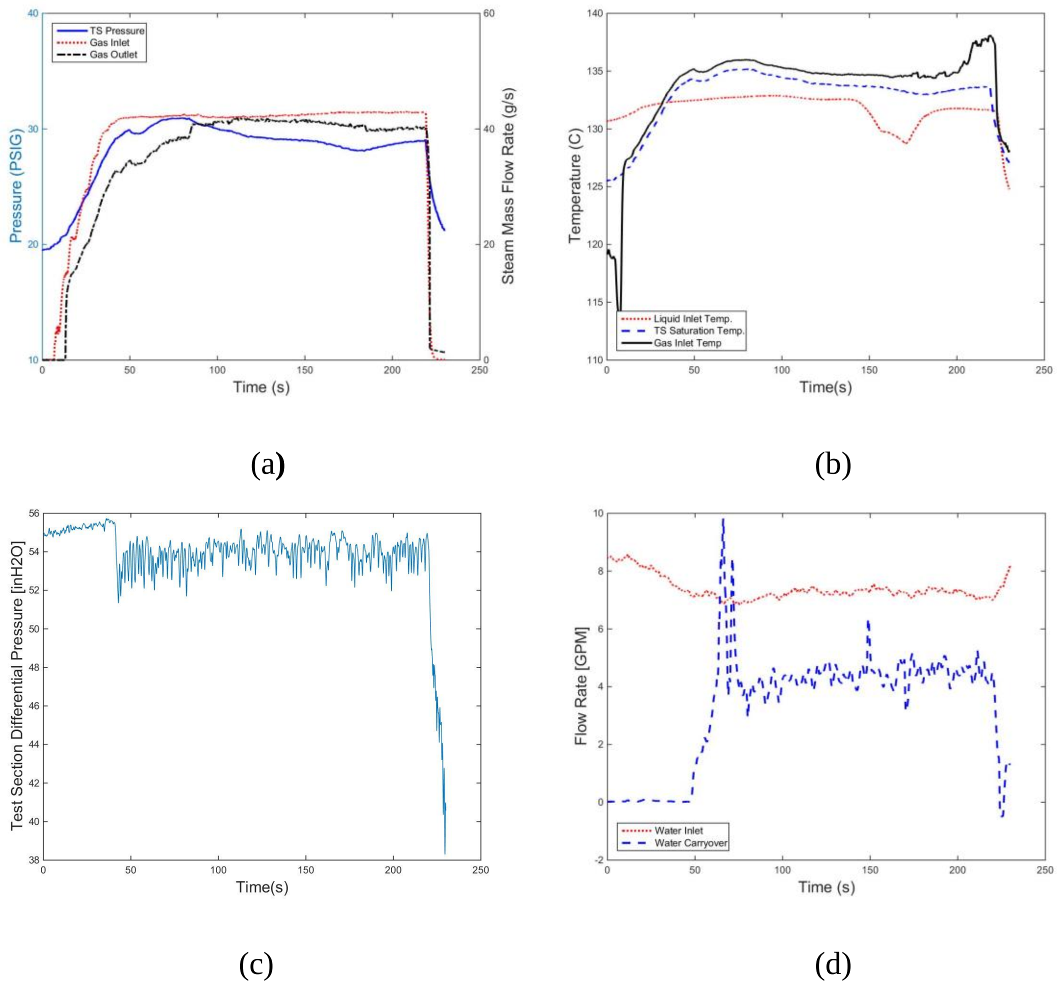
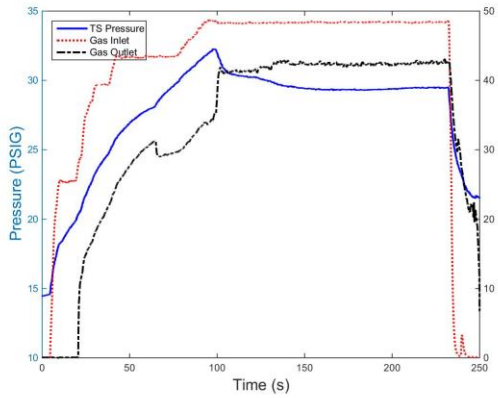
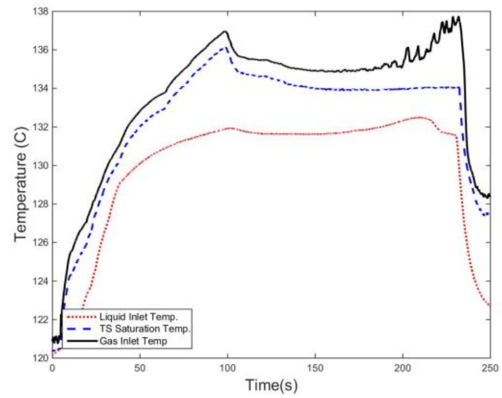


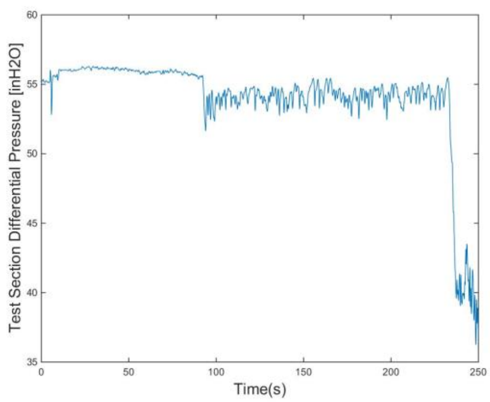
Figure B28: Raw data for steam/water test "*2015_12_13_test01*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



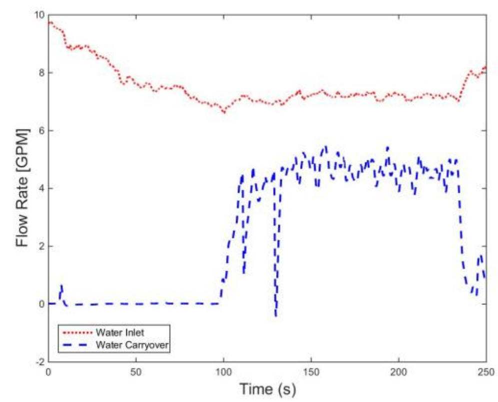
(a)



(b)

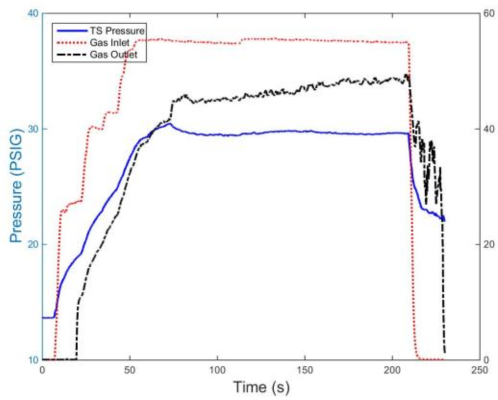


(c)

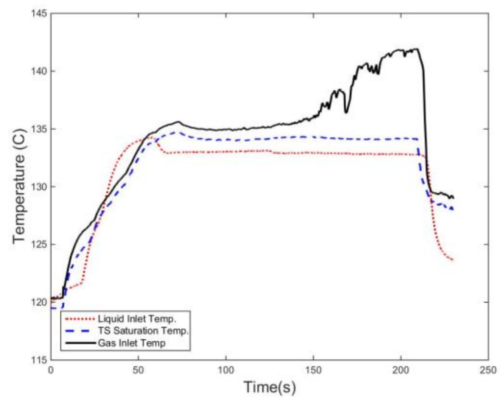


(d)

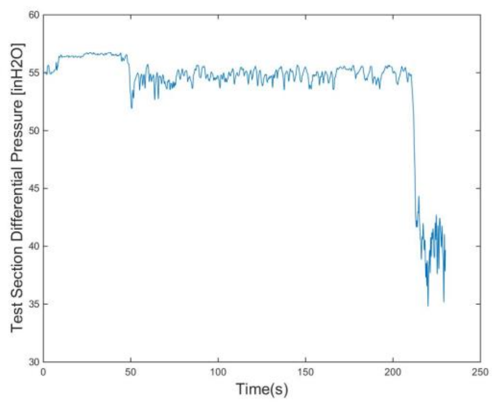
Figure B29: Raw data for steam/water test "*2015_12_13_test02*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



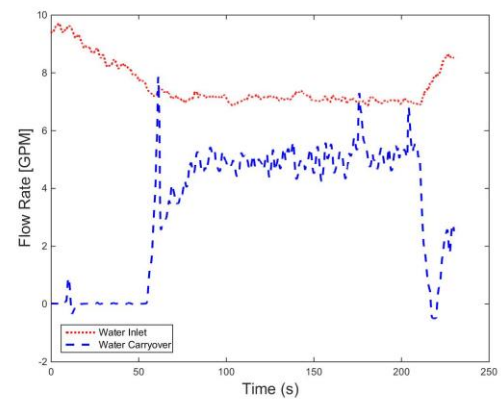
(a)



(b)

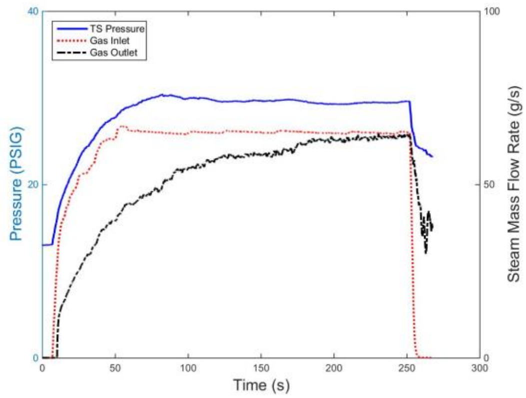


(c)

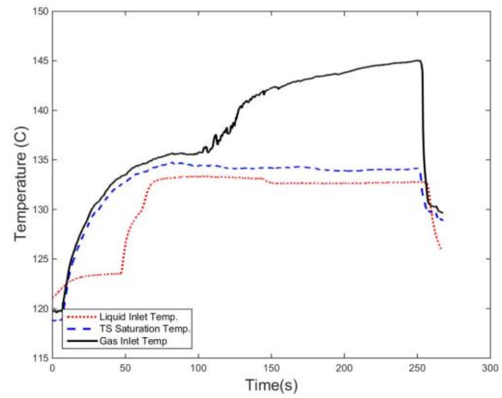


(d)

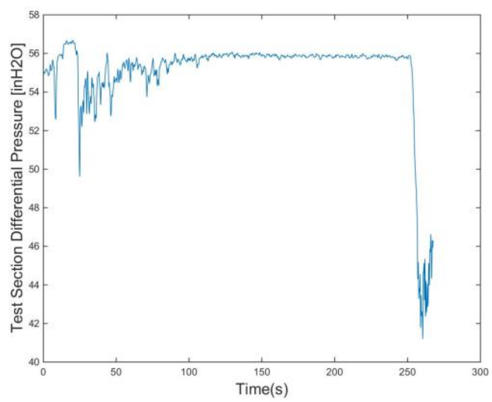
Figure B30: Raw data for steam/water test "*2015_12_13_test03*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



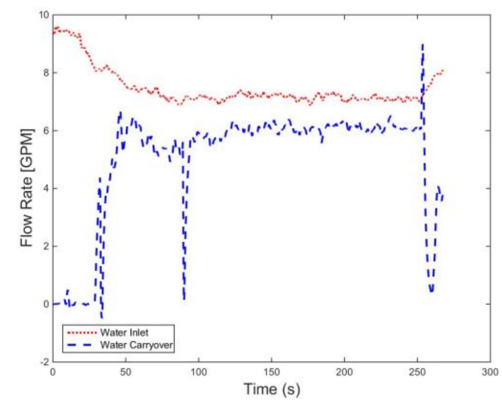
(a)



(b)

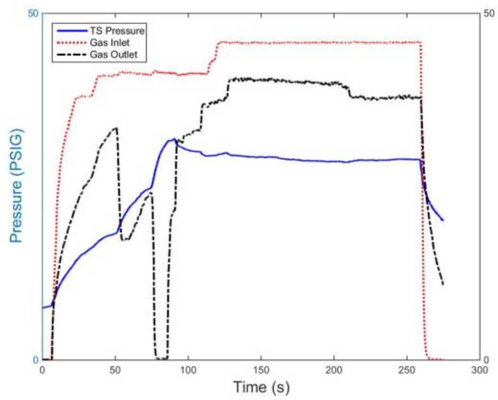


(c)

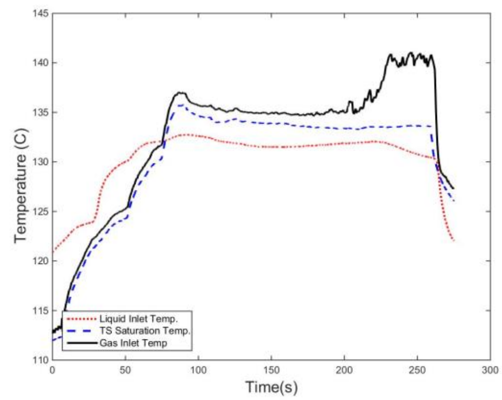


(d)

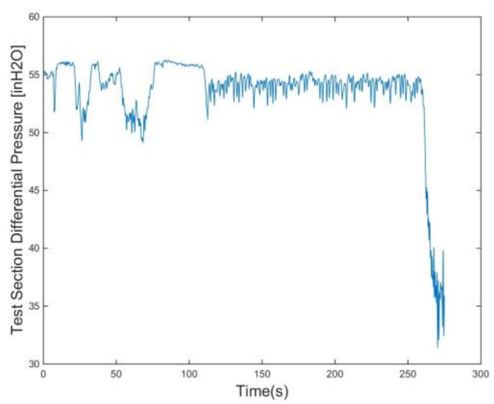
Figure B31: Raw data for steam/water test "*2015_12_13_test04*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



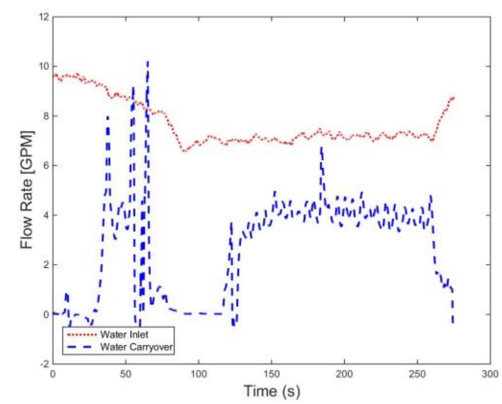
(a)



(b)

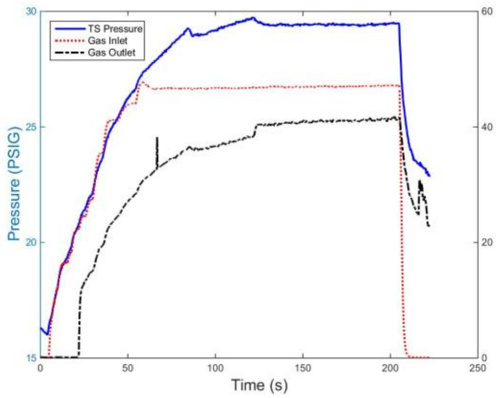


(c)

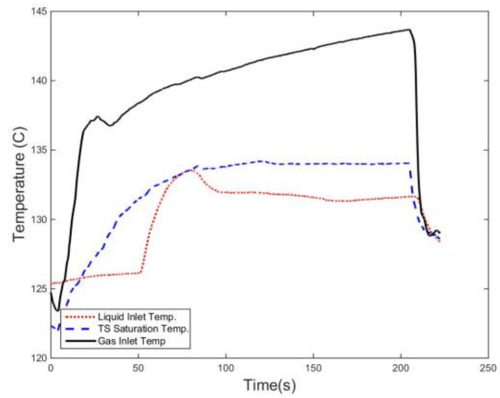


(d)

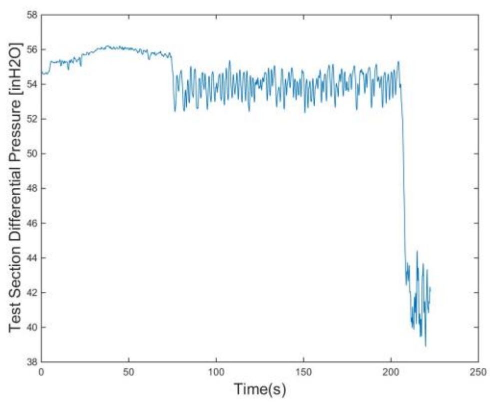
Figure B32: Raw data for steam/water test "*2015_12_13_test05*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



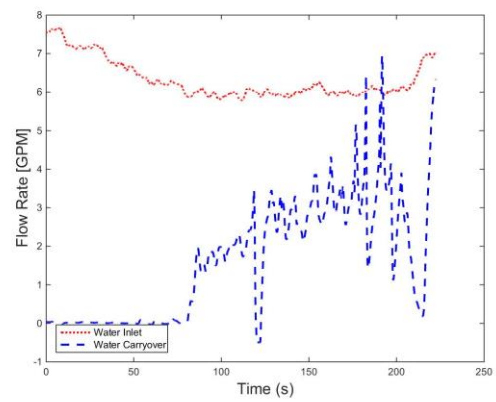
(a)



(b)

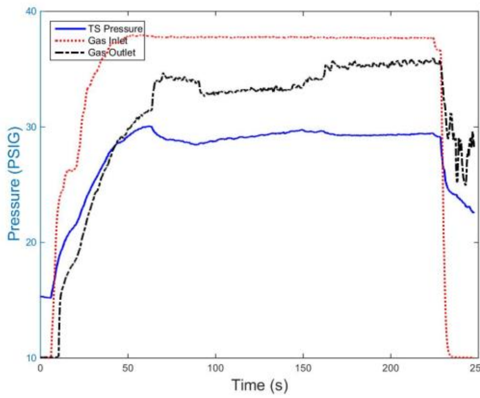


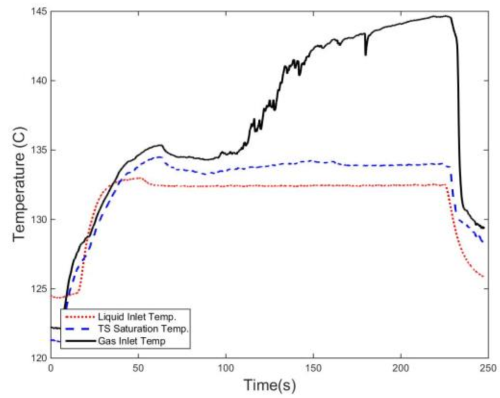
(c)



(d)

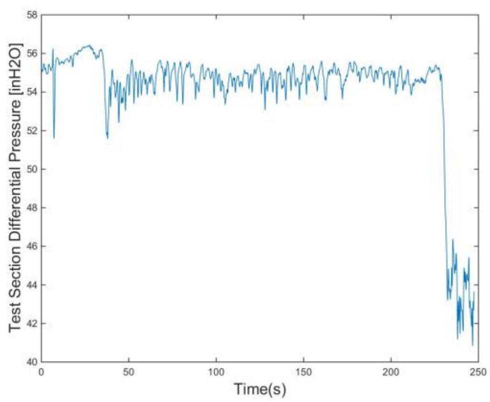
Figure B33: Raw data for steam/water test "*2015_12_13_test06*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.

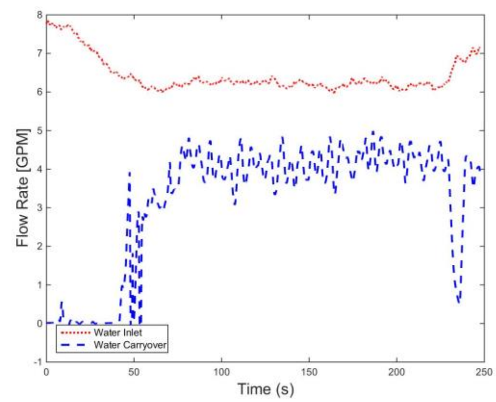




(a)

(b)

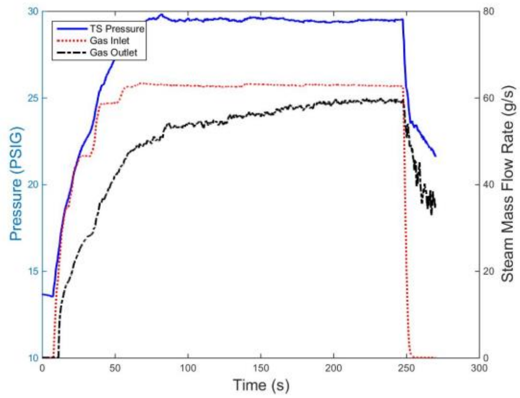




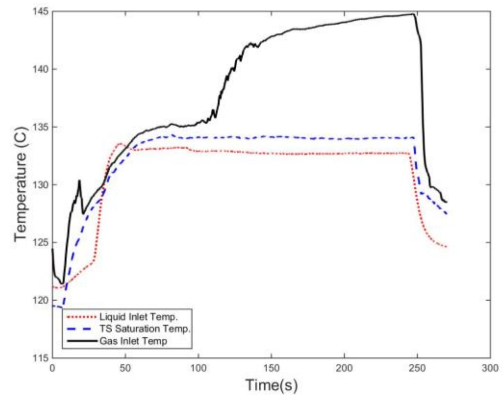
(c)

(d)

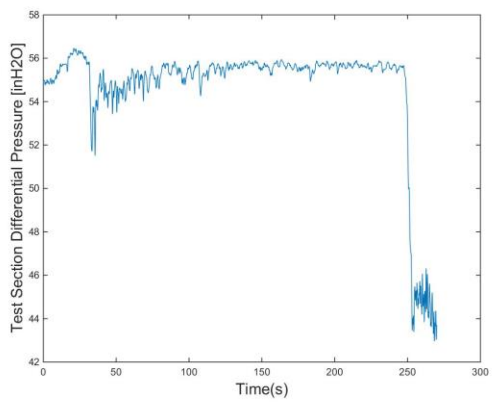
Figure B34: Raw data for steam/water test "*2015_12_13_test07*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



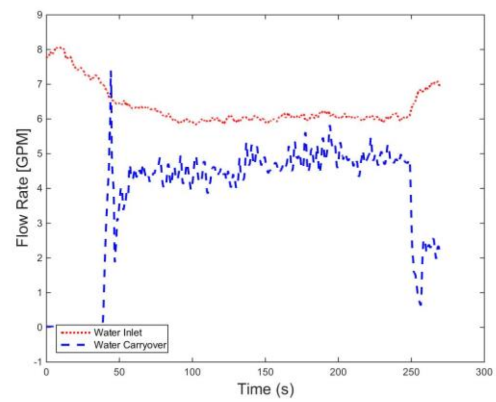
(a)



(b)

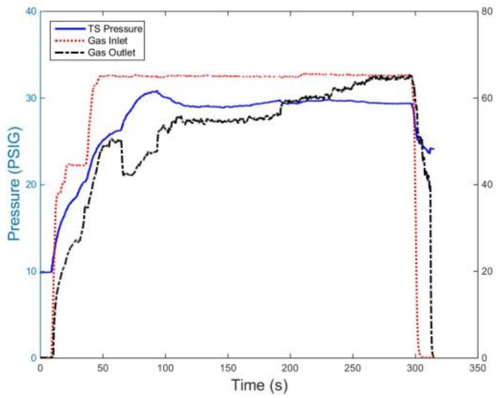


(c)

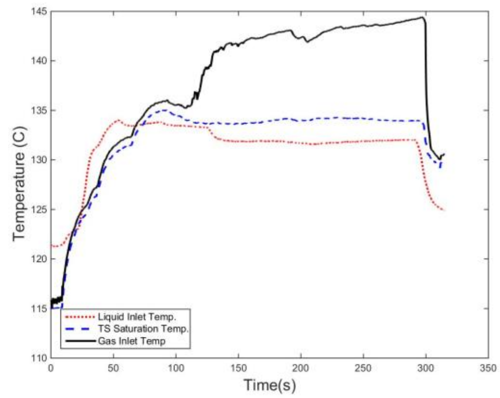


(d)

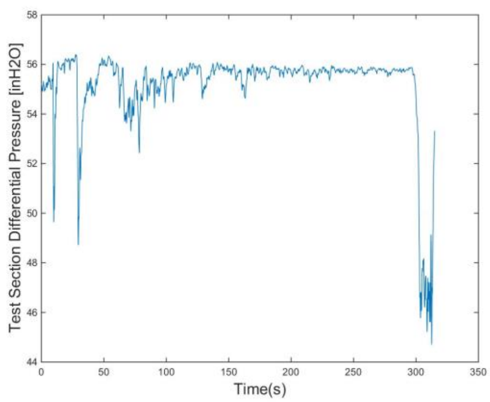
Figure B35: Raw data for steam/water test "*2015_12_13_test08*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



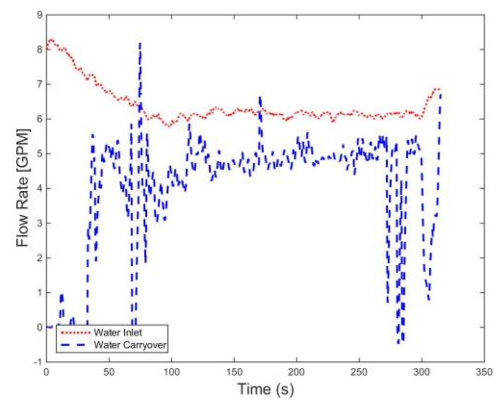
(a)



(b)

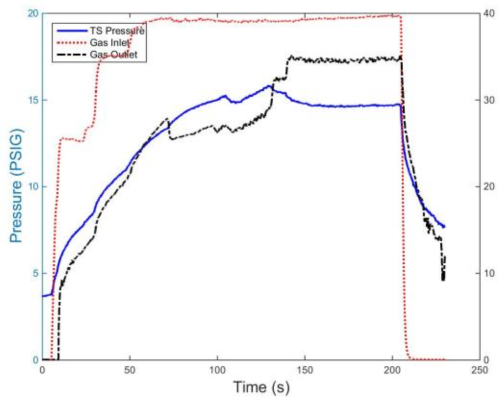


(c)

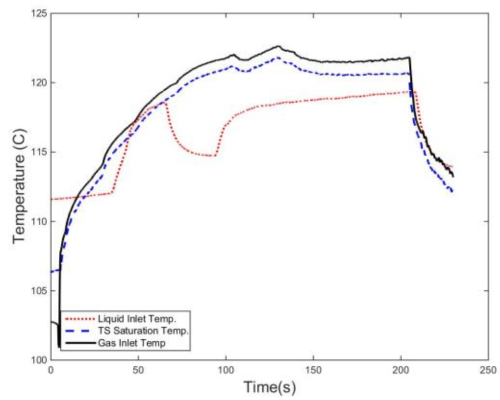


(d)

