DESALINATION OF SEAWATER USING A HIGH-EFFICIENCY JET EJECTOR

A Thesis

by

MANOHAR D. VISHWANATHAPPA

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2005

Major Subject: Chemical Engineering

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ABSTRACT

Desalination of Seawater Using a High-Efficiency Jet Ejector. (May 2005)

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Chair of Advisory Committee: Dr. Mark T. Holtzapple

The ability to produce potable water economically is the primary focus of seawater desalination research. There are numerous methods to desalinate water, including reverse osmosis, multi-stage flash distillation, and multi-effect evaporation. These methods cost more than potable water produced from natural resources; hence an attempt is made in this research project to produce potable water using a modified high-efficiency jet ejector in vapor-compression distillation.

The greater efficiency of the jet ejector is achieved by properly mixing propelled and motive streams. From experiments conducted using air, the pressure rise across the jet ejector is better in case of one or two mixing vanes and the highest back pressure (pinch valve closed 83.33%). At other pinch valve closings, the air velocity through the jet ejector was high, so the extra surface area from the mixing vanes caused excessive friction and lowered the efficiency.

DEDICATION

To my parents, Vishala and Vishwanath and my brother, Sudhakar

for all their love, encouragement, and support.

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I would like to express my sincere gratitude to my advisor Dr. Mark T. Holtzapple for all his guidance and unwavering belief in me. I am truly grateful to Dr. Richard Davison not only for serving on my committee, but also for all his indispensable advice and encouragement over the past couple of years. I would like to thank Dr. Cady Engler for his invaluable advice and for agreeing to serve on my committee. This work would not have been completed without all the help and facilities provided by Carrabba Industries, StarRotor Corporation, Dr. Gary Noyes, and Mr. Andrew Rabroker. I thank my group members, Xu Li, Brent Haas, Jonathan O'Dwyer, Cesar Granda, Frank Agbogbo, Brian Lipscomb, Somsak Watanawanavet, Jorge Lara, Stanley Coleman, Zhihong Fu, Maxine Jones, Randy Miles, Andrew Moody, Lambert Titzman, Li Zhu, and Rocio Ramirez for all their support and encouragement. Finally, I would like to thank the Department of Chemical Engineering for giving me the wonderful opportunity of pursuing my studies in this reputable university.

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CHAPTER I

INTRODUCTION

Earth is a water-rich planet, which is fortunate because water is key to man's progress. It is essential for agricultural and industrial growth and is required to support growing urban populations.

I.1 Water Sources

Most of the available water on earth is seawater. Of all the earth's water, 97% is in oceans and about 2% is in glaciers and ice caps (Table I.1). The rest is available in lakes, rivers, and underground. All natural waters contain dissolved salts. Also industries produce saline waters, which are not suitable for direct use.

Table I.1 Water distribution throughout the world [1].

Oceans	97.23%
Ice Caps and Glaciers	2.14%
Groundwater	0.61%
Freshwater Lakes	0.01%
Other	0.01%

This thesis follows the style and format of Desalination.

I.2 Water Demands

The four most important uses of water are

1. Drinking
2. Domestic
3. Agricultural
4. Industrial

The minimum per-capita water requirements have been estimated at 1100 L/day [2]. The actual amount varies and depends on the standard of living. In the USA for example, the per-capita consumption of water is 6600 L/day [2], which includes industrial and agricultural use.

I.3 Water Problem

The annual precipitation on earth is adequate for the needs of the earth's population; however, its distribution is not uniform. In many parts of the world (especially the Middle East), which have limited or no water resources, rainfall is almost non-existent. Also, most of it is unfit for human consumption without treatment [3]. Another factor, which compounds the water shortage problem, is rapid population growth. In the past 50 years, the world's population has more than doubled. This rapid growth is more pronounced in water-short areas [4]. Other factors are rising standards of living, urban growth, industrialization, expansion of irrigation agriculture, pollution of natural water reserves (by industrial waste and sewage), and cultural development [5].

Water shortages are not confined to arid lands, which comprise more than 60% of the earth's total surface. Even in countries where plenty of water is available, many supply and quality problems exist and some areas experience shortages [3].

I.4 Solution to the Water Problem

The demand for a steady, economical supply of water is constantly increasing around the world. Often it does not match the available supply. It does not seem possible that supply will equal demand in the near future [6]; therefore, sound water resources development and management is and will be a constant challenge. In many countries, water policy will be an essential ingredient of economic policy. There are many solutions to the water problem, including control of water consumption, conservation, improved distribution and storage, reclamation, purification and reuse, crops that use less water, tapping of new sources, etc. Desalination is seriously considered only when all the other possibilities have been ruled out [7].

Seawater desalination plants have been constructed in many countries, especially the arid Middle East, only because there were no other available alternatives. The objective of desalination is to provide water with salinity below 500 ppm [7]. The major problems associated with desalination have been very high capital and operating costs. Over the past several years, the cost of desalting has gone down but it is still quite high. It still cannot compete with the cost of natural fresh water, which has the advantage that it requires minimal treatment to make it potable [6].

Though many methods have been proposed to desalt saline waters, only a few have been developed to commercial viability. The majority of commercial desalination processes have been perfected over the past 50 years. The applicability of any process depends on the amount of salts contained in the available feed water and on process economics.

I.5 Classification of Desalination Process

Desalination processes are divided into (i) thermal methods, which involve heating water to its boiling point to produce water vapor, and (ii) membrane processes, which use a membrane to move either water or salt into two zones, one salty and one fresh. The main thermal method employed is distillation, where saline water is progressively heated in subsequent vessels at lower pressures. Brief descriptions of the main desalination processes are provided below.

I.5.1 Distillation processes

Multi-Stage Flash Distillation is the most widely used desalination method. It involves heating saline water to high temperatures and passing it though vessels of decreasing pressures, which flashes off water vapor. The flashed water vapor condenses on heat exchanger surfaces that preheat the incoming salt water. The condensed vapor is collected as fresh water [2].

Multi-Effect Distillation uses multiple vessels of decreasing pressure, similar to multistage flash distillation. The major difference is that evaporation occurs at the heat exchanger surface, which can lead to fouling [7].

Vapor-Compression Distillation uses a compressor to pressurize water vapors from the evaporating saline water. The compressed water vapors condense providing the heat needed to evaporate water from the salt solution. This process is driven by the work invested in the compressor [5].

I.5.2 Membrane processes

Reverse Osmosis is a pressure-driven process, which forces water through a selective membrane, leaving salts behind [8, 9].

Electrodialysis is a voltage-driven process and uses an electric potential to move salts selectively through a membrane, leaving fresh water behind [5].

Ion Exchange passes water through beds of ion exchange resins where cations are exchanged with hydrogen ions attached to the resin, and anions are exchanged with hydroxide ions attached to a different type of resin. The ion exchange resins are rejuvenated using acids and bases [3].

I.6 Objective

This research is concerned with desalinating seawater using vapor compression technology that employs a high-efficiency steam jet ejector. The primary focus of this work is to test the efficiency of the steam jet ejector. The new design needs to tested and further optimized for greater pressure rise across the jet ejector. For experimental convenience, its efficiency is measured using compressed air rather than steam. Air is easy to regulate, readily available, and the motive stream (compressed air) and propelled stream (atmospheric air) can mix properly and be discharged safely. Also, the results obtained will be similar for the both fluids. To test the efficiency, compressed air is passed through the nozzle into the jet ejector for different numbers of mixing vanes and various back pressures.

CHAPTER II

DESALINATION METHODS

A desalting device essentially separates saline water into two streams: the fresh water stream (low salts) and the concentrate or brine stream (high salts). The device requires energy to operate and can use a number of different technologies for the separation. This section briefly elaborates on various desalting processes.

II.1 Multi-Stage Flash Distillation

As shown in Figure II.1, multi-stage flash distillation (MSF), seawater is heated in a vessel called the *brine heater* [10]. This is generally done by condensing steam on a bank of tubes that passes through the vessel, which in turn heats the seawater. This heated seawater then flows into another vessel, called a *stage*, where the reduced pressure causes the water to boil or flash [11]. Generally, only a small percentage of this water is converted to steam, because boiling will continue only until the water cools (furnishing the heat of vaporization) to the boiling point [12].

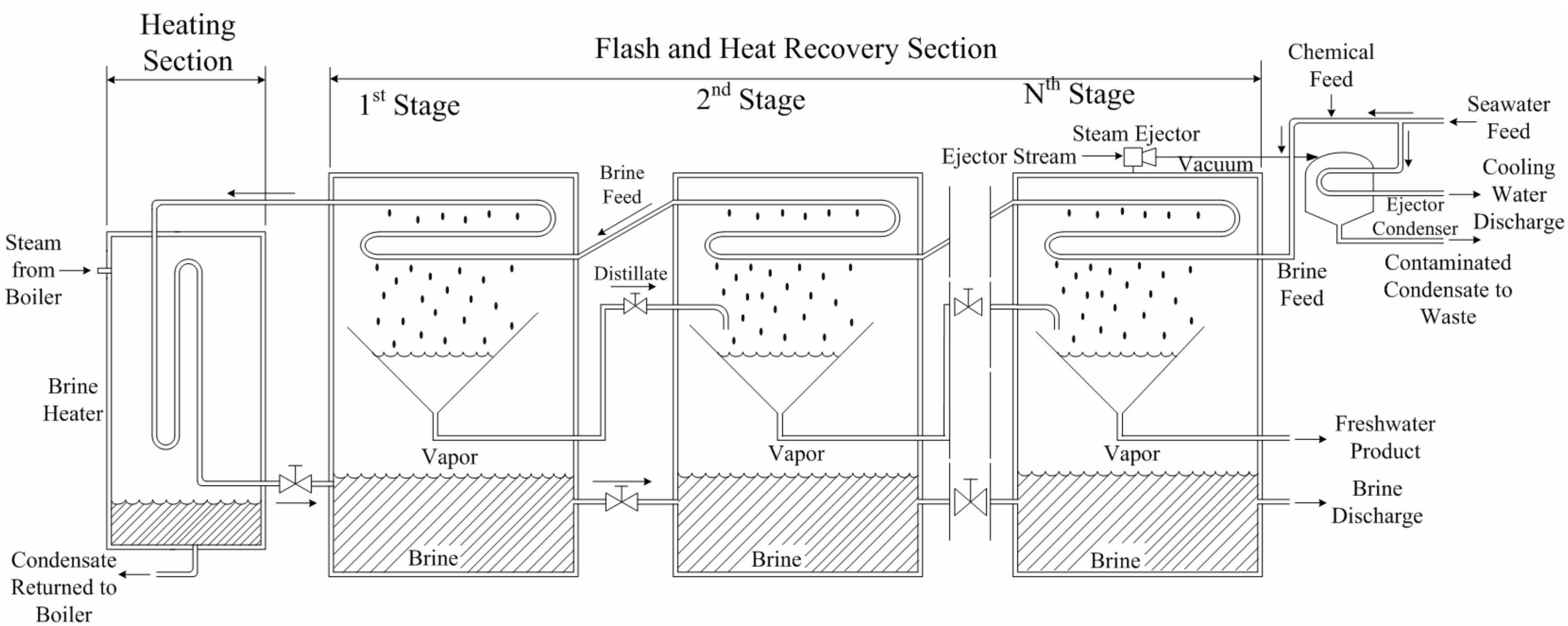

Figure II.1 Diagram of a multi-stage flash distillation plant [after 24].

The flashed steam generated is converted to fresh water by condensing on heat exchanger tubes that run through each stage. The tubes are cooled by the incoming feed water going to the brine heater. This, in turn, warms the feed water thereby reducing the amount of thermal energy needed in the brine heater to raise the temperature of the seawater.

The concept of distilling water with a vessel operating at a reduced pressure is not new and has been used for well over century. MSF plants have been built commercially since the 1950s. Typically, an MSF plant can contain from 4 to about 40 stages (not to be confused with effects). They are generally built in units of about 4000 to 30,000 m^3/day [13]. The MSF plants usually operate with top feed temperatures (after the brine heater) of 90 – 120^oC [14]. One factor that affects the thermal efficiency of the plant is the difference in temperature from the brine heater to the condenser on the cold end of the plant. Operating a plant at the higher temperature limits of 120^oC increases the efficiency, but it also increases the potential for detrimental scale formation and accelerated corrosion of metal surfaces [14].

II.2 Multiple–Effect Distillation

Multiple-effect distillation (MED) has been used for industrial distillation for a long time. Some of the early water distillation plants used MED, but this process was displaced by MSF units because of cost factors and their resistance to fouling. However, in the past decade, interest in MED has renewed, and a number of new designs have been built. Most new MED units operate at lower temperatures [15].

Like MSF, MED occurs in a series of vessels (effects) with each subsequent effect operated at a lower pressure (see Figure II.2). This permits the seawater feed to undergo multiple boiling without supplying additional heat after the first effect [15]. In an MED plant, the seawater enters the first effect and is heated to the boiling point after being preheated in tubes. Seawater is either sprayed or otherwise distributed onto the surface of evaporator tubes in a thin film to promote rapid boiling and evaporation. The tubes are heated by steam from a boiler, or other source, which is condensed on the opposite side of the tubes. The condensate from the boiler steam is recycled to the boiler for reuse [16].

Only a portion of the seawater applied to the tubes in the first effect is evaporated. The remaining feed water is fed to the second effect, where it is again applied to a tube bundle. In turn, these tubes are heated by the vapors created in the first effect. This vapor is condensed to fresh water product, while giving up heat to evaporate a portion of the remaining seawater feed in the next effect. This continues for several effects, with 8 or 16 effects being found in a typical large plant [16].

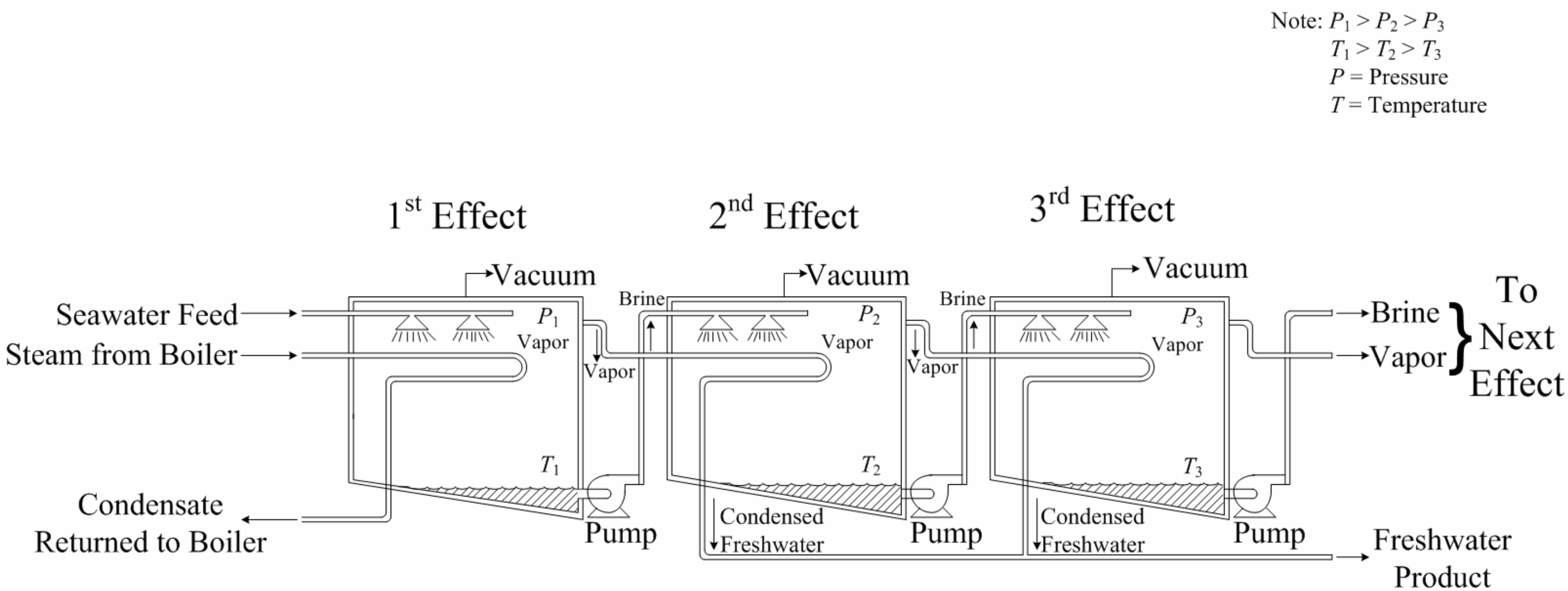

Figure II.2 Diagram of a multi-effect distillation plant [after 24].

Usually, the remaining seawater in each effect must be pumped to the next effect to apply it to the next tube bundle. Additional condensation occurs in each effect on tubes that bring the feed water from its source through the plant to the first effect. This warms the feed water before it is evaporated in the first effect [15].

MED plants are typically built in units of 2000 to 10,000 m^3/day [16]. Some of the more recent plants have been built to operate with a top temperature (in the first effect) of about 70^oC, which reduces the potential for scaling of sea water within the plant, but it increases the need for additional heat transfer area in the form of tubes [15]. Although the number of MED plants is still relatively small compared to MSF plants, their numbers have been increasing [16].

II.3 Reverse Osmosis

In comparison to distillation and electrodialysis, RO is relatively new, with successful commercialization occurring in the early 1970's. RO is a membrane separation process in which the water from a pressurized saline solution is separated from the solutes [17]. No heating or phase change is necessary for this separation. The major energy required for desalting is for pressurizing the feed water [18].

In practice, the saline water is pumped into a closed vessel where it is pressurized against the membrane (see Figure II.3). As a portion of the water passes through the membrane, the remaining feed water increases in

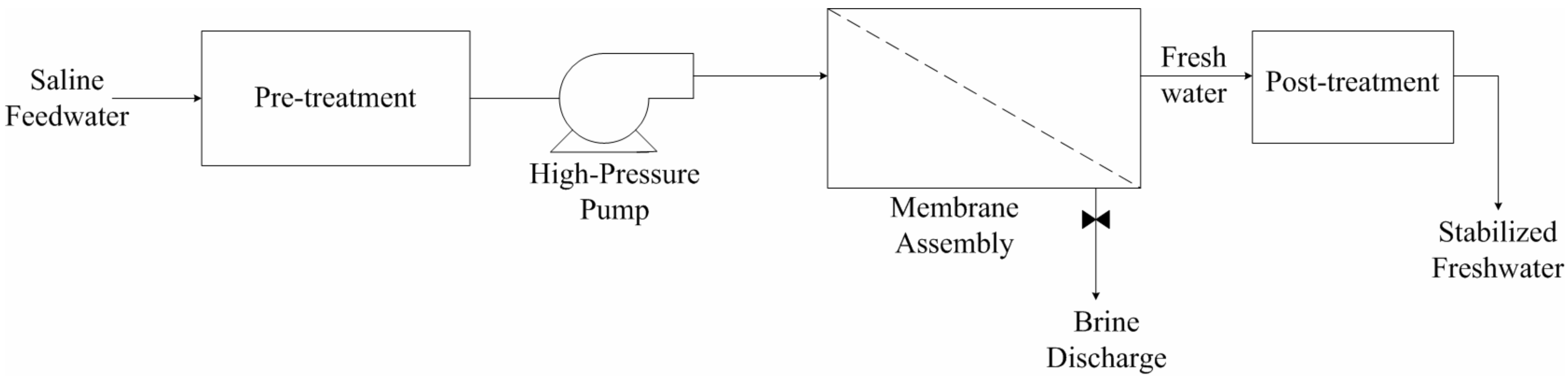

Figure II.3 Basic components of a reverse osmosis plant [after 24].

salt content [19]. At the same time, a portion of this feed water is discharged without passing through the membrane. Without this controlled discharge, the pressurized feed water would continue to increase in salt concentration, creating such problems as precipitation of supersaturated salts and increased osmotic pressure across the membranes [19]. The amount of the feed water discharged to waste in this brine stream varies from 20 to 70% of the feed flow, depending on the salt content of the feed water [20].

