Feasibility Study of Developing a Virtual Chilled Water Flow Meter at Air Handling Unit Level

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ABSTRACT

In this paper, a virtual Air handling unit (AHU) level water flow meter is explored by using a control valve as a measurement device. The flow through the valve is indirectly calculated using differential pressure over both the valve and its associated coil and valve stem position. Thus, the non-intrusive virtual flow meter introduced in this paper provides a solution to one of the measurement barriers and challenges: a low cost, reliable energy metering system at the AHU level. Mathematical models were built and the preliminary experiments were conducted to investigate the feasibility of the virtual flow meter applications. As a result, the valve flow meter can be a cost effective means for water flow measurements at the AHU and thus provides an effective index for detecting and diagnosing the AHU operation faults.

INTRODUCTION

Operation faults of heating, ventilation and air-conditioning (HVAC) systems are typically associated with two major consequences: comfort problems and energy wastes. The comfort problems can be identified easily with occupants' cold or hot complains for facility operators to fix the problems. However, some of the HVAC system faults which result in the energy wastes with no comfort problems can go unnoticed for years unless drastic increases in utility bills occur [Katipamula and Brambley 2005]. To identify the energy wastes in early time, cooling and heating consumption measurements at AHU levels are needed. In addition, a unit level energy metering system is necessary to understand the building energy load distribution and thus provides a means for intelligent building operation when it is integrated with the smart grid [Scherf 2002] [Holmberg and Bushby 2009].

To measure the cooling and heating energy consumption, the chilled water and hot water flow measurements are critical. Although conventionally, there are many water flow meters available, such as differential pressure meters (orifice, venturi etc.), momentum meters (turbine, propeller etc.), ultrasonic meters, vortex-shedding meters and laser flow meters [Baker 2002]. However, these flow meters are either intrusive for the HVAC system operation or the installation and maintenance costs are prohibitive for the AHU level applications [Song and Joo, 2011]. As a result, a virtual water flow measurement which uses pump characteristics curve to calculate water flow rate has been investigated and implemented through industry practices [Joo et al. 2007 and 2003] [Liu 2006, Liu et al. 2007]. The pump flow meter is developed from the operating pump characteristics. It is not applicable for the AHU level applications, where typically no pumps are available. Thus, the non-intrusive virtual flow meter introduced in this paper provides a solution to one of the measurement barriers and challenges: a low cost, reliable energy metering system at the AHU level [Pellegrino et al. 2010].

In this paper, the non-intrusive flow measurement concept is explored by using a control valve as a measurement device, which is installed at the AHU level to modulate chilled water flow through cooling coils or hot water flow through heating coils [ASHRAE handbook 2008]. Theoretically, valve water flow can be expressed by

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valve positions and differential pressure across both the valve and the coil. The differential pressure can be easily measured by a differential pressure gauge. However, the valve stem position is not easily measureable. Instead, valve control commands or actuator positioner readings from Building Automation System (BAS) can be used as a valve stem position indicator to calculate the valve water flow with the consideration of valve hysteresis corrections. This non-intrusive method requires minimal installations since most of the chiller water coils have a valve that is equipped with pressure gauge ports. This flow measurement requires minimum maintenance because minimum additional parts are needed.

In this paper, the mathematical models of the virtual flow meter are presented first and preliminary experiments are carried out for testing the accuracy and feasibility of using the control valve as a flow measuring device.

MODELING

INHERENT VALVE CHARACTERISTICS

All control valves have an inherent flow characteristic that defines the relationship between "valve opening" and flow ratio under **constant pressure conditions**. Different valve plug shapes make it different. For example, as shown in Figure 1, comparing linear and equal percentage valves, a linear valve might have a 25% valve opening for a certain pressure drop and 25% flow rate, whilst an equal percentage valve might have a 65% valve opening for exactly the same water flow rate [Hegberg 2000] [Boyes 2002].