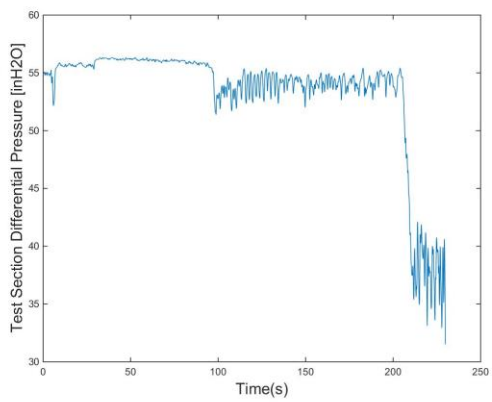
Figure B36: Raw data for steam/water test "*2015_12_13_test09*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



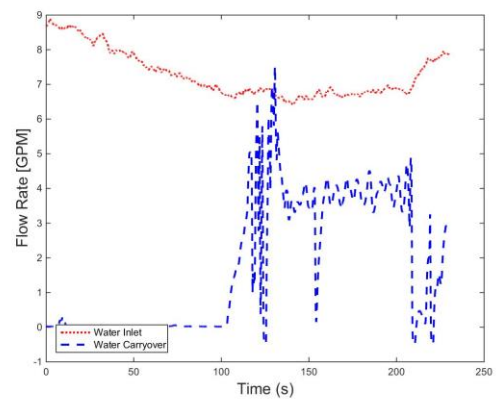
(a)



(b)

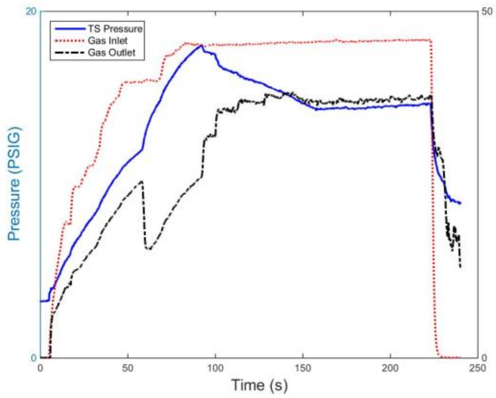


(c)

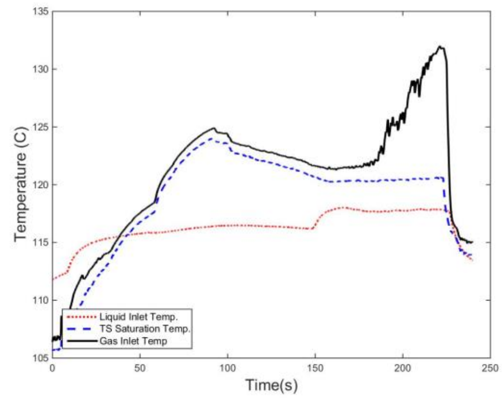


(d)

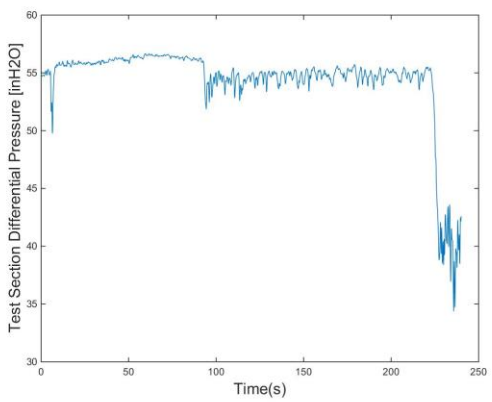
Figure B37: Raw data for steam/water test "*2015_12_14_test01*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



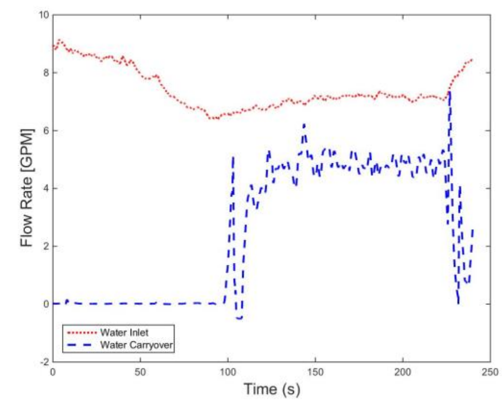
(a)



(b)

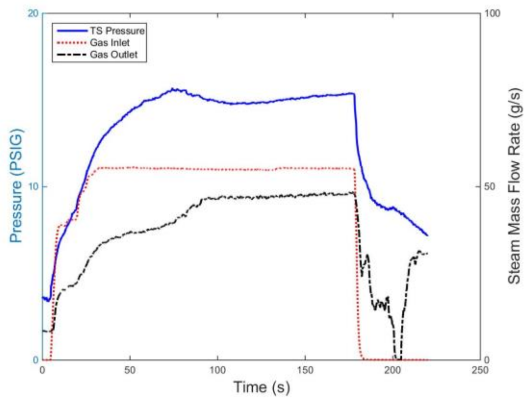


(c)

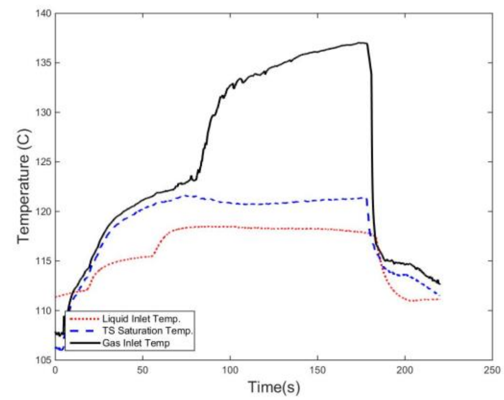


(d)

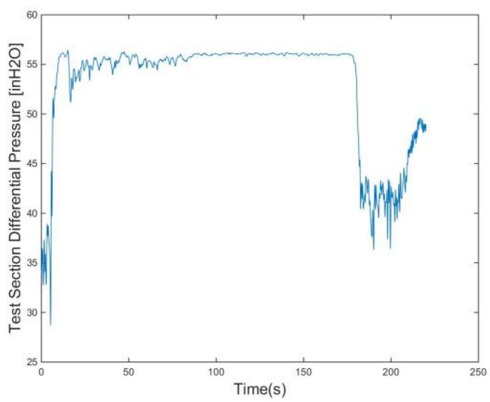
Figure B38: Raw data for steam/water test "*2015_12_14_test02*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



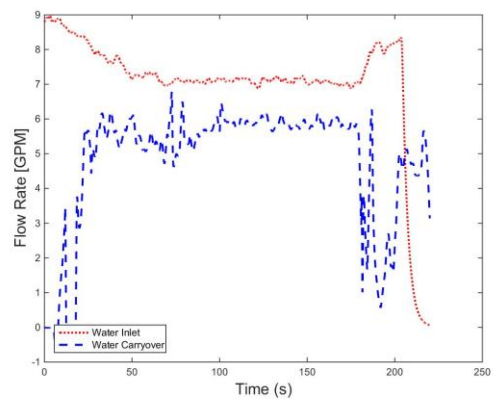
(a)



(b)

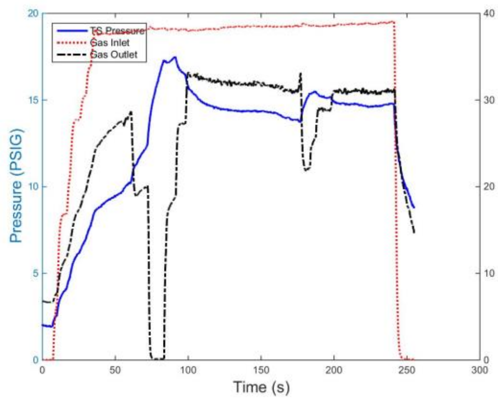


(c)

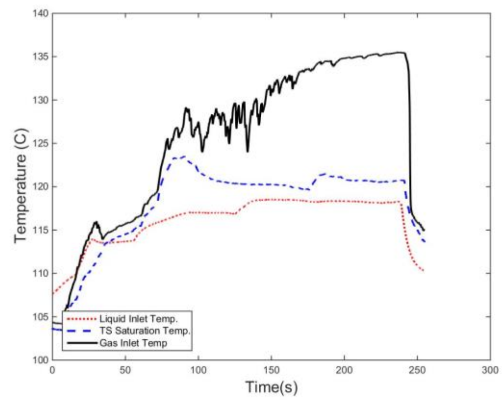


(d)

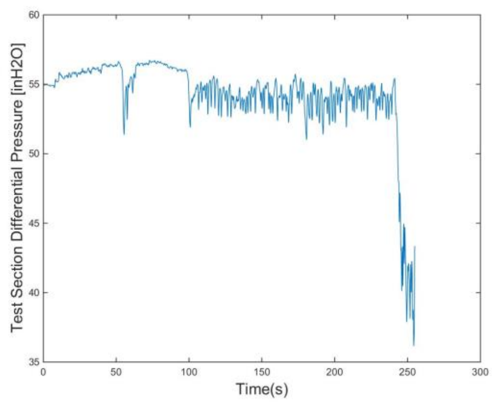
Figure B39: Raw data for steam/water test "*2015_12_14_test03*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



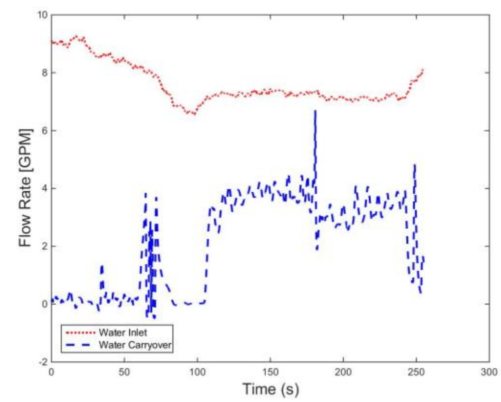
(a)



(b)

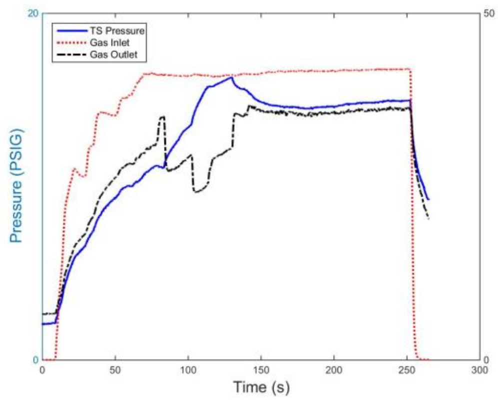


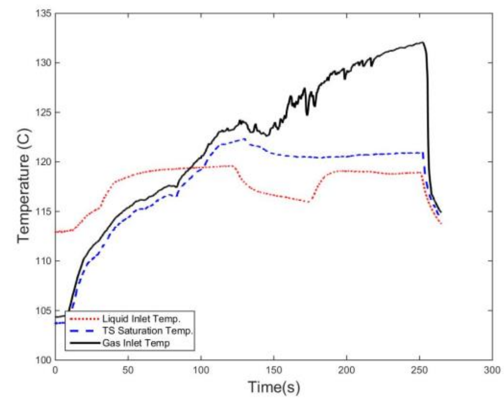
(c)



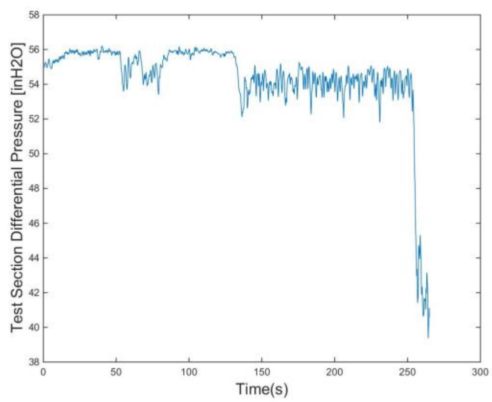
(d)

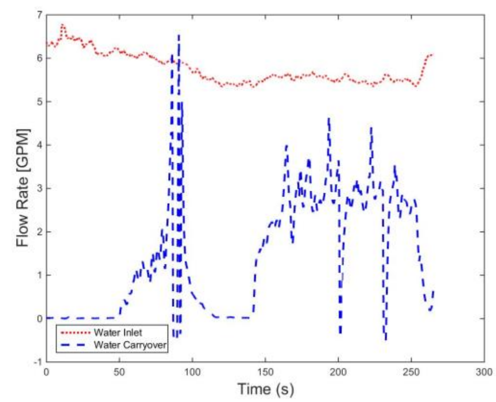
Figure B40: Raw data for steam/water test "*2015_12_14_test04*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.





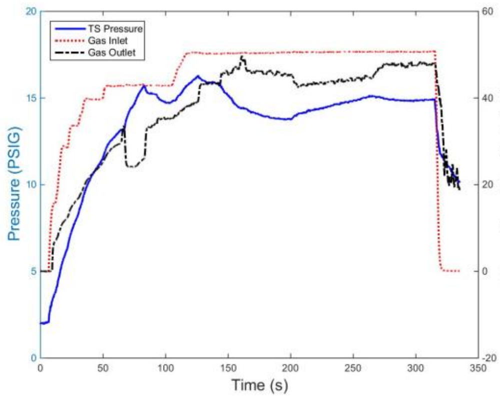
(a)　　　　(b)



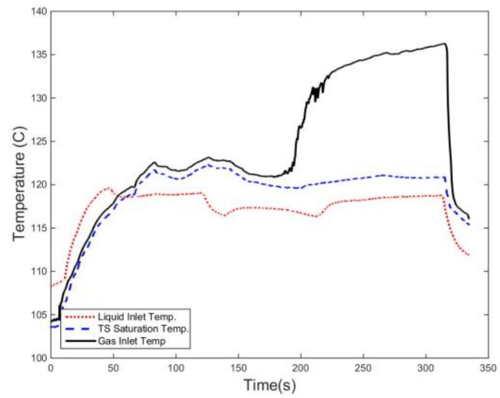


(c)　　　　(d)

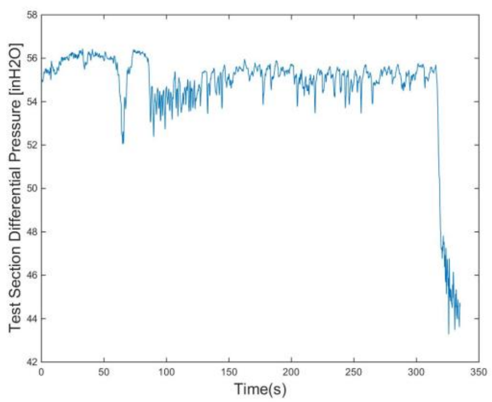
Figure B41: Raw data for steam/water test "*2015_12_14_test05*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



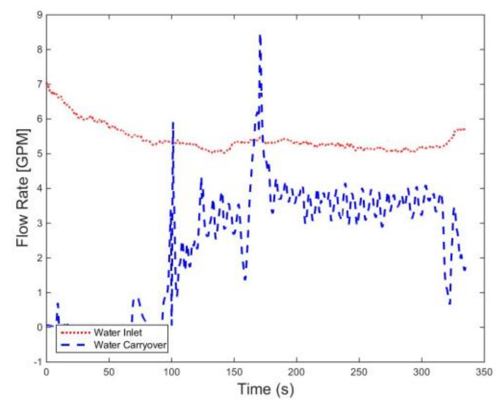
(a)



(b)

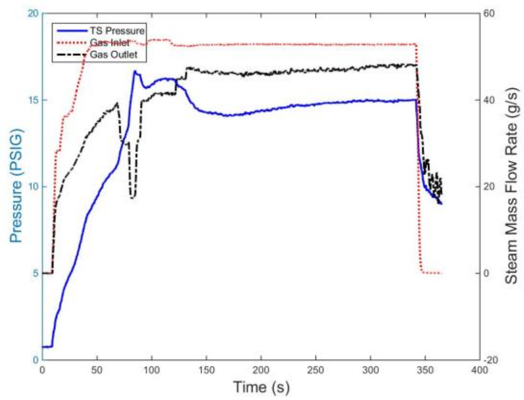


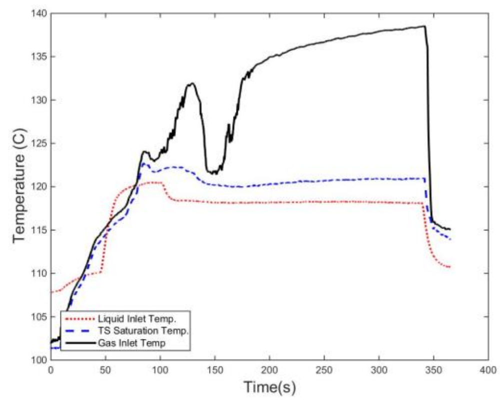
(c)



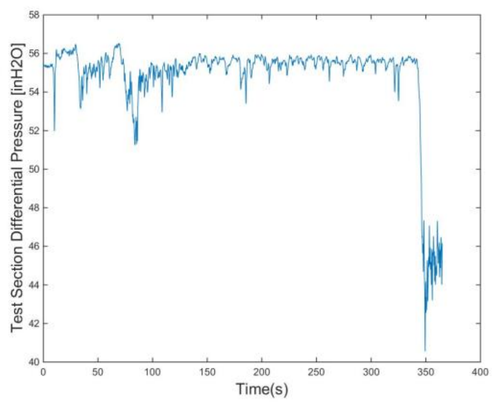
(d)

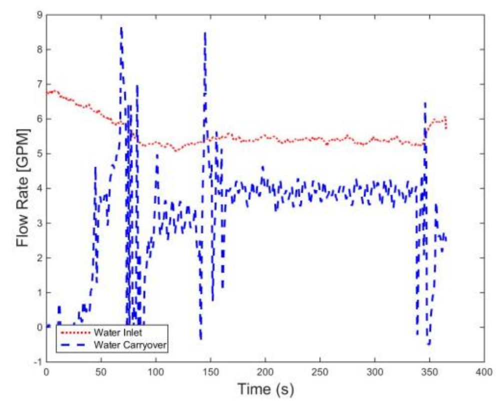
Figure B42: Raw data for steam/water test "*2015_12_14_test06*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.





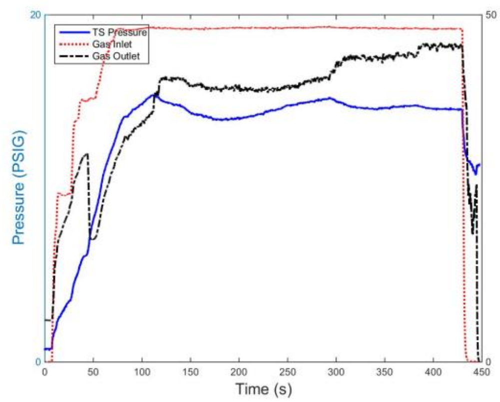
(a) (b)



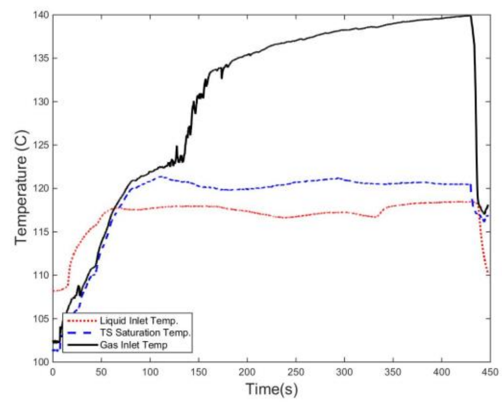


(c) (d)

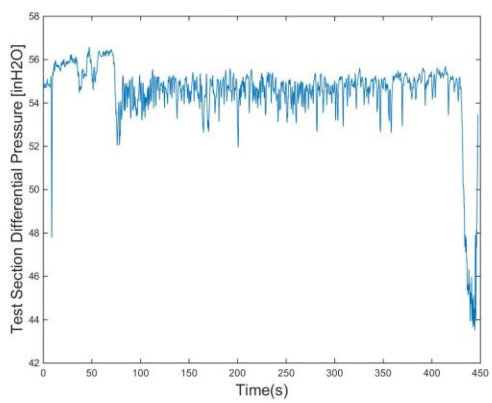
Figure B43: Raw data for steam/water test "*2015_12_14_test07*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



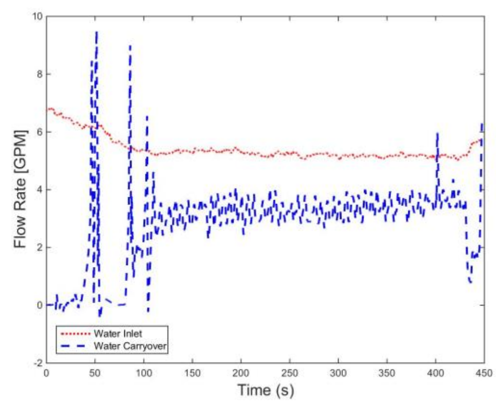
(a)



(b)

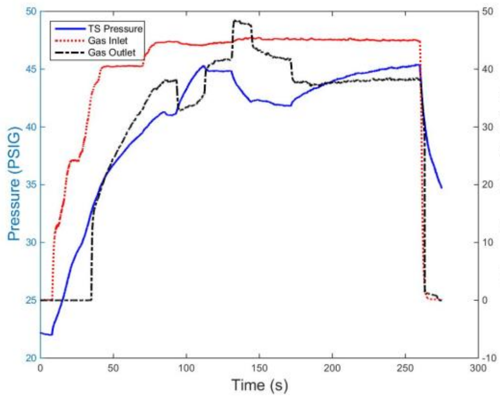


(c)

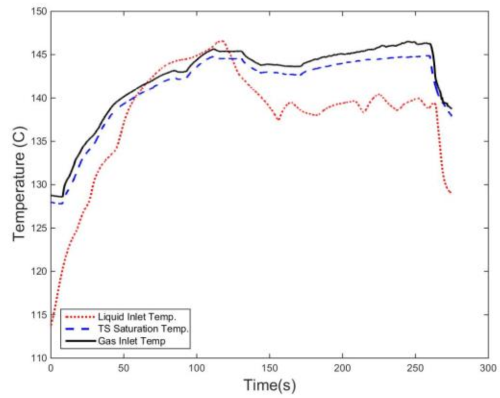


(d)

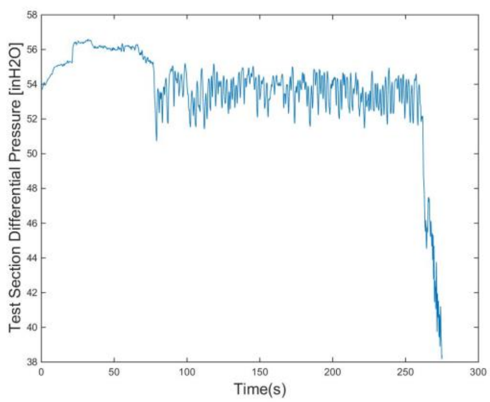
Figure B44: Raw data for steam/water test "*2015_12_14_test08*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



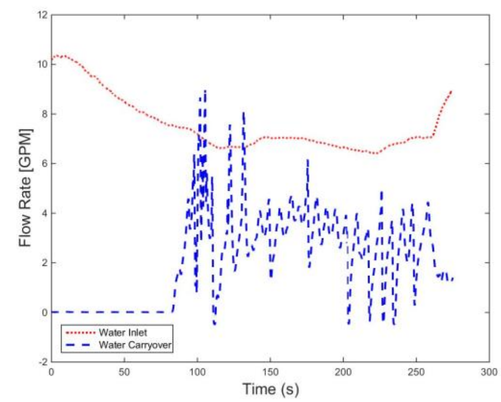
(a)



(b)

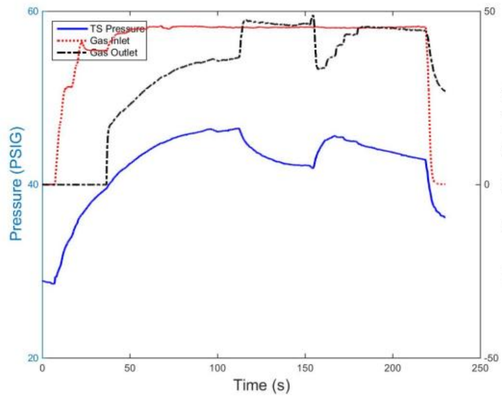


(c)

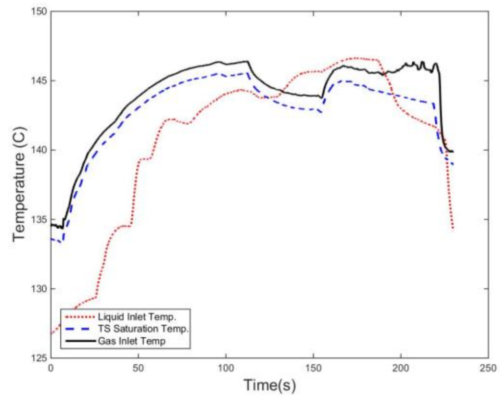


(d)

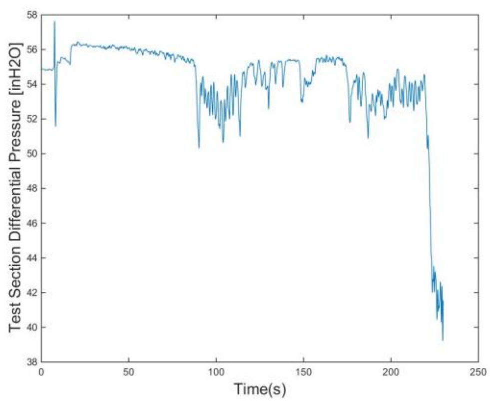
Figure B45: Raw data for steam/water test "*2016_01_04_test01*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



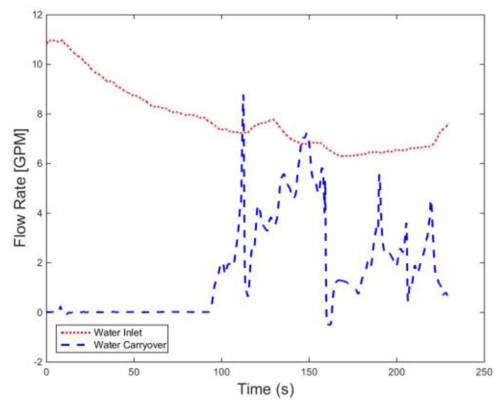
(a)



(b)