An RO system has the following basic components [20]:

- Pretreatment
- High-pressure pump
- Membrane assembly
- Post-treatment

Pretreatment is important in RO because the feed water must pass through very narrow passages during the process; therefore, suspended solids must be removed and the water pre-treated so that salt precipitation or microorganism growth does not occur on the membrane. Usually, the pretreatment consists of fine filtration and the addition of acid or other chemicals to inhibit precipitation [21].

The high-pressure pump supplies the pressure needed to enable the water to pass through the membrane and have the salts rejected. This pressure ranges from 250 to 400 psig for brackish water and from 800 to 1180 psig for seawater [20].

The membrane assembly consists of a pressure vessel and a membrane that permits the feed water to be pressurized against the membrane. The membrane must withstand the entire pressure drop across it. The semi-permeable membranes are fragile and vary in their ability to pass fresh water and reject the passage of salts [21]. No membrane is perfect in its ability to reject salts, so a small amount of salts passes through the membrane and appears in the product water.

RO membranes are made in variety of configurations. Two of the most commercially successful are spiral-wound sheet and hollow fine fiber [20]. Both of these configurations are used to desalt both brackish and sea water, although the construction of the membrane and pressure vessel will vary depending on the manufacturer and expected salt content of the feed water.

Post-treatment consists of stabilizing the water and preparing it for distribution. This post-treatment might consist of removing gases such as hydrogen sulfide and adjusting the pH [21].

Two developments have helped to reduce the operating costs of RO plants during the past decade [20]: (1) membranes that operate efficiently with lower pressures and (2) energy recovery devices. Low-pressure membranes are being widely used to desalt brackish water. The energy recovery devices connect to the concentrate stream as it leaves the pressure vessel. The water in the concentrate stream loses only about the 15 to 60 psig relative to the applied pressure from the high-pressure pump, so turbines can convert the remaining pressure drop to rotating energy, which is reinvested in the pumps [21].

II.4 Electrodialysis

Electrodialysis was commercially introduced in the early 1960's, about 10 years before reverse osmosis (RO). The development of electrodialysis provided a cost-effective way to desalt brackish water and spurred considerable interest in this area.

Electrodialysis depends on the following general principles [22]:

- Most salts dissolved in water are ionic, being positively (cationic) or negative (anionic) charged.
- These ions are attracted to electrodes with an opposite electric charge.
- Membranes can be constructed to permit selective passage of either anions or cations.

The dissolved ionic constituents in a saline solution such as sodium (+), chloride (-), calcium (++), and carbonate (--) are dispersed in water, effectively neutralizing their individual charges [22]. When electrodes connected to an outside source of direct current are placed in a container of saline water, electrical current is carried through the solution, with the ions tending to migrate to the electrode with the opposite charge (see Figure II.4).

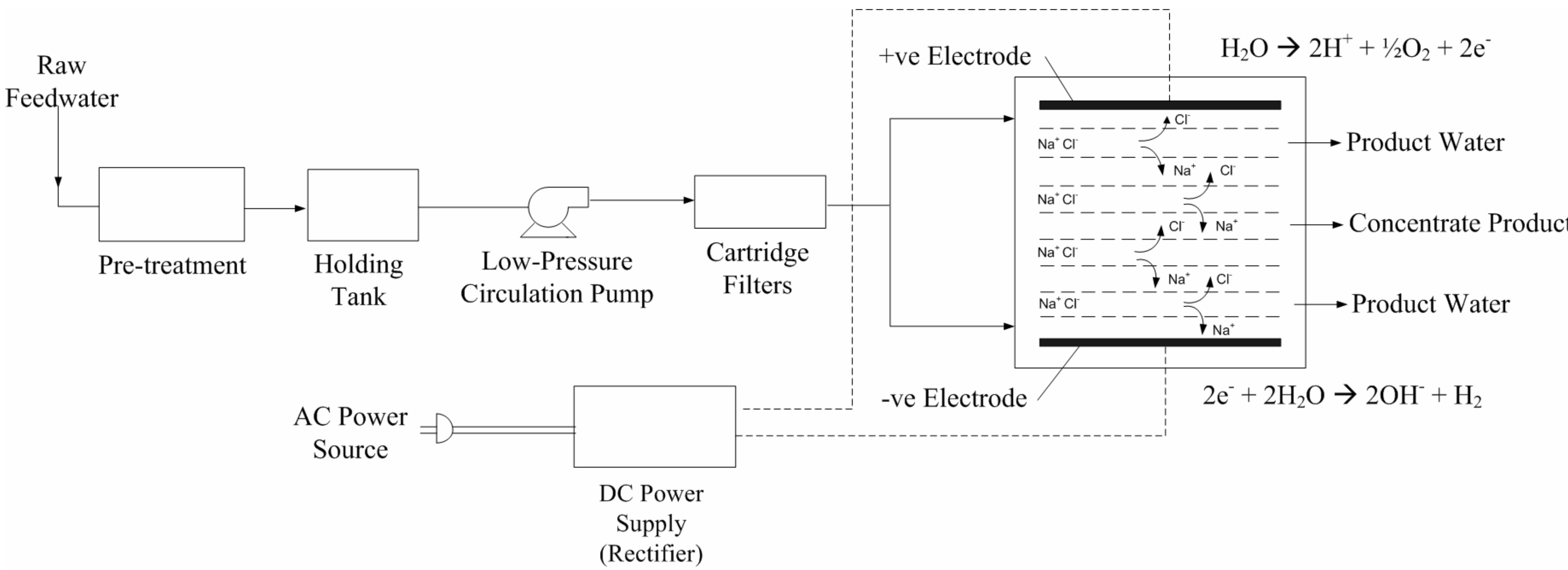

Figure II.4 Basic components of an electrodialysis plant [after 24].

For these phenomena to desalinate water, membranes that will allow either cations or anions (but not both) to pass are placed between a pair of electrodes. These membranes are arranged alternatively with an anion selective membrane followed by a cation-selective membrane. A spacer sheet that permits water to flow along the face of the membrane is placed between each pair of membranes.

One spacer provides a channel that carries feed (and product) water, whereas the next carries brine. As the electrodes are charged and saline feed water flows along the product water spacer at right angles to the electrodes, the anions in the water are attracted and diverted toward the positive electrode. This dilutes the salt content of the water in the product water channel. The anions pass through the anion-selective membrane, but cannot pass any farther than the cation-selective membrane, which blocks its path and traps the anion in the brine. Similarly, cations under the influence of the negative electrode move in the opposite direction through the cation-selective membrane to the concentrate channel on the other side. Here, the cations are trapped because the next membrane is anion selective and prevents further movement towards the electrode.

By this arrangement, concentrated and diluted solutions are created in the spaces between alternating membranes. These spaces, bounded by the two membranes (one anionic and the other cationic) are called cells [23]. A cell pair consists of two cells, one from which the ions migrated (the dilute cell for the product water) and the other in which the ions concentrate (the concentrate cell for the brine stream) [22].

The basic electrodialysis unit consists of several hundred cell pairs bound together with electrodes on the outside and is referred to as a membrane stack. Feed water passes simultaneously in parallel paths through all of the cells to provide a continuous flow of desalted product water and brine to emerge from the stack. Depending on the design of the system, chemicals may be added to the streams in the stack to reduce the potential for scaling [23].

II.4.1 Application

Electrodialysis has the following characteristics that lend it to various applications [22]:

- Capability for high recovery.
- Energy usage that is proportional to the salts removed.
- Ability to treat water with a higher level of suspended solids than RO.
- Lack of effect by non-ionic substances such as silica.
- Low chemical usage for pretreatment.

II.5 Other Processes

A number of other processes have been used to desalt saline waters. These processes have not achieved the commercial success of distillation, electrodialysis, vapor compression, and RO, but they may prove valuable under special circumstances or with further development. The most significant of these processes are freezing, membrane distillation, and solar humidification [22].

Vapor-compression distillation (both thermal and mechanical) is discussed in detail in the next chapter.

II.6 Summary

The drinking water crisis announced for 2000 – 2020 has elicited strong interest in rapidly developing desalination techniques that are cheaper, simpler, hardier, more reliable, and if possible, less energy-consuming and more environmental friendly. The cost of producing fresh water through desalination, once quite high, has considerably dropped: it can dip below \$1/m^3 for large-capacity units [12].

CHAPTER III

VAPOR-COMPRESSION DISTILLATION

Vapor-compression (VC) distillation is generally used for small- and medium-scale water desalting units. Vapor compression distillation plants are known to be compact and efficient systems that require shaft work to perform compression [25]. One of the main advantages of VC is the reuse of the vapor generated in the last effect, after elevating its pressure and temperature by compression.

The vapor is usually compressed by either mechanical (MVC) or thermal (TVC) means. In MVC, mechanically driven compressors are used whereas in TVC, steam jet boosters are used [26]. In this section, first thermal vapor compression is discussed along with the high-efficiency steam jet ejector and later the mechanical compressor (MVC) is discussed along with Roots blower-operated MVC. VC units have been built in a variety of configurations to promote heat exchange to evaporate seawater.

III.1 Thermal Vapor-Compression

Steam jet ejectors are employed in the chemical process industries and refineries in numerous and often unusual ways. They provide, in most cases, the best way to produce a vacuum in process plants because they are rugged and simple; therefore, they are easily maintained. Their capacities can vary from the very smallest to enormous quantities.

Because of their simplicity and the manner of their construction, difficulties are unusual even under the most extreme conditions. Ejectors, which are properly designed for a given situation, are very forgiving of errors in estimated quantities to be handled and of upsets in operation and are found to be easily changed to give the exact results [26].

To become fully versed in the essential elements of a steam jet ejector, the principle of operation will be considered first. An ejector is a device in which a high-velocity jet of fluid mixes with a second fluid stream; the mixture is discharged into a region at a pressure higher than the source of the second fluid [25].

Figure III.1 shows the following parts [27]:

a. The steam chest through which the propelling steam is admitted.
b. The steam nozzle through which the propelling steam expands and converts its pressure energy into kinetic energy.
c. The vapor chamber through which the vapor to be evacuated enters and distributes itself around the steam nozzle.

The diffuser through which the steam and entrained load is compressed and discharged at a pressure higher than the suction.

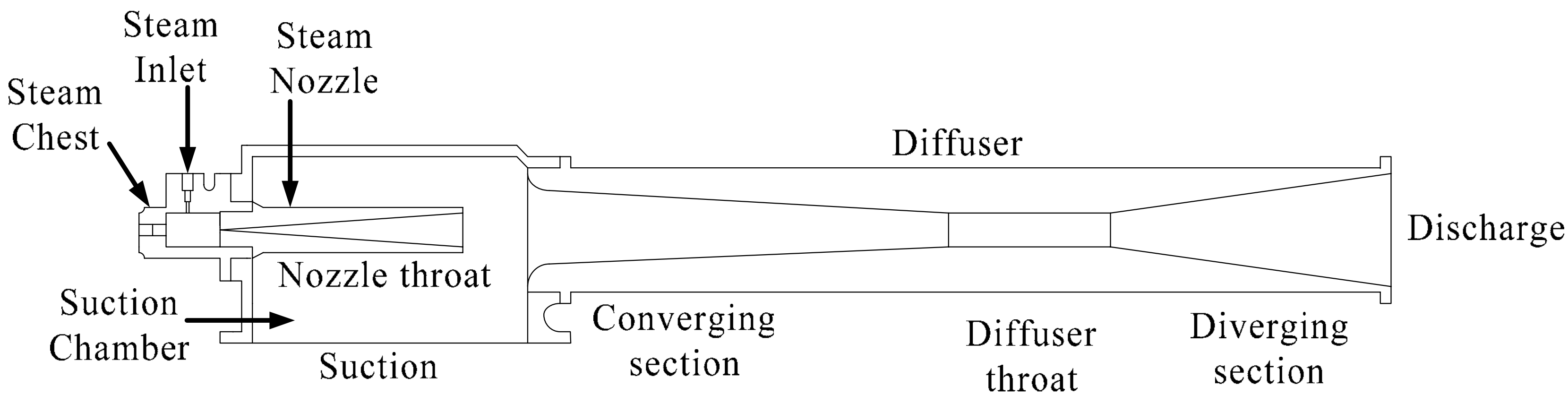

Figure III.1 Basic jet ejector assembly [28].

To explain how an ejector operates, a simple ejector (Figure III.2) mounted on a vacuum vessel will be used. Even though an ejector operates continuously, the illustrations are broken into stages for simplicity [29].

STAGE 1: High-pressure steam is fed, at relatively low velocity, into the motive fluid connector, 1.

Nozzle Head: (Steam Chest) This is simply a nozzle holder. It connects the nozzle to the high-pressure steam line and aligns it with the diffuser.

Motive and Propelled Fluids: Steam is used as the motive fluid because it is readily available. However an ejector can be designed to work with other gases or vapors if their thermodynamic properties are known. Water and other liquids are sometimes good propelled fluids as they condense large quantities of vapor instead of having to compress them. Liquids will also handle small amounts of non-condensable gases.

STAGE 2: The motive high-pressure steam enters the nozzle and issues into the suction head as high-velocity, low-pressure jet.

Nozzle: This is a device for converting the pressure and thermal energy of high-pressure steam or other fluid into kinetic energy.

Suction Head: This is the vacuum chamber and connects to the system being evacuated. The high-velocity steam jet issues from the nozzle and rushes through the suction head.

STAGE 3: A low absolute pressure at 2 (inside suction head) entrains all of the adjacent gases in the vacuum vessel, accelerates them to a high velocity and sweeps them into the diffuser.

The Diffuser: The process in the diffuser is the reverse of that in the nozzle. It converts a high-velocity, low-pressure jet stream into a high-pressure, low-velocity stream.

STAGE 4: In the final stage, the high-velocity stream, passing through the diffuser, is compressed and exhausted at the pressure of the discharge line.

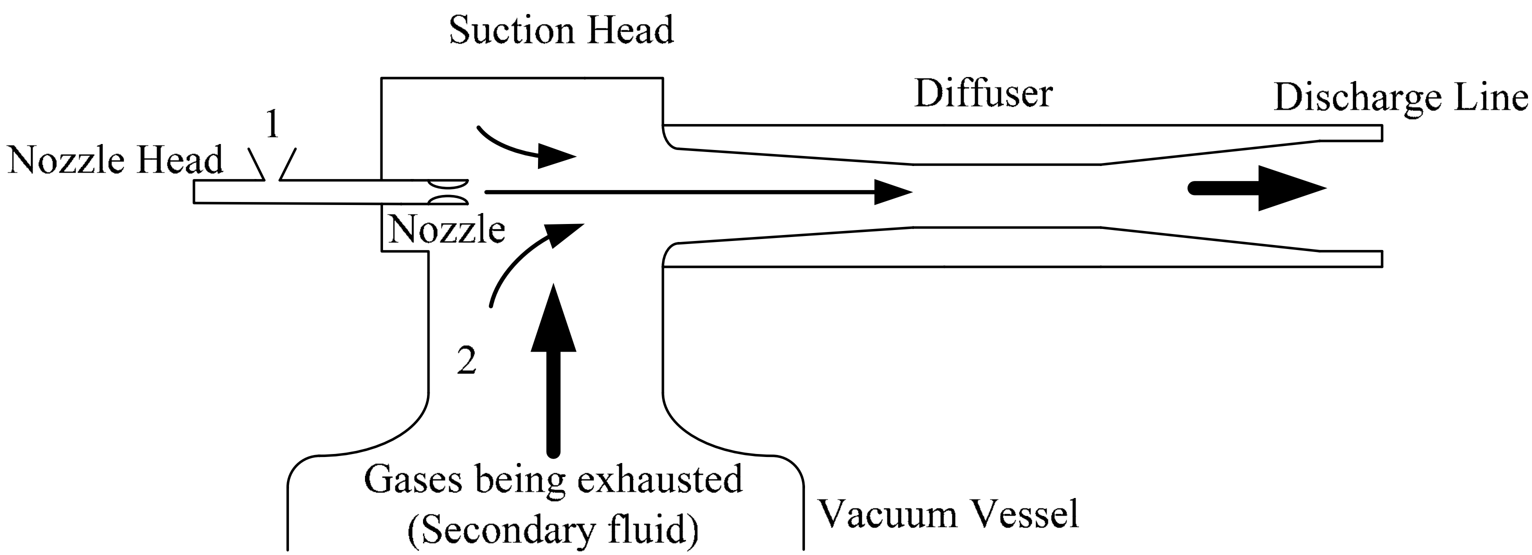

Figure III.2 Simple jet ejector mounted on vacuum vessel [30].

III.1.1 Shock wave in the diffuser

A simple tube could be used as a diffuser, but its efficiency is too low for most applications. The inlet can be tapered to provide a smoother path for the load fluid to enter and mix with the jet fluid, and the outlet can be tapered to reduce the velocity of the mixture in a manner that converts kinetic energy into pressure energy [25]. In the converging section of the diffuser, mixing becomes complete and there is some rise in pressure. When a supersonic stream enters the straight section of the diffuser, a very sharp pressure rise occurs along with a slowing of the stream, which is known as *compression shock* [31]. In the diverging section of the diffuser, pressure builds to the exhaust line and velocity is lowered to where it is just sufficient to keep the mass moving [25].

III.1.2 Variation of velocity and pressure in a stage

Figure III.3 shows how velocity and pressure vary for the motive and suction materials through an ejector stage. Both streams flow toward the lowest-pressure spot in the stage and mix together in a violent and rapid manner. Then the mixture slows down and the pressure rises before the mixture emerges at low velocity at the discharge. The discharge pressure is usually somewhere between the motive and suction pressure [32].