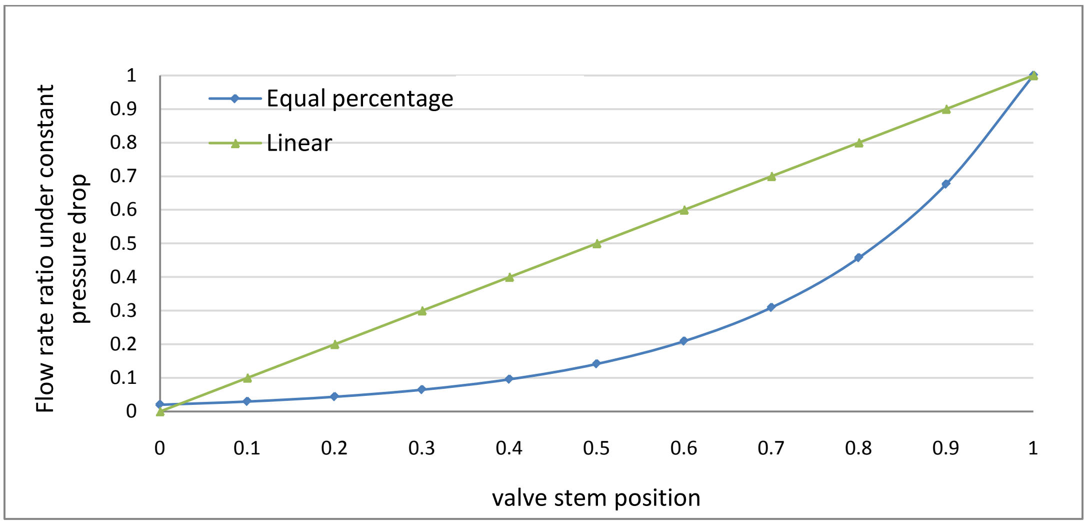

Figure 1: Characteristic curve for different valve plug shapes

In this study, the inherent valve characteristics are expressed by $f(x)$, which can be substituted by the specific characteristic equation of any types of valves. For example, the equal percentage valve, the valve characteristics can be expressed by $f(x) = R^{x-1}$. $f(x)$ represents water flow rate ratio under constant pressure drops across the valve, which can be expressed in Equation (1).

$$f(x) = \overline{Q}_x = \frac{Q_x}{Q_d} \quad (1)$$

Where:

x represents valve stem position (0 means completely close and 1 means completely open).

Q_x and Q_d represent water flow rate at valve partial open position (x) and rated valve water flow rate at valve fully open position (Gal/min or m^3/s).

$\overline{Q}_x$ represents flow ratio of the water flow rate at valve partial open position and the rated valve flow rate at fully open position.

INSTALLED VALVE CHARACTERISTICS:

Installed valve characteristics are the valve characteristics that are plotted after the valve is installed in an actual system, apart from the inherent valve characteristics which is plotted under the constant valve pressure drop condition. In most applications, the installed characteristics tend to change as compared with the inherent characteristics because the differential pressure across the valve under the actual working conditions is no longer kept constant. The parameters which affect the valve flow are the differential pressure, lift of valve stem besides the inherent valve characteristics, valve authority and valve coefficient. The relationship among all the inputs is presented through mathematical models below.

- Modeling:

In reality, the differential pressure cannot be measured explicitly across the valve only. In this case, the valve authority needs to be introduced in order to understand how the valve flow varies with the valve stem position changes.