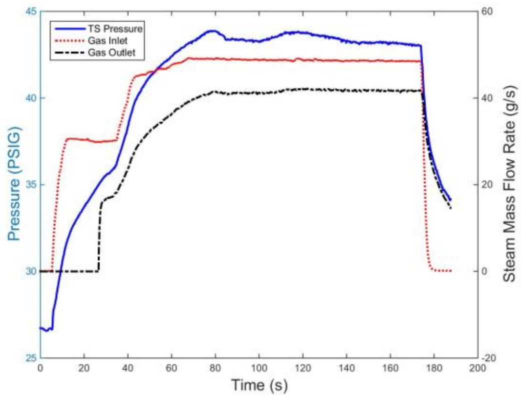


(c)

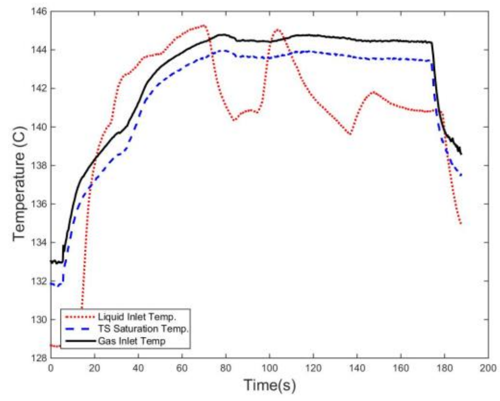


(d)

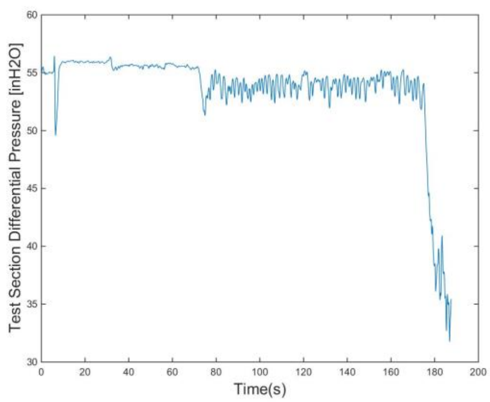
Figure B46: Raw data for steam/water test "*2016_01_04_test02*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



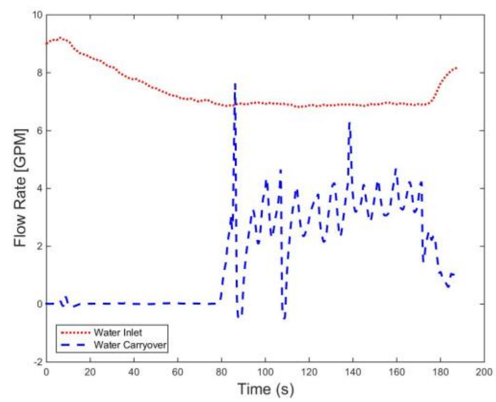
(a)



(b)

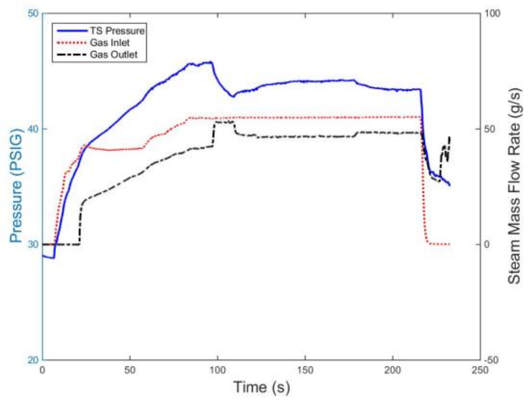


(c)

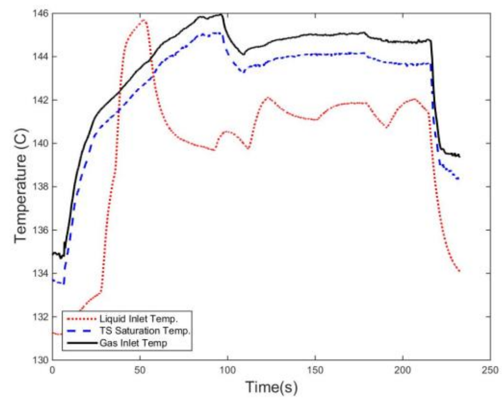


(d)

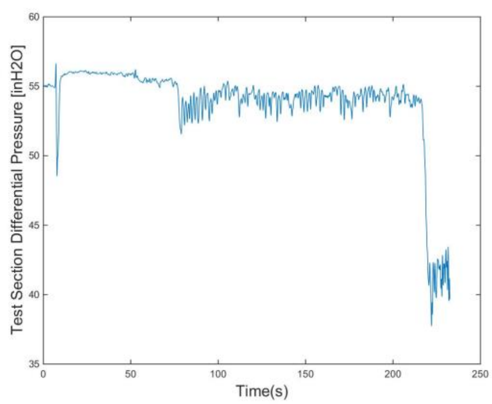
Figure B47: Raw data for steam/water test "*2016_01_04_test03*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



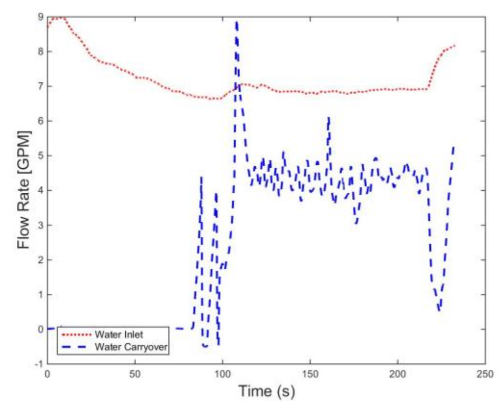
(a)



(b)

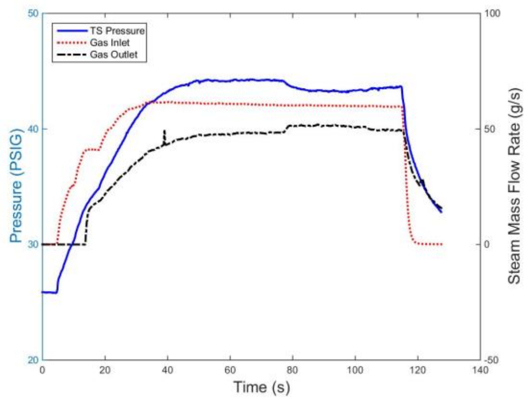


(c)

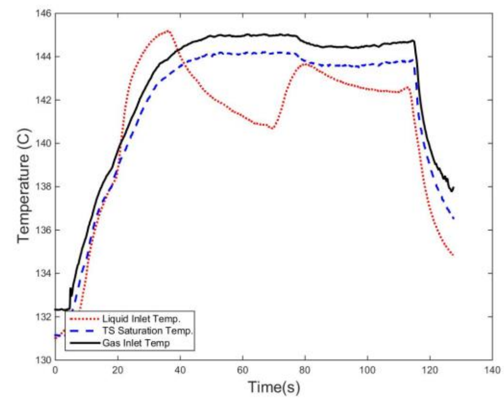


(d)

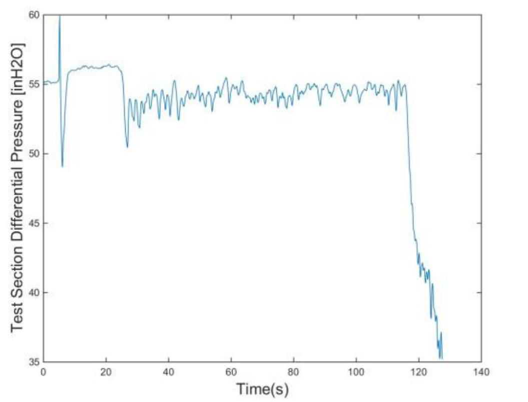
Figure B48: Raw data for steam/water test "*2016_01_04_test04*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



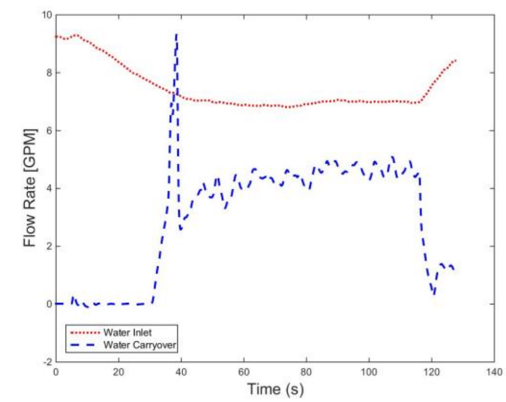
(a)



(b)

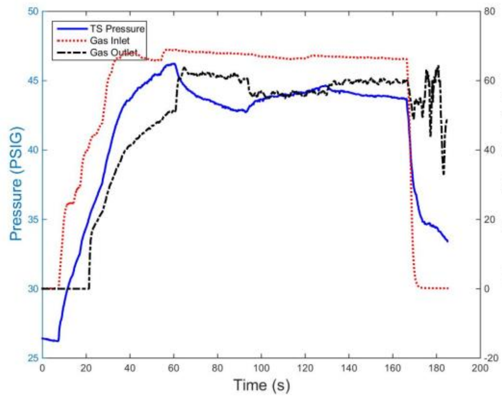


(c)

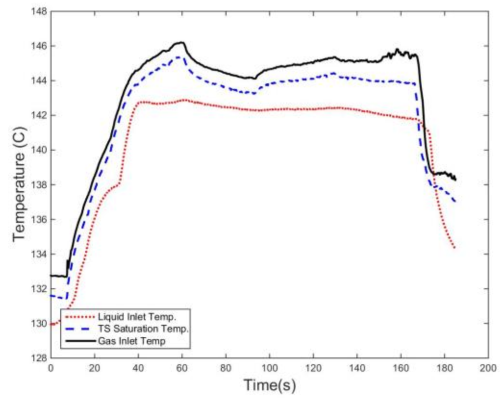


(d)

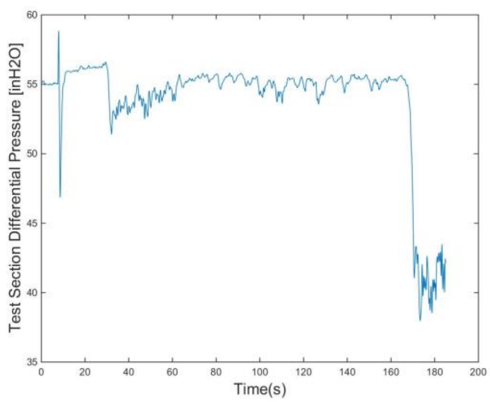
Figure B49: Raw data for steam/water test "*2016_01_04_test05*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



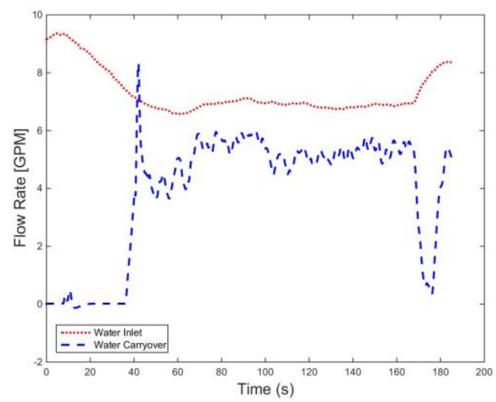
(a)



(b)

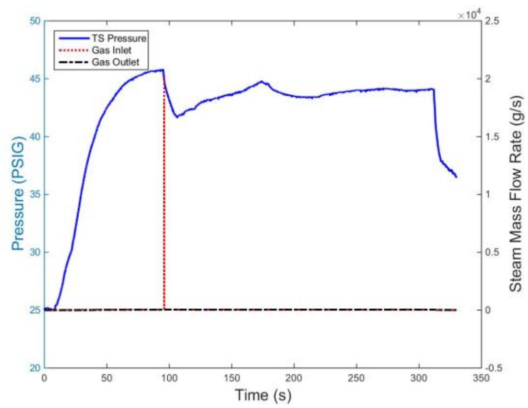


(c)

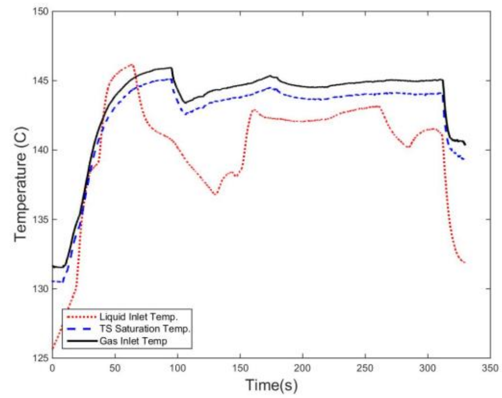


(d)

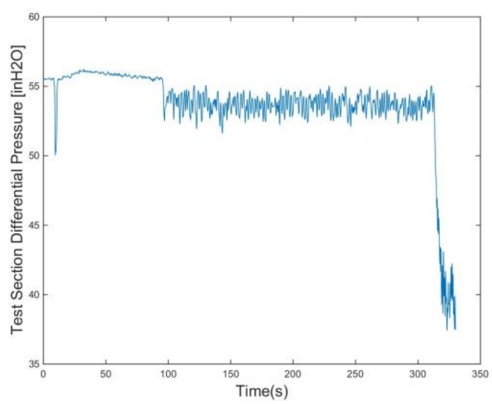
Figure B50: Raw data for steam/water test "*2016_01_04_test06*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



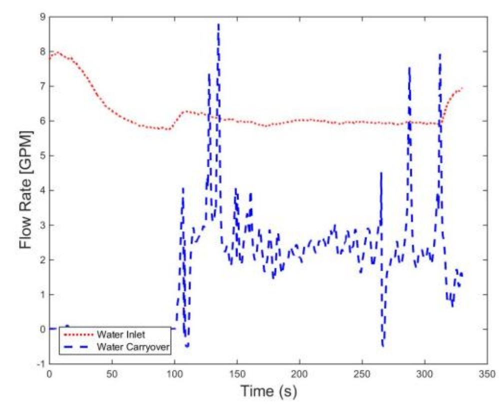
(a)



(b)

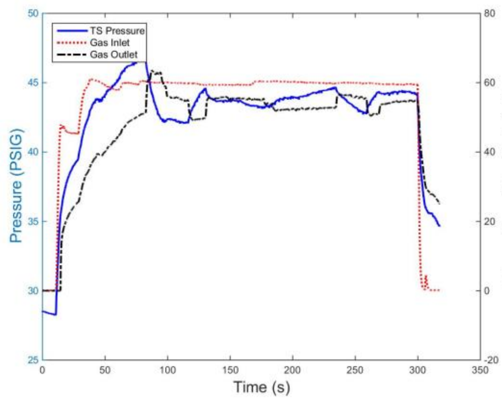


(c)

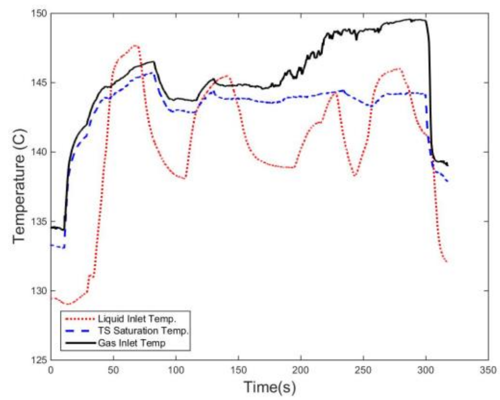


(d)

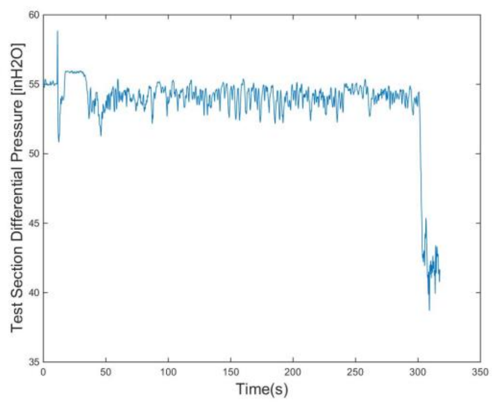
Figure B51: Raw data for steam/water test "*2016_01_04_test07*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



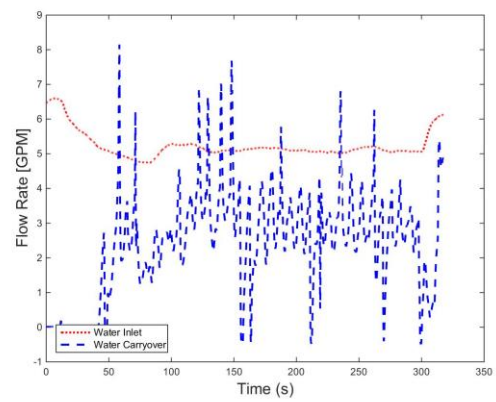
(a)



(b)

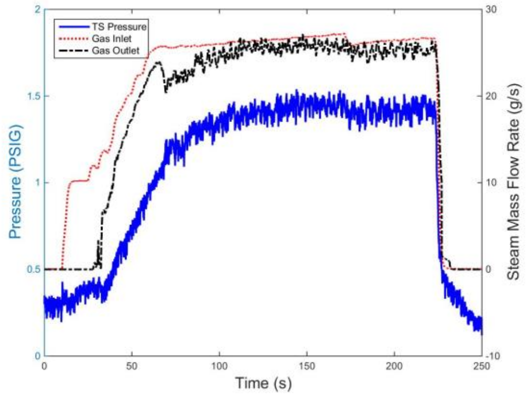


(c)

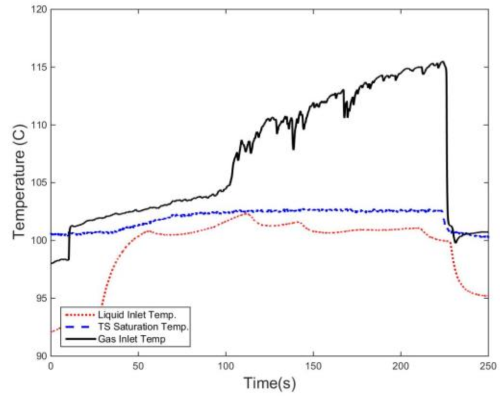


(d)

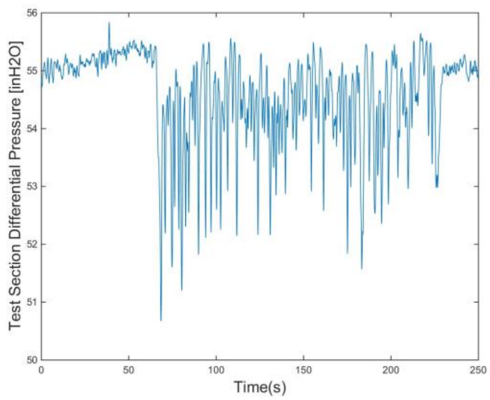
Figure B52: Raw data for steam/water test "*2016_01_04_test08*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



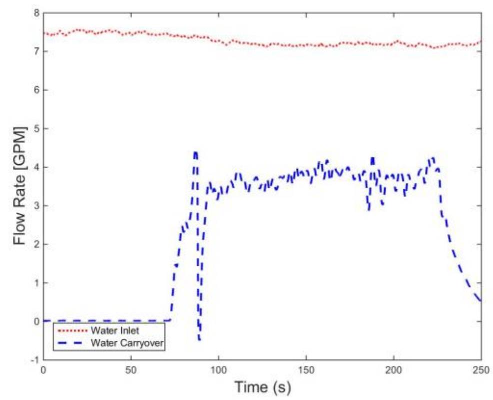
(a)



(b)

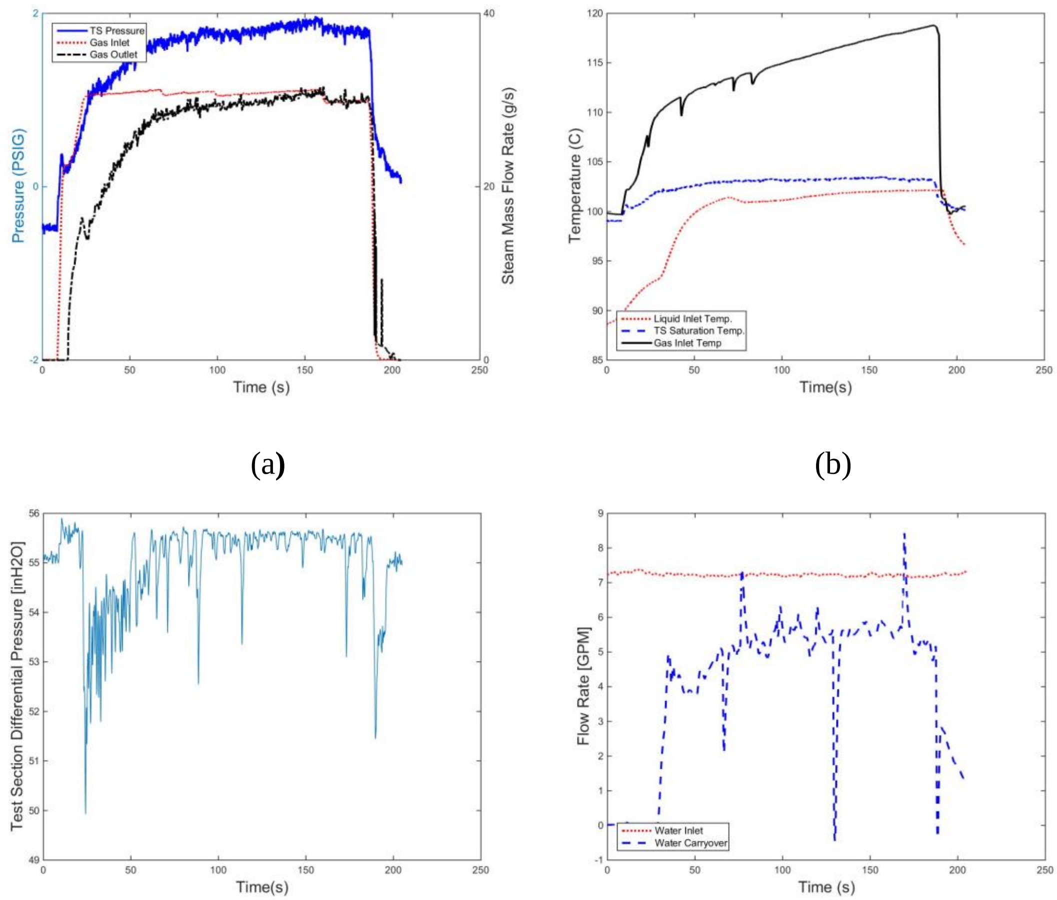


(c)



(d)

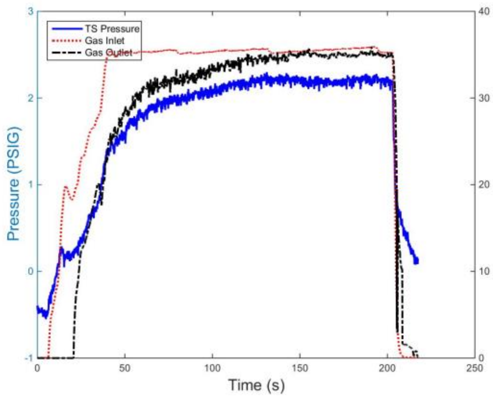
Figure B53: Raw data for steam/water test "*2016_01_19_test01*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



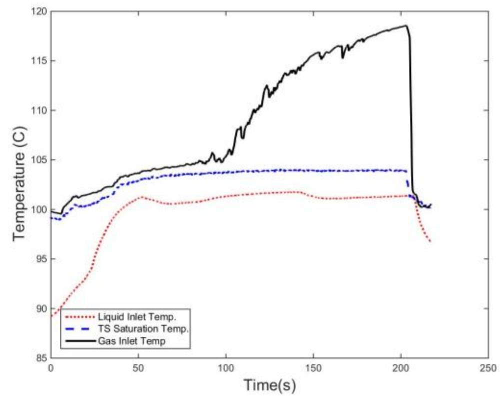
(a) (b)

(c) (d)

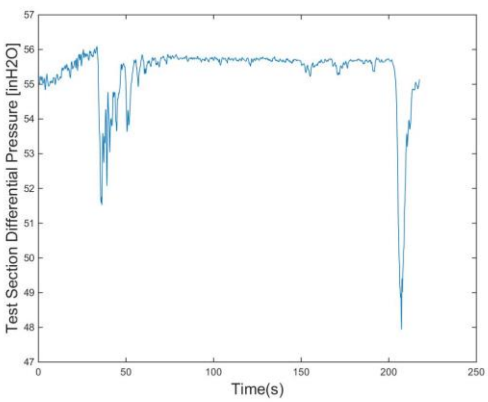
Figure B54: Raw data for steam/water test "*2016_01_19_test02*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



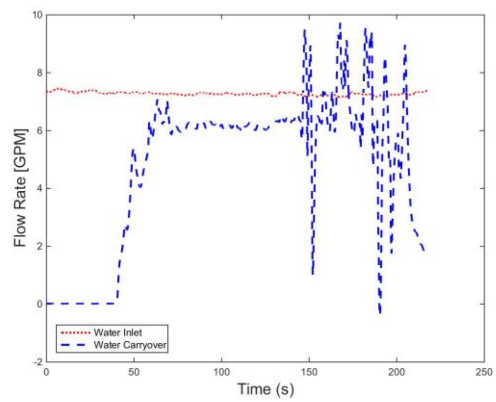
(a)



(b)

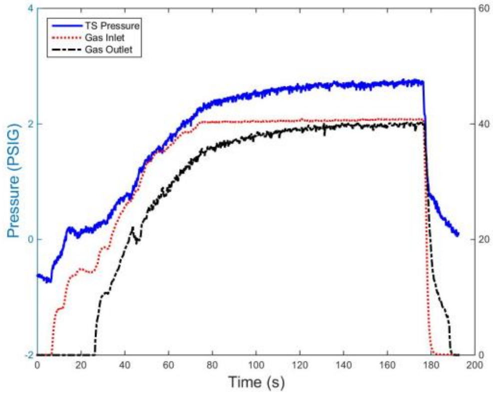


(c)

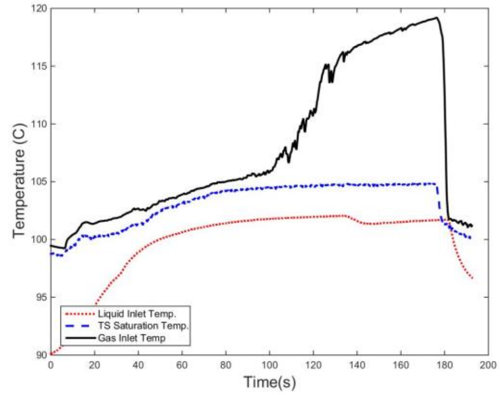


(d)