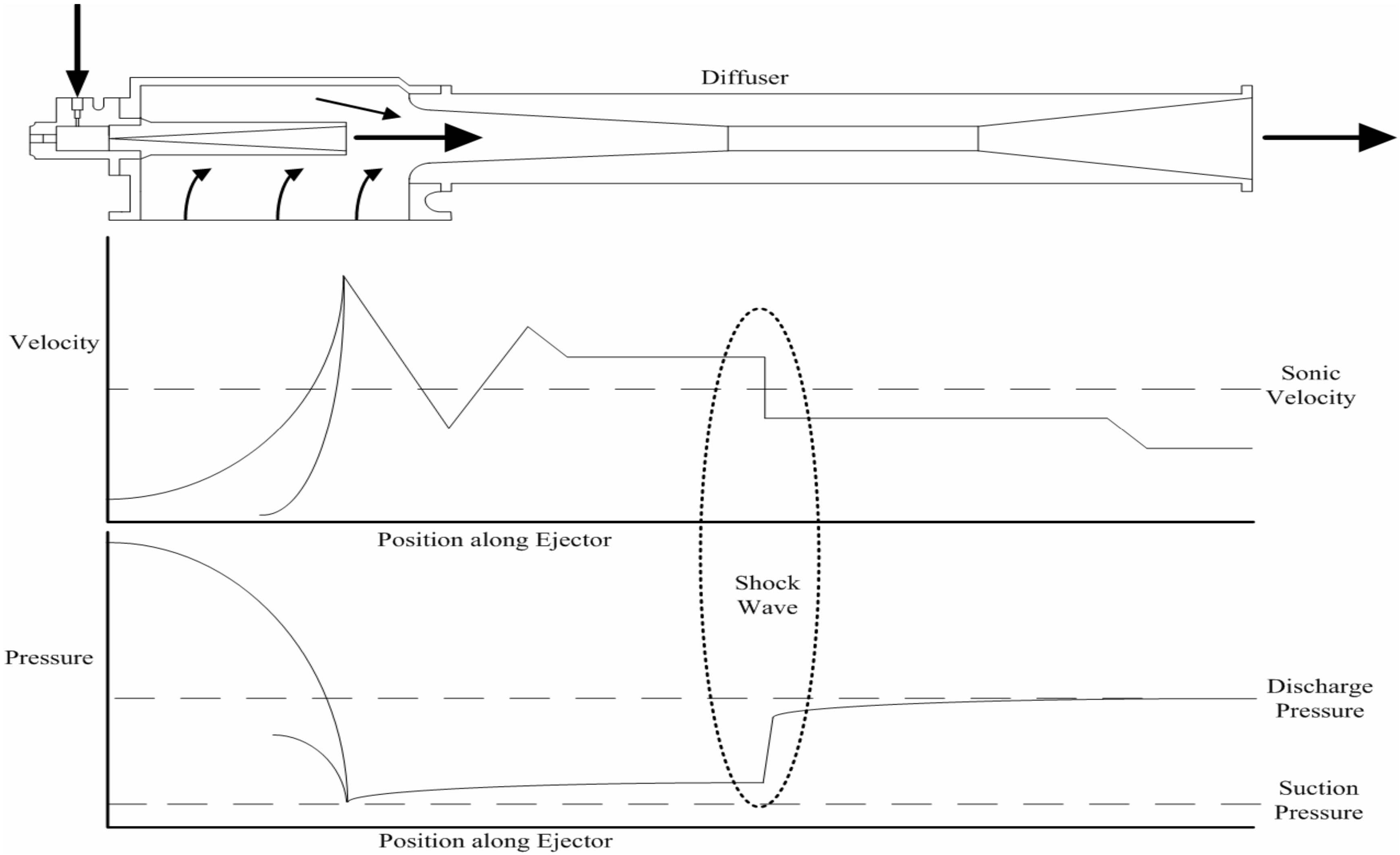

Figure III.3 Variation of velocity and pressure in a jet ejector [33].

In TVC, a steam jet compressor is operated by external motive steam of higher pressure and temperature, typically supplied by a boiler (see Figure III.4). The motive steam sucks the vapor produced in the last effect by expansion in an ejector to a pressure slightly lower than that of this effect [25]. The mixture of vapors is then compressed in a diffuser to a pressure that meets the requirement in the top effect. An amount equivalent to the withdrawn vapor proceeds down into the MEB system whereas the rest returns to the boiler loop [27].

The efficiency of the steam jet ejector is quite low, 25-30% [26], and it drops rapidly whenever design conditions are altered. Moreover, the ejector can operate only across a limited number of effects otherwise the amount of motive steam required would increase significantly.

III.1.3 Ejector family

Ejectors are extremely versatile from two viewpoints: They can be made of almost any solid material, and they can use a wide variety of pressurized gases or liquids to pump gases, liquids, and even granular solids. Table III.1 is an overview of the ejector family. It categorizes ejectors by motive fluid and load (suction) material. This is simply one display of selected applications [25,27].

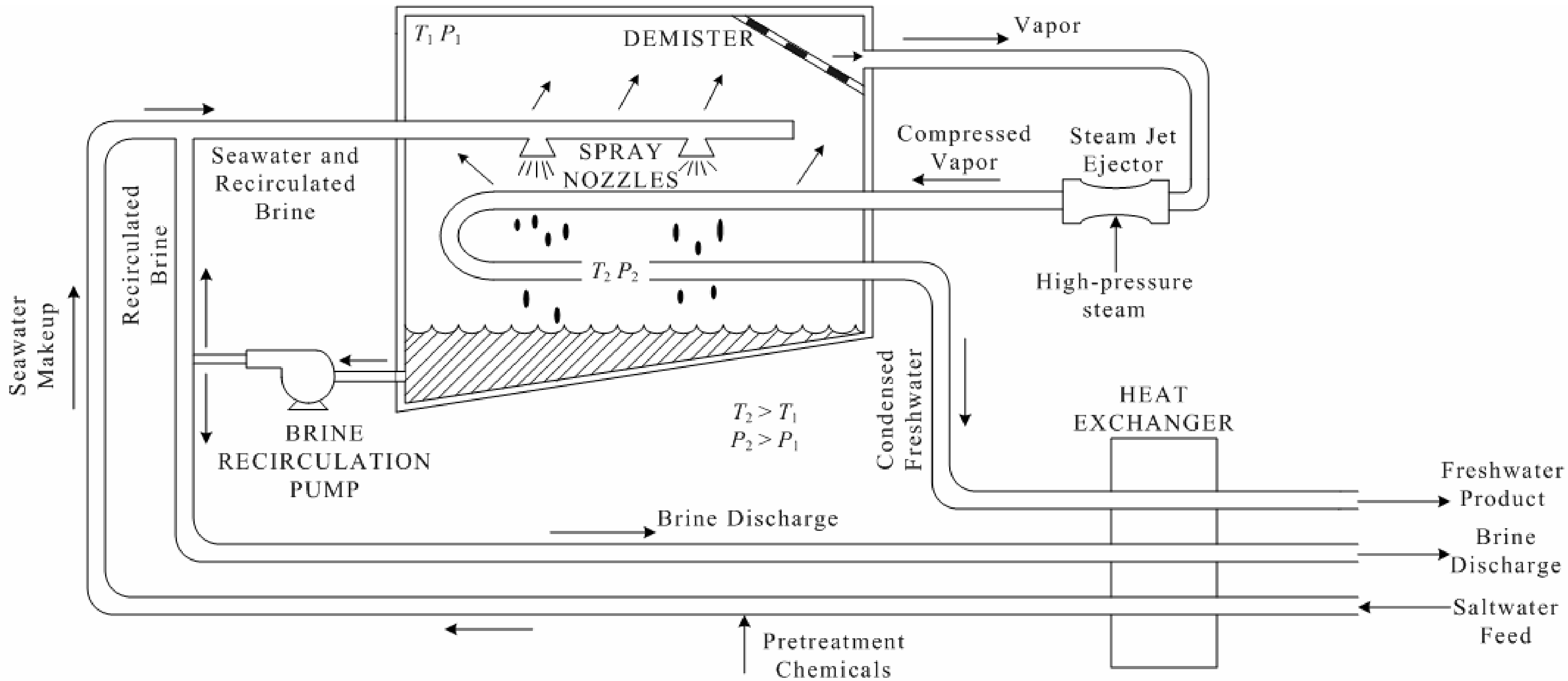

Figure III.4 Diagram of a thermal vapor-compression plant [24].

Table III.1 Ejector applications based on the motive and load streams [25, 27].

Fluid	Load materials				
	Water Vapor, Steam	Air	Gas, Vapor	Liquid	Solids
Steam	Refrigeration, stripping, drying, compressor	Vacuum, compressor	Vacuum, compressor	Pump, heater, injector	
Air		Vacuum, compressor	Vacuum, compressor	Sampling, mixing	Conveyor
Gas, Vapor		"BTU controller," vacuum	Compressor, vacuum	Sampling, mixing	Conveyor
Liquid	Vacuum, condenser	Vacuum, pump priming	Vacuum	Pump, mixing	Conveyor, mixing

III.2 High-Efficiency Jet Ejector

This section discusses the high-efficiency jet ejector invented and designed by Dr. Mark T. Holtzapple. So far, no papers have been published and this section is completely based on the patent disclosure by Dr. Holtzapple [34 to 38].

The jet ejector is designed to be very efficient. Conventional jet ejectors add motive stream to the propelled stream in a single stage. Because the velocities of the two streams are very different, this is an inefficient process. In contrast, a high-efficiency jet ejector (Figure III.5) introduces the motive stream to the propelled stream in a series of stages, which is more efficient. The critical feature of this design is that it allows the motive stream and propelled stream to be blended in a manner that minimizes the velocity differences between the two streams, thus optimizing efficiency. As part of the research work, the jet ejector efficiency was determined by using compressed air instead of steam because it is easy to regulate, readily available, and the motive stream (compressed air) and propelled stream (atmospheric air) can mix properly and safely discharged. The experimental procedure and the results obtained are discussed in the next chapter. The experimental data (in FPS and SI units) and details of all the equipment are documented in Appendix section.

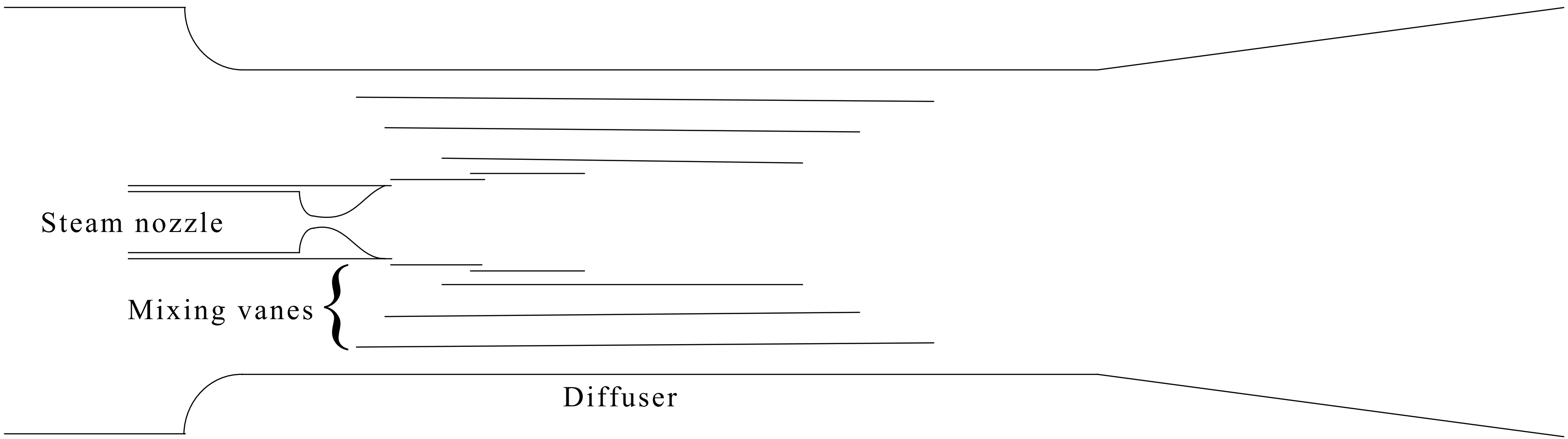

Figure III.5 A schematic representation of a high-efficiency jet ejector.

Figure III.6 shows the experimental desalination process using a high-efficiency jet ejector. Salt-containing feed flows through the degassifier into the primary heat exchanger. The salt-containing liquid boils, producing low-pressure vapors. The vapors are removed from the primary heat exchanger using a jet ejector. Superheated steam is injected into the jet ejectors at supersonic speed. The pressurized vapor exiting the jet ejector condenses in a primary heat exchanger. The heat of condensation provides the heat of evaporation for the salt solution. The vapors also flow into the secondary heat exchanger, where they condense. Distilled liquid water is recovered from all the heat exchangers and concentrated salt solution from the primary heat exchanger. The distilled product water is used to preheat the incoming salt-containing liquid so that, when steady operation is reached, the net energy required is only that necessary to drive the compressor.

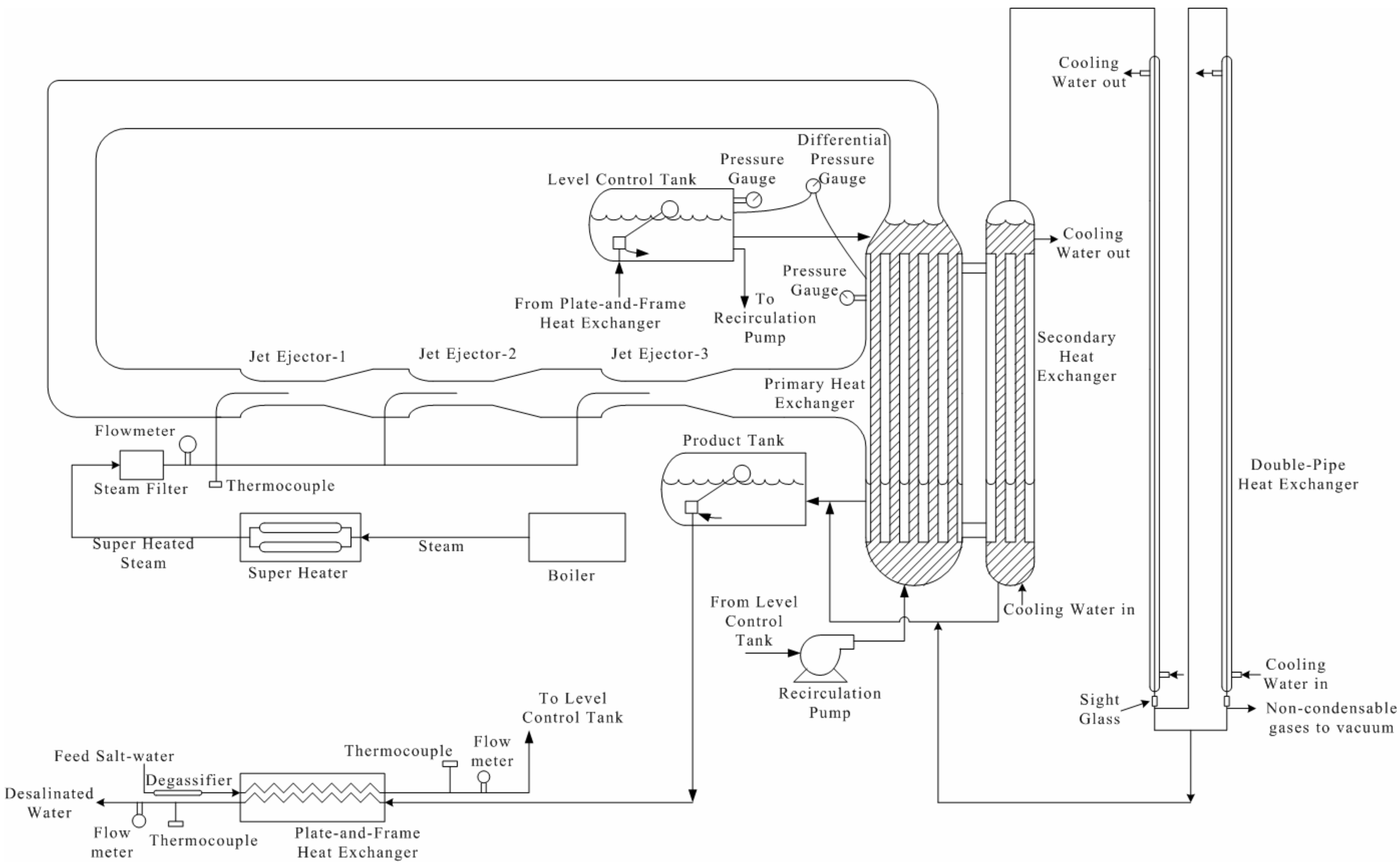

Figure III.6 Desalination process using high-efficiency jet ejector.

Three jet ejectors are connected in series in a loop with the primary heat exchanger. The superheated steam is the motive fluid and vapor from the heat exchanger is the propelled fluid in this process. The superheated steam and vapor from the primary heat exchanger are mixed in the jet ejector. The process instrumentation includes temperature measurement of superheated steam, salt-containing feed, and distilled water (product). The flow rates of salt-containing feed, superheated steam, and distilled water were measured using flow meters. The superheated steam is passed through the steam filter to remove liquid droplets. The pressure gauges are used to measure the gauge pressure at condensing and boiling sides of the primary heat exchanger. A vacuum pump is connected to the double-pipe heat exchanger to remove air from the desalination system, so the unit can be operated under vacuum. A differential pressure gauge is used to measure the pressure rise between the boiling and condensing side of the heat exchanger.

III.3 Mechanical Vapor-Compression

VC distillation was first applied during World War II for shipboard use. This was due to the very large number of vessels propelled by diesel engines, which were better suited to furnish mechanical energy than steam [39]. The VC distiller was extensively used also in advance base military operations, where the distiller with its internal combustion-engine drive would be skid-mounted for high portability [40]. These units had the virtue of using the same fuel as the accompanying automotive transport equipment, as well as being much easier to operate than equivalent thermal distillers.

Following World War II, many of these small units were used by those engaged in oil production in remote areas. Efforts to build larger units of the same type culminated in several installations for the U.S. Air Force, each producing approximately 200,000 gallons per day (gpd) [39]. Each of these installations, exemplified by the one at Kindley Air Force Base in Bermuda, had four identical units operating in parallel. Each unit had a Roots blower-type VC, a single condenser-evaporator, and a three-fluid heat exchanger for preheating the incoming seawater by cooling the brine and condensate [41]. These vapor compressors were very expensive and appeared to be as large as was practical with the Roots blower-type design. This type of compressor was preferred because it overcame the problem of evaporator scaling; as scale accumulated, the discharge pressure could be increased to produce an increased steam pressure on the condensing side and thus maintain the rated output [42]. Water produced by these units was expensive, and careful review of operating data indicated that reductions in water cost would require the prevention of scale deposition, the improvement of heat-transfer coefficients in the evaporator, and increased compressor efficiency [43].

The MVC system (Figure III.7) raises the vapor temperature to a level higher than that of the saturation conditions in the top effect. The difference in temperature is essential for the evaporation process in this effect [44]. Capacities and possible pressure ratios of the available vapor compressors play major roles in the limitations imposed on MVC systems; hence, a small number of effects with small inter-effect temperature differences are applied to minimize the mechanical energy input required to drive the compressor. Usually, compression ratios of about 1.58 are recommended [45]. Compressor maintenance for smooth operation presents a big problem for the operator. Carryover can cause difficulties and affect the unit performance. This could be reduced by using demisters, but the pressure drop across the compressor would increase, giving a higher compression ratio. Moreover operating at low temperatures increases the handled volume considerably and the compressor power would increase accordingly. Thus, it is common practice to use MVC for a limited number of effects at temperatures close to atmospheric pressure [44].