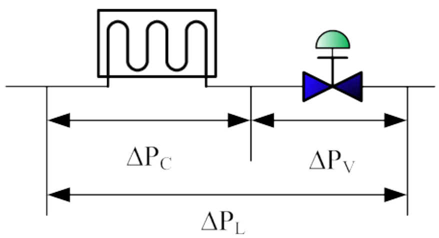

Figure 2: Schematic diagram for a control loop

As presented in Figure 2, the valve authority is defined as a ratio of the pressure drop across the valve (ΔP_v) as compared to the total pressure drop across the entire loop (ΔP_L) under the design condition. The design condition is referred to, in this paper, the condition that the design rated valve flow rate for the valve at the fully open position. The loop can be defined differently based on locations where differential pressure (DP) meters are located: the valve only, the valve and a section of pipe, or the valve and the coil. Different locations of the DP sensor define the different values for the valve authority. Since pressure differential sensors are preferred to be installed on each valve for the flow meter application, the loop in this study is referred to the loop with single vale and single coil.

$$N = \frac{\Delta P_{v,d}}{\Delta P_{L,d}} \quad (2)$$

where

N represents the valve authority.

$\Delta P_{v,d}$ = Pressure drop across the valve under the design conditions (lbm/in^2 or Pa).

$\Delta P_{L,d}$ = pressure drop across the loop under the design conditions (lbm/in^2 or Pa).

Thus, under the design condition, the pressure drop across the valve can be determined as Equation (3). The resistance coefficients of the coil, valve and loop are calculated by Equations (4), (5) and (6) respectively.

$$\Delta P_{v,d} = \Delta P_{L,d} - \Delta P_{c,d} \quad (3)$$

$$K_{c,d} = \frac{\Delta P_{c,d}}{\bar{Q}_d^2} \quad (4)$$

$$K_{v,d} = \frac{\Delta P_{v,d}}{\bar{Q}_d^2} \quad (5)$$

$$K_{L,d} = K_{c,d} + K_{v,d} \quad (6)$$

where ΔP_c = differential pressure across the cooling coil (lbm/in^2 or Pa).

Though it can be calculated using pressure drops and flow rates, the resistance coefficient is caused by frictions from pipe wall friction and fittings, i.e. the resistance coefficient of the loop remains constant as long as there is no geometrical changes in the loop. For the system presented in Figure 2, the resistance coefficient only changes as valve stem position varies. Under operating conditions (valve is partially open at x position), the resistance coefficient of the cooling coil is assumed to be constant ($K_{c,d} = K_{c,x}$), so its pressure drop is proportional to the product of the square of the water flow rate ratio ($\bar{Q}_x$) and its pressure drop under the design condition ($\Delta P_{c,d}$). The pressure drop across the valve at any valve open positions ($\Delta P_{v,x}$) can be obtained using difference between the pressure drop across the entire loop and the pressure drop across the coil, as shown in Equation (7).

$$\Delta P_{v,x} = \Delta P_L - \bar{Q}_x^2 \cdot \Delta P_{c,d} \quad (7)$$

$\Delta P_{v,d}$ = Pressure drop across the valve under partially open position x (lbm/in^2 or Pa).

Equation (8) shows the valve resistance calculated using inherent valve characteristics (the pressure drop across the valve is also constant) and Equation (9) shows the valve resistance coefficient calculated using installed valve characteristics (the pressure across the valve no longer holds constant). Since the same valve stem position determines the valve resistance coefficient, the valve resistance coefficient is kept constant under both the inherent and installed circumstances as long as the valve stem position is the same. The water flow rate ratios through at any valve stem position (x) can be determined by Equation (10).

$$K_{v,x} = \frac{\Delta P_{v,d}}{f^2(x)} \quad (8)$$

$$K_{v,x} = \frac{\Delta P_{v,x}}{\bar{Q}_x^2} \quad (9)$$

$$\bar{Q}_x^2 = \frac{\Delta P_{v,x}}{\Delta P_{v,d}} f^2(x) \quad (10)$$

If the term $\Delta P_{v,x}$ in Equation (10) is substituted by Equation (7), the valve water flow rate ratio can be expressed by Equation (11).

$$\overline{Q}_x^2 = \frac{\Delta P_{L,d}}{\Delta P_{v,d} + f^2(x) \cdot \Delta P_{c,d}} f^2(x) \quad (11)$$