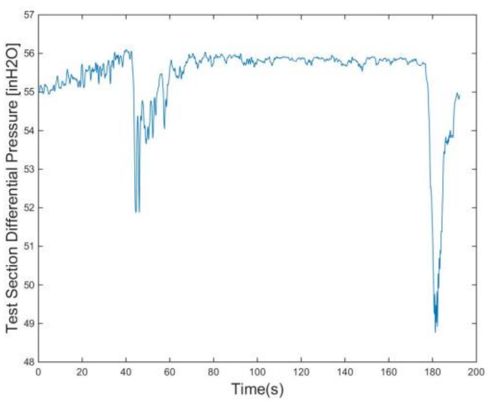
Figure B55: Raw data for steam/water test "*2016_01_19_test03*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



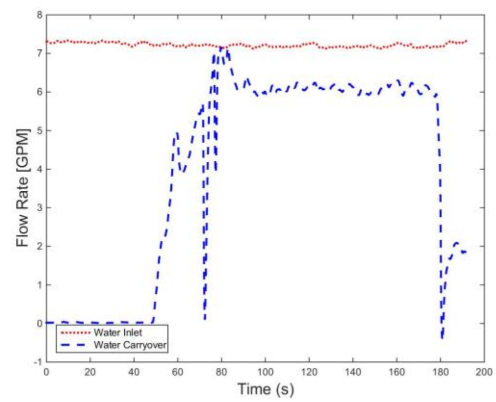
(a)



(b)

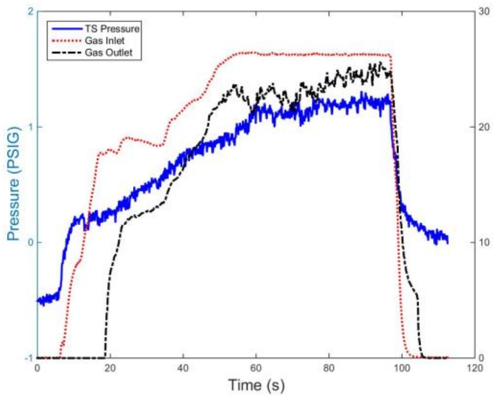


(c)

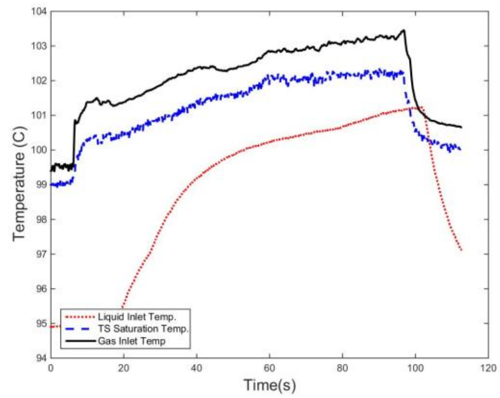


(d)

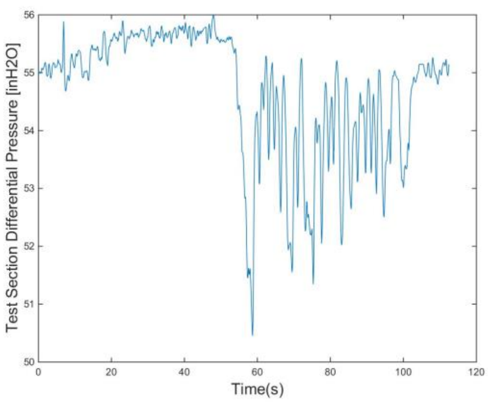
Figure B56: Raw data for steam/water test "*2016_01_19_test04*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



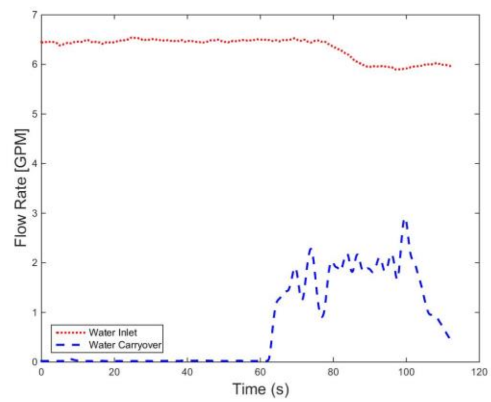
(a)



(b)

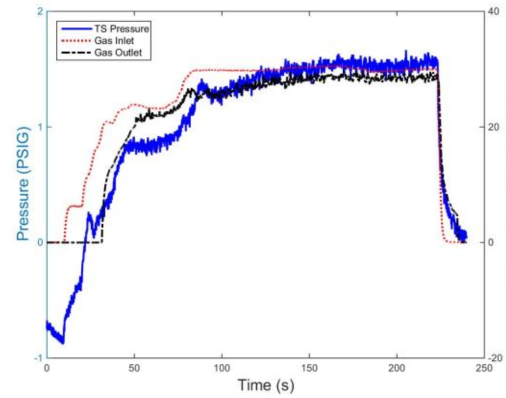


(c)

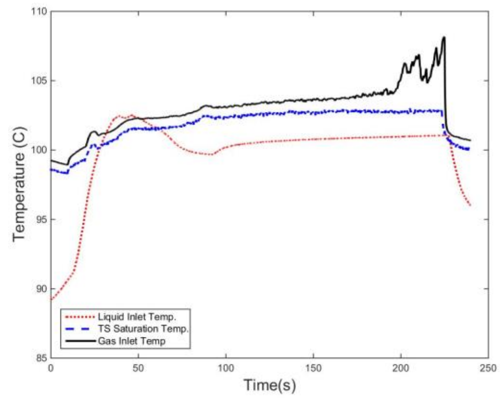


(d)

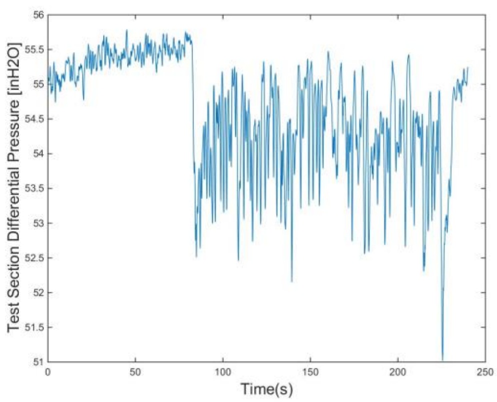
Figure B57: Raw data for steam/water test "*2016_01_19_test05*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



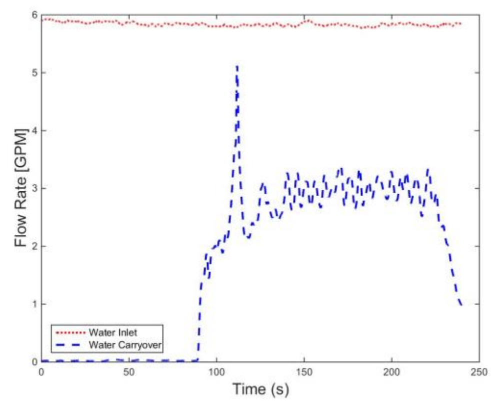
(a)



(b)

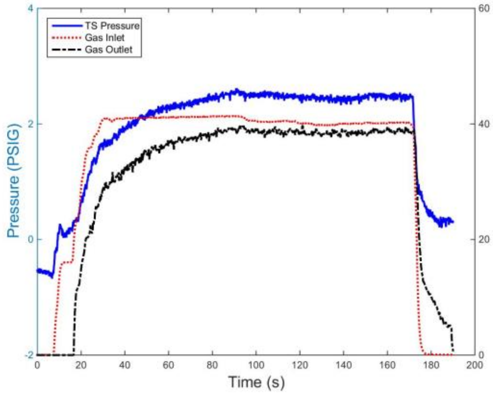


(c)

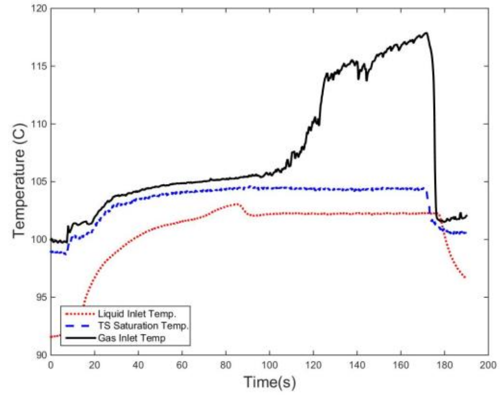


(d)

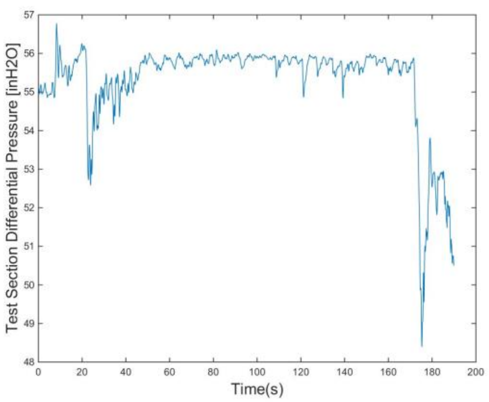
Figure B58: Raw data for steam/water test "*2016_01_19_test06*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



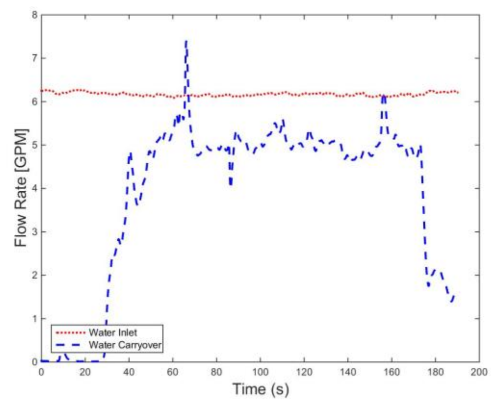
(a)



(b)

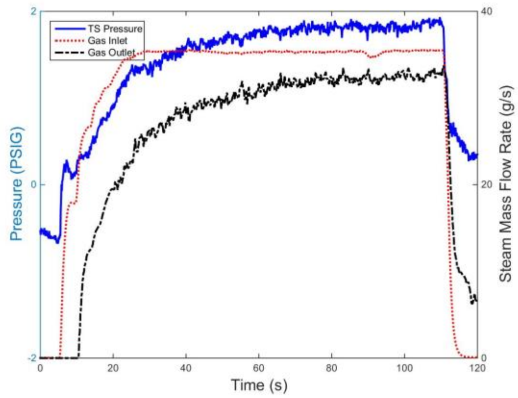


(c)

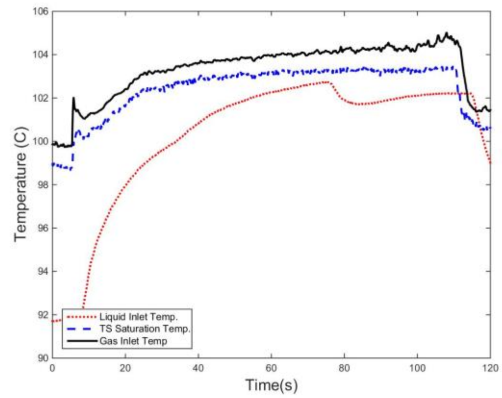


(d)

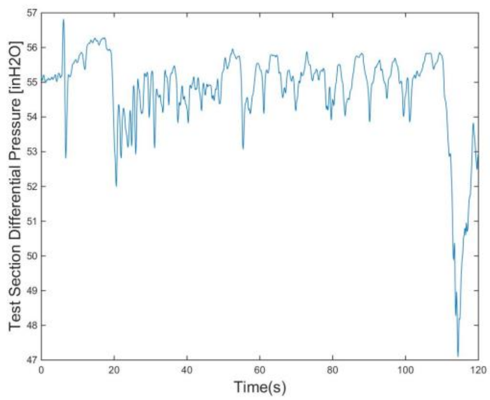
Figure B59: Raw data for steam/water test "*2016_01_19_test07*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



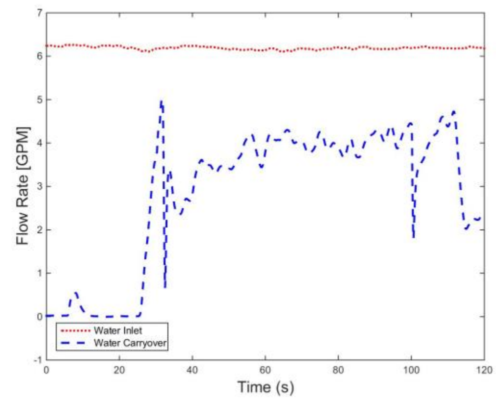
(a)



(b)

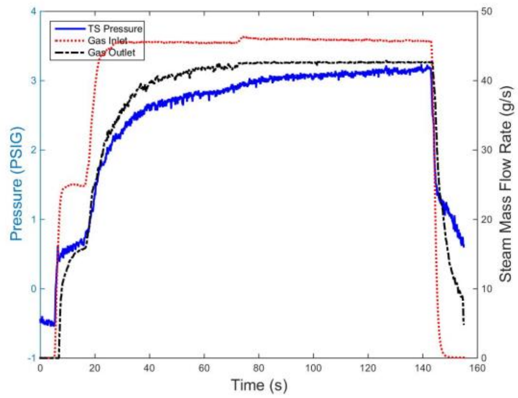


(c)

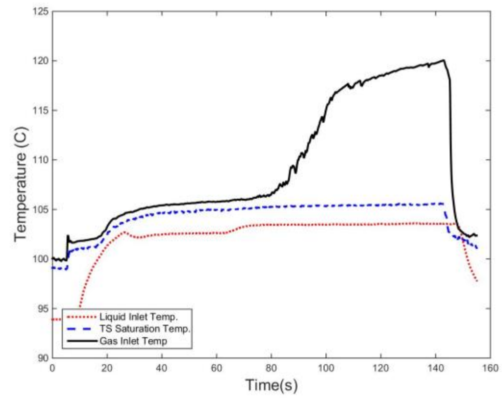


(d)

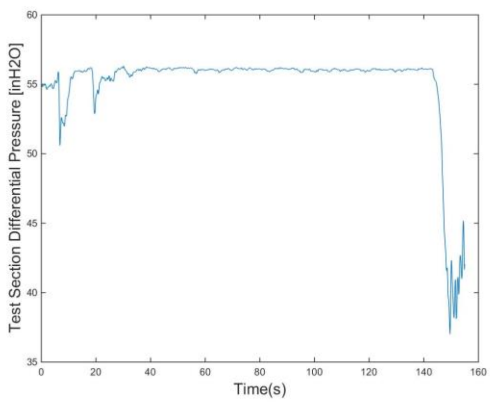
Figure B60: Raw data for steam/water test "*2016_01_19_test08*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



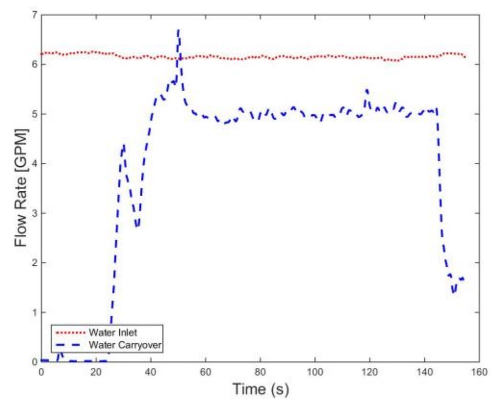
(a)



(b)

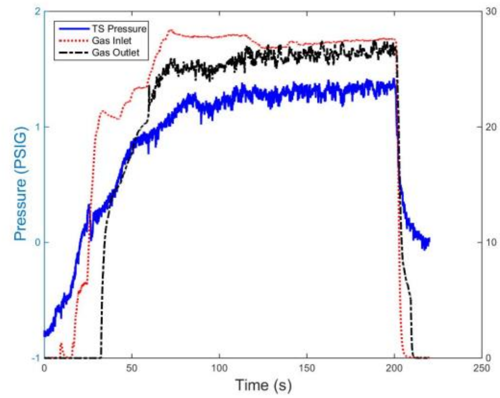


(c)

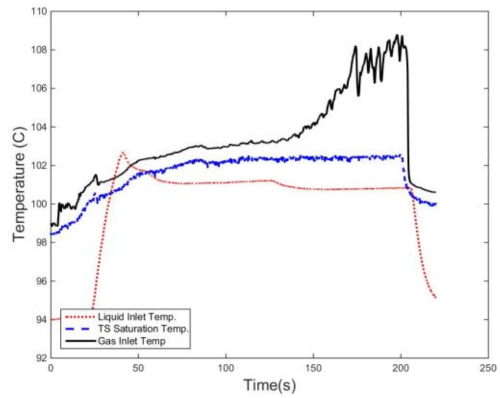


(d)

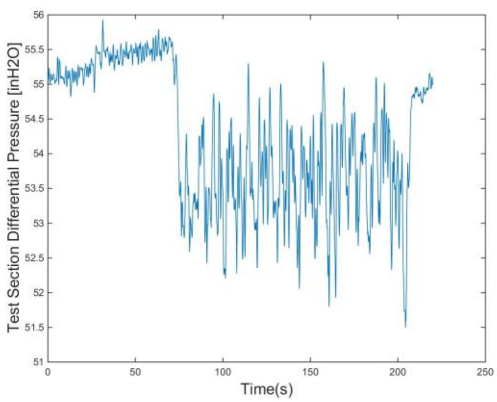
Figure B61: Raw data for steam/water test "*2016_01_19_test09*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



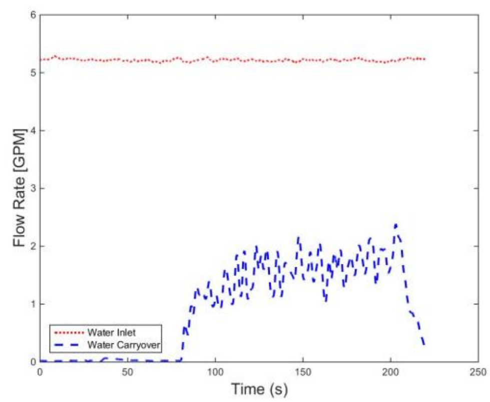
(a)



(b)

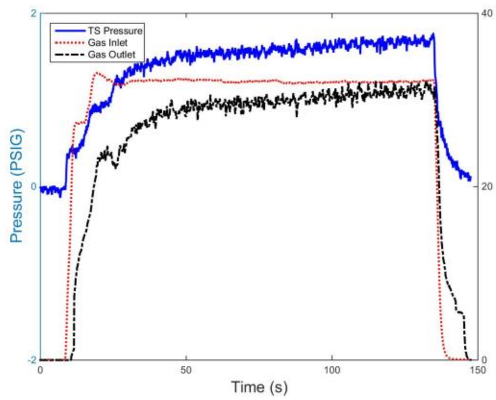


(c)

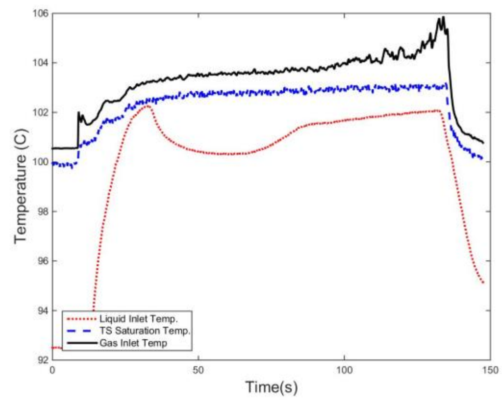


(d)

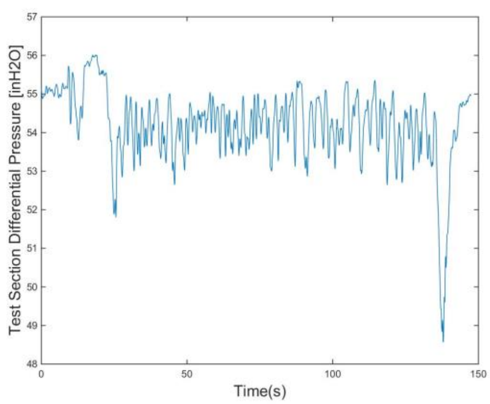
Figure B62: Raw data for steam/water test "*2016_01_19_test10*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



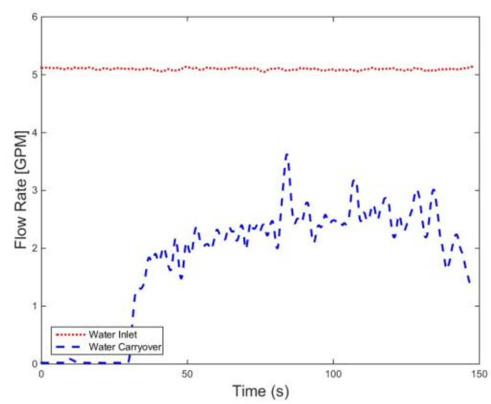
(a)



(b)



(c)



(d)

Figure B63: Raw data for steam/water test "*2016_01_19_test11*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.

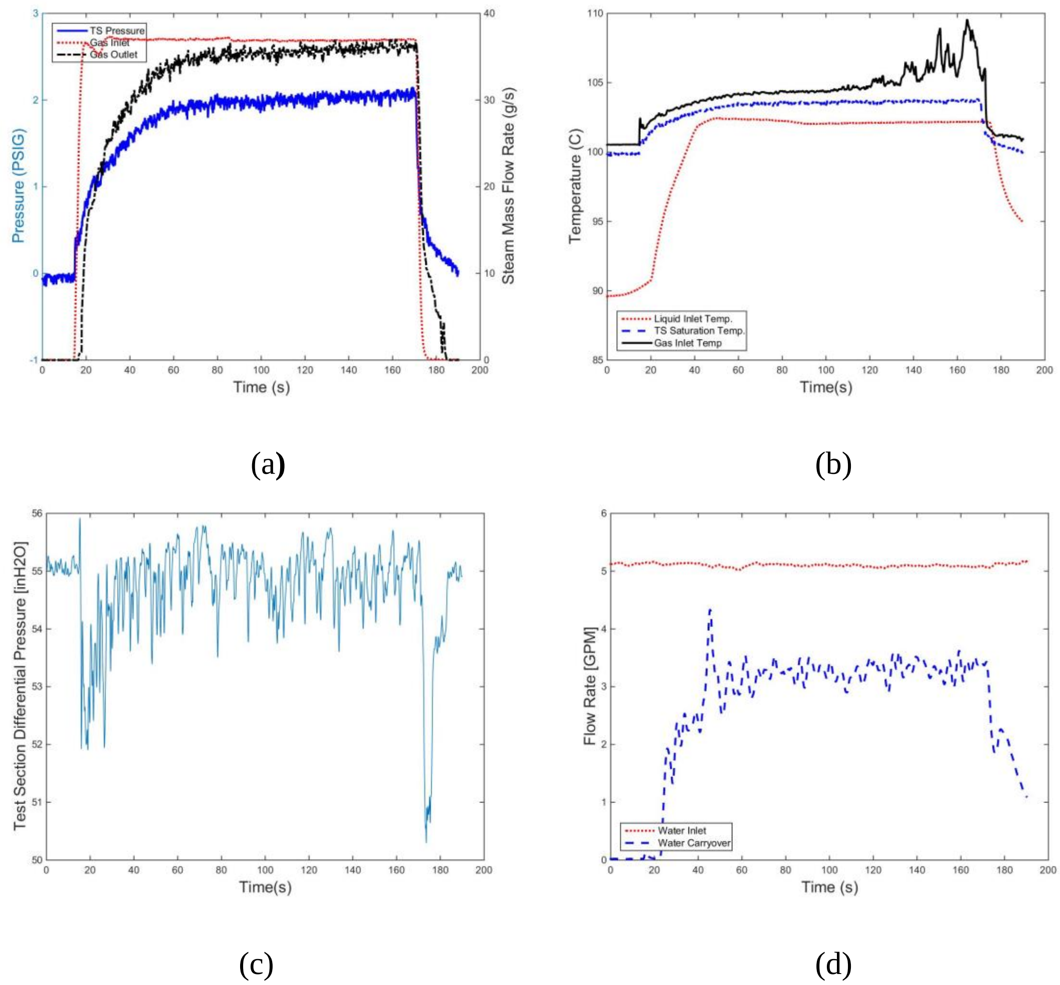
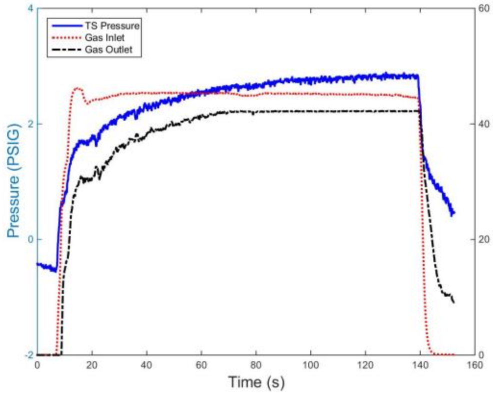
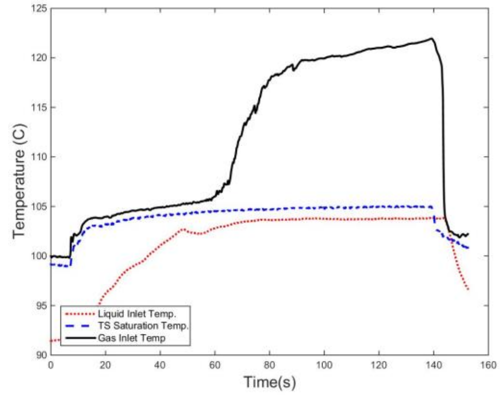


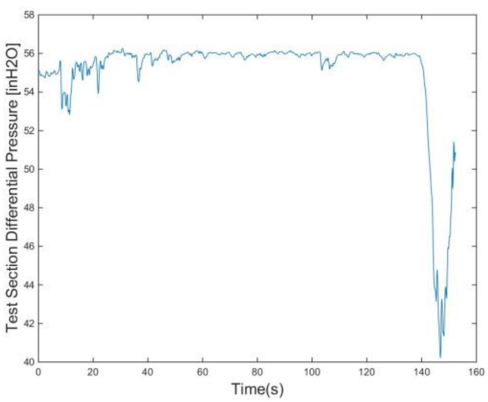
Figure B64: Raw data for steam/water test "*2016_01_19_test12*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