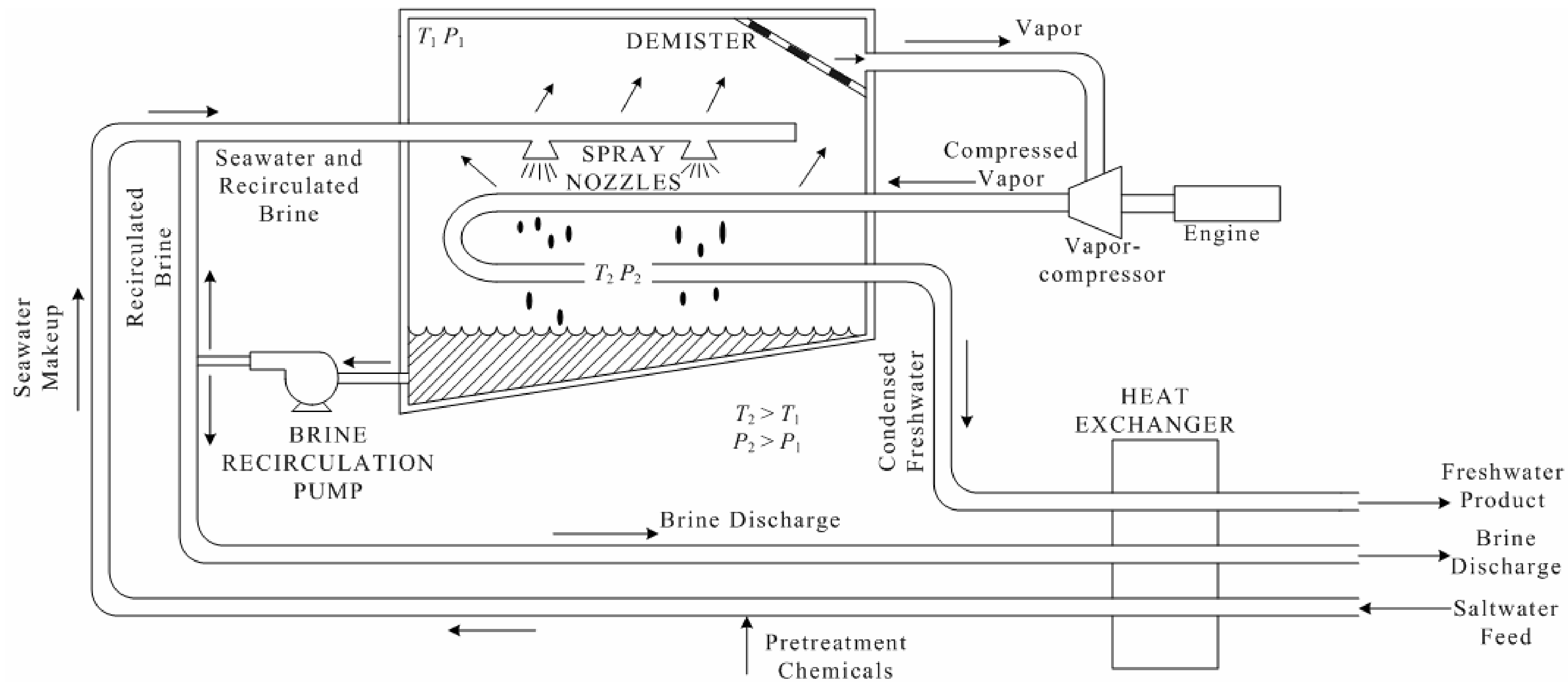

Figure III.7 Diagram of a mechanical vapor-compression plant [after 24].

III.4 Roots Blower VC

A Roots compressor/blower (Figure III.8) is a positive-displacement machine that uses two or more rotating lobes in a specially shaped cylinder [47]. The lobes, each of which looks like a figure 8, intermesh with each other using timing gears and suck gas in from inlet to the outlet.

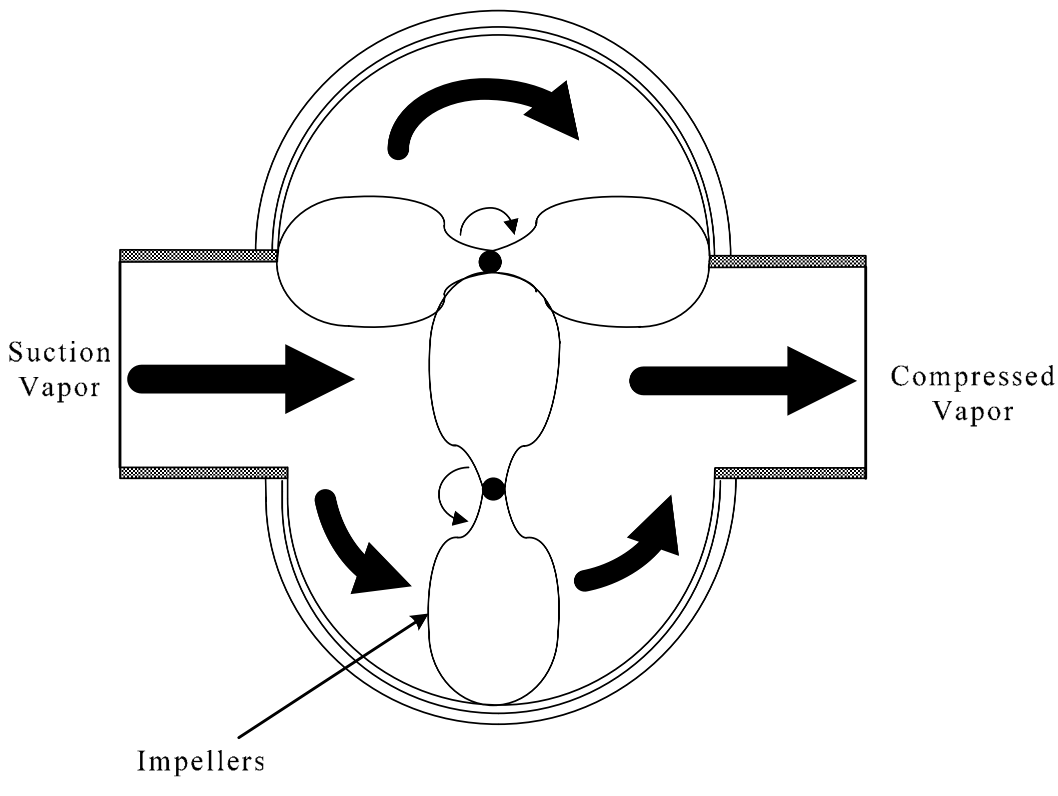

Figure III.8 Roots blower compressor [47].

The Roots blower does not actually compress the gas; it is simply a gas mover. Compression occurs because the gas is forced into a closed conduit; thereby causing the gas to become pressurized after it leaves the Roots blower [47].

The rotating impellers intermesh quite closely, but contact is avoided by using precision timing gears. Although these gears are splash lubricated, because they are external to the cylinder barrel, the machine provides oil-free gas.

The existing VC desalination unit was supplemented with the Roots blower (Figure III.9) to increase its capacity. The Roots blower compresses the vapor (propelled stream) before it passes to the jet ejectors. The Roots blower was operated with a variable-speed electric motor at 900 rpm, 1050 rpm, 1200 rpm, and 1500 rpm.

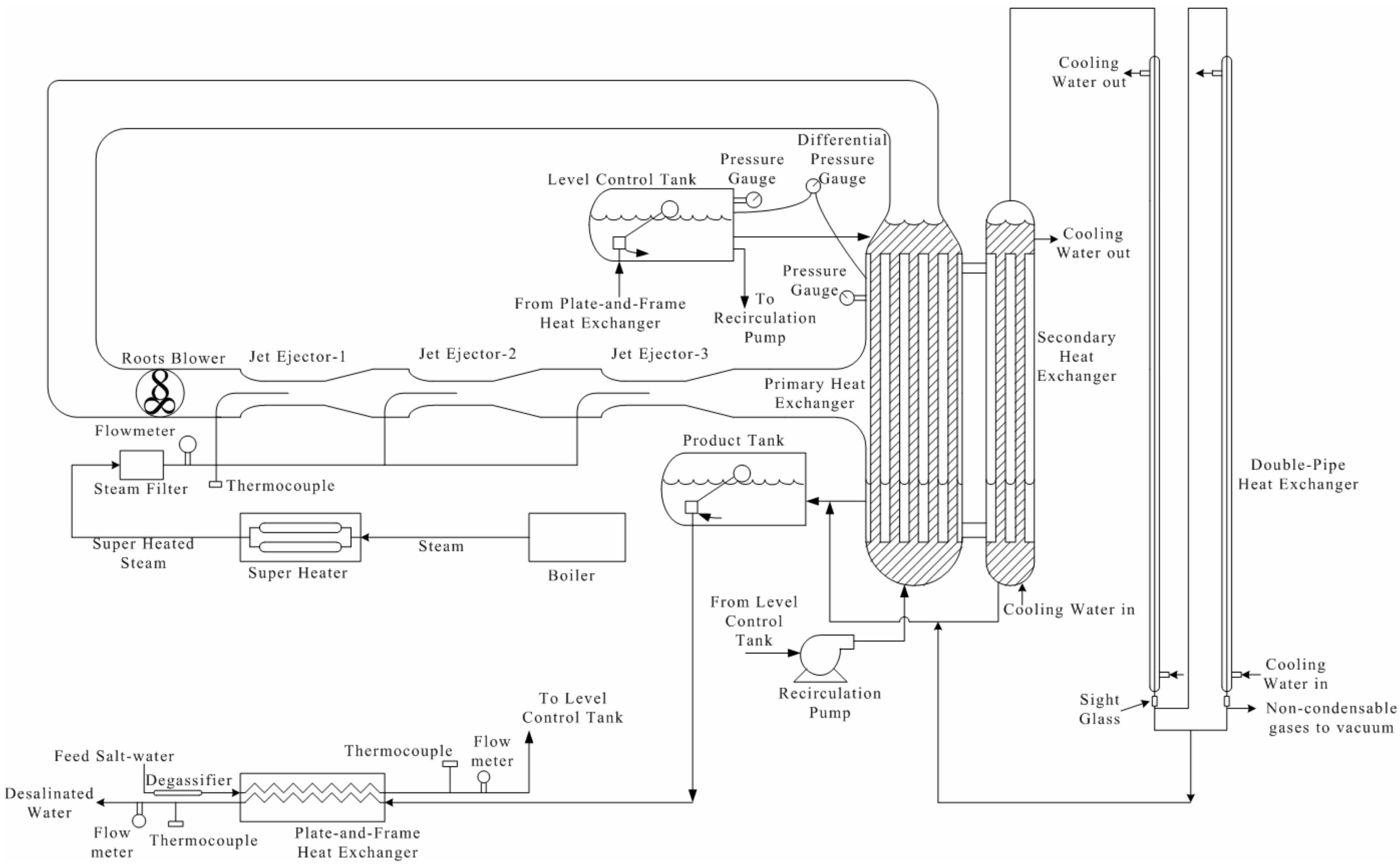

Figure III.9 Roots blower-type mechanical vapor compressor.

III.5 Comparison of various desalination processes

At present, seawater is desalted using various thermal processes or by reverse osmosis, whereas brackish water is converted into drinking water mainly by reverse osmosis and electrodialysis [48]. Table III.2, shows the classification of desalination processes, and Table III.3 shows the key process data of different desalination process.

Table III.2 Overview of commercial desalination process [48]

Process Group (Phase Change)	**Process**	**Form of Energy Required**
DISTILLATION (Liquid to Vapor)	MSF	Heat
	MED	Heat
	VC or MVC	Heat or Mechanical energy
MEMBRANE PROCESSES (no phase change)	Reverse osmosis	Mechanical energy
	Electrodialysis	Electrical energy

Table III.3 Key process data [48]

	MSF	MED	TVC	MVC	RO	ED
Operating temperature (°C)	<120	<70	<70	<70	<45	<45
Form of energy	Steam	Steam	Steam	Mechanical (electrical)	Mechanical (electrical)	Electrical
Electrical energy consumption (kWh/m^3)	3.5	1.5	1.5	8 – 14	4 – 7	1.0
Typical salt content of raw water (ppm TDS)	30,000 – 100,000	30,000 – 100,000	30,000 – 100,000	30,000 – 50,000	1000 – 45,000	100 – 3000
Product water quality (ppm TDS)	<10	<10	<10	<10	<500	<500
Current single train capacity (m^3/d)	5000 – 60,000	500 – 12,000	100 – 20,000	10 – 2500	1 – 10,000	1 – 12,000

III.6 Summary

MVC requires expensive items such as the compressor with all its limitations and drawbacks whereas TVC requires a steam boiler. However, for both systems, practical limitations are imposed on the capacity and number of effects. The capacity of vapor compression distillation is rarely above 600 m^3/day and in some designs it reaches 1500 m^3/day [14]. However, a VC system could play a bigger role in the desalination industry if larger plants were built and/or higher performance ratios were attained. VC units are usually built in the 0.005 to 0.5 mgd range. They are often used for resorts, industries, and drilling sites where fresh water is not readily available.

CHAPTER IV

RESULTS, DISCUSSION AND CONCLUSION

The process specification requires steam at rate of 300 lb/hr and 100 psig, but the boiler is undersized and produces steam at a rate of 180 lb/hr and 100 psig. Hence, the options were: (i) to purchase a new boiler, which can produce steam at rate of 300 lb/hr and 100 psig, or (ii) use existing compressed air tank, which can discharge compressible air at rate of 300 lb/hr and 100 psig. The first option was ruled out as it required more capital investment and also time to install and test if it works at process specification. Hence, the experiments were conducted at StarRotor Corporation to determine the efficiency of the jet ejector using compressed air.

Air is easy to regulate, readily available, and the motive stream (compressed air) and propelled stream (atmospheric air) can mix properly and be discharged safely. Also, the results obtained will be similar for the both fluids (steam, air). The efficiency was determined for various mass flow rates, different number of mixing vanes and for various back pressures. The newly constructed thermal vapor compression desalination unit was operated with tap water and later supplemented with the Roots Blower, but the data was not obtained at this point, as this is the first design and testing of a high-efficiency jet ejector operated desalination unit, which requires further optimization of jet ejectors.

IV.1 Experimental Procedure

Compressed air was passed through the nozzle shown in Figure IV.1. The temperature and pressure were measured at the inlet and outlet of the nozzle (Tables B.6, B.7). From these values, the velocity of the motive stream exiting the nozzle was calculated (Table IV.1) using the compressible flow velocity equation.

Pressurized air from a fixed-volume tank was supplied to the nozzle. The air exiting the nozzle passed through the jet ejector with five the mixing vanes and with no pinch valve closings (Figure IV.2). The inlet pressure, inlet temperature, pressure rise across the jet ejector, and outlet dynamic pressure were noted for each run (Tables B.8, B.9). The jet ejector was back pressurized by closing the pinch valve inch-by-inch for a given number of mixing vanes. The readings were noted at each pinch valve closing (Tables B.8, B.9). The above steps were repeated for different numbers of mixing vanes and for various Pinch valve closings (Tables B.10 to B.17). From these values, the velocity and mass flow rate through the jet ejector was calculated for different numbers of mixing vanes and for various pinch valve closings (Tables IV.2 to IV.6). The experimental setup and the MixAlco pilot plant pictures are shown in Figures A.1 to A.32.

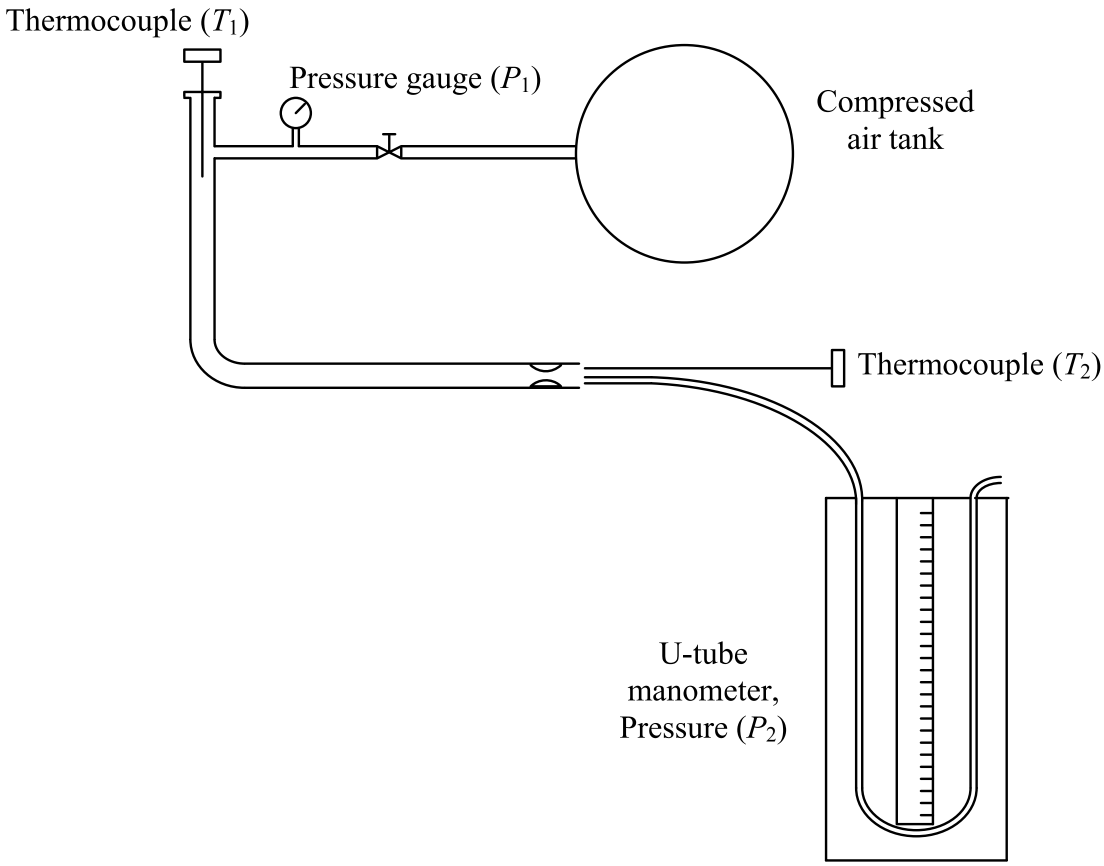

Figure IV.1 Experimental setup of high-efficiency jet ejector nozzle.

Table IV.1 Calculated values at the outlet of the nozzle (Figure IV.1) for the motive air mass flow rate.

Dens (kg/m^3)	V_1 (m/s)	$V_2 = V_m$ (m/s)	M_m (kg/s)	Efficiency (%)
1.25	722.13	562.86	0.020	94.02
1.25	690.12	527.86	0.019	94.07
1.25	652.34	490.03	0.018	94.56
1.25	606.08	448.95	0.016	94.58
1.25	546.12	411.19	0.015	94.91

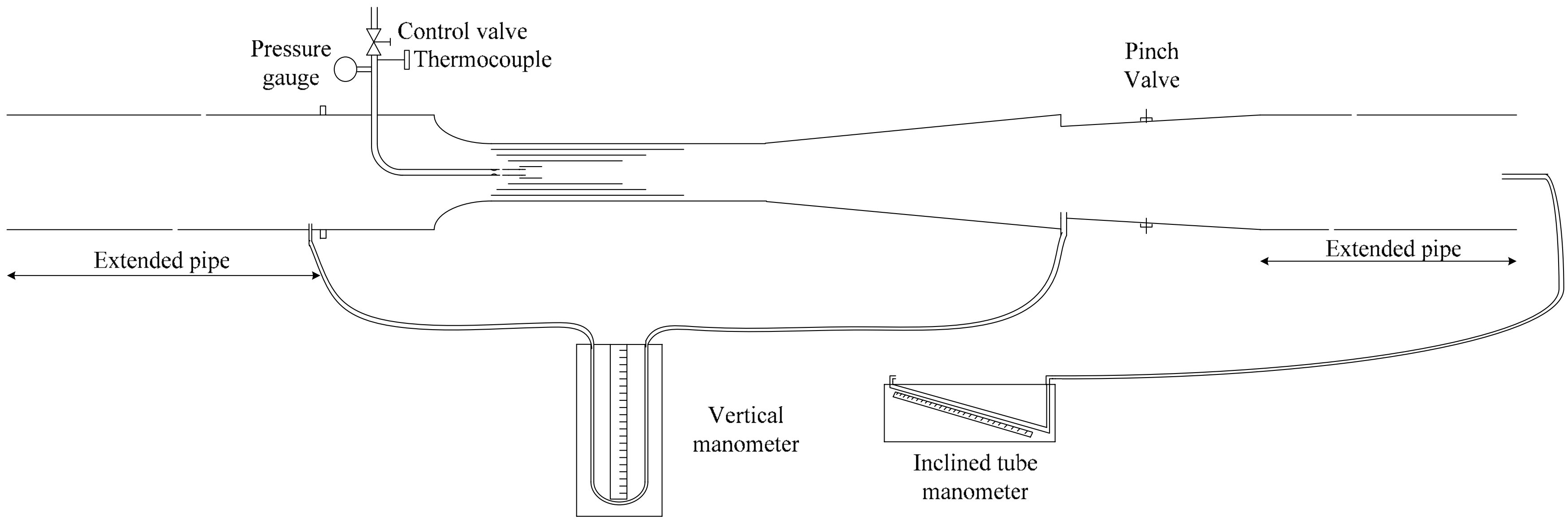

Figure IV.2 Experimental setup of jet ejector with five mixing vanes and no pinch valve closing.