The valve flow coefficient (C_v) is an amount of 60˚F water flow that will flow through a valve with a unit differential pressure across the valve. It is defined by Equation (12).

$$C_v = \frac{Q_d}{\sqrt{\Delta P_{v,d}}} \quad (12)$$

Integrated Equations (2), (11) and (12), the water flow rate in the loop is defined by Equation (13).

$$Q_x = C_v \cdot f(x) \sqrt{\frac{\Delta P_{L,d} N}{N + f^2(x)(1-N)}} \quad (13)$$

As presented in Equation (13), the virtual water flow readings can be calculated by two measurable inputs: valve stem position (x) and the differential pressure across the loop (ΔP_L) and three other inputs: the valve inherent characteristics (f(x)), the valve flow coefficient (C_v) and the valve authority (N). Since the three constants are determined when the system is designed and do not change afterwards, the water flow readings can be formulated by Equation (12).

$$Q_x = \sqrt{K_{L.x}(x) \cdot \Delta P_L} \quad (12)$$

Where

$$K_{L.x}(x) = {(C_v \cdot f(x))^2 N}\Big/{[N + f^2(x)(1-N)]},$$

Which is named the loop resistance coefficient at the valve opening position of x.

Though the differential pressure (DP) measurements can be easily measured using a DP transducer with high accuracy, a calibration process is needed to identify the in-situ loop resistance coefficient ($K_{L.x}$) curve under different valve stem positions (x). In addition, it is challenging to obtain accurate flow readings because the valve stem position is typically not readable. However, the valve control command or sometimes actuator positioner readings are available from the BAS instead. Valve dead band and response time cause errors when valve control command or actuator positioner readings are used to represent the valve stem position. Valve dead band is majorly caused by friction, backflash or/and relay dead zone in the process of valve assemblies [Control valve handbook 2005]. The same handbook presents measurement results of comparing three ball valves with three different dead bands ranging from 1% (Valve A), 5% (Valve B), and 10% (Valve C) in Figure 3.

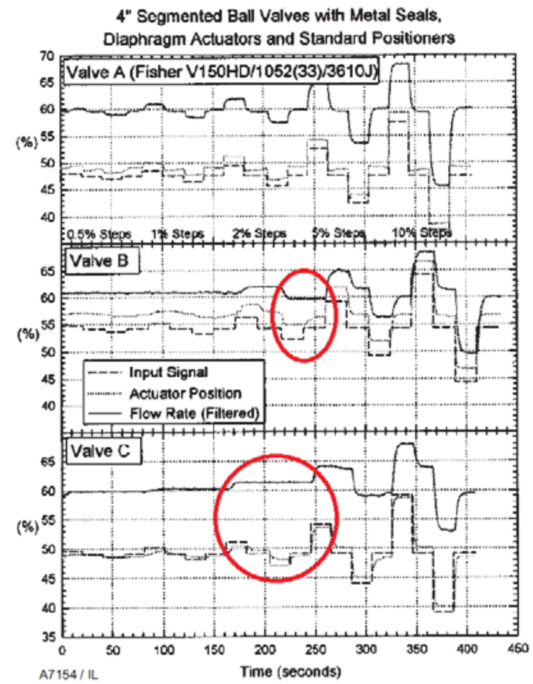

Figure 3: Valve characteristic comparison

As shown in Figure 3, the actuator positions respond to input control signals very well for all three valves, while for Valve B and Valve C, the flow has no responses to the input control signals and actuator position changes in around 70 seconds, as shown in the red circles in Figure 3. It shows when the valve dead band is above 5%, special corrections are needed for accurate flow readings when the valve control command or stem positioned signal are used for the flow calculations.

EXPERIMENTS

In this section, two stages of experiments are introduced. Stage I is to simply validate the concept by monitoring a control valve in real operation; Stage II experiments were carried out for 1) identifying an appropriate calibration procedure for obtaining the in-situ loop resistance coefficient curves; 2) investigating the impacts of the valve dead band on the flow readings.