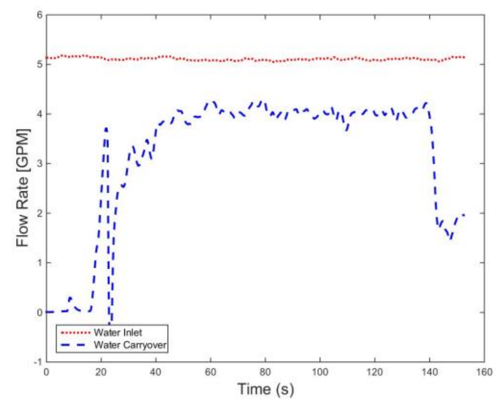
(a)



(b)

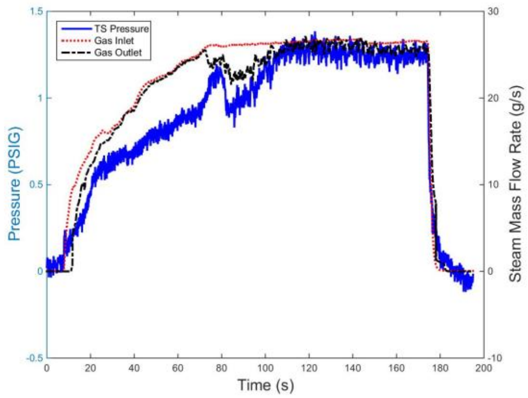


(c)

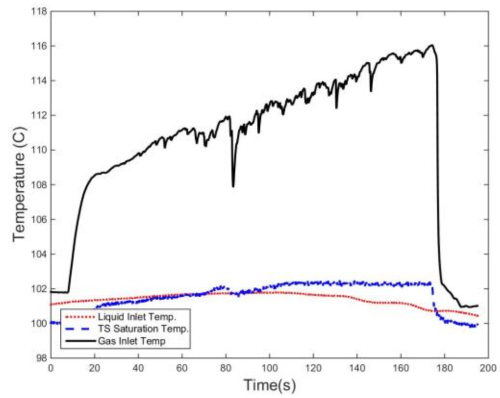


(d)

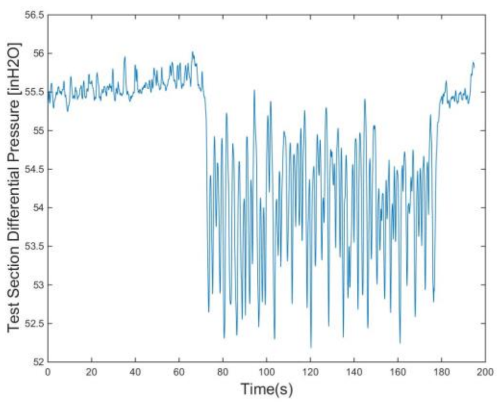
Figure B65: Raw data for steam/water test "*2016_01_19_test13*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



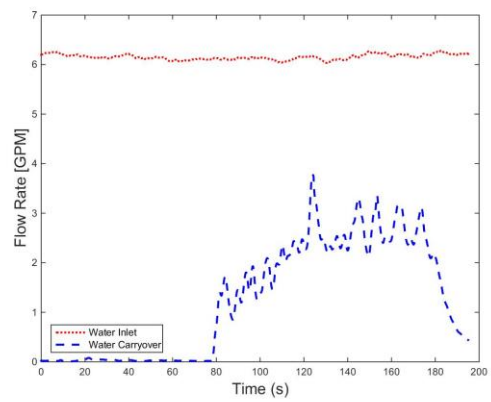
(a)



(b)

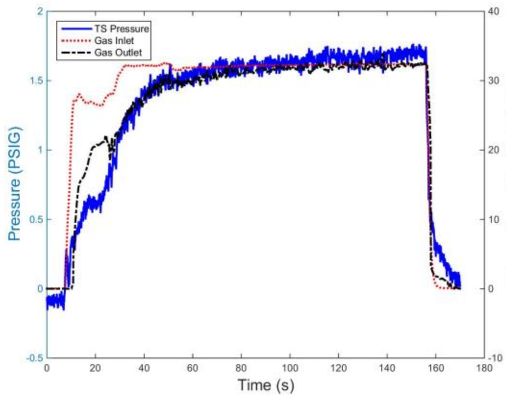


(c)

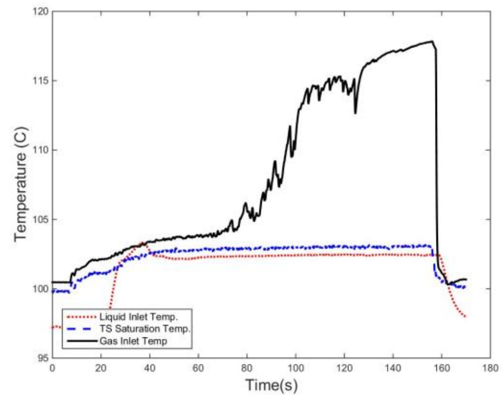


(d)

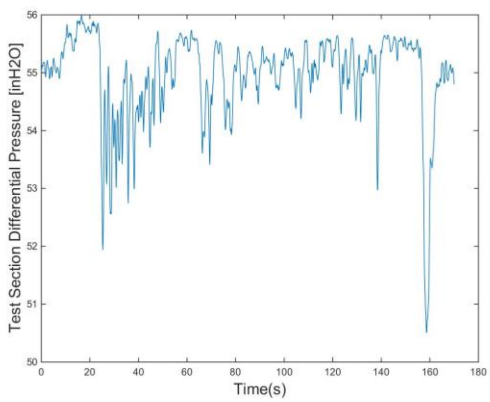
Figure B66: Raw data for steam/water test "*2016_01_20_test01*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



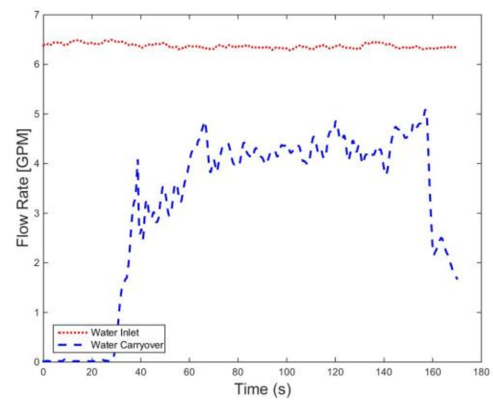
(a)



(b)

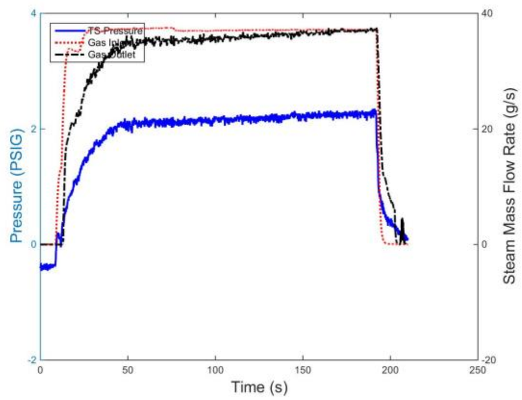


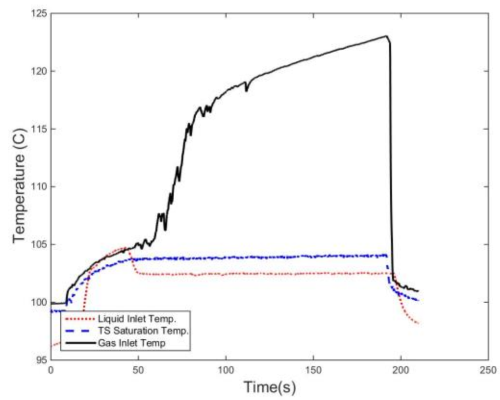
(c)



(d)

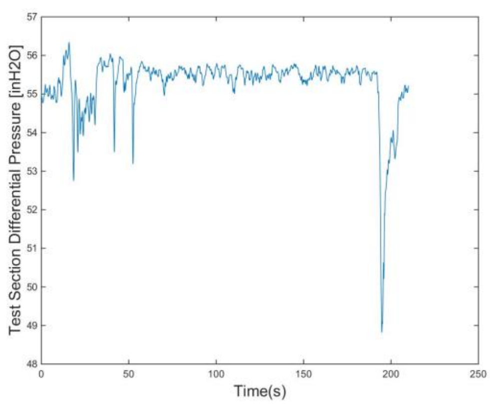
Figure B67: Raw data for steam/water test “*2016_01_20_test02*”. The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.

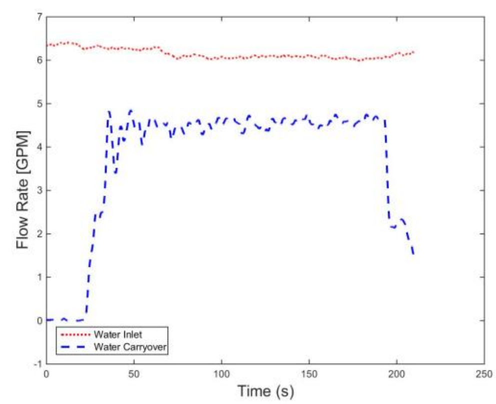




(a)

(b)

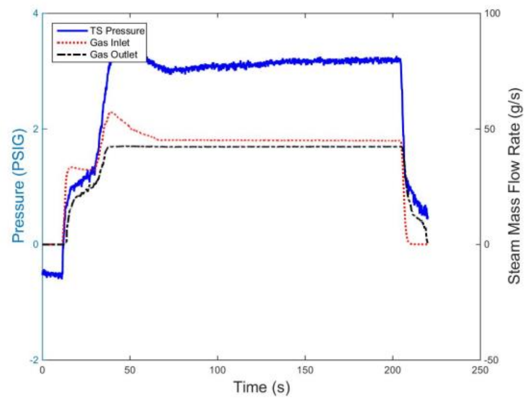




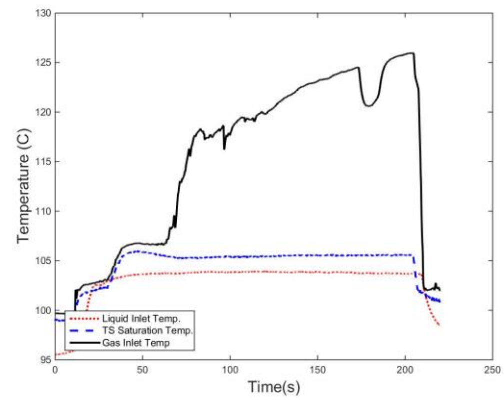
(c)

(d)

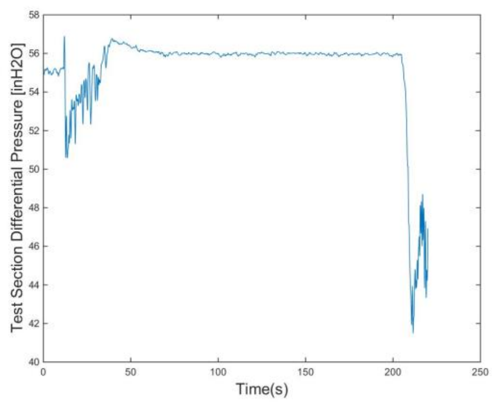
Figure B68: Raw data for steam/water test "*2016_01_20_test03*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.



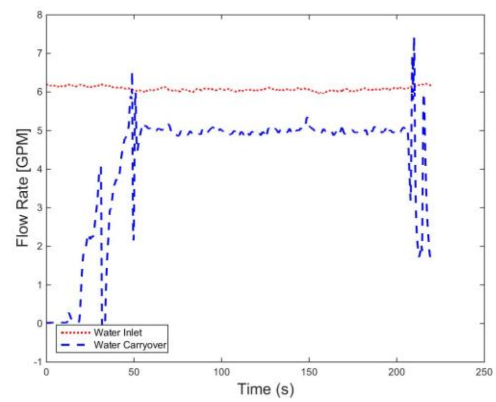
(a)



(b)



(c)



(d)

Figure B69: Raw data for steam/water test "*2016_01_20_test04*". The plots included are of (a) the gas inlet and outlet flow rate with the test section pressure, (b) the liquid inlet saturation and the gas inlet temperatures, (c) the test section differential pressure and (d) the water inlet and water carryover flow rates.

APPENDIX C: MATLAB SCRIPTS

This section contains the MATLAB scripts that were used to either perform the calculations to reduce the data or the MATLAB scripts that were used to plot the raw data.

C.1 Raw Data Plotting Script

```
% initialize the cell array
my_files = dir('Z:\Research\Matlab\Steam\PracticeAuto1\Data\*.dat'); %
structure containing your *.dat files
[numoffiles one]=size(my_files);
Final=zeros(numoffiles,36);
numoffiles
TS_D=0.0762; %Test Section Diameter [m]
TS_Area=((TS_D/2)^2)*pi; %Test Section Flow Area [m^2]
g=9.81; %Constant for gravity [m/s^2]
%Loop to load data and make calculations
for k=1:numoffiles
    k
    cvin= load(my_files(k).name); % load .dat file recursively
    CurrentFile=my_files(k).name
    testdateandname=regexp(my_files(k) .name, '\w*test\w*', 'match');
    fileID=testdateandname(1);

    %Pull specific parameters that need to be plotted from the dat
files.
    TSDP=cvin(:,111);
    TSDPfulltest=TSDP(SOT(k):EOT(k));
    TSDPtrimmedplot=TSDP(BFOS(k):EFOS(k));
    T_fi=cvin(:,56);
    T_fi_ft=T_fi(SOT(k):EOT(k));
    T_fi_tp=T_fi(BFOS(k):EFOS(k));
    T_gi=cvin(:,28);
    T_gi_ft=T_gi(SOT(k):EOT(k));
    T_gi_tp=T_gi(BFOS(k):EFOS(k));
    T_go=cvin(:,50);
    T_go_ft=T_go(SOT(k):EOT(k));
    T_go_tp=T_go(BFOS(k):EFOS(k));
    T_satTS=cvin(:,102);
    T_satTS_ft=T_satTS(SOT(k):EOT(k));
    T_satTS_tp=T_satTS(BFOS(k):EFOS(k));
    Q_fmagmi=cvin(:,72);
    Q_fmagmi_ft=Q_fmagmi(SOT(k):EOT(k));
    Q_fmagmi_tp=Q_fmagmi(BFOS(k):EFOS(k));
    Q_fc=cvin(:,77);
    Q_fc_ft=Q_fc(SOT(k):EOT(k));
    Q_fc_tp=Q_fc(BFOS(k):EFOS(k));
    mdot_gi=cvin(:,84)*10^3;
    mdot_gi_ft=mdot_gi(SOT(k):EOT(k));
    mdot_gi_tp=mdot_gi(BFOS(k):EFOS(k));
```

```
    mdot_go=(cvin(:,92));
    mdot_go_ft=mdot_go(SOT(k):EOT(k));
    mdot_go_tp=mdot_go(BFOS(k):EFOS(k));
    P_TSpsig=cvin(:,101)-14.6959494;
    P_TSpsig_ft=P_TSpsig(SOT(k):EOT(k));
    P_TSpsig_tp=P_TSpsig(BFOS(k):EFOS(k));
    Q_fd=Q_fmagmi-Q_fc;
    Q_fd_ft=Q_fd(SOT(k):EOT(k));
    Q_fd_tp=Q_fd(BFOS(k):EFOS(k));
    SOTtime=SOT(k)/10;
    EOTtime=EOT(k)/10;
    BFOStime=BFOS(k)/10;
    EFOStime=EFOS(k)/10;
    time=0:0.1:EOTtime-SOTtime;
    trimmedtime=BFOStime-SOTtime:0.1:(EFOStime-SOTtime);
    time=time';
    trimmedtime=trimmedtime';
    %Set the name for the specific plots to change with each test.
    nameTSDP=char(strcat(fileID, '_TSDP.jpg'));
    nameTemps=char(strcat(fileID, '_Temps.jpg'));
    nameWaterFlow=char(strcat(fileID, '_waterflow.jpg'));
    namePandGasIn=char(strcat(fileID, '_PandGasIn.jpg'));

%     nameTSDPtrimmed=char(strcat(fileID, '_TSDPtrimmed.jpg'));
%     nameTempstrimmed=char(strcat(fileID, '_Tempstrimmed.jpg'));
%     nameWaterFlowtrimmed=char(strcat(fileID,
'_waterflowtrimmed.jpg'));
%     namePandGasIntrimmed=char(strcat(fileID,
'_PandGasIntrimmed.jpg'));

    %TSDP Plots

        TSDPplot=plot(time,TSDPfulltest);
        xlabel('Time(s)', 'fontsize', 16);
        ylabel('Test Section Differential Pressure [inH2O]',
'fontsize', 16);
        print('-djpeg', nameTSDP);

%         TSDPtrimmedplot=plot(trimmedtime,TSDPtrimmedplot);
%         xlabel('Time(s)', 'fontsize', 16);
%         ylabel('Test Section Differential Pressure [inH2O]',
'fontsize', 16);
%         print('-djpeg', nameTSDPtrimmed);
%
    %Temps Plots

        plot(time,T_fi_ft,'LineStyle',':','Color','r');
        xlabel('Time(s)','fontsize',16);
        ylabel('Temperature (C)','fontsize',16);
        hold on;
        plot(time,T_satTS_ft,'LineStyle','--','Color','b');
        plot(time,T_gi_ft,'Color','k');
```

```
        hold off;
        legend('Liquid Inlet Temp.', 'TS Saturation Temp.','Gas Inlet
Temp');
        legend('location','SouthWest');
        print('-djpeg', nameTemps);

%          plot(trimmedtime,T_fi_tp,':');
%          xlabel('Time(s)','fontsize',16);
%          ylabel('Temperature (C)','fontsize',16);
%          hold on;
%          plot(trimmedtime,T_satTS_tp,'--');
%          plot(trimmedtime,T_gi_tp);
%          hold off;
%          legend('Liquid Inlet Temp.', 'TS Saturation Temp.','Gas Inlet
Temp');
%          legend('location','SouthWest');
%          print('-djpeg', nameTempstrimmed);

    %Water Flow Rate Plots

        plot(time,Q_fmagmi_ft,'LineStyle',':','Color','r')
        xlabel('Time (s)','fontsize',16);
        ylabel('Flow Rate [GPM]','fontsize', 16);
        hold on;
        plot(time,Q_fc_ft,'LineStyle','--','Color','b');
        %plot(time,Q_fd_ft,'-.');
        hold off;
        legend('Water Inlet','Water Carryover');
        legend('location','SouthWest');
        print('-djpeg',nameWaterFlow);

%          plot(trimmedtime,Q_fmagmi_tp,':')
%          xlabel('Time (s)','fontsize',16);
%          ylabel('Flow Rate [GPM]','fontsize', 16);
%          hold on;
%          plot(trimmedtime,Q_fc_tp,'--');
%          %plot(trimmedtime,Q_fd_tp,'-.');
%          hold off;
%          legend('Water Inlet','Water Carryover');
%          legend('location','SouthWest');
%          print('-djpeg',nameWaterFlowtrimmed);
%

[ax,L1,L2]=plotyy(time,P_TSpsig_ft,[time,time],[mdot_gi_ft,mdot_go_ft])
;
    xlabel(ax(1),'Time (s)');
    ylabel(ax(1),'Pressure (PSIG)');
    ylabel(ax(2),'Steam Mass Flow Rate (g/s)');
    L1.LineWidth=1;
    L2(1).LineWidth=1;
    L2(2).LineWidth=1;
    L2(1).LineStyle=':';
    L2(2).LineStyle='-.';
```

```
    L1.Color='r';
    L2(1).Color='b';
    L2(2).Color='k';

    legend('TS Pressure','Gas Inlet','Gas Outlet');
    legend('location','NorthWest');
    print('-djpeg', namePandGasIn);

%
[ax,L1,L2]=plotyy(trimmedtime,P_TSpsig_tp,[trimmedtime,trimmedtime],[md
ot_gi_tp,mdot_go_tp]);
%     xlabel(ax(1),'Time (s)');
%     ylabel(ax(1),'Pressure (PSIG)');
%     ylabel(ax(2),'Steam Mass Flow Rate (g/s)');
%     L1.LineWidth=1;
%     L2(1).LineWidth=1;
%     L2(2).LineWidth=1;
%     L2(1).LineStyle=':';
%     L2(2).LineStyle='-.';
%     legend('TS Pressure','Gas Inlet','Gas Outlet');
%     legend('location','NorthEast');
%     print('-djpeg', namePandGasIntrimmed);


end
```

C.2 Data Reduction Script

```
my_files = dir('Y:\Research\Matlab\Steam\PracticeAuto1\Data\*.dat'); %
structure containing your *.dat files
[numoffiles one]=size(my_files);
Final=zeros(numoffiles,36);
numoffiles
TS_D=0.0762; %Test Section Diameter [m]
TS_Area=((TS_D/2)^2)*pi; %Test Section Flow Area [m^2]
g=9.81; %Constant for gravity [m/s^2]
%Loop to load data and make calculations
for k=1:numoffiles
  k
  %AmountLeft=numoffiles-k
    cvin= load(my_files(k).name); % load .dat file recursively
    CurrentFile=my_files(k).name
  %Sets the data from the cvin array to specific variables
  %to allow for calculations to be made
  TSDP=cvin(:,110);
  T_fi=cvin(:,56);
  T_gi=cvin(:,28);
  T_go=cvin(:,50);
  T_satTS=cvin(:,102);
  T_wall=cvin(:,41);
  Q_fmagmi=cvin(:,72);
  Q_fc=cvin(:,77);
  mdot_gi=cvin(:,84);
  mdot_go=(cvin(:,92))*10^(-3);
  P_TSpsia=cvin(:,101);
  P_TSpsig=cvin(:,101)-14.6959494;
  rho_gi=cvin(:,82);
  rho_go=cvin(:,91);
  rho_fmagmi=cvin(:,73);
  %Adjust the starting frame of study and ending frame of study
  %to allow for parameters to steady
  SSP=BFOS(k)+50;
  ESP=EFOS(k);
  %Take average of all of the variables that have just been set
  %for the area of interest


  AvgT_fi=mean(T_fi([SSP:ESP])); %Average Temp of Water In [C]
  AvgT_gi=mean(T_gi([SSP:ESP])); %Average Temp of Gas In   [C]
  AvgT_go=mean(T_go([SSP:ESP])); %Average Temp of Gas Out  [C]
  AvgT_satTS=mean(T_satTS([SSP:ESP])); %Average Saturation Temp in TS
[C]
  AvgT_wall=mean(T_wall([SSP:ESP])); %Average Temp of wall [C]
  AvgQ_fmagmi=mean(Q_fmagmi([SSP:ESP])); %Average Water In Flow Rate at
Mag Meter[GPM]
  AvgQ_fc=mean(Q_fc([SSP:ESP])); %Average Water carryover flow rate
[GPM]
  Avgmdot_gi=mean(mdot_gi([SSP:ESP])); %Average mass flow rate of gas
in [kg/s]
```

```
  Avgmdot_go=mean(mdot_go([SSP:ESP])); %Average mass flow rate of gas
out [kg/s]
  AvgP_TSpsia=mean(P_TSpsia([SSP:ESP])); %Average Pressure in TS [psia]
  AvgP_TSpsig=mean(P_TSpsig([SSP:ESP])); %Average Pressure in TS [psig]
  Avgrho_gi=mean(rho_gi([SSP:ESP])); %Average density of gas in
[kg/m^3]
  Avgrho_go=mean(rho_go([SSP:ESP])); %Average density of gas out
[kg/m^3]
  Avgrho_fmagmi=mean(rho_fmagmi([SSP:ESP])); %Average density of water
in at mag flow meter [kg/m^3]
  %Convert pressure to be in bars for XSteam look up to work

  AvgP_TSbar=(AvgP_TSpsia)/(14.5037738007); %Average Pressure of TS in
bar
  %Use XSteam to look up neccessary gas and liquid parameters
  Avgrho_f=XSteam('rho_pT',AvgP_TSbar,AvgT_fi); %Average density of
water in [kg/m^3]
  Avgsigma_f=XSteam('st_T',AvgT_fi); %Average surface tension of water
in TS [N/m]
  Cp=XSteam('Cp_pT',AvgP_TSbar,AvgT_fi); %Specific isobaric heat
capacity of water in TS [kJ/(kg C)]
  h_sti=XSteam('h_pT',AvgP_TSbar,AvgT_gi); %Enthalpy of steam etering
TS [kJ/kg]
  h_sto=XSteam('h_pT',AvgP_TSbar,AvgT_go); %Enthalpy of steam exiting
TS [kJ/kg]
  h_f=XSteam('h_pt',AvgP_TSbar,AvgT_fi); %Enthalpy of water entering TS
[kJ/kg]

  %Compute calculations for all neccessary values

  %Calculates the actual volumetric flow rate of water going into the
test
  %section accounting for the density change from the water going
through
  %the inlet water heater.
  AvgQ_fi=(AvgQ_fmagmi*Avgrho_fmagmi)/(Avgrho_f); %Average Water In
flow rate [GPM]

  %Calculates the volumetric flow rate of the water going down the tube
by
  %subtracting the avg water caryover from the average water in. This
  %assumes that the density of the water doesn't change much from
entering
  %and exiting the test section.
  AvgQ_fd=AvgQ_fi-AvgQ_fc; %Average water down flow rate [GPM]

  %Calculate the superficial velocities for the inlet gas outlet gas
and
  %water falling down the test section.

  Avgj_gi=(Avgmdot_gi)/(Avgrho_gi*TS_Area); %Superficial Velocity of
gas entering TS [m/s]
```

```
  Avgj_go=(Avgmdot_go)/(Avgrho_go*TS_Area); %Superficial Velocity of
gas leaving TS [m/s]
  Avgj_fd=(AvgQ_fd*(0.00006309))/(TS_Area); %Superficial Velocity of
water falling down test section [m/s]
  Avgj_fi=(AvgQ_fi*(0.00006309))/(TS_Area);
  Avgj_fc=(AvgQ_fc*(0.00006309))/(TS_Area);
  %Calculate the kutateladze parameter for gas in, gas out, and water
down.
  %Kutateladze Parameter of Gas In to test section [unitless]
  K_gi=(((Avgrho_gi)^(1/2))*(Avgj_gi))/(g*Avgsigma_f*((Avgrho_f-
Avgrho_gi)^(1/4)));
  %Kutateladze Parameter of Gas Out of test section [unitless]
  K_go=(((Avgrho_go)^(1/2))*(Avgj_go))/(g*Avgsigma_f*((Avgrho_f-
Avgrho_go)^(1/4)));
  %Kutateladze Parameter of water down test section [unitless]
  K_fd=(((Avgrho_f)^(1/2))*(Avgj_fd))/(g*Avgsigma_f*((Avgrho_f-
Avgrho_gi)^(1/4)));

  K_fi=(((Avgrho_f)^(1/2))*(Avgj_fi))/(g*Avgsigma_f*((Avgrho_f-
Avgrho_gi)^(1/4)));
  K_fc=(((Avgrho_f)^(1/2))*(Avgj_fc))/(g*Avgsigma_f*((Avgrho_f-
Avgrho_gi)^(1/4)));
  %Calculate the square root of the kutateladze parameters as that is
how
  %they will be plotted.
  K_gisqr=sqrt(K_gi);
  K_gosqr=sqrt(K_go);
  K_fdsqr=sqrt(K_fd);
  K_fisqr=sqrt(K_fi);
  K_fcsqr=sqrt(K_fc);

  k_fc_over_k_fi=(K_fcsqr)/(K_fisqr);
  k_fi_over_k_fc=(K_fisqr)/(K_fcsqr);
  %Calculate the f parameter from the Williams Thesis to test how her
  %correlation stands up against data for this research.
%
f_i_williams=((AvgQ_fmagmi*Avgrho_fmagmi*0.00006309)*Cp*(AvgT_satTS-
AvgT_wall))/(Avgmdot_gi*(h_sti-h_f));
%
f_o_williams=((AvgQ_fmagmi*Avgrho_fmagmi*0.00006309)*Cp*(AvgT_satTS-
AvgT_wall))/(Avgmdot_gi*(h_sto-h_f));
%   K_ge_i=K_gi*(1-f_i_williams);
%   K_ge_isqr=sqrt(K_ge_i);
%   K_ge_o=K_gi*(1-f_o_williams);
%   K_ge_osqr=sqrt(K_ge_o);
  %Calculate Effective Kutateladze parameter for gas flow
  %Set the values in a final array that can be used for plotting
  %or recording
  Final(k,1)=AvgT_fi;
  Final(k,2)=AvgT_gi;
  Final(k,3)=AvgT_go;
  Final(k,4)=AvgT_satTS;
  Final(k,5)=AvgT_wall;
```

```
  Final(k,6)=AvgQ_fmagmi;
  Final(k,7)=AvgQ_fi;
  Final(k,8)=AvgQ_fc;
  Final(k,9)=AvgQ_fd;
  Final(k,10)=Avgmdot_gi;
  Final(k,11)=Avgmdot_go;
  Final(k,12)=AvgP_TSpsig;
  Final(k,13)=Avgrho_f;
  Final(k,14)=Avgrho_fmagmi;
  Final(k,15)=Avgrho_gi;
  Final(k,16)=Avgrho_go;
  Final(k,17)=Avgsigma_f;
  Final(k,18)=Avgj_gi;
  Final(k,19)=Avgj_go;
  Final(k,20)=Avgj_fd;
  Final(k,21)=Cp;
  Final(k,22)=h_sti;
  Final(k,23)=h_sto;
  Final(k,24)=h_f;
  Final(k,25)=K_gi;
  Final(k,26)=K_go;
  Final(k,27)=K_fd;
  Final(k,28)=K_gisqr;
  Final(k,29)=K_gosqr;
  Final(k,30)=K_fdsqr;
  Final(k,31)=f_i_williams;
  Final(k,32)=f_o_williams;
  Final(k,33)=K_ge_i;
  Final(k,34)=K_ge_isqr;
  Final(k,35)=K_ge_o;
  Final(k,36)=K_ge_osqr;

% Final(k,1)=K_fi;
% Final(k,2)=K_fc;
% Final(k,3)=K_fisqr;
% Final(k,4)=K_fcsqr;
% Final(k,5)=k_fc_over_k_fi;
% Final(k,6)=k_fi_over_k_fc;
  Final(k,1)=std(P_TSpsig([SSP:ESP]));
  Final(k,2)=std(mdot_gi([SSP:ESP]));
  Final(k,3)=std(Q_fmagmi([SSP:ESP]));

end
% dlmwrite('FinalSteamMatrixArray2Jan242016.txt',Final)
  %dlmwrite('Kuratios.txt.',Final)
```