Table IV.2 Calculated values for the data obtained with five mixing vanes (Figures IV.2, A.3 to A.5) for various pinch valve closings.

Jet ejector with five mixing vanes with no pinch valve closing							
M_m (kg/s)	**V_m (m/s)**	**M_p (kg/s)**	**M_t (kg/s)**	**V_t (m/s)**	**Efficiency (%)**	**M_p/M_m**	**ΔP (Pa)**
0.020	562.86	0.45	0.47	20.81	90.48	22.40	264.02
0.019	527.86	0.43	0.45	19.83	91.52	22.68	234.13
0.018	490.03	0.40	0.42	18.80	92.43	22.33	201.75
0.016	448.95	0.38	0.40	17.72	95.00	24.00	171.86
0.015	411.19	0.35	0.37	16.56	94.67	23.67	124.54
Jet ejector with five mixing vanes with Pinch Valve Closing 1							
M_m (kg/s)	**V_m (m/s)**	**M_p (kg/s)**	**M_t (kg/s)**	**V_t (m/s)**	**Efficiency (%)**	**M_p/M_m**	**ΔP (Pa)**
0.020	562.86	0.44	0.46	20.23	90.50	22.00	405.99
0.019	527.86	0.41	0.43	19.22	91.56	21.63	343.73
0.018	490.03	0.39	0.41	18.27	92.64	21.78	281.46
0.016	448.95	0.37	0.39	17.38	93.89	23.38	219.18
0.015	411.19	0.36	0.37	16.32	94.67	23.67	156.92
Jet ejector with five mixing vanes with Pinch Valve Closing 2							
M_m (kg/s)	**V_m (m/s)**	**M_p (kg/s)**	**M_t (kg/s)**	**V_t (m/s)**	**Efficiency (%)**	**M_p/M_m**	**ΔP (Pa)**
0.020	562.86	0.43	0.45	19.83	90.49	21.50	592.79
0.019	527.86	0.41	0.43	19.22	91.56	21.63	498.15
0.018	490.03	0.39	0.41	18.27	92.64	21.78	435.88
0.016	448.95	0.37	0.39	17.38	93.89	23.38	343.73
0.015	411.19	0.36	0.37	16.32	94.67	23.67	249.07
Jet ejector with five mixing vanes with Pinch Valve Closing 3							
M_m (kg/s)	**V_m (m/s)**	**M_p (kg/s)**	**M_t (kg/s)**	**V_t (m/s)**	**Efficiency (%)**	**M_p/M_m**	**ΔP (Pa)**
0.020	562.86	0.33	0.35	15.44	89.53	16.50	1556.72
0.019	527.86	0.32	0.34	14.92	90.83	16.89	1307.65
0.018	490.03	0.31	0.33	14.65	92.13	17.33	1120.84
0.016	448.95	0.30	0.32	14.24	93.66	19.00	871.76
0.015	411.19	0.30	0.31	13.96	94.60	19.67	622.69

Table IV.3 Calculated values for the data obtained with three mixing vanes (Figures A.6 to A.9) for various pinch valve closings.

Jet ejector with three mixing vanes with no pinch valve closing							
M_m (kg/s)	**V_m (m/s)**	**M_p (kg/s)**	**M_t (kg/s)**	**V_t (m/s)**	**Efficiency (%)**	**M_p/M_m**	**ΔP (Pa)**
0.020	562.86	0.48	0.50	22.10	90.46	24.00	311.35
0.019	527.86	0.45	0.47	21.09	91.54	23.74	281.45
0.018	490.03	0.43	0.45	20.03	92.59	24.00	234.13
0.016	448.95	0.40	0.42	18.59	93.81	25.25	201.75
0.015	411.19	0.38	0.39	17.15	94.60	25.00	139.48
Jet ejector with three mixing vanes with Pinch Valve Closing 1							
M_m (kg/s)	**V_m (m/s)**	**M_p (kg/s)**	**M_t (kg/s)**	**V_t (m/s)**	**Efficiency (%)**	**M_p/M_m**	**ΔP (Pa)**
0.020	562.86	0.47	0.49	21.65	90.49	23.50	420.94
0.019	527.86	0.44	0.46	20.52	91.56	23.21	358.67
0.018	490.03	0.42	0.44	19.63	92.62	23.44	326.29
0.016	448.95	0.40	0.42	18.48	93.81	25.25	234.02
0.015	411.19	0.38	0.39	17.15	94.60	25.00	171.86
Jet ejector with three mixing vanes with Pinch Valve Closing 2							
M_m (kg/s)	**V_m (m/s)**	**M_p (kg/s)**	**M_t (kg/s)**	**V_t (m/s)**	**Efficiency (%)**	**M_p/M_m**	**ΔP (Pa)**
0.020	562.86	0.45	0.47	21.00	90.52	22.50	717.34
0.019	527.86	0.42	0.44	19.73	91.58	22.16	607.75
0.018	490.03	0.41	0.43	19.01	92.63	22.89	530.53
0.016	448.95	0.39	0.41	18.05	93.84	24.63	388.56
0.015	411.19	0.37	0.38	16.68	94.64	24.33	296.39
Jet ejector with three mixing vanes with Pinch Valve Closing 3							
M_m (kg/s)	**V_m (m/s)**	**M_p (kg/s)**	**M_t (kg/s)**	**V_t (m/s)**	**Efficiency (%)**	**M_p/M_m**	**ΔP (Pa)**
0.020	562.86	0.35	0.37	16.32	89.85	17.50	1868.06
0.019	527.86	0.33	0.35	15.70	90.98	17.42	1589.11
0.018	490.03	0.33	0.35	15.44	92.35	18.44	1384.86
0.016	448.95	0.32	0.34	14.92	93.78	20.25	1043.63
0.015	411.19	0.32	0.33	14.51	94.67	21.00	717.34

Table IV.4 Calculated values for the data obtained with two mixing vanes (Figures A.10 to A.13) for various pinch valve closings.

Jet ejector with two mixing vanes with no pinch valve closing							
M_m (kg/s)	**V_m (m/s)**	**M_p (kg/s)**	**M_t (kg/s)**	**V_t (m/s)**	**Efficiency (%)**	**M_p/M_m**	**ΔP (Pa)**
0.020	562.86	0.52	0.54	23.71	90.60	26.00	343.72
0.019	527.86	0.49	0.51	22.33	91.66	25.84	311.34
0.018	490.03	0.46	0.48	21.41	92.73	25.67	264.02
0.016	448.95	0.43	0.45	19.67	93.90	27.13	219.18
0.015	411.19	0.40	0.41	17.75	93.78	26.33	156.92
Jet ejector with two mixing vanes with Pinch Valve Closing 1							
M_m (kg/s)	**V_m (m/s)**	**M_p (kg/s)**	**M_t (kg/s)**	**V_t (m/s)**	**Efficiency (%)**	**M_p/M_m**	**ΔP (Pa)**
0.020	562.86	0.50	0.52	23.01	90.70	25.00	513.09
0.019	527.86	0.47	0.49	21.69	91.75	24.79	450.83
0.018	490.03	0.45	0.47	20.76	92.77	25.11	405.99
0.016	448.95	0.42	0.44	19.16	93.57	26.50	296.39
0.015	411.19	0.38	0.39	17.42	94.81	25.00	201.75
Jet ejector with two mixing vanes with Pinch Valve Closing 2							
M_m (kg/s)	**V_m (m/s)**	**M_p (kg/s)**	**M_t (kg/s)**	**V_t (m/s)**	**Efficiency (%)**	**M_p/M_m**	**ΔP (Pa)**
0.020	562.86	0.49	0.51	22.49	90.73	24.50	871.76
0.019	527.86	0.46	0.48	21.13	91.78	24.26	747.23
0.018	490.03	0.44	0.46	20.17	92.80	24.56	637.63
0.016	448.95	0.41	0.43	18.74	93.47	25.88	513.09
0.015	411.19	0.38	0.39	17.18	94.80	25.00	358.67
Jet ejector with two mixing vanes with Pinch Valve Closing 3							
M_m (kg/s)	**V_m (m/s)**	**M_p (kg/s)**	**M_t (kg/s)**	**V_t (m/s)**	**Efficiency (%)**	**M_p/M_m**	**ΔP (Pa)**
0.020	562.86	0.36	0.38	16.95	90.18	18.00	2490.75
0.019	527.86	0.35	0.37	16.47	91.39	18.47	1868.07
0.018	490.03	0.34	0.36	15.98	92.60	19.00	1618.99
0.016	448.95	0.33	0.35	15.48	93.97	20.88	1183.11
0.015	411.19	0.33	0.34	14.95	94.84	21.67	841.87

Table IV.5 Calculated values for the data obtained with one mixing vane (Figures A.14 to A.17) for various pinch valve closings.

Jet ejector with one mixing vane with no pinch valve closing							
M_m (kg/s)	V_m (m/s)	M_p (kg/s)	M_t (kg/s)	V_t (m/s)	Efficiency (%)	M_p/M_m	ΔP (Pa)
0.020	562.86	0.56	0.58	25.56	91.14	28.00	530.53
0.019	527.86	0.52	0.54	23.87	92.20	27.42	435.88
0.018	490.03	0.49	0.51	22.41	93.19	27.33	388.56
0.016	448.95	0.45	0.47	20.75	94.34	28.38	296.39
0.015	411.19	0.41	0.42	18.63	95.05	27.00	201.75
Jet ejector with one mixing vane with Pinch Valve Closing 1							
M_m (kg/s)	V_m (m/s)	M_p (kg/s)	M_t (kg/s)	V_t (m/s)	Efficiency (%)	M_p/M_m	ΔP (Pa)
0.020	562.86	0.55	0.57	24.93	91.19	27.50	670.13
0.019	527.86	0.51	0.53	23.45	92.24	26.89	560.42
0.018	490.03	0.49	0.51	22.24	93.19	27.33	498.15
0.016	448.95	0.44	0.46	20.17	94.38	27.75	358.67
0.015	411.19	0.41	0.42	18.31	95.05	27.00	364.02
Jet ejector with one mixing vane with Pinch Valve Closing 2							
M_m (kg/s)	V_m (m/s)	M_p (kg/s)	M_t (kg/s)	V_t (m/s)	Efficiency (%)	M_p/M_m	ΔP (Pa)
0.020	562.86	0.56	0.58	25.65	91.14	28.00	1011.25
0.019	527.86	0.49	0.51	22.51	92.30	25.84	809.49
0.018	490.03	0.46	0.48	21.23	93.29	25.67	747.23
0.016	448.95	0.42	0.44	19.57	94.44	26.50	575.36
0.015	411.19	0.40	0.41	17.75	95.07	26.33	388.56
Jet ejector with one mixing vane with Pinch Valve Closing 3							
M_m (kg/s)	V_m (m/s)	M_p (kg/s)	M_t (kg/s)	V_t (m/s)	Efficiency (%)	M_p/M_m	ΔP (Pa)
0.020	562.86	0.34	0.36	15.86	90.10	17.00	2615.29
0.019	527.86	0.33	0.35	15.48	91.36	17.42	2241.68
0.018	490.03	0.32	0.34	15.11	92.62	17.89	1838.17
0.016	448.95	0.31	0.33	14.82	94.10	19.63	1369.92
0.015	411.19	0.31	0.32	14.55	95.02	20.33	934.33

Table IV.6 Calculated values for the data obtained with no mixing vanes (Figures A.18 to A.21) for various pinch valve closings.

Jet ejector with no mixing vanes with no pinch valve closing							
M_m (kg/s)	V_m (m/s)	M_p (kg/s)	M_t (kg/s)	V_t (m/s)	Efficiency (%)	M_p/M_m	ΔP (Pa)
0.020	562.86	0.65	0.67	29.59	93.67	32.50	684.96
0.019	527.86	0.61	0.63	27.65	94.53	32.16	637.63
0.018	490.03	0.55	0.57	25.24	95.29	30.67	468.26
0.016	448.95	0.50	0.52	22.93	96.21	31.50	358.67
0.015	411.19	0.45	0.46	20.46	96.88	29.67	234.13
Jet ejector with no mixing vanes with Pinch Valve Closing 1							
M_m (kg/s)	V_m (m/s)	M_p (kg/s)	M_t (kg/s)	V_t (m/s)	Efficiency (%)	M_p/M_m	ΔP (Pa)
0.020	562.86	0.61	0.63	27.79	93.77	30.50	856.82
0.019	527.86	0.57	0.59	25.86	94.60	30.05	732.28
0.018	490.03	0.53	0.55	23.95	95.30	29.56	607.75
0.016	448.95	0.47	0.49	21.77	96.21	29.63	468.26
0.015	411.19	0.43	0.44	19.26	96.85	28.33	326.28
Jet ejector with no mixing vanes with Pinch Valve Closing 2							
M_m (kg/s)	V_m (m/s)	M_p (kg/s)	M_t (kg/s)	V_t (m/s)	Efficiency (%)	M_p/M_m	ΔP (Pa)
0.020	562.86	0.57	0.59	26.17	93.78	28.50	1153.22
0.019	527.86	0.54	0.56	24.44	94.58	28.47	1028.68
0.018	490.03	0.50	0.52	22.76	95.27	27.89	841.87
0.016	448.95	0.45	0.47	20.65	96.17	28.38	622.69
0.015	411.19	0.42	0.43	18.74	96.83	27.67	435.88
Jet ejector with no mixing vanes with Pinch Valve Closing 3							
M_m (kg/s)	V_m (m/s)	M_p (kg/s)	M_t (kg/s)	V_t (m/s)	Efficiency (%)	M_p/M_m	ΔP (Pa)
0.020	562.86	0.37	0.39	17.18	91.92	18.50	2179.41
0.019	527.86	0.36	0.38	16.71	93.09	19.00	1853.12
0.018	490.03	0.34	0.36	16.11	94.00	19.00	1556.72
0.016	448.95	0.33	0.35	15.48	95.39	20.88	1120.84
0.015	411.19	0.33	0.34	14.95	96.32	21.67	794.55

Air density is given by

$$d = \frac{M_W (P_b + P_a)}{RT}$$

where, d = Density of air (kg/m^3)

P_a = Barometric pressure (Pa)

P_b = Gauge pressure (Pa)

T = Absolute temperature (K)

R = Gas constant (Pa·m^3/mol·K)

M_w = Air molecular weight = 0.029 kg/mol

The compressible air velocity is given by [46]

$$V = \sqrt{\left(\frac{2\gamma}{\gamma - 1}\right)\left(\frac{P_s}{d}\right)\left[\left(\frac{P_{stag}}{P_s}\right)^{\left(\frac{\gamma-1}{\gamma}\right)} - 1\right]}$$

where, V = Compressed air velocity (m/s)

$\gamma = C_p/C_v$ = 1.4 for air

P_s = Static pressure (Pa)

d = Density of air (kg/m^3)

P_{stag} = Stagnation pressure (Pa)

The mass flow rate is given by

$$m = AVd$$

where, m = Mass flow rate (kg/s)

d = Density of air (kg/m^3)

V = Velocity (m/s)

A = Area of the outlet ($= \pi r^2$)

r = Radius of the exiting pipe (m)

The nozzle efficiency [44] is calculated as follows

$$\eta = \frac{\frac{1}{2} m_m \left(V_m^2 - V_1^2\right)}{m_m \left(\frac{2\gamma}{\gamma - 1}\right)\left(\frac{RT}{MW}\right)\left[\left(\frac{P_2}{P_1}\right)^{\left(\frac{\gamma-1}{\gamma}\right)} - 1\right]}$$

where, V_1 = Velocity at inlet of nozzle (m/s)

V_m = Velocity at outlet of nozzle (m/s)

P_1 = Pressure at inlet of nozzle (Pa)

P_2 = Pressure at outlet of nozzle (Pa)

The efficiency of the jet ejector (Somsak Watanawanavet, graduate student, Texas A&M University) is given by

$$\eta = \frac{\text{Energy at ejector outlet}}{\text{Energy at ejector inlet}}$$

$$\eta = \frac{\text{Kinetic energy} + \text{Flow energy} + \text{Pressure energy}}{\text{Kinetic energy} + \text{Flow energy}}$$

$$\eta = \frac{\frac{1}{2} m_t V_t^2 + m_m P_m v_m + m_p P_p v_p + m_m \left(\frac{\gamma}{\gamma - 1}\right)\left(\frac{RT}{MW}\right)\left[\left(\frac{P_t}{P_m}\right)^{\left(\frac{\gamma-1}{\gamma}\right)} - 1\right] + m_p \left(\frac{\gamma}{\gamma - 1}\right)\left(\frac{RT}{MW}\right)\left[\left(\frac{P_t}{P_p}\right)^{\left(\frac{\gamma-1}{\gamma}\right)} - 1\right]}{\frac{1}{2} m_m V_m^2 + \frac{1}{2} m_p V_p^2 + m_m P_m v_m + m_p P_p v_p}$$

where, η = Efficiency of the jet ejector

m_t = Total mass flow rate at the outlet of the jet ejector (kg/s)

m_p = Propelled mass flow rate (kg/s)

m_m = Motive mass flow rate (kg/s)

V_t = Total velocity at the outlet of the jet ejector (m/s)

V_m = Motive velocity (m/s)

V_p = Propelled velocity (m/s)

v_m = Volume of motive stream at nozzle exit (m^3/kg)

v_p = Volume of propelled stream at inlet (m^3/kg)

P_t = Static pressure at the outlet of the jet ejector (Pa)

P_m = Static pressure at the nozzle outlet (Pa)

P_p = Static pressure at the inlet of the jet ejector (Pa)

IV.2 Results and Discussion

From Table IV.6, the data obtained for the jet ejector with no back pressure and no internal vanes is

P_b = 2.2 inches of water (gauge) = 547.96 Pa (gauge)

T = 302.09 K

P_a = Ambient pressure = 32 inches of mercury = 108,365.73 Pa (absolute)