EXPERIMENT FOR CONCEPT VALIDATIONS

Theoretical deduction has proven that the valve flow rate (Qx) can be expressed by the DP measurements (ΔP_L) and the valve stem opening positions (x). Therefore, it is theoretically feasible to use the control valve operating conditions to monitor the water flow rate through the valve. However, there are some physical limitations which can provide challenges to the accuracy of the valve flow meter: 1) the control input command is adopted as the valve stem position indicator which might cause error due to the control system response time and the valve response time delays; 2) the valve hysteresis characteristics can also introduce a significant amount of uncertainty to the virtual valve flow meter. However, the limitations are typically considered to be highly sensitive to a high frequency dynamical system, but they can be possibly compensated by the fact that the HVAC system is a low-frequency dynamic system. Especially for the cooling coil control valve operation, the cooling coil load changes are dominant disturbances, which typically oscillate in a 24 hour cycle. Thus, the slow oscillations of the load disturbance on the valve operation can compensate the two limitations for the virtual valve flow meter application. For unstable valve operation, i.e. valve hunting, which is caused by improper tuning of the control loop and flow turbulence, the impacts of the high frequency oscillation can be eliminated by adopting a moving average method. To validate the concept, Stage I Experiment was conducted on a 6" control valve, which is used to modulate the chilled water flow through a 150-ton cooling coil. The DP transducer is shown in Figure 4. The DP across the valve and the cooling coil is designed to be maintained at constant of 9 PSI by a building chilled water pump.

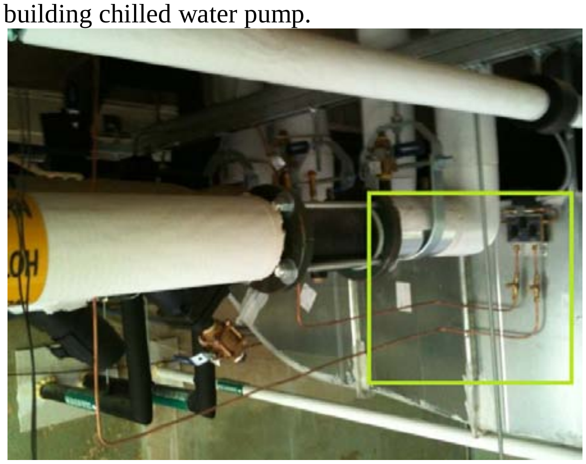

Figure 4: Valve used in Experiment I

A portable ultrasonic flow meter was installed on the chilled water return pipe for flow measurements and the valve stem position and DP measurements across the cooling coil and the valve were trended through BAS at one minute intervals. The experiment was carried out for a little over two days (a total of 53 hours). The valve was in normal daily operation. As shown in Figure 5, the valve stem command on the left ordinate and the water flow rate on the right ordinate are tracking each other very well. The DP measurements are presented in Figure 6. Even though the DP set point is 9 PSI, the actual DP measurements have some overshoots and oscillations which might be caused by flow turbulence or/and the control loop oscillations, but the average is maintained at 9 PSI.