APPENDIX D: REDUCED DATA

This section contains the reduced data in tabulated form. The tests are listed based on their name, and their names correspond with the raw plots in Appendix A or Appendix B.

Table D1: Reduced data for Steam/Water atmospheric flooding tests.

Test Name	Test Pressure (psig)	Inlet Gas Flowrate (g/s)	Outlet Gas Flowrate (g/s)	$Q_{f,in}$ (GPM)	$Q_{f,carryover}$ (GPM)	$Q_{f,down}$ (GPM)	$T_{f,in}$ (°C)	T_{sat} (°C)	$T_{g,in}$ (°C)	$(K_{g,in})^{1/2}$	$(K_{fd})^{1/2}$	Qualify?
2016_01_19_test1	1.42	26.47	25.40	7.22	3.69	3.53	101.12	102.57	111.51	1.51	0.69	Yes
2016_01_19_test2	1.70	30.67	28.29	7.24	5.09	2.15	100.92	103.07	115.10	1.62	0.54	Yes
2016_01_19_test3	2.12	35.44	33.75	7.28	6.42	0.86	101.22	103.79	110.72	1.73	0.34	Yes
2016_01_19_test4	2.62	40.55	38.90	7.22	6.08	1.14	101.74	104.63	112.37	1.84	0.39	Yes
2016_01_19_test5	1.17	26.26	23.56	6.32	1.59	4.72	100.67	102.13	103.06	1.51	0.79	Yes
2016_01_19_test6	1.47	29.97	27.86	5.85	2.77	3.07	100.70	102.67	103.95	1.60	0.64	Yes
2016_01_19_test7	2.42	40.58	38.03	6.18	5.04	1.14	102.13	104.31	109.48	1.85	0.39	Yes
2016_01_19_test8	1.75	35.32	31.20	6.21	3.80	2.41	101.93	103.16	104.08	1.74	0.57	Yes
2016_01_19_test9	2.96	45.76	42.01	6.18	5.02	1.16	103.20	105.19	111.39	1.95	0.39	Yes
2016_01_19_test10	1.32	27.31	26.33	5.24	1.65	3.58	100.81	102.40	105.73	1.54	0.69	Yes
2016_01_19_test11	1.60	32.12	30.11	5.12	2.43	2.69	101.24	102.89	103.95	1.66	0.60	Yes
2016_01_19_test12	2.02	36.88	35.77	5.12	3.29	1.83	102.12	103.63	105.63	1.77	0.50	Yes
2016_01_19_test13	2.64	45.17	41.43	5.14	3.97	1.17	103.19	104.68	114.78	1.95	0.40	Yes
2016_01_20_test1	1.25	26.49	25.79	6.15	2.49	3.65	101.42	102.28	114.16	1.52	0.70	Yes
2016_01_20_test2	1.65	32.26	31.87	6.38	4.30	2.08	102.41	102.98	112.50	1.67	0.53	Yes
2016_01_20_test3	2.20	37.10	36.26	6.09	4.56	1.53	102.48	103.94	120.31	1.78	0.45	Yes
2016_01_20_test4	3.15	45.00	42.29	6.08	4.98	1.10	103.82	105.51	121.97	1.93	0.39	Yes

Table D2: Reduced data for Steam/Water 15 PSIG flooding tests.

Test Name	Test Pressure (psig)	Inlet Gas Flowrate (g/s)	Outlet Gas Flowrate (g/s)	$Q_{f,in}$ (GPM)	$Q_{f,carryover}$ (GPM)	$Q_{f,down}$ (GPM)	$T_{f,in}$ (°C)	T_{sat} (°C)	$T_{g,in}$ (°C)	$(K_{g,in})^{1/2}$	$(K_{fd})^{1/2}$	Qualify?
2015_12_01_test1	14.62	40.86	34.39	5.97	2.78	3.18	119.31	120.55	122.03	1.69	0.67	Yes
2015_12_01_test2	12.40	50.84	42.57	5.98	4.16	1.82	116.61	118.07	119.05	1.91	0.51	Yes
2015_12_01_test3	14.01	49.41	47.78	5429.21	5.02	5424.19	120.17	119.88	129.24	6.83	18.87	No
2015_12_01_test4	15.96	54.29	51.12	6.07	4.81	1.26	121.08	121.97	129.26	1.93	0.42	Yes
2015_12_01_test5	15.53	46.65	40.19	6.17	3.84	2.33	119.52	121.51	122.40	1.79	0.58	Yes
2015_12_02_test1	14.89	43.54	35.44	6.46	4.53	1.93	111.98	120.84	131.25	1.71	0.52	No
2015_12_02_test2	15.01	41.33	33.50	6.16	3.01	3.15	119.36	120.96	126.81	1.69	0.67	Yes
2015_12_02_test3	15.57	44.26	36.26	6.18	3.40	2.78	119.74	121.56	122.72	1.74	0.63	Yes
2015_12_02_test4	15.75	52.10	45.42	6.13	4.49	1.65	118.42	121.75	126.50	1.89	0.48	Yes
2015_12_02_test5	15.32	47.33	38.79	6.18	3.90	2.28	118.69	121.29	131.72	1.81	0.57	Yes
2015_12_14_test1	14.67	39.51	34.59	6.80	3.70	3.10	119.04	120.60	121.57	1.66	0.66	Yes
2015_12_14_test2	14.48	45.71	37.14	7.19	4.83	2.36	117.74	120.39	124.35	1.78	0.58	Yes
2015_12_14_test3	15.03	55.12	47.27	7.12	5.88	1.25	118.24	120.99	135.08	1.95	0.42	Yes
2015_12_14_test4	14.81	38.75	30.61	7.17	3.24	3.93	118.23	120.75	135.01	1.64	0.74	Yes
2015_12_14_test5	14.72	41.72	35.79	5.55	2.66	2.89	118.07	120.65	128.61	1.70	0.64	Yes
2015_12_14_test6	14.93	50.65	46.79	5.17	3.57	1.59	118.56	120.88	135.36	1.87	0.47	Yes
2015_12_14_test7	14.89	52.79	47.38	5.40	3.83	1.58	118.21	120.84	137.60	1.91	0.47	Yes
2015_12_14_test8	14.64	48.04	44.58	5.20	3.52	1.68	118.03	120.57	139.28	1.83	0.49	Yes

Table D3: Reduced data for Steam/Water 30 PSIG flooding tests.

Test Name	Test Pressure (psig)	Inlet Gas Flowrate (g/s)	Outlet Gas Flowrate (g/s)	$Q_{f,in}$ (GPM)	$Q_{f,carryover}$ (GPM)	$Q_{f,down}$ (GPM)	$T_{f,in}$ (°C)	T_{sat} (°C)	$T_{g,in}$ (°C)	$(K_{g,in})^{1/2}$	$(K_{fd})^{1/2}$	Qualify?
2015_12_11_test1	29.08	46.49	42.02	5.14	2.25	2.89	130.50	133.73	134.63	1.67	0.65	Yes
2015_12_11_test2	29.19	52.42	48.58	6.65	4.45	2.20	133.71	133.82	135.71	1.79	0.57	Yes
2015_12_11_test3	29.32	61.81	58.88	5.51	4.12	1.40	133.16	133.92	135.36	1.93	0.46	Yes
2015_12_11_test4	30.37	65.64	56.77	5.52	4.15	1.36	133.00	134.73	142.12	1.98	0.45	Yes
2015_12_13_test1	29.22	42.25	41.44	7.32	4.42	2.90	132.10	133.84	134.78	1.59	0.66	Yes
2015_12_13_test2	29.40	48.39	42.41	7.27	4.63	2.64	131.93	133.98	135.44	1.71	0.63	Yes
2015_12_13_test3	29.62	55.21	46.95	7.15	5.06	2.08	132.92	134.16	137.48	1.83	0.56	Yes
2015_12_13_test4	29.53	65.09	61.38	7.21	6.09	1.12	132.76	134.08	143.20	1.98	0.41	Yes
2015_12_13_test5	28.77	45.78	38.73	7.27	4.06	3.21	131.65	133.49	137.22	1.67	0.69	Yes
2015_12_13_test6	29.42	46.99	40.95	6.05	3.14	2.91	131.53	134.00	142.73	1.68	0.66	Yes
2015_12_13_test7	29.41	55.43	49.61	6.22	4.20	2.02	132.44	133.99	143.07	1.83	0.55	Yes
2015_12_13_test8	29.49	62.90	57.13	6.07	4.73	1.34	132.75	134.05	142.20	1.95	0.45	Yes
2015_12_13_test9	29.54	65.30	62.42	6.18	4.65	1.53	131.81	134.09	143.38	1.98	0.48	Yes

Table D4: Reduced data for Steam/Water 45 PSIG flooding tests.

Test Name	Test Pressure (psig)	Inlet Gas Flowrate (g/s)	Outlet Gas Flowrate (g/s)	$Q_{f,in}$ (GPM)	$Q_{f,carryover}$ (GPM)	$Q_{f,down}$ (GPM)	$T_{f,in}$ (°C)	T_{sat} (°C)	$T_{g,in}$ (°C)	$(K_{g,in})^{1/2}$	$(K_{fd})^{1/2}$	Qualify?
2015_12_12_test1	42.00	52.17	51.30	6.55	4.24	2.31	141.06	142.78	143.69	1.70	0.60	Yes
2015_12_12_test2	44.39	53.92	48.54	6.34	3.58	2.76	142.64	144.27	148.75	1.72	0.65	Yes
2015_12_12_test3	43.43	53.60	46.27	6.52	3.57	2.95	140.98	143.68	144.68	1.71	0.67	Yes
2015_12_12_test4	44.16	58.18	51.72	6.41	4.00	2.41	142.92	144.13	146.14	1.79	0.61	Yes
2015_12_12_test5	44.04	65.49	59.33	6.53	4.78	1.74	141.54	144.06	147.97	1.89	0.52	Yes
2015_12_12_test6	43.83	48.51	42.94	6.05	3.01	3.03	141.35	143.93	148.14	1.63	0.68	Yes
2015_12_12_test7	44.14	53.24	49.88	5.83	3.05	2.78	143.34	144.12	148.72	1.71	0.66	Yes
2015_12_12_test8	43.93	57.89	50.11	5.98	3.58	2.40	142.89	143.99	145.70	1.79	0.61	Yes
2015_12_12_test9	44.19	65.18	58.01	5.91	4.05	1.86	142.24	144.15	147.16	1.89	0.54	Yes
2015_12_12_test10	43.84	52.30	41.96	5.21	2.36	2.85	131.75	143.94	148.92	1.66	0.65	No
2015_12_12_test11	43.12	55.51	50.43	4.86	2.40	2.47	142.28	143.49	144.54	1.75	0.62	Yes
2015_12_12_test12	43.65	60.05	54.49	4.78	2.29	2.49	141.23	143.82	145.95	1.81	0.62	Yes
2015_12_12_test13	43.28	65.07	59.97	4.76	3.15	1.61	141.92	143.59	149.15	1.90	0.50	Yes
2016_01_04_test1	44.99	44.98	38.15	6.86	2.42	4.44	139.45	144.64	146.07	1.55	0.82	Yes
2016_01_04_test2	44.37	45.28	44.50	2739.77	2.09	2737.69	145.31	144.26	145.74	6.07	17.51	No
2016_01_04_test3	43.33	48.62	41.77	6.95	3.45	3.50	140.95	143.62	144.53	1.63	0.73	Yes
2016_01_04_test4	44.11	54.90	46.66	6.88	4.23	2.65	141.49	144.10	144.99	1.73	0.64	Yes
2016_01_04_test5	43.76	60.29	49.44	7.00	4.42	2.59	142.26	143.88	144.73	1.82	0.63	Yes
2016_01_04_test6	44.07	66.62	58.35	6.92	5.20	1.72	142.22	144.07	145.21	1.91	0.51	Yes
2016_01_04_test7	43.83	48.67	42.78	6.02	2.37	3.65	142.01	143.93	144.83	1.63	0.75	Yes
2016_01_04_test8	44.02	59.79	53.81	5.15	2.86	2.29	142.82	144.05	148.64	1.81	0.59	Yes

Table D5: Reduced data for Steam/Water atmospheric repeatability flooding tests.

Test Name	Test Pressure (psig)	Inlet Gas Flowrate (g/s)	Outlet Gas Flowrate (g/s)	$Q_{f,in}$ (GPM)	$Q_{f,carryover}$ (GPM)	$Q_{f,down}$ (GPM)	$T_{f,in}$ (°C)	T_{sat} (°C)	$T_{g,in}$ (°C)	$(K_{g,in})^{1/2}$	$(K_{fd})^{1/2}$	Qualify?
2016_01_20_test5	1.49	32.09	29.66	6.21	3.46	2.76	101.87	102.70	110.85	1.67	0.61	Yes
2016_01_20_test6	1.49	32.17	28.37	6.24	3.26	2.99	101.45	102.70	106.24	1.67	0.63	Yes
2016_01_20_test7	1.61	32.11	29.74	6.18	3.43	2.75	102.27	102.91	109.93	1.67	0.61	Yes
2016_01_20_test8	1.51	32.06	29.24	6.28	3.40	2.89	102.15	102.74	105.77	1.67	0.62	Yes
2016_01_20_test9	1.61	32.11	29.44	6.20	3.37	2.83	102.24	102.92	109.15	1.67	0.62	Yes
2016_01_20_test10	1.63	32.13	29.68	6.25	3.65	2.60	101.81	102.94	107.52	1.66	0.59	Yes
2016_01_20_test11	1.45	32.17	28.90	6.23	3.45	2.77	101.56	102.63	108.12	1.67	0.61	Yes
2016_01_20_test12	1.57	32.12	29.02	6.24	3.41	2.83	101.84	102.83	108.48	1.66	0.62	Yes
2016_01_20_test13	1.53	32.01	30.13	6.26	3.56	2.70	102.14	102.78	108.87	1.67	0.60	Yes
2016_01_20_test14	1.49	32.12	29.46	6.21	3.44	2.77	102.17	102.71	103.75	1.67	0.61	Yes

Table D6: Reduced data for Steam/Water 15 PSIG repeatability flooding tests.

Test Name	Test Pressure (psig)	Inlet Gas Flowrate (g/s)	Outlet Gas Flowrate (g/s)	$Q_{f,in}$ (GPM)	$Q_{f,carryover}$ (GPM)	$Q_{f,down}$ (GPM)	$T_{f,in}$ (°C)	T_{sat} (°C)	$T_{g,in}$ (°C)	$(K_{g,in})^{1/2}$	$(K_{fd})^{1/2}$	Qualify?
2015_12_15_test1	14.93	48.32	42.60	6.63	4.81	1.82	117.99	120.88	123.87	1.82	0.51	Yes
2015_12_15_test2	14.52	46.31	39.59	6.92	5.40	1.52	117.08	120.43	134.23	1.79	0.46	Yes
2015_12_15_test3	14.89	45.39	35.03	6.94	4.37	2.57	117.08	120.84	132.24	1.77	0.60	Yes
2015_12_15_test4	14.39	45.06	37.60	7.07	5.00	2.07	118.14	120.30	134.27	1.78	0.54	Yes
2015_12_15_test5	14.80	45.30	38.16	7.05	4.83	2.22	118.35	120.74	136.91	1.78	0.56	Yes
2015_12_15_test6	14.76	45.38	40.47	6.83	4.60	2.23	117.93	120.69	130.46	1.77	0.56	Yes
2015_12_15_test7	14.60	45.72	35.74	6.94	4.51	2.43	117.72	120.52	130.24	1.78	0.59	Yes
2015_12_15_test8	14.78	45.38	37.31	6.85	4.51	2.34	117.53	120.72	133.78	1.77	0.57	Yes
2015_12_15_test9	14.59	45.04	38.94	7.00	4.58	2.43	118.68	120.52	135.28	1.77	0.59	Yes
2015_12_15_test10	14.74	45.35	37.38	7.03	4.96	2.07	118.01	120.68	135.61	1.78	0.54	Yes

Table D7: Reduced data for Steam/Water 30 PSIG repeatability flooding tests.

Test Name	Test Pressure (psig)	Inlet Gas Flowrate (g/s)	Outlet Gas Flowrate (g/s)	$Q_{f,in}$ (GPM)	$Q_{f,carryover}$ (GPM)	$Q_{f,down}$ (GPM)	$T_{f,in}$ (°C)	T_{sat} (°C)	$T_{g,in}$ (°C)	$(K_{g,in})^{1/2}$	$(K_{fd})^{1/2}$	Qualify?
2016_01_04_test9	29.26	54.99	46.07	6.76	4.68	2.08	131.02	133.87	137.57	1.82	0.55	Yes
2016_01_04_test10	29.60	55.21	46.03	6.36	4.09	2.28	132.11	134.13	138.33	1.82	0.58	Yes
2016_01_04_test11	29.62	55.47	46.76	6.31	4.07	2.24	131.96	134.15	139.68	1.83	0.58	Yes
2016_01_04_test12	29.23	55.23	45.84	6.32	4.01	2.32	131.65	133.85	137.15	1.83	0.59	Yes
2016_01_04_test13	29.64	54.96	45.85	6.28	4.00	2.28	131.69	134.17	142.85	1.82	0.58	Yes
2016_01_04_test14	29.30	55.10	44.36	6.35	3.95	2.39	130.86	133.90	135.59	1.82	0.59	Yes
2016_01_04_test15	29.65	54.75	46.59	6.41	4.20	2.21	131.40	134.18	135.56	1.81	0.57	Yes
2016_01_04_test16	29.51	55.08	43.43	6.37	4.01	2.36	131.32	134.07	136.21	1.82	0.59	Yes
2016_01_04_test18	29.17	54.88	44.09	6.34	3.92	2.42	131.08	133.80	134.72	1.82	0.60	Yes
2016_01_04_test19	29.85	55.13	45.77	6.27	4.00	2.27	131.22	134.33	137.60	1.82	0.58	Yes

Table D8: Reduced data for Air/Water atmospheric flooding tests.

Test Name	Test Pressure (psig)	Inlet Gas Flowrate (g/s)	$Q_{f,in}$ (GPM)	$Q_{f,carryover}$ (GPM)	$Q_{f,down}$ (GPM)	$T_{f,in}$ (°C)	$T_{g,in}$ (°C)	$(K_{g,in})^{1/2}$	$(K_{fd})^{1/2}$	Qualify?
2016_01_21_test01	1.52	44.56	5.26	2.21	3.05	27.84	25.45	1.47	0.58	Yes
2016_01_21_test02	1.51	44.68	5.06	1.94	3.12	27.87	21.77	1.47	0.59	Yes
2016_01_21_test03	2.08	51.95	5.12	3.76	1.37	28.03	17.61	1.57	0.39	Yes
2016_01_21_test04	5.54	82.13	4.75	2.82	1.93	27.98	14.75	1.87	0.46	No
2016_01_21_test05	2.76	59.02	5.09	4.28	0.81	28.20	16.45	1.65	0.30	Yes
2016_01_21_test06	3.40	64.77	5.25	3.99	1.26	28.15	17.02	1.71	0.37	Yes
2016_01_21_test07	1.31	38.94	6.07	1.50	4.57	28.20	18.82	1.37	0.71	Yes
2016_01_21_test08	1.67	45.12	6.05	2.66	3.39	28.25	15.80	1.47	0.61	Yes
2016_01_21_test09	2.20	51.93	6.06	3.72	2.34	28.33	13.56	1.56	0.51	Yes
2016_01_21_test10	2.95	59.39	5.98	4.39	1.59	28.42	13.70	1.65	0.42	Yes
2016_01_21_test11	1.63	42.66	6.95	3.28	3.68	28.75	11.94	1.43	0.64	Yes
2016_01_21_test12	2.18	50.02	6.89	4.36	2.53	28.84	9.60	1.53	0.53	Yes
2016_01_21_test13	2.95	56.90	6.82	5.50	1.32	28.75	9.59	1.61	0.38	Yes
2016_01_21_test14	3.61	61.86	6.82	5.77	1.04	28.62	9.51	1.66	0.34	Yes
2016_01_21_test15	1.30	39.14	6.05	1.51	4.54	28.39	13.93	1.37	0.71	Yes

Table D9: Reduced data for Air/Water 30 PSIG flooding tests.

Test Name	Test Pressure (psig)	Inlet Gas Flowrate (g/s)	$Q_{f,in}$ (GPM)	$Q_{f,carryover}$ (GPM)	$Q_{f,down}$ (GPM)	$T_{f,in}$ (°C)	$T_{g,in}$ (°C)	$(K_{g,in})^{1/2}$	$(K_{f,d})^{1/2}$	Qualify?
2015_12_30_test01	28.80	67.41	6.83	2.91	3.92	19.43	12.05	1.39	0.65	Yes
2015_12_30_test02	29.44	66.88	7.09	2.93	4.16	19.40	10.94	1.38	0.67	Yes
2015_12_30_test03	29.47	57.32	7.00	1.26	5.74	19.41	10.99	1.27	0.79	Yes
2015_12_30_test04	28.61	70.94	7.18	3.57	3.60	19.40	10.14	1.42	0.63	Yes
2015_12_30_test05	29.13	74.62	6.86	3.62	3.24	19.37	9.86	1.45	0.59	Yes
2015_12_30_test07	28.85	61.67	5.83	0.63	5.20	19.44	9.98	1.32	0.75	Yes
2015_12_30_test08	28.67	68.08	5.82	1.53	4.28	19.40	9.81	1.39	0.68	Yes
2015_12_30_test09	29.10	64.91	5.90	1.10	4.80	19.43	9.86	1.36	0.72	Yes
2015_12_30_test10	28.44	79.50	6.06	3.08	2.98	19.44	9.41	1.51	0.57	Yes
2015_12_30_test11	28.39	75.87	4.94	0.97	3.97	19.46	9.43	1.47	0.66	Yes
2015_12_30_test12	29.28	65.60	4.85	0.04	4.82	19.46	9.92	1.36	0.72	Yes
2015_12_30_test13	29.00	66.34	4.95	0.02	4.93	19.49	9.77	1.37	0.73	Yes
2015_12_30_test14	29.53	74.62	4.71	0.79	3.92	19.52	9.63	1.45	0.65	Yes
2015_12_30_test15	29.45	84.25	4.72	1.43	3.29	19.47	9.50	1.54	0.60	Yes

Table D10: Reduced data for Air/Water 45 PSIG flooding tests.