The air density at the above data is,

$$d = \frac{M_W (P_b + P_a)}{R\,T}$$

$$d = \frac{\left(\dfrac{0.029\ \text{kg}}{\text{mol}}\right)(547.96\ \text{Pa} + 108365.728\ \text{Pa})}{\left(\dfrac{8.315\ \text{Pa}\cdot\text{m}^3}{\text{mol}\cdot\text{K}}\right)(302.09\ \text{K})}$$

$$d = 1.25\ \text{kg/m}^3$$

From Table 1b, the motive velocity and motive mass flow rate for the compressible air were calculated as follow:

$$V = \sqrt{\left(\frac{2\,\gamma}{\gamma - 1}\right)\left(\frac{P_s}{d}\right)\left[\left(\frac{P_{stag}}{P_s}\right)^{\left(\frac{\gamma-1}{\gamma}\right)} - 1\right]}$$

$$V = \sqrt{\left(\frac{(2)\ (1.4)}{(1.4-1)}\right)\left(\frac{101325\ \text{Pa}}{1.25\ \dfrac{\text{kg}}{\text{m}^3}}\right)\left[\left(\frac{101325\ \text{Pa} + 379212\ \text{Pa}}{101325\ \text{Pa}}\right)^{\left(\frac{1.4-1}{1.4}\right)} - 1\right]}$$

$$V = 562.861\ \text{m/s}$$

The mass flow rate is,

$$m = A\,V\,d$$

$$m = \pi\, r^2\ V\ d$$

$$m = \pi\ \left[0.003\ \text{m}\right]^2 \left(562.861\ \frac{\text{m}}{\text{s}}\right)\left(\frac{1.25\ \text{kg}}{\text{m}^3}\right)$$

$$m = 0.020\ \text{kg/s}$$

The nozzle efficiency is,

$$\eta = \frac{\frac{1}{2} m_m \left(V_m^2 - V_1^2\right)}{m_m \left(\frac{2\gamma}{\gamma - 1}\right)\left(\frac{RT}{MW}\right)\left[\left(\frac{P_2}{P_1}\right)^{\left(\frac{\gamma-1}{\gamma}\right)} - 1\right]}$$

$$\eta = \frac{\frac{1}{2}\left(0.02\,\frac{\text{kg}}{\text{s}}\right)\left[\left(562.86\,\frac{\text{m}}{\text{s}}\right)^2 - \left(722.13\,\frac{\text{m}}{\text{s}}\right)^2\right]}{\left(0.02\,\frac{\text{kg}}{\text{s}}\right)\left(\frac{(2)(1.4)}{1.4-1}\right)\left(\frac{\left(8.325\,\frac{\text{Pa}\cdot\text{m}^3}{\text{mol}\cdot\text{K}}\right)(305.9\text{ K})}{\left(0.029\,\frac{\text{kg}}{\text{mol}}\right)}\right)\left[\left(\frac{379211.6\text{ Pa}}{896318.4\text{ Pa}}\right)^{\left(\frac{1.4-1}{1.4}\right)} - 1\right]}$$

$$\eta = 94.02\%$$

The jet ejector efficiency is,

$$\eta = \frac{\text{Energy at ejector outlet}}{\text{Energy at ejector inlet}}$$

$$\eta = \frac{\frac{1}{2} m_t V_t^2 + m_m P_m v_m + m_p P_p v_p + m_m\left(\frac{\gamma}{\gamma-1}\right)\left(\frac{RT}{MW}\right)\left[\left(\frac{P_t}{P_m}\right)^{\left(\frac{\gamma-1}{\gamma}\right)} - 1\right] + m_p\left(\frac{\gamma}{\gamma-1}\right)\left(\frac{RT}{MW}\right)\left[\left(\frac{P_t}{P_p}\right)^{\left(\frac{\gamma-1}{\gamma}\right)} - 1\right]}{\frac{1}{2} m_m V_m^2 + \frac{1}{2} m_p V_p^2 + m_m P_m v_m + m_p P_p v_p}$$

Solving the above equation part by part

$$\frac{1}{2} m_t V_t^2 + m_m P_m v_m + m_p P_p v_p$$

$$= \frac{1}{2}\left(0.47\,\frac{\text{kg}}{\text{s}}\right)\left(20.81\,\frac{\text{m}}{\text{s}}\right)^2 + \left(0.02\,\frac{\text{kg}}{\text{s}}\right)(102481.56\text{ Pa})\left(0.8\,\frac{\text{m}^3}{\text{kg}}\right)$$

$$+ \left(0.45\,\frac{\text{kg}}{\text{s}}\right)(103694.32\text{ Pa})\left(0.8\,\frac{\text{m}^3}{\text{kg}}\right)$$

$$= 38974.55\,\frac{\text{J}}{\text{s}}$$

$$\frac{1}{2}m_m V_m^2 + \frac{1}{2}m_p V_p^2 + m_m P_m v_m + m_p P_p v_p$$

$$= \frac{1}{2}\left(0.02\frac{\text{kg}}{\text{s}}\right)\left(562.86\frac{\text{m}}{\text{s}}\right)^2 + \frac{1}{2}\left(0.45\frac{\text{kg}}{\text{s}}\right)\left(3.39\frac{\text{m}}{\text{s}}\right)^2$$
$$+\left(0.02\frac{\text{kg}}{\text{s}}\right)(102481.56\ \text{Pa})\left(0.8\ \frac{\text{m}^3}{\text{kg}}\right)+\left(0.45\frac{\text{kg}}{\text{s}}\right)(103694.32\ \text{Pa})\left(0.8\ \frac{\text{m}^3}{\text{kg}}\right)$$

$$= 42140.36\frac{\text{J}}{\text{s}}$$

$$m_m\left(\frac{\gamma}{\gamma-1}\right)\left(\frac{RT}{MW}\right)\left[\left(\frac{P_t}{P_m}\right)^{\left(\frac{\gamma-1}{\gamma}\right)}-1\right]$$

$$=\left(0.02\frac{\text{kg}}{\text{s}}\right)\left(\frac{1.4}{1.4\text{-}1}\right)\left(\frac{\left(8.325\frac{\text{Pa}\cdot\text{m}^3}{\text{mol}\cdot\text{K}}\right)(307\ \text{K})}{0.029\ \frac{\text{kg}}{\text{mol}}}\right)\left[\left(\frac{101328.6\ \text{Pa}}{102481.56\ \text{Pa}}\right)^{\left(\frac{1.4-1}{1.4}\right)}-1\right]$$

$$= -19.91\frac{\text{J}}{\text{s}}$$

$$m_p\left(\frac{\gamma}{\gamma-1}\right)\left(\frac{RT}{MW}\right)\left[\left(\frac{P_t}{P_p}\right)^{\left(\frac{\gamma-1}{\gamma}\right)}-1\right]$$

$$=\left(0.45\frac{\text{kg}}{\text{s}}\right)\left(\frac{1.4}{1.4\text{-}1}\right)\left(\frac{\left(8.325\frac{\text{Pa}\cdot\text{m}^3}{\text{mol}\cdot\text{K}}\right)(307\ \text{K})}{0.029\ \frac{\text{kg}}{\text{mol}}}\right)\left[\left(\frac{101328.6\ \text{Pa}}{103694.32\ \text{Pa}}\right)^{\left(\frac{1.4-1}{1.4}\right)}-1\right]$$

$$= -912.26\frac{\text{J}}{\text{s}}$$

$$\eta = \frac{\left(38974.55\frac{\text{J}}{\text{s}}\right) + \left(-19.91\frac{\text{J}}{\text{s}}\right) + \left(-912.26\frac{\text{J}}{\text{s}}\right)}{\left(42140.36\frac{\text{J}}{\text{s}}\right)}$$

$$\eta = 90.47\%$$

The plots of ratio of propelled to motive mass (m_p/m_m), pressure rise (ΔP), and efficiency (η) for various mass flow rates and numbers of mixing vanes for various back pressures are shown in Figures IV.3 to IV.14. From the plots of pressure rise versus number of mixing vanes, it is observed that as the back pressure increases, the pressure rise across the jet ejector also increases in the case of one and two mixing vanes compared to zero mixing vanes. The plots of efficiency for various motive mass flow rates versus number of mixing vanes for various back pressures show that the efficiency increases with decreasing motive mass and decreasing back pressure. At other pinch valve closings, the air velocity through the jet ejector was high, so the extra surface area from the mixing vanes caused excessive friction and lowered the efficiencies. The slope of the efficiency and ratio of propelled to motive mass curve decreases with increase in the back pressure for any given motive mass flow rate.

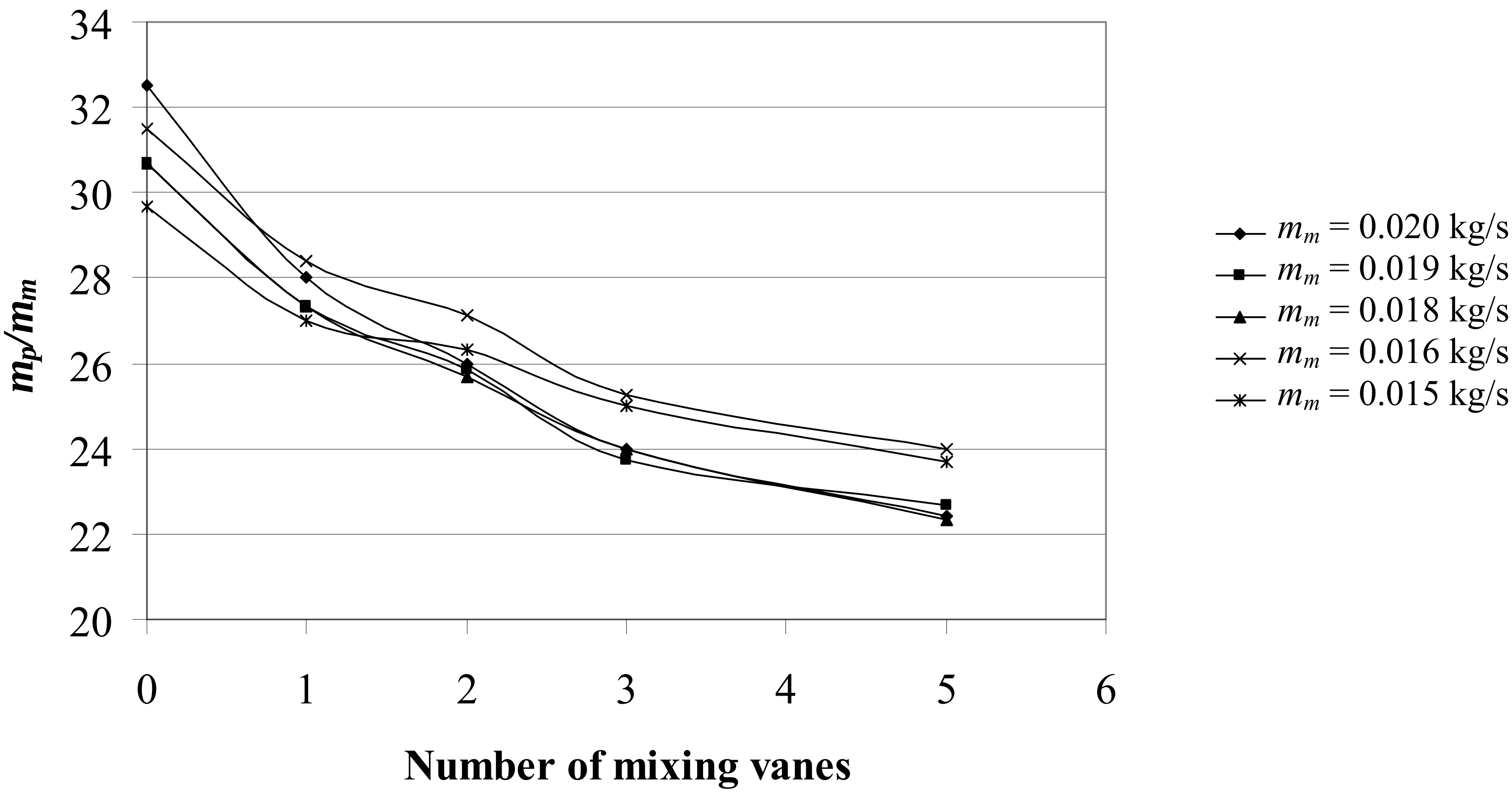

Figure IV.3 Plot of propelled to motive mass ratio vs. number of mixing vanes for various mass flow rates and no pinch valve closing (Figures A.2, A.6, A.10, A.14, A.18).

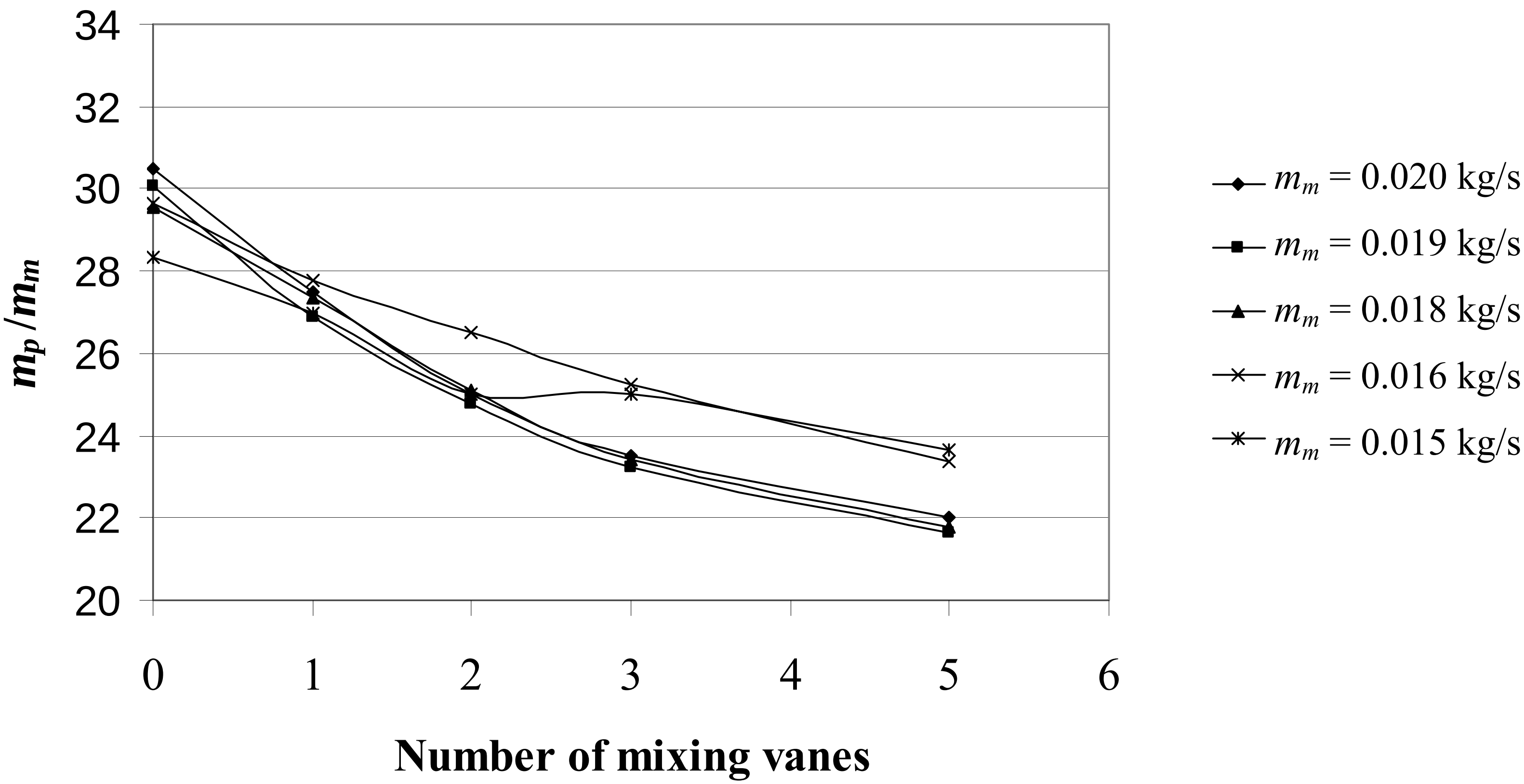

Figure IV.4 Plot of propelled to motive mass ratio vs. number of mixing vanes for various mass flow rates and Pinch Valve Closing 1 (Figures A.3, A.7, A.11, A.15, A.19).

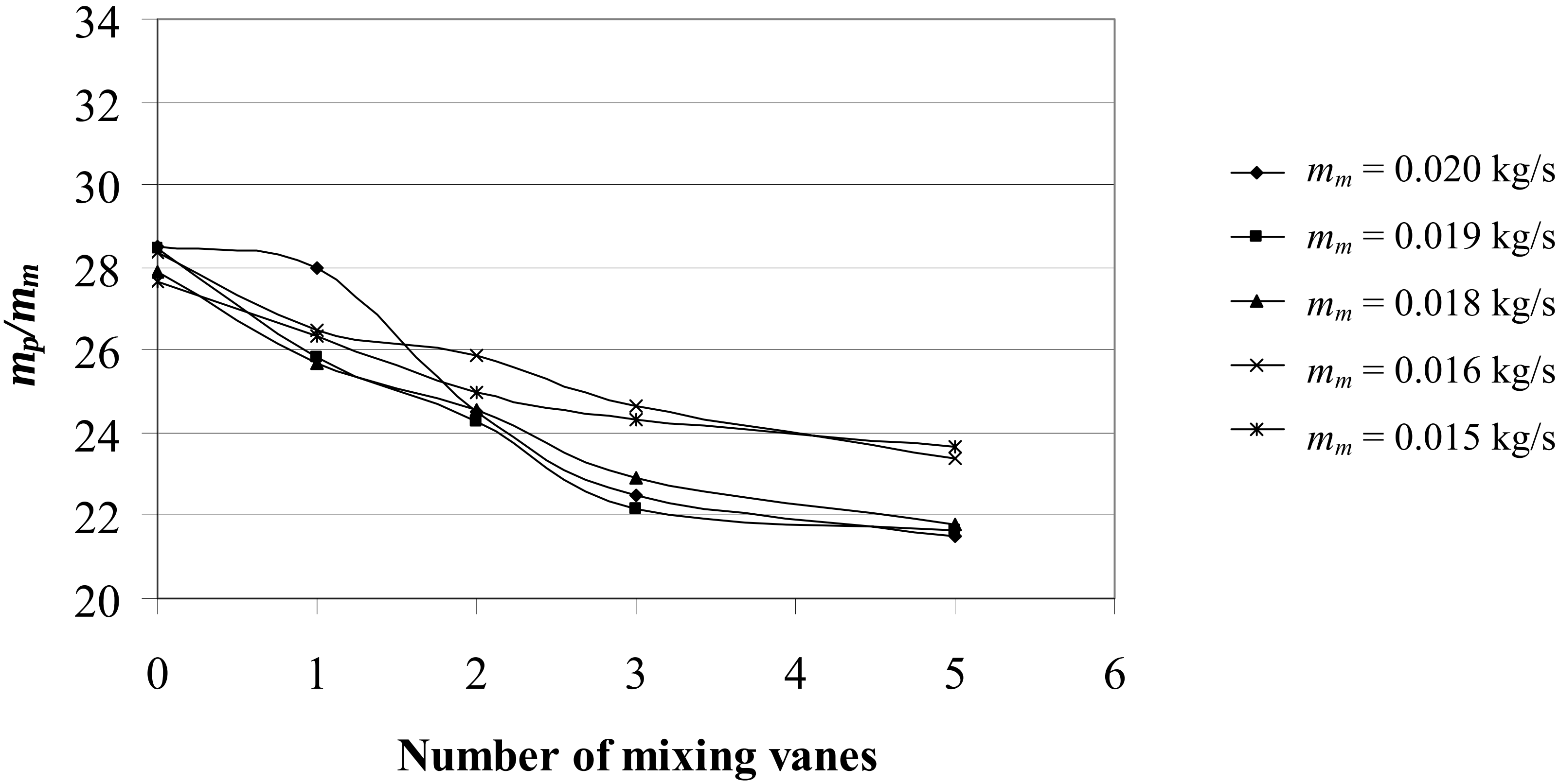

Figure IV.5 Plot of propelled to motive mass ratio vs. number of mixing vanes for various mass flow rates and Pinch Valve Closing 2 (Figures A.4, A.8, A.12, A.16, A.20).