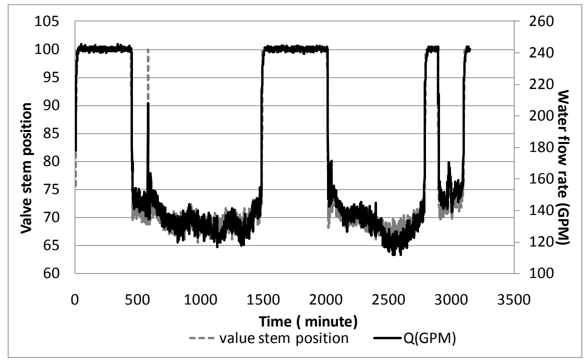

Figure 5: Valve stem command and water flow rate comparison of Experiment I

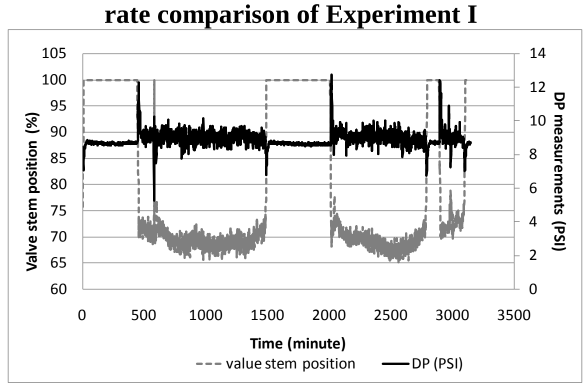

Figure 6: DP measurements in Experiment I

To get rid of the oscillations, a 10-minute interval moving average is calculated to investigate the relationship between water flow rate and valve stem commands from the BAS. The results are presented in Figure 7. It is very obvious that the water flow rate is correlated with the BAS stem command very well, which is evident that for AHU operation, the BAS valve command can be used to indicate the valve stem position for the valve flow meter application. However, it is also very obvious that the correlation curve is also scattered, which can result in around 10% error over the full range if considering the full range is 300GPM. It is expected that the investigation on the valve hysteresis will solve the problem and improve the accuracy greatly. The analysis will be done in next phase study.

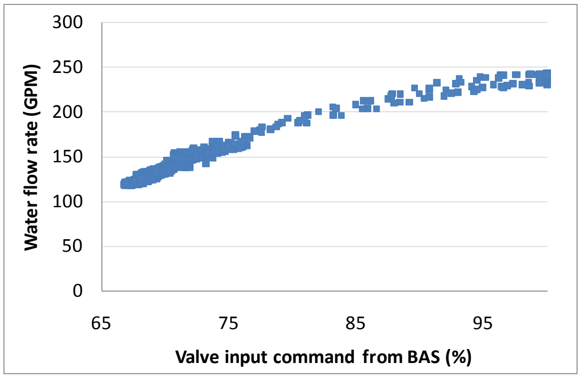

Figure 7: Valve BAS command v.s. water flow rate

EXPERIMENT FOR DEVELOPING IN-SITU LOOP RESISTANCE CURVE

As discussed in the Modeling section, the in-situ loop resistance characteristic curve is critical for the accuracy of the valve flow meter. This experiment is designed in order to verify the feasibility of obtaining an in-situ loop resistance curve. Experiment II was conducted on a size of 1/2" (12 mm) ball valve with the design valve flow rate of 40GPM (9.1 m^3/s) with the purpose that the results from the two experiments can also be compared to investigate if there is any possible different valve behavior caused by different valve sizes. The valve is used to modulate the chilled water flow through a 3-ton cooling coil, as shown in Figure 8. The yellow highlighted square boxes indicate the experimental valve and the DP transducer for DP measurement. The valve command was trended through BAS and the portable ultrasonic flow meter was installed for valve characteristics calibration and flow measurement verifications.

Figure 8: Valve used in Experiment II

A calibration process was conducted for the control valve to obtain the loop resistance coefficient curves. To eliminate the impacts of the valve dead band, valve response time and control system response time, the valve was manually forced open from 0% to 100% every 15 minutes for an ascending curve and then forced close from 100% to 0% every 15minutes for a descending curve. For each valve position, 15 measurements were recorded, one measurement per a minute. The measured variables are the valve position commands, DP measurements and water flow rates. The reciprocal of the loop resistance coefficient is presented in Figure 9. The squares represent the ascending loop resistance curve and the diamonds represent the descending curve. Each dot is an average of 10 measurements at each valve position. Two curves are approximately overlapped most of time except for the range of 50% to 65% opening position.