Test Name	Test Pressure (psig)	Inlet Gas Flowrate (g/s)	$Q_{f,in}$ (GPM)	$Q_{f,carryover}$ (GPM)	$Q_{f,down}$ (GPM)	$T_{f,in}$ (°C)	$T_{g,in}$ (°C)	$(K_{g,in})^{1/2}$	$(K_{fd})^{1/2}$	Qualify?
2015_12_30_test16	43.09	73.15	4.76	0.03	4.73	19.54	11.36	1.35	0.72	Yes
2015_12_30_test17	43.83	75.84	4.80	0.21	4.59	19.51	11.15	1.37	0.71	Yes
2015_12_30_test18	43.79	90.48	5.08	1.73	3.35	19.50	10.81	1.49	0.60	Yes
2015_12_30_test19	42.92	83.44	4.90	0.80	4.10	19.51	10.84	1.44	0.67	Yes
2015_12_30_test21	43.02	72.67	6.26	1.68	4.58	19.54	11.22	1.34	0.71	Yes
2015_12_30_test22	43.58	75.46	6.06	1.40	4.65	19.53	11.07	1.36	0.71	Yes
2015_12_30_test23	43.84	84.76	6.12	2.53	3.58	19.54	10.89	1.44	0.62	Yes
2015_12_30_test24	42.86	98.91	6.24	4.16	2.07	19.54	10.63	1.56	0.48	Yes
2015_12_30_test25	43.57	94.13	6.13	3.43	2.71	19.52	10.87	1.52	0.54	Yes
2015_12_30_test26	44.02	69.33	7.18	2.75	4.43	19.55	11.20	1.31	0.69	Yes
2015_12_30_test27	43.92	68.43	6.98	1.98	4.99	19.59	11.45	1.30	0.74	Yes
2015_12_30_test28	43.51	79.08	7.11	3.50	3.61	19.60	11.11	1.40	0.63	Yes
2015_12_30_test29	43.72	89.10	7.07	4.10	2.97	19.57	10.88	1.48	0.57	Yes
2015_12_30_test30	43.47	99.31	6.97	5.36	1.61	19.57	10.70	1.56	0.42	Yes

Table D11: Reduced data for Air/Water atmospheric repeatability flooding tests.

Test Name	Test Pressure (psig)	Inlet Gas Flowrate (g/s)	$Q_{f,in}$ (GPM)	$Q_{f,carryover}$ (GPM)	$Q_{f,down}$ (GPM)	$T_{f,in}$ (°C)	$T_{g,in}$ (°C)	$(K_{g,in})^{1/2}$	$(K_{fd})^{1/2}$	Qualify?
2016_01_21_test16	1.70	45.13	6.15	2.87	3.28	28.40	9.81	1.46	0.60	Yes
2016_01_21_test17	1.69	45.01	6.13	2.75	3.37	28.41	9.83	1.46	0.61	Yes
2016_01_21_test18	1.71	45.05	6.14	2.77	3.37	28.42	8.95	1.46	0.61	Yes
2016_01_21_test19	1.70	44.85	6.12	2.80	3.31	28.44	9.07	1.46	0.61	Yes
2016_01_21_test20	1.70	45.03	6.11	2.80	3.31	28.38	8.66	1.46	0.61	Yes
2016_01_21_test21	1.70	45.05	6.11	2.79	3.32	28.48	8.94	1.46	0.61	Yes
2016_01_21_test22	1.69	45.03	6.10	2.72	3.38	28.34	8.20	1.46	0.61	Yes
2016_01_21_test23	1.70	45.09	6.11	2.77	3.35	28.30	8.31	1.46	0.61	Yes
2016_01_21_test24	1.69	44.97	6.11	2.72	3.39	28.34	8.17	1.46	0.61	Yes
2016_01_21_test25	1.70	45.03	6.12	2.73	3.39	28.36	7.77	1.46	0.61	Yes

Table D12: Reduced data for Air/Water 30 PSIG repeatability flooding tests.

Test Name	Test Pressure (psig)	Inlet Gas Flowrate (g/s)	$Q_{f,in}$ (GPM)	$Q_{f,carryover}$ (GPM)	$Q_{f,down}$ (GPM)	$T_{f,in}$ (°C)	$T_{g,in}$ (°C)	$(K_{g,in})^{1/2}$	$(K_{f,d})^{1/2}$	Qualify?
2016_01_25_test01	29.02	70.04	6.92	3.83	3.09	25.40	15.45	1.43	0.58	Yes
2016_01_25_test02	29.07	70.01	6.93	3.91	3.02	25.44	15.27	1.43	0.58	Yes
2016_01_25_test03	29.00	69.83	6.95	4.01	2.94	25.44	14.99	1.42	0.57	Yes
2016_01_25_test04	29.07	69.86	6.94	3.77	3.17	25.47	14.81	1.42	0.59	Yes
2016_01_25_test05	28.98	69.75	6.98	3.92	3.07	25.50	14.72	1.42	0.58	Yes
2016_01_25_test06	29.09	69.85	6.95	3.95	3.00	25.51	14.79	1.42	0.57	Yes
2016_01_25_test07	29.01	69.83	6.98	4.07	2.92	25.55	14.63	1.42	0.57	Yes
2016_01_25_test08	28.86	69.53	6.96	4.22	2.74	25.59	14.76	1.42	0.55	Yes
2016_01_25_test09	29.10	69.97	7.00	4.04	2.96	25.61	14.60	1.43	0.57	Yes
2016_01_25_test10	29.06	69.62	6.97	3.85	3.12	25.66	14.68	1.42	0.59	Yes

APPENDIX E: KUTATELADZE CURVES

This section contains plots of the Kutateladze curves for a specific inlet water flow rate or a specific test section pressure. This allows for one to observe the dependencies on inlet water flow rate or test section pressure on the flooding curves.

E.1 Kutateladze Curves with Constant Inlet Water Flowrate

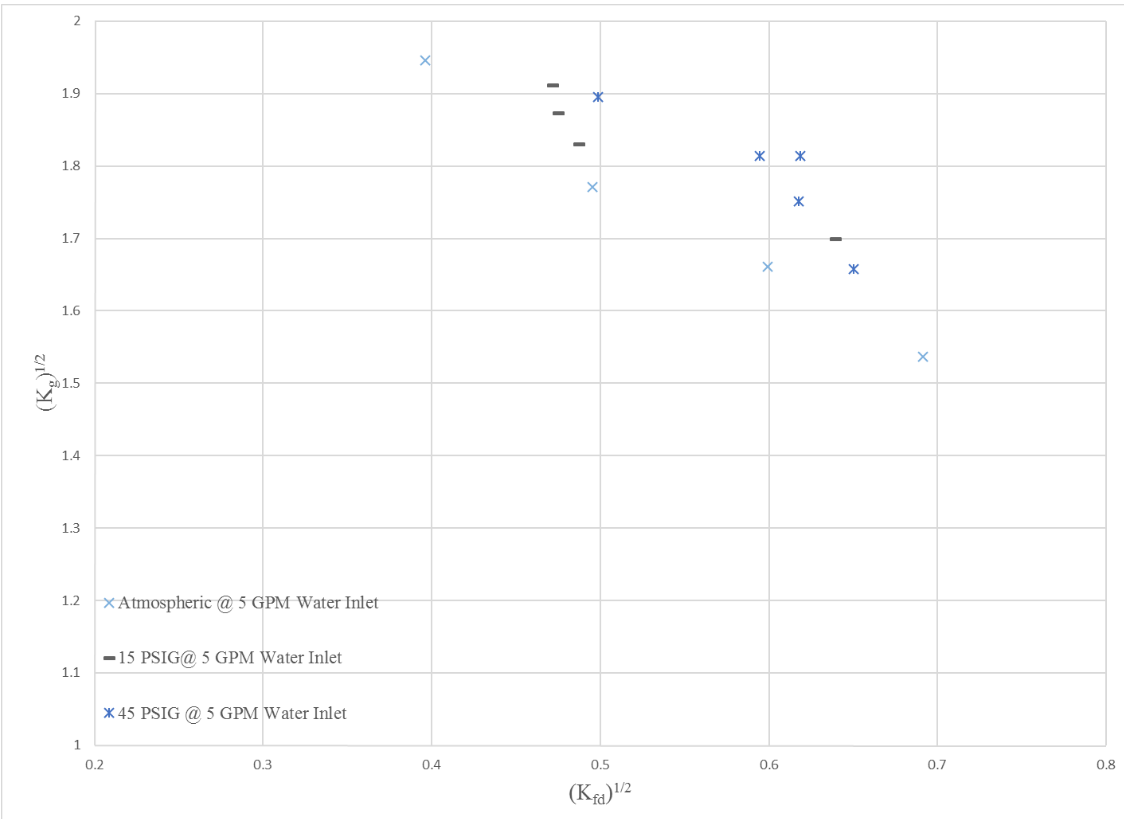


Figure E.1.1: Kutateladze Steam/Water flooding curves with constant inlet water flow rate of 5 GPM.

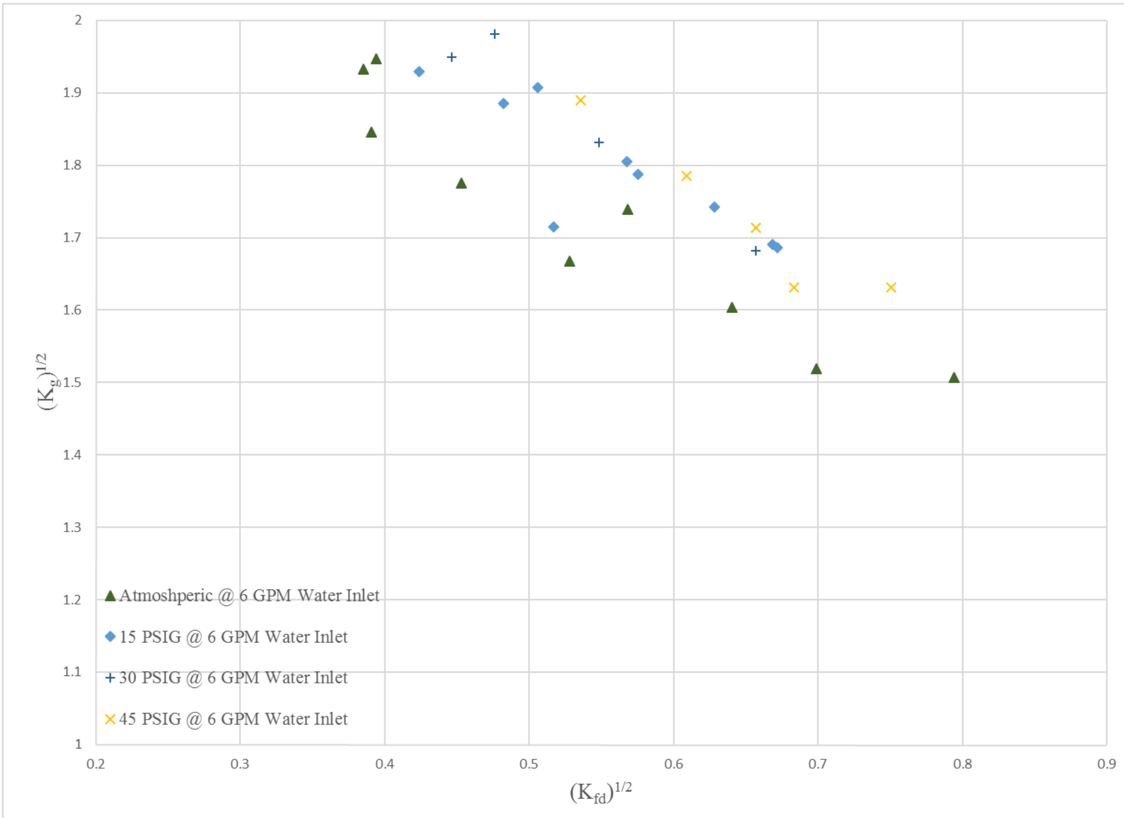


Figure E.1.2: Kutateladze Steam/Water flooding curves with constant inlet water flow rate of 6 GPM.

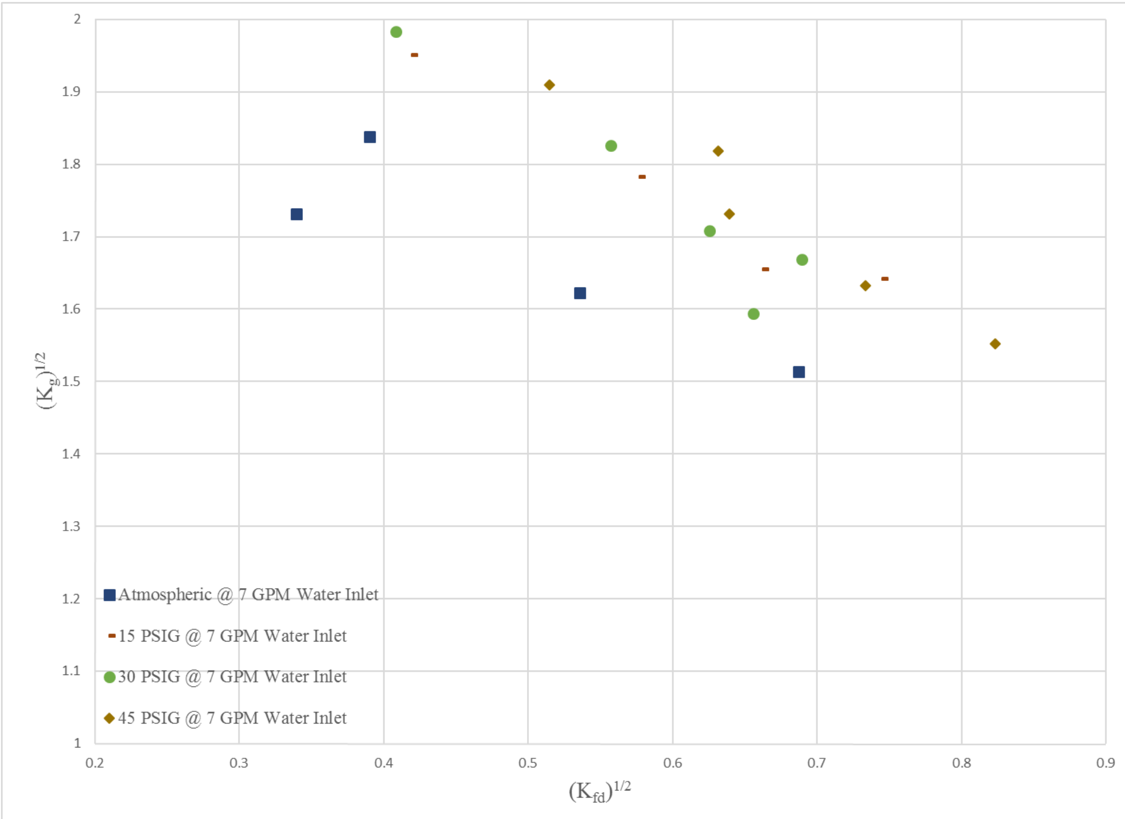


Figure E.1.3: Kutateladze Steam/Water flooding curves with constant inlet water flow rate of 7 GPM.

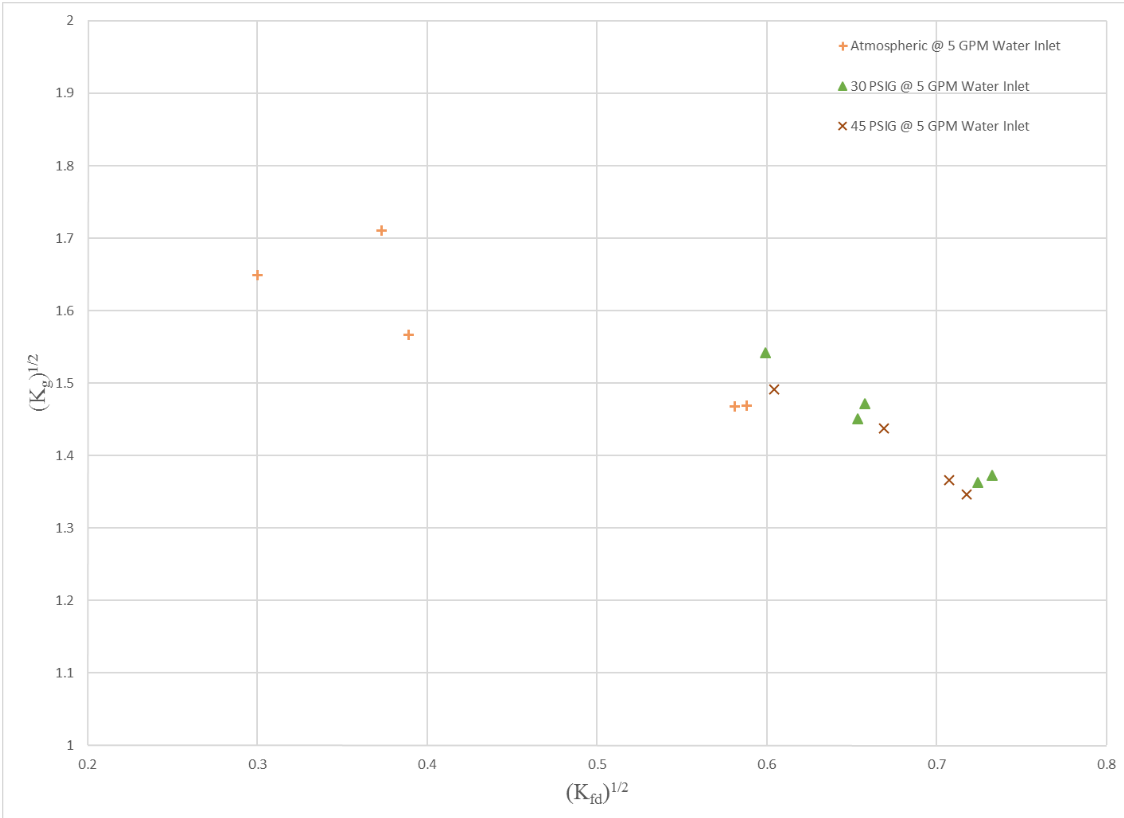


Figure E.1.4: Kutateladze Air/Water flooding curves with constant inlet water flow rate of 5 GPM.

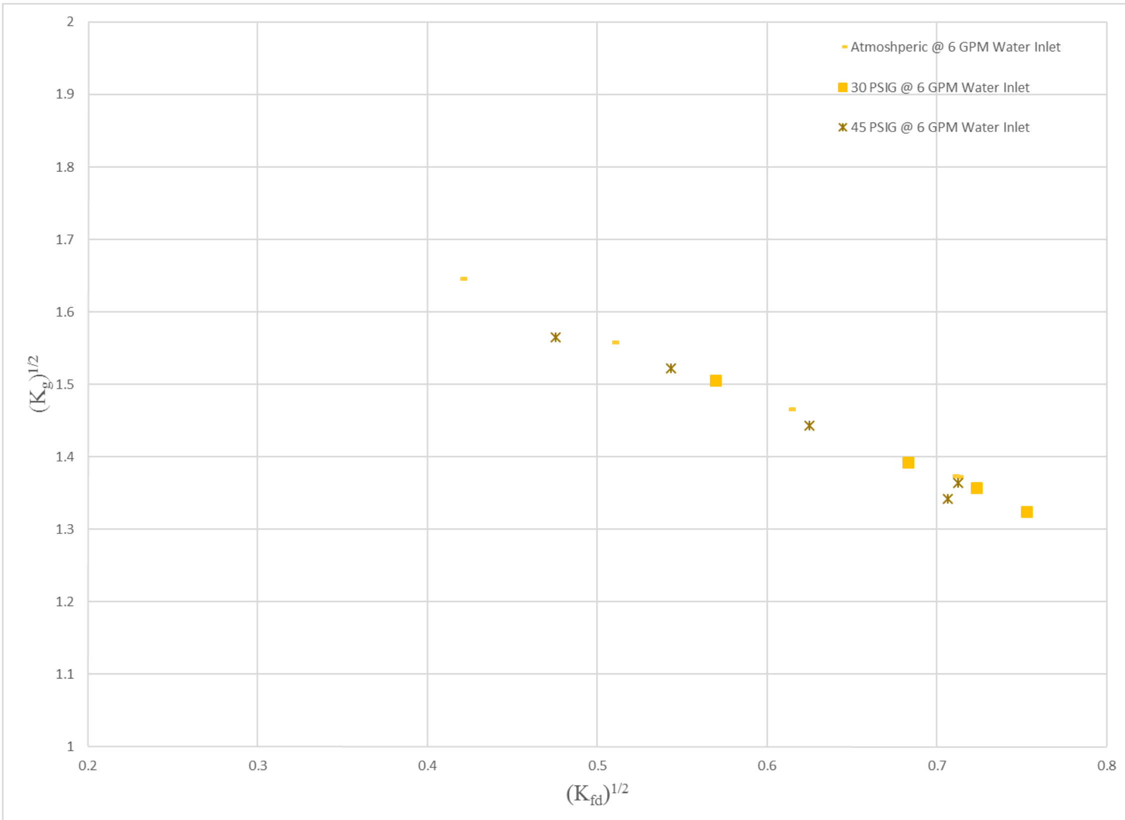


Figure E.1.5: Kutateladze Air/Water flooding curves with constant inlet water flow rate of 6 GPM.

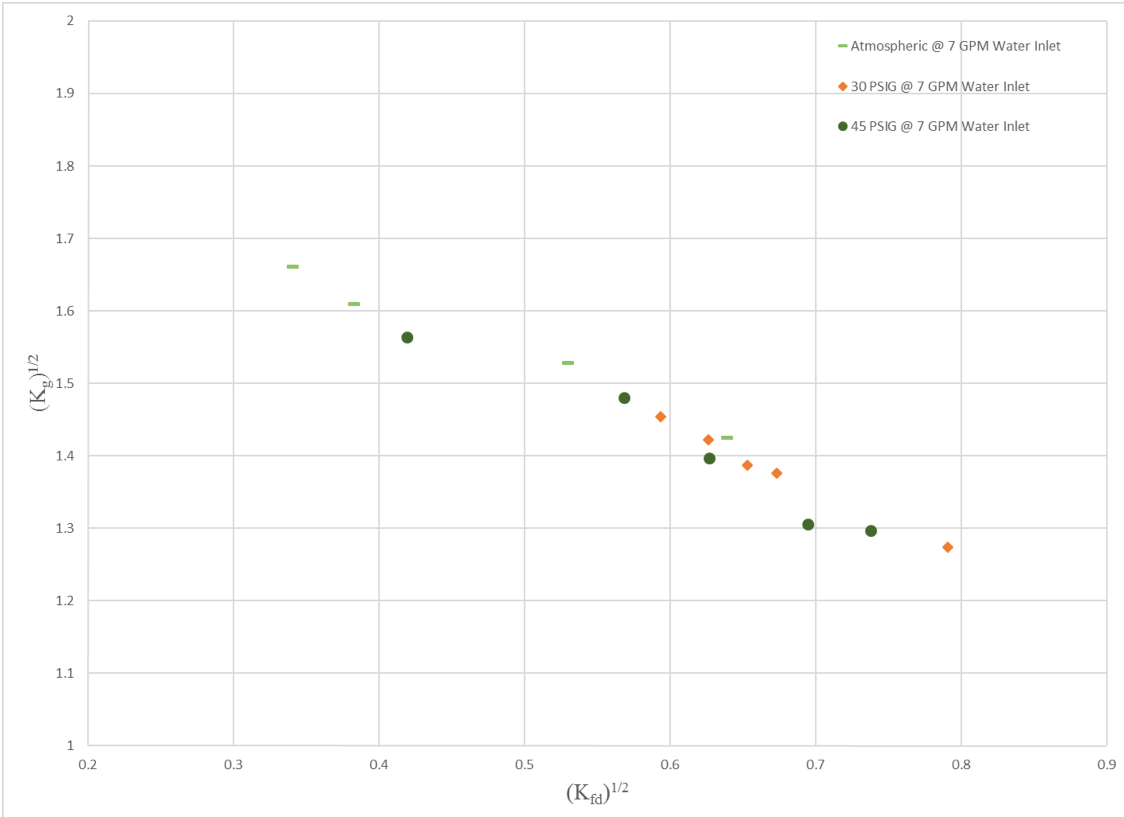


Figure E.1.5: Kutateladze Air/Water flooding curves with constant inlet water flow rate of 7 GPM.

E.2 Kutateladze Curves with Constant Test Section Pressure

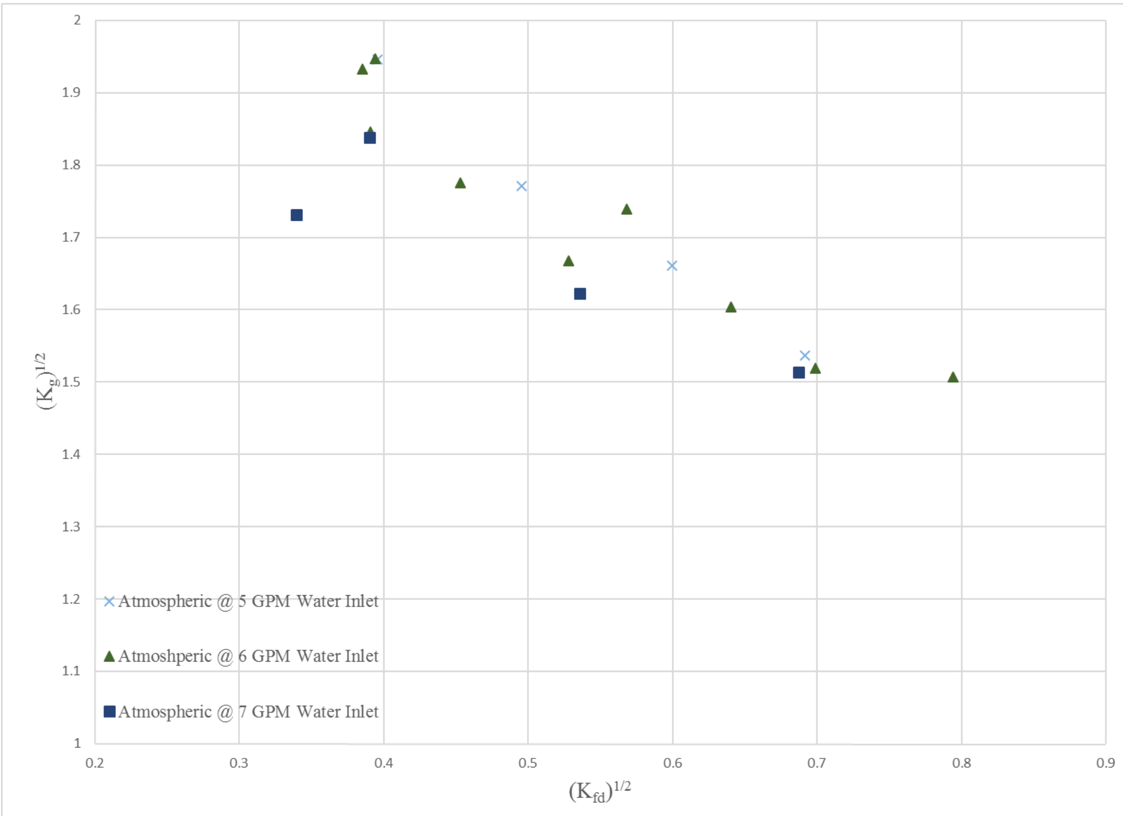


Figure E.2.1: Kutateladze Steam/Water flooding curves with constant test section pressure of atmospheric pressures.