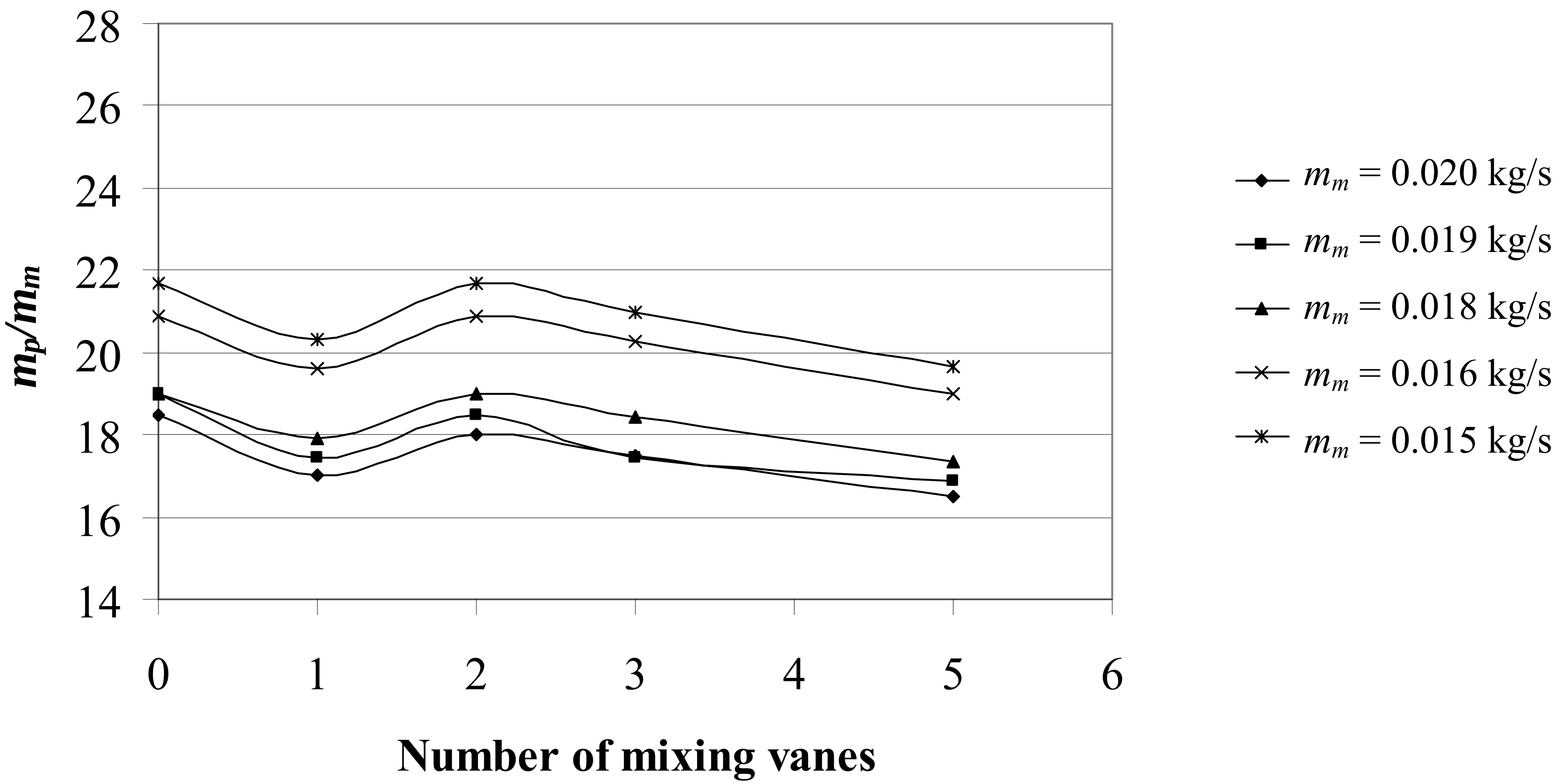

Figure IV.6 Plot of propelled to motive mass ratio vs. number of mixing vanes for various mass flow rates and Pinch Valve Closing 3 (Figures A.5, A.9, A.13, A.17, A.21).

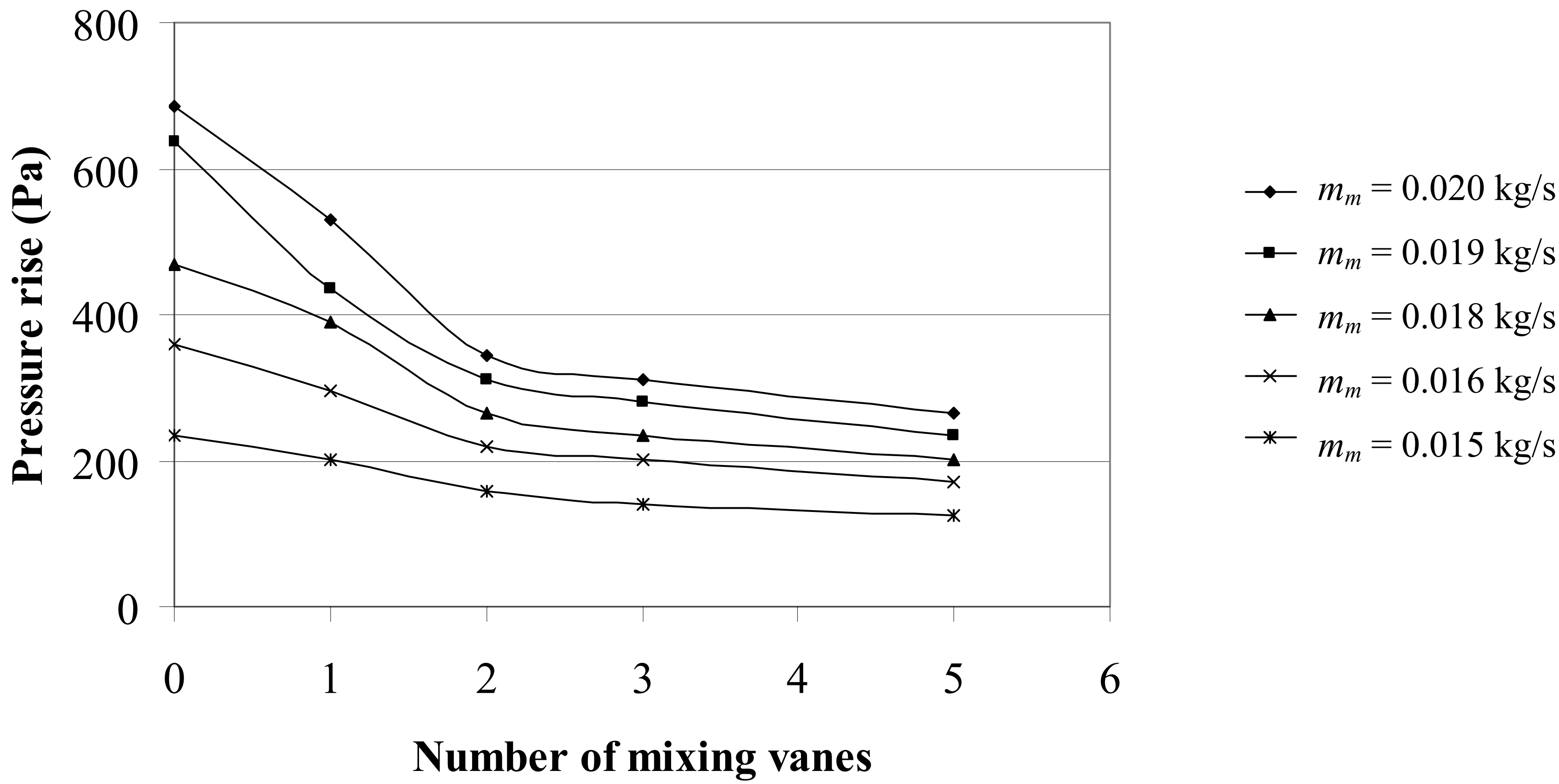

Figure IV.7 Plot of pressure rise across the jet ejector vs. number of mixing vanes for various mass flow rates and no pinch valve closing (Figures A.2, A.6, A.10, A.14, A.18).

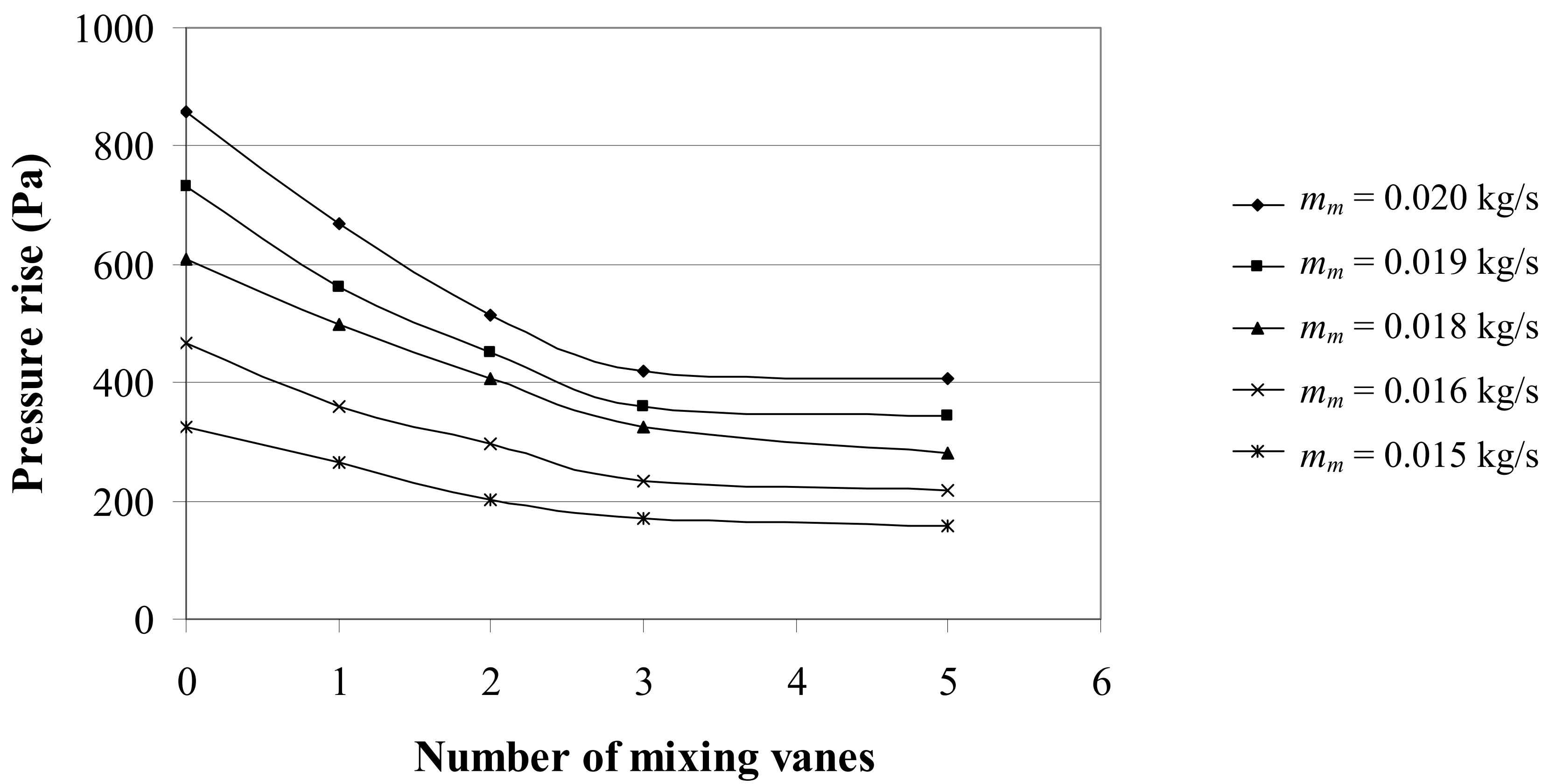

Figure IV.8 Plot of pressure rise across the jet ejector vs. number of mixing vanes for various mass flow rates and Pinch Valve Closing 1 (Figures A.3, A.7, A.11, A.15, A.19).

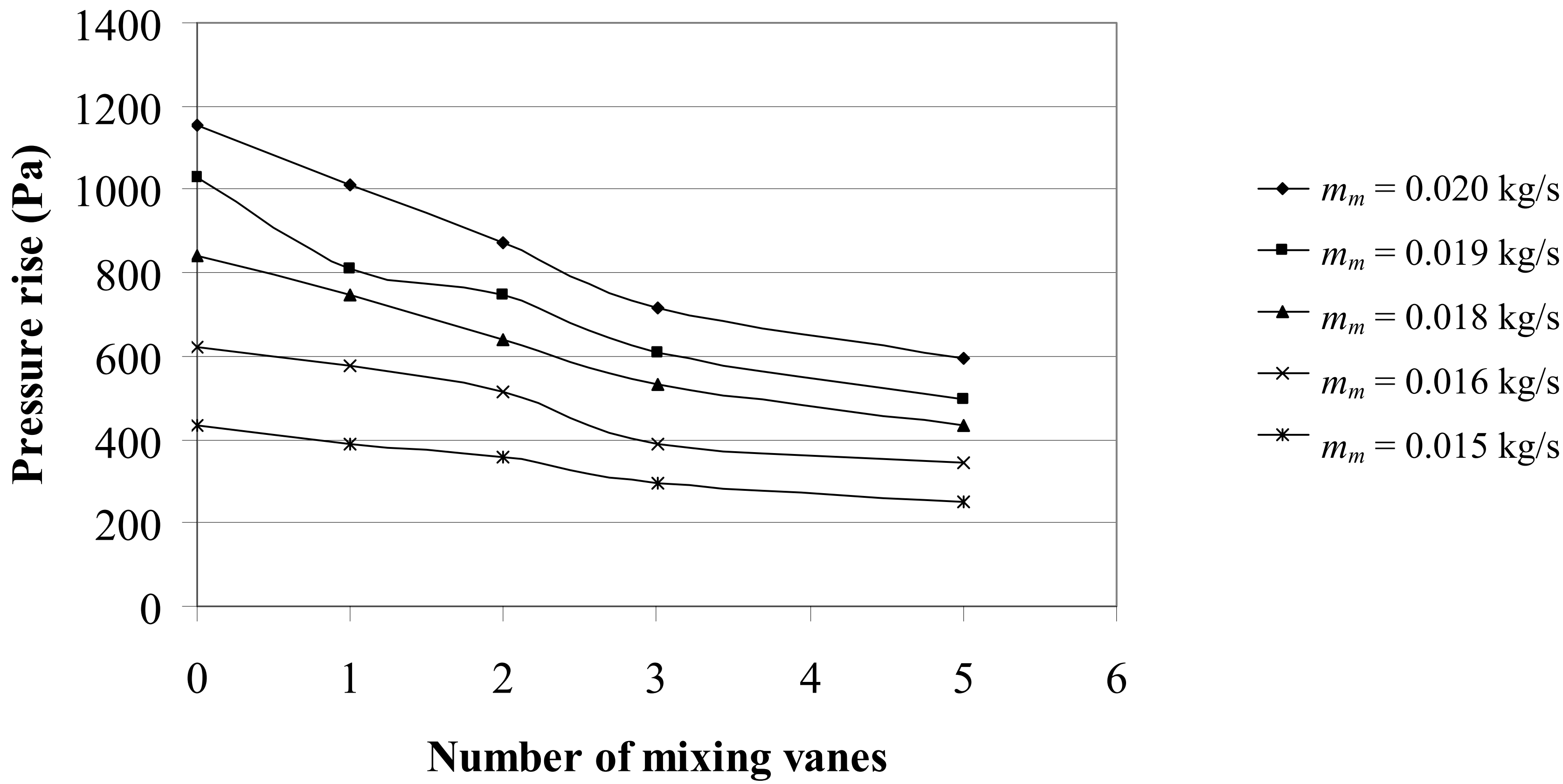

Figure IV.9 Plot of pressure rise across the jet ejector vs. number of mixing vanes for various mass flow rates and Pinch Valve Closing 2 (Figures A.4, A.8, A.12, A.16, A.20).

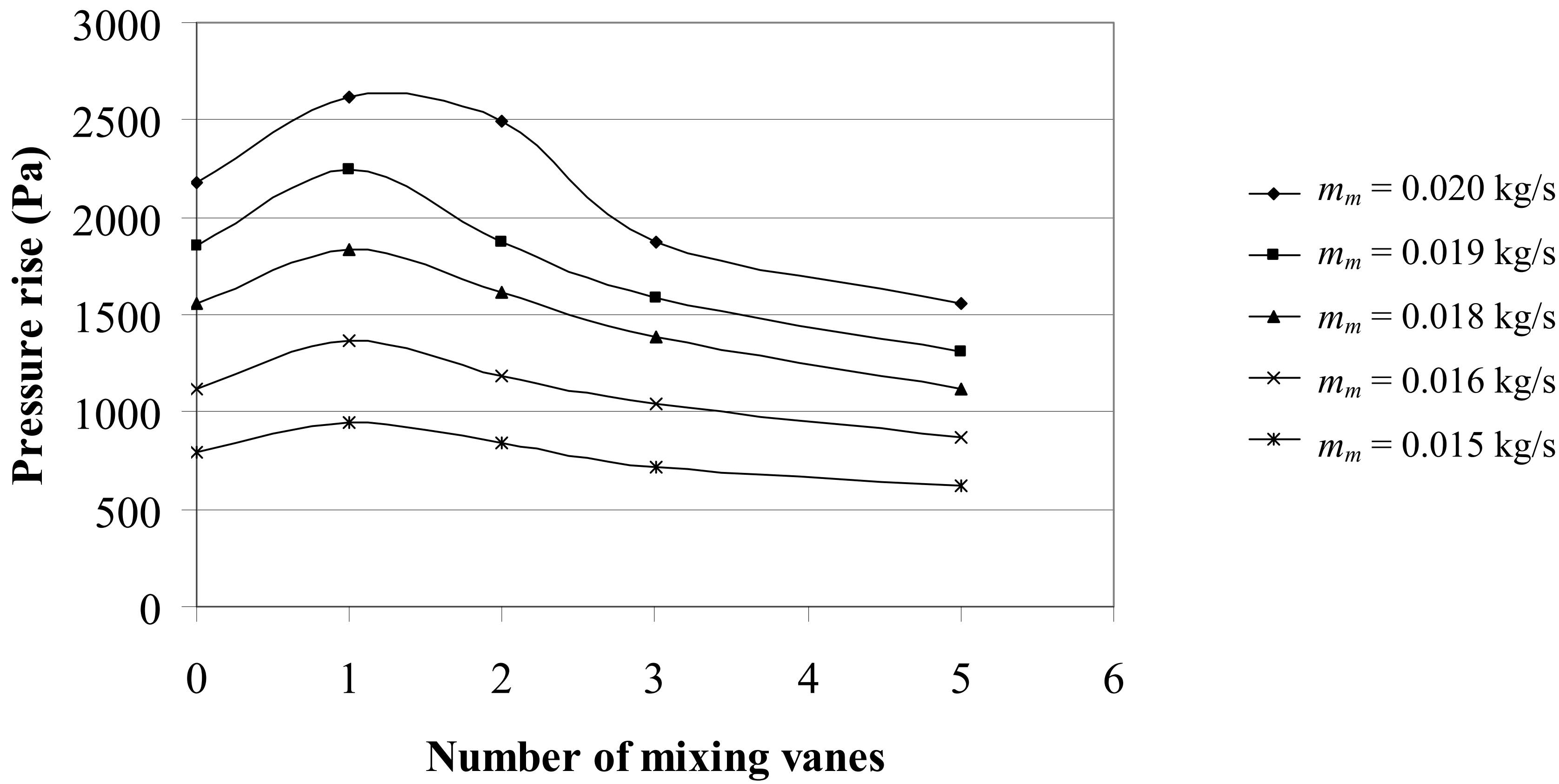

Figure IV.10 Plot of pressure rise across the jet ejector vs. number of mixing vanes for various mass flow rates and Pinch Valve Closing 3 (Figures A.5, A.9, A.13, A.17, A.21).