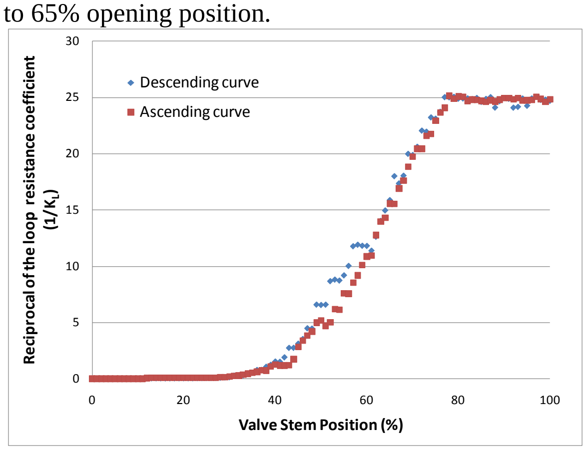

Figure 9: Loop resistance coefficient curves

As indicated in Figure 10, the valve performance curves including the both ascending and descending curves can be divided into four regions. Region I is defined as a region with a constant maximum loop resistance where the valve opening position is between 0% and 30%. As show by the diamonds in Figure 10, the reciprocal of the loop resistance coefficient is close to zero, i.e. the valve presents significant resistance to the loop and the water flow rate through the loop is negligible. The second region is defined as a region where the reciprocal of the loop resistance coefficient changes in a third-order polynomial relationship as the valve stem opening positions. For the ascending curve, Region II is where the valve opening position ranges from 31% to 50%, while for the descending curve Region II is where the valve opening position ranges from 31% to 59%. The third region is defined where the reciprocal of the loop resistance coefficient changes in a linear relationship as the valve stem opening position changes. For the ascending curve, Region III is where the valve opening position ranges from 51% to 78% and for the descending curve Region III is where the valve opening position ranges from 60% to

78%. In this region, the loop resistance reduces rapidly as the valve opens and the water flow rate reaches the maximum value when the valve is at 80% open position. In Region IV where the valve opening position ranges from 79% to 100% for both curves, the changes of the loop resistance are negligible. The water flow rate through the loop is at the maximum value for the entire range.

Through Experiment II, it is shown that the in-situ loop resistance coefficient curve can be obtained and regressed by four different equations, which make the valve flow meter application feasible.

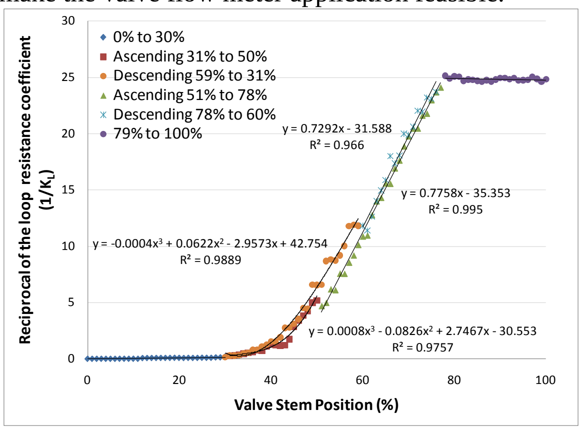

Figure 10: Loop resistance curve analysis

CONCLUSION

In this paper, a virtual flow meter concept was introduced by using a control valve installed on the cooling or heating coils as a measurement device. Theoretically, the flow through the valve is indirectly calculated using the DP measurements and in-situ loop resistance coefficient curve which is a function of the valve stem position for any coil-valve configuration. Since the DP measurements can be easily obtained by using DP transducers, the main challenges are to obtain the valve stem position and the in-situ loop resistance coefficient curves.

To solve the challenge of the valve stem position, it is desired to use valve control commands as the valve stem position indicator in the real applications. However, depending on the controller resolution, the valve response time and control system response time, the errors of using the control command as an indicator of the valve stem position might be significant. In this paper, an experiment was carried out to study the feasibility of using the control command as the valve stem position indicator and the results provide positive evidence. The second experiment also shows that it is feasible obtain the in-situ loop resistance coefficient curves, which can be programmed into the virtual valve flow meter.

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