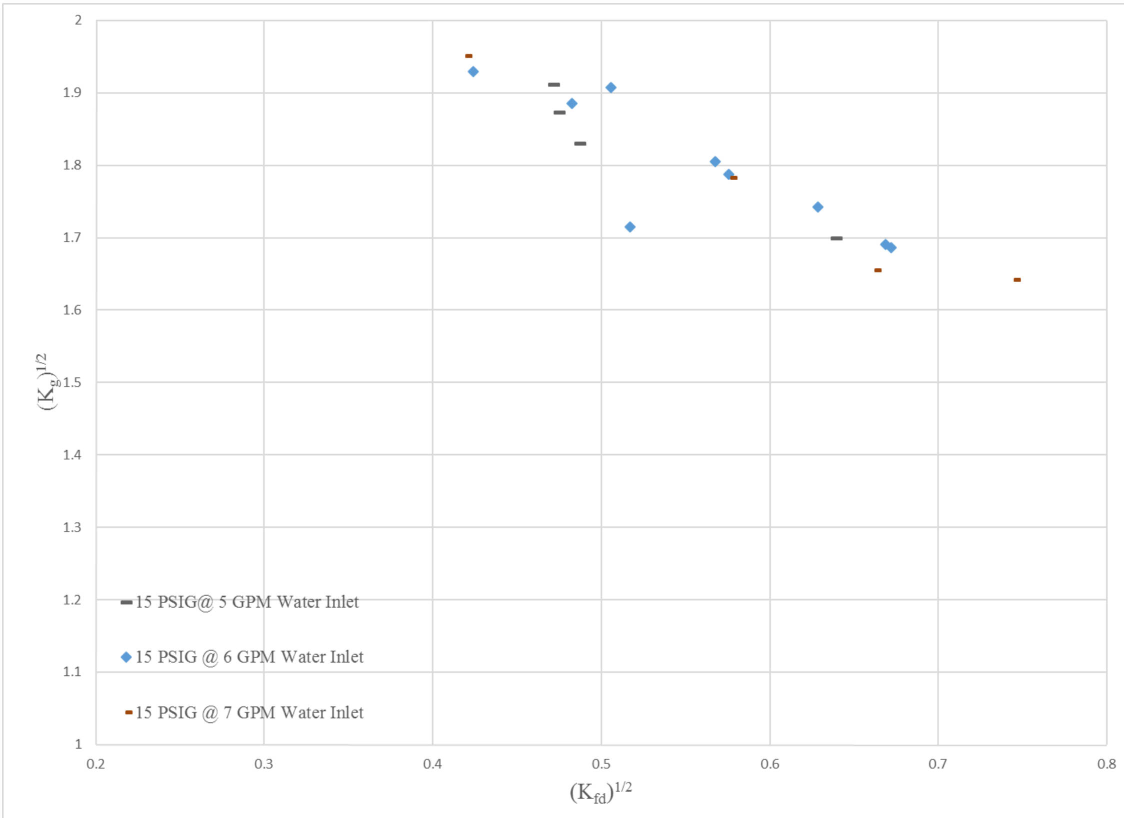


Figure E.2.2: Kutateladze Steam/Water flooding curves with constant test section pressure of 15 PSIG.

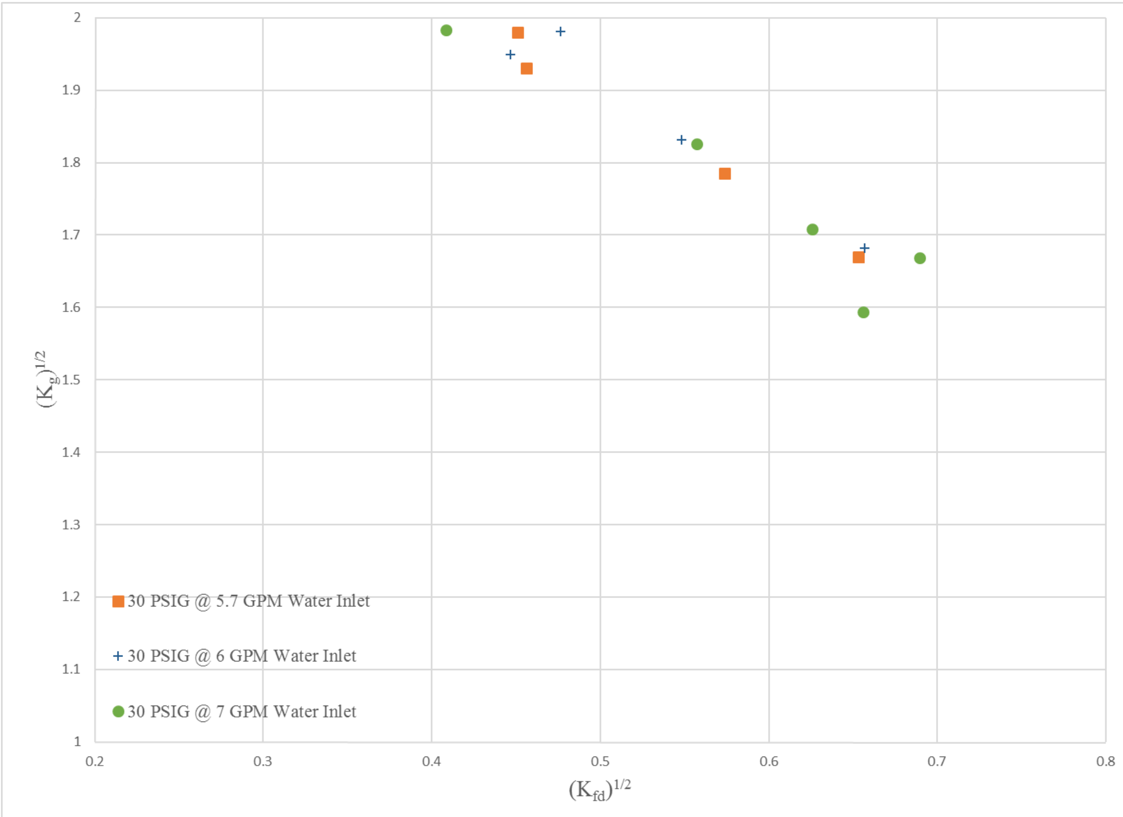


Figure E.2.3: Kutateladze Steam/Water flooding curves with constant test section pressure of 30 PSIG.

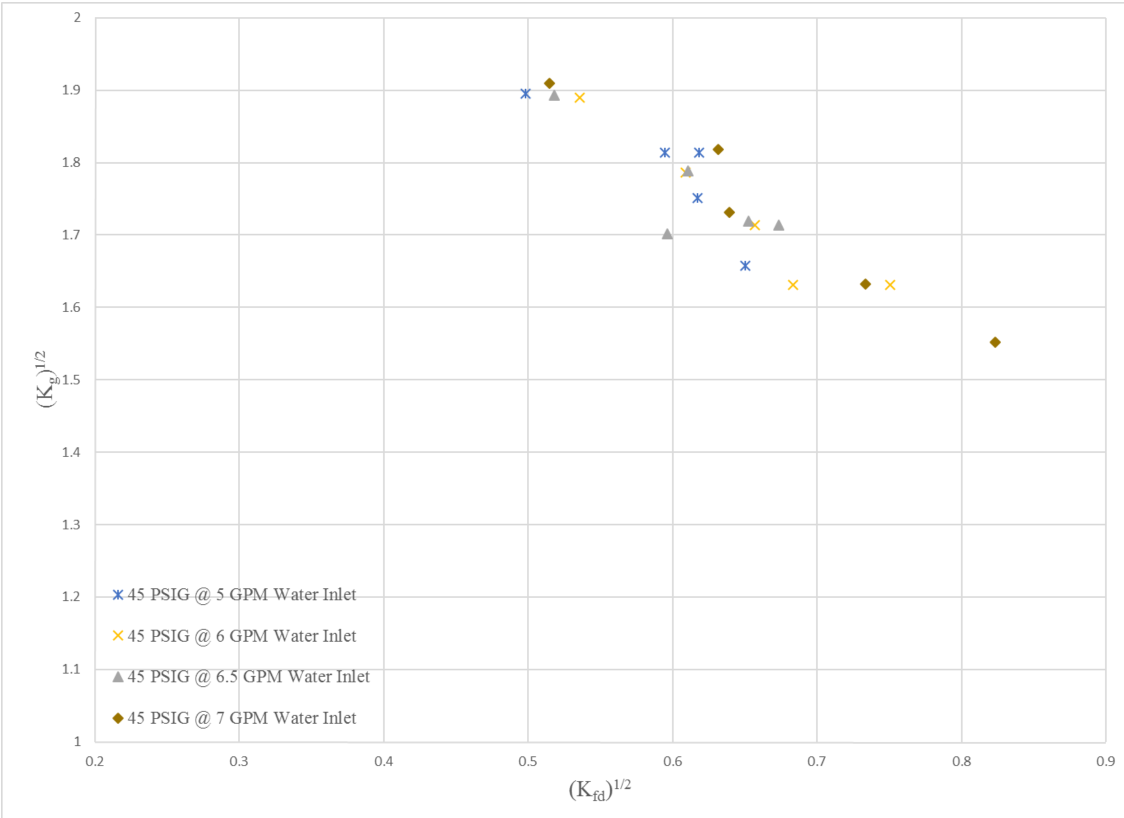


Figure E.2.4: Kutateladze Steam/Water flooding curves with constant test section pressure of 45 PSIG.

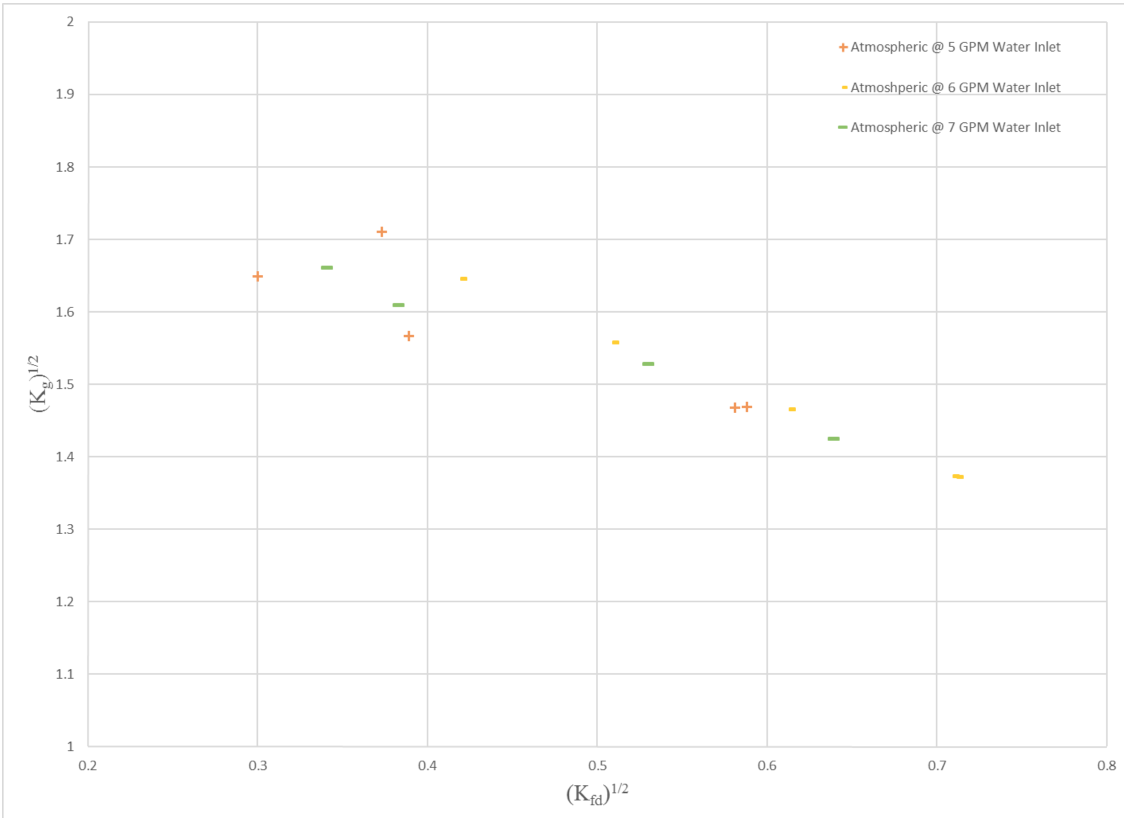


Figure E.2.5: Kutateladze Air/Water flooding curves with constant test section pressure of atmospheric pressures.

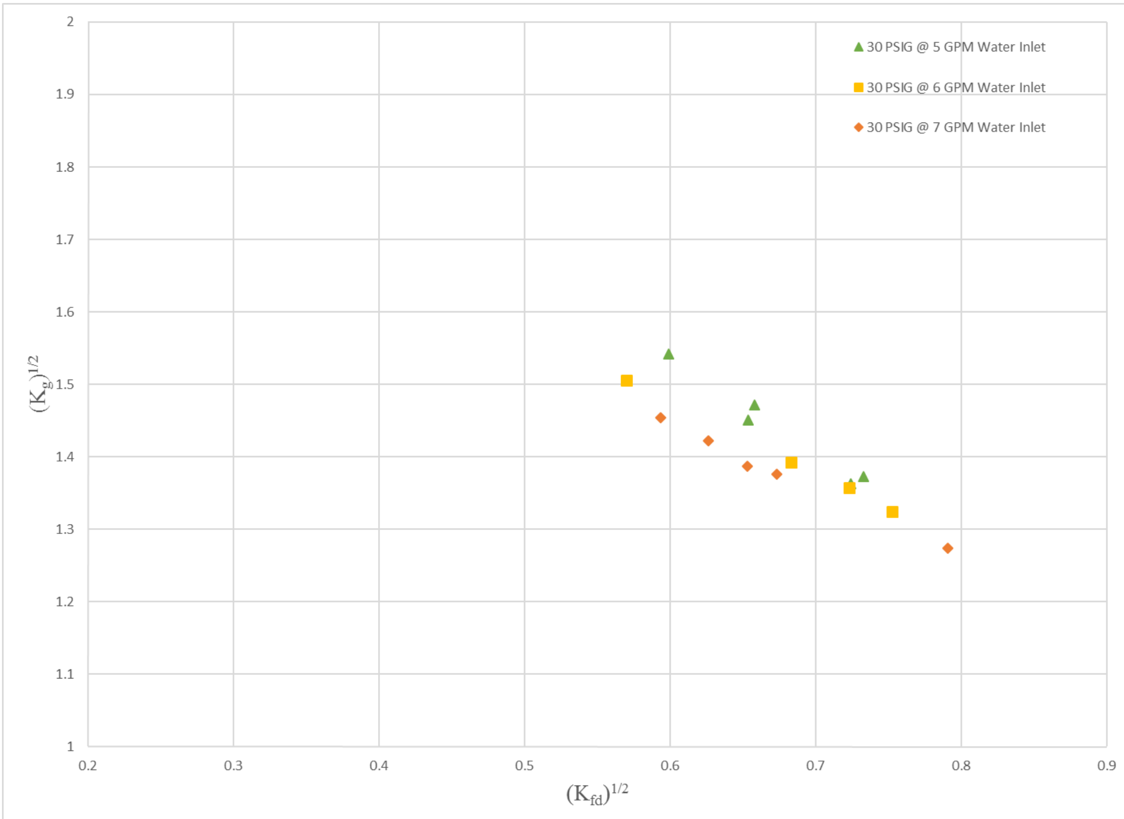


Figure E.2.6: Kutateladze Air/Water flooding curves with constant test section pressure 30 PSIG.

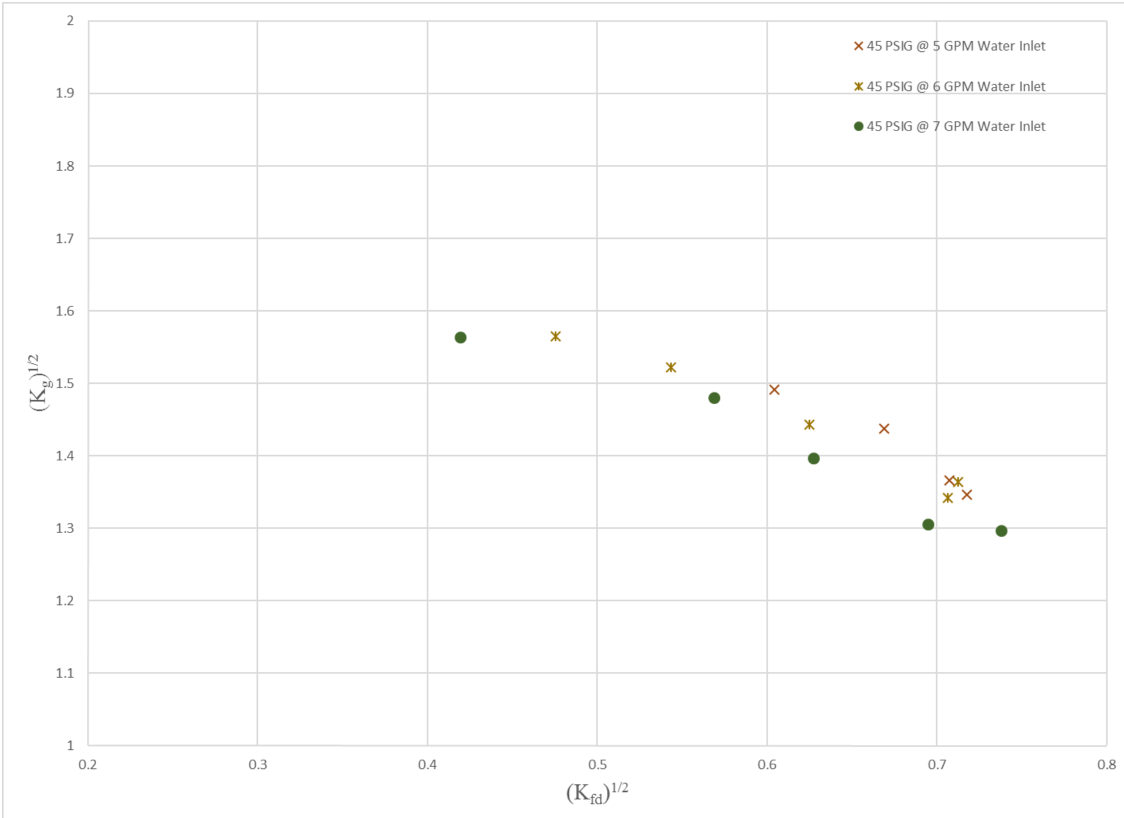


Figure E.2.7: Kutateladze Air/Water flooding curves with constant test section pressure 45 PSIG.

APPENDIX F: EXPERIMENTAL INSTRUMENTATION

This section contains a table, Table F1, with the details for the instrumentation that is used in the facility. This information includes the instrument location, the manufacturer, the model, the range that it is rated to operate at and the its accuracy. This table is taken directly from the Wynne thesis, as all the instrumentation remained the same between the Wynne research and the current research [3].

Table F1: Information for instrumentation used throughout the test facility **[3].**

Instrument	Location	Model	Range	Accuracy
Thermocouples	Throughout Facility	Omega Type T	-250-350 °C	0.5 °C
Absolute Pressure Transmitter	Gas Inlet	Honeywell ST3000 STA940	0-130 psia	0.1% Span
Absolute Pressure Transmitter	Gas Outlet	Honeywell ST3000 STA940	0-100 psia	0.1% Span
Absolute Pressure Transmitter	Steam Generator	Honeywell ST3000 STA940	0-150 psia	0.1% Span
Absolute Pressure Transmitter	Test Section	Keller Valueline	0-150 psia	0.1% Span
Differential Pressure Transmitter	Steam Generator Level	Honeywell ST3000 STD924	0-110 inH2O	0.075% Span
Differential Pressure Transmitter	Water Supply Tank Level	Honeywell ST3000 STD924	0-80 inH2O	0.075% Span
Differential Pressure Transmitter	Test Section	Honeywell ST3000 STD924	0-100 inH2O	0.075% Span
Differential Pressure Transmitter	Holdup Tank Level	Rosemount 3051S	0-25 inH2O	0.035% Span
Gauge Pressure Transmitter	Holdup Tank	Dwyer 673-7	0-100 psig	0.25% Span
Gauge Pressure Transmitter	Water Supply Tank	Dwyer 673-7	0-100 psig	0.25% Span
Gauge Pressure Transmitter	Water Inlet	Dwyer 673-7	0-100 psig	0.25% Span
Vortex Flow Meter	Gas Inlet	Foxboro Model 83W-A	0-2400 Hz	1% Value
Vortex Flow Meter	Gas Outlet	Foxboro Model 84F	0-140 CFM	1% Value
Magnetic Flow Meter	Water Inlet	Azbil MagneW 3000 Plus	0-20 GPM	0.5% Value
Magnetic Flow Meter	Water Carryover	Azbil MagneW 3000 Plus	0-10 GPM	0.5% Value
Hygrometer	Gas Inlet	Dwyer HHT	0-100% RH	2% Value

APPENDIX G: FACILITY COMPONENT LOCATION DESCRIPTION

This section gives a description of the facility valve and facility component locations that are mentioned in the operational procedures, Section 4. This section is meant to be used in conjuncture with the facility P&ID, Figure 3.1, as an aid to someone that is new to the facility and is not sure where a specific valve or a specific component is located.

Component	Location Description
Air Supply Regulator	On the air compressor to steam generator pipeline directly to above and behind the refrigerated dryer.
Data Acquisition Computer (DAQ)	On a desk to the South East side of the test facility.
DC Power Supply	Above and to the left of the DAQ.
Drive Belt	On the South East face of the air compressor within the mesh cage.
Electric Panel	Electric panel directly North of the air compressor.
Electronic Drain Valve	On the North West face of the air compressor near the floor.
Holdup Tank Differential Pressure Transmitter	Near the floor on the North West side of the Holdup tank.
Lubricant Level Gauge	In the crankcase below the motor of the air compressor. A cylindrical shape that is easy to pull out to check the dipstick.
Outlet Gas Vortex Flow Meter	Above and to the right of remote computer monitor if facing the remote computer monitor on the steam outlet piping.
RCIC pump	The more north pump of the two pumps below the Water Supply Tank.
Refrigerated Power Switch	On the large blue box to the left of the DAQ desk. The switch is on the upper left side of the front face dryer.
Remote Computer Monitor	Hanging off the support structure directly to the left of the throttle valve, if facing the throttle valve.
SCXI Chassis	Above and to the right of the DAQ.
Steam Trap #1	The vertical pipe that is open to the lab on the north side of the water holdup tank.
Test Section Differential Pressure Transmitter	Attached to the support structure directly above the holdup tank.

V-01 Throttle Valve	On the steam inlet pipeline, near the steam generator. Red Valve on the South West side of the steam generator.
V-02 Secondary Throttle Valve	Directly behind the throttle valve if facing the throttle valve from while on top of the orange ladder.
V-05	When on top of the facility platform, tallest point able to stand, the valve on the horizontal pipe that crosses from West to East.
V-06	On the steam inlet pipeline just before the test section. On the North East side of the test section.
V-09 Steam Generator Fill Valve	Approximately 1 foot off the ground between the main facility structure and the steam generator.
V-13 Vacuum Breaker Valve	On the North side of the steam generator to the left of the heaters panel if facing the heaters panel.
V-16 Steam Generator Vent Valve	Steam generator vent valve located on the North East wall of the laboratory directly behind the steam generator.
V-19 Hygrometer Isolation Valve	Valve at the beginning of the pipeline that is connected to the hygrometer. This pipe runs North East to South West on the West side of the main facility structure.
V-20 Inlet Water Heater Isolation Valve	Just after the tee on the secondary side pipeline. Below the hygrometer supply pipeline.
V-34 RCIC Sparger Valve	On top/towards the south side of the Water Supply Tank.
V-35 Air Space Sparger Valve	On top/towards the north side of the Water Supply Tank.
V-36 SRV Sparger Valve	Same general location as the RCIC Sparger Valve.
V-51	Directly below V-53
V-53	On the North East face of the Water Supply Tank.
V-61 Bypass Valve	On the East face of the Water Supply Tank approximately 3 feet off the ground off a tee on the pump discharge line.
V-63 Flow Control Valve	Large Red Valve to the right of the bypass valve directly before the 90-degree elbow.
V-80 Supply Pump Discharge Valve	Slightly above the floor on the South side of the water supply tank.
V-81 Water supply pump suction valve	Below and to the left of V-61
V-82 RCIC pump suction valve	On the suction pipeline near the floor before the RCIC pump below the water supply tank.
V-83 (A&B)	Directly to the West of the inlet water heater.
V-84 Recirculation Valve	On top of the platform towards the East side on a vertical down section of pipe just after a 90-degree elbow.
V-85	In between the recirculation pump and the rotameter.

V-85 Recirculation Control Valve	On the recirculation pump discharge line just before the rotameter.
V-86 Water Supply Tank Vent	On the North West side of the Water Supply Tank directly above the blowdown drum.
V-87 Water Supply Tank air space fill valve.	Same general location as V-88.
V-88 Air Hose Vent Valve	On top of and the south side of the Water Supply Tank.
V-89 Air Hose Fill Valve	Directly to the left of the air regulator. Behind and above the refrigerated dryer.
V-89 Air Hose Valve	Above and behind the refrigerated dryer.
V-90 Air Isolation Valve	On the air compressor to steam generator pipeline on the North East side of the steam generator.
V-91 Steam Trap #2	On the bottom of the pipe section that is open to the atmosphere between the steam generator and the facility structure.
V-93 Steam Condenser Water Supply Valve	On the steam condenser supply line on the north side of the facility below the platform.
V-94 Heat Exchanger Domestic Water Supply Valve	Just prior to the rotameter on the heat exchanger supply PVC pipeline.
V-95 Auxiliary Domestic Water Valve	Red valve below the facility platform on the North side, after a tee.
V-96 Facility Steam Vent	In between the backpressure regulator and the steam condenser. Directly above the blowdown drum.
V-97 Facility Air Vent	Just after the backpressure regulator, the valve that leads to the air vent off the tee.