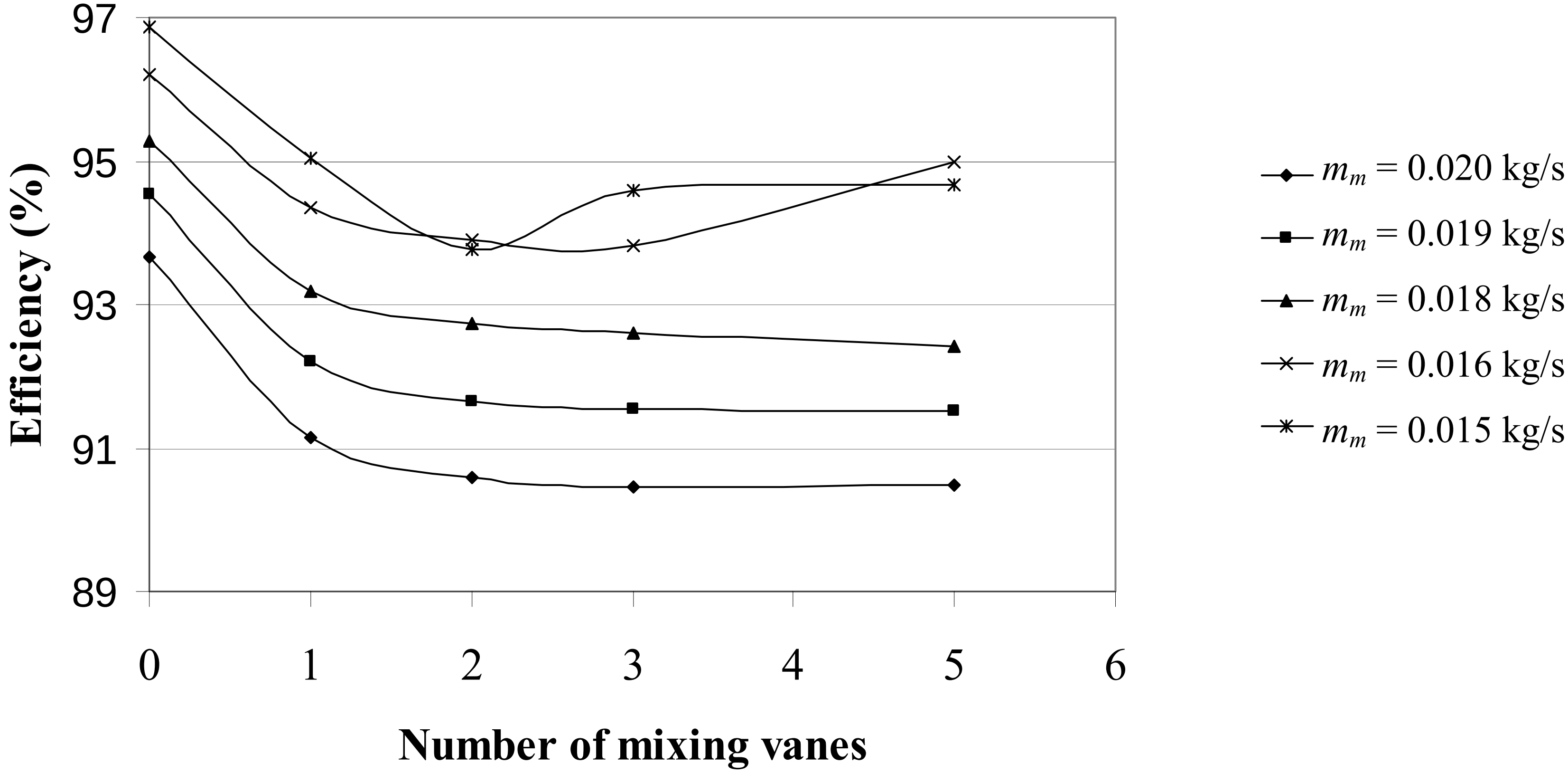

Figure IV.11 Plot of efficiency of the jet ejector vs. number of mixing vanes for various mass flow rates and no pinch valve closing (Figures A.2, A.6, A.10, A.14, A.18).

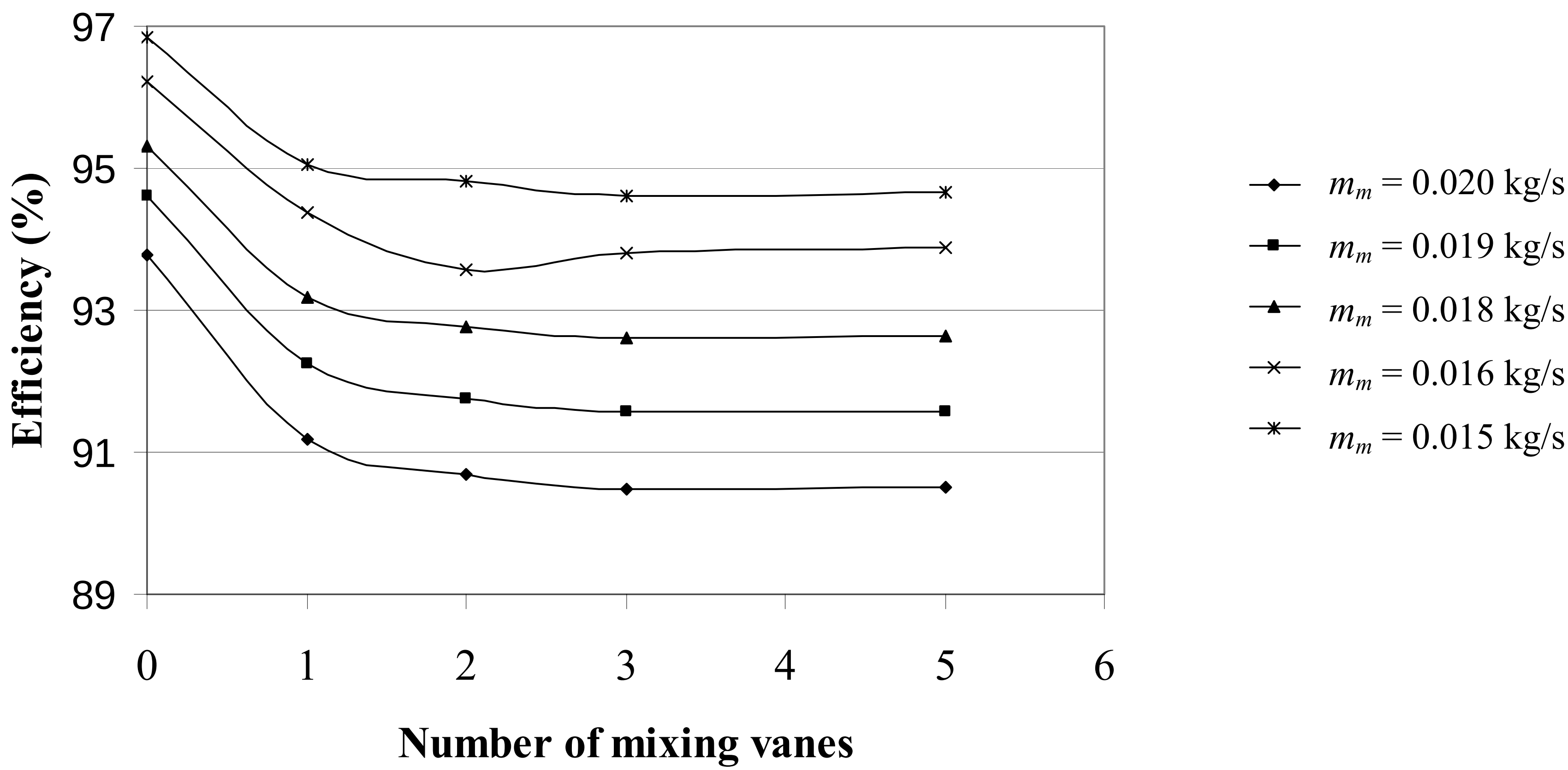

Figure IV.12 Plot of efficiency of the jet ejector vs. number of mixing vanes for various mass flow rates and Pinch Valve Closing 1 (Figures A.3, A.7, A.11, A.15, A.19).

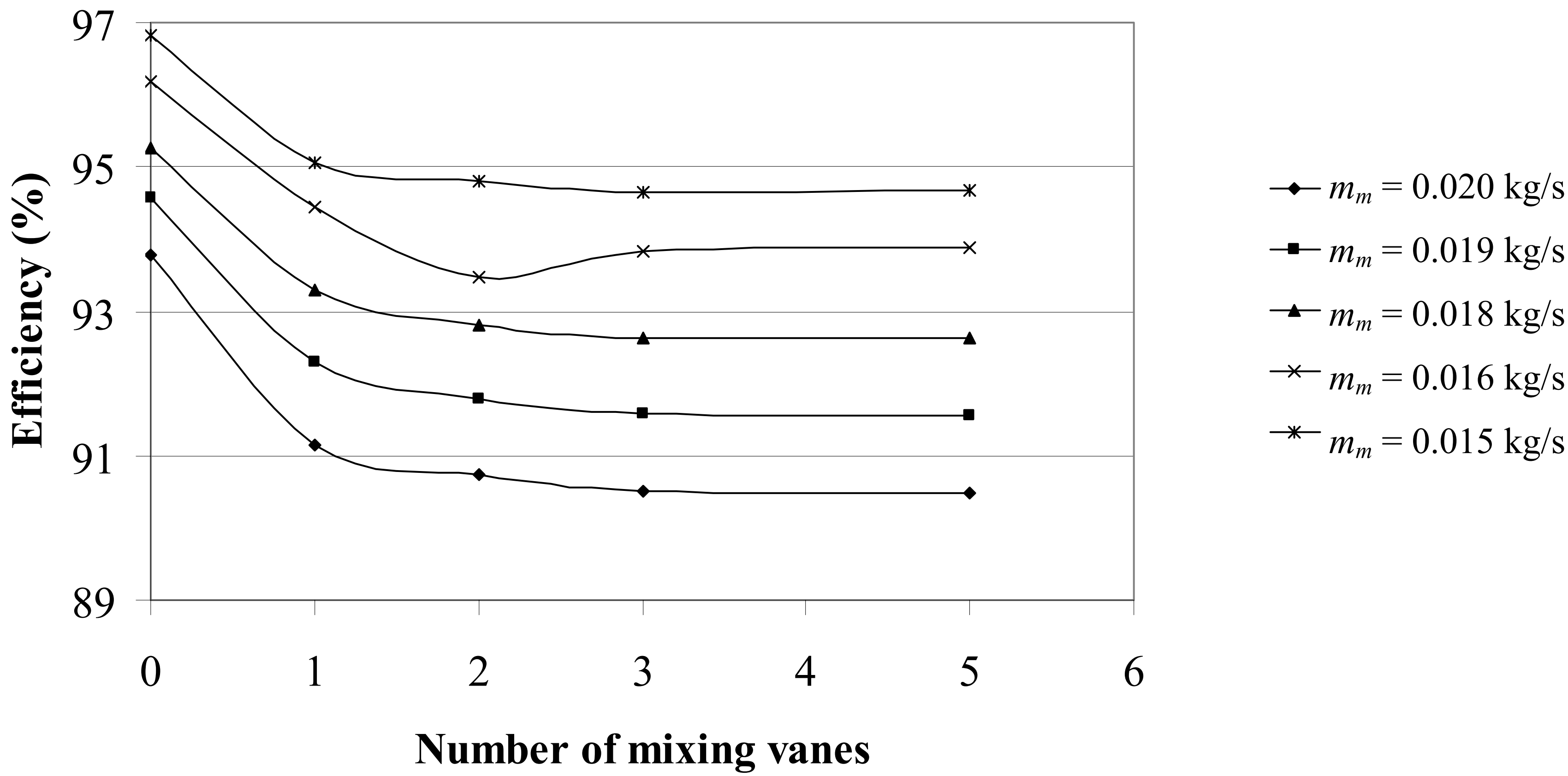

Figure IV.13 Plot of efficiency of the jet ejector vs. number of mixing vanes for various mass flow rates and Pinch Valve Closing 2 (Figures A.4, A.8, A.12, A.16, A.20).

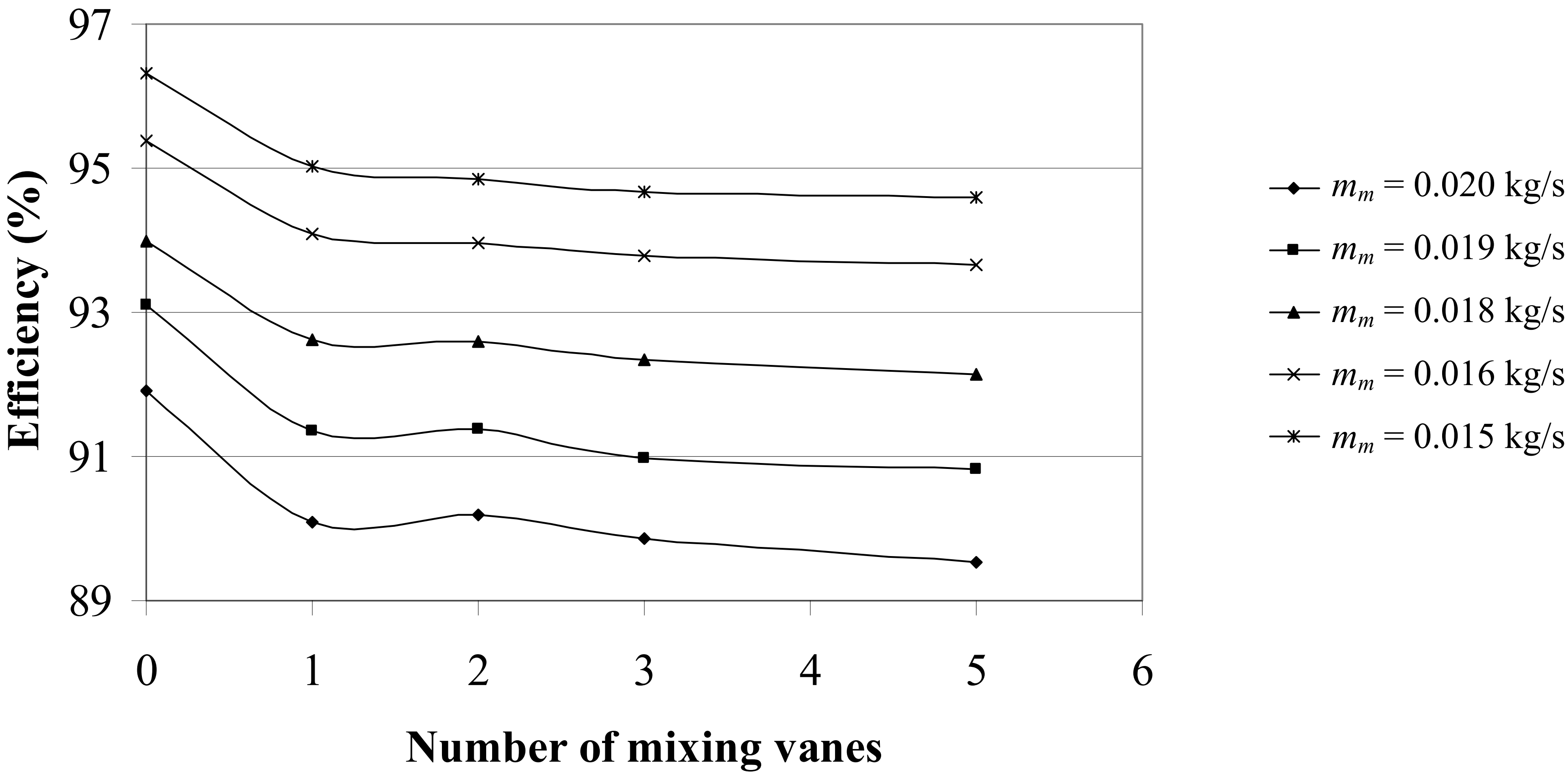

Figure IV.14 Plot of efficiency of the jet ejector vs. number of mixing vanes for various mass flow rates and Pinch Valve Closing 3 (Figures A.5, A.9, A.13, A.17, A.21).

IV.3 Conclusion

The two important objectives of this newly designed jet ejector are (i) to improve the efficiency of the jet ejector, and (ii) eliminate the shock wave in the diffuser of jet ejector. The first objective was achieved by placing the nozzle at the converging section of the diffuser, which helps to pre-accelerate the propelled stream and mix more efficiently with the motive stream. The lower the difference in the velocity of two streams, the more efficient is the mixing. This can be observed in Figures IV.11 to IV.14, the efficiency increases with decreasing motive mass flow rate.

The conventional jet ejector has lower efficiency of 25 – 30%, where as the newly designed jet ejector has efficiency greater than 90%. The low efficiency in the conventional jet ejector is due to higher momentum (mass x velocity) difference of propelled and motive streams. The propelled stream has zero momentum where as the propelled stream is at higher momentum, which results in inefficient mixing of two streams and lower pressure rise across the jet ejectors. The high efficiency is due to the following reasons: (i) low velocity difference between the propelled and motive stream, (ii) new efficiency equation formulated considering the kinetic energy, flow energy and pressure energy, and (iii) elimination of the shock wave in the diffuser.

IV.4 Future Work and Recommendations

The jet ejector can be optimized using computer modeling. The high-efficiency jet ejector should be tested at greater pressure rise across the jet ejector with higher back pressures for one or two mixing vanes compared to zero mixing vanes. Further, it is important to study the effect of nozzle diameter and placement. After implementing the necessary changes from the above studies, it is important to retest the jet ejector in the vapor-compression desalination unit.

REFERENCES

[1] E. D. Howe. Fundamentals of Water Desalination, Marcel Dekker INC. New York, (1974), pp. 1–20.

[2] A. H. Khan. Desalination Processes and Multistage Flash Distillation Practice, Elsevier, Amsterdam, (1986), pp. 1–135.

[3] R. Popkin. Desalination, McGraw-Hill, Chicago, (1968), pp. 3—102.

[4] A. Porteous. Saline Water Distillation Processes, Longman, New York, (1975), pp. 6–73.

[5] A. Porteous. Desalination Technology – Developments and Practice, McGraw-Hill, London, (1983), pp. 1–264.

[6] H. Heitmann. Saline Water Processing, VCH, New York, (1990), pp. 1–228.

[7] K.S. Spiegler. Principles of Desalination, Academic Press, London, (1966), pp. 1–114.

[8] U. Merten. Desalination by Reverse Osmosis, McGraw-Hill, New York, (1966), pp. 1–18.

[9] T. N. Eisenberg and E. J. Middlebrooks. Reverse Osmosis Treatment of Drinking Water, Addison Wesley, Boston (1986), pp. 1–247.

[10] H. El-Dessouky and H. Alttouney. Desalination, Marcel Dekker INC., New York, (1997), pp. 114–253.

[11] R. Rautenbach and B. Artz. Desalination, Academic Press, London, (1985), pp. 56–261.

[12] H. Mosry, D. Larger and K. Genther. Desalination, McGraw-Hill, New York, (1994), pp. 59–96.

[13] A. El – Nashar and A.A. Qamhiyah. Desalination, VCH Publishers, New York, (1991), pp. 82–164.

[14] O. J. Morin. Desalination, IBM Press, London, United Kingdom, (1993), pp. 69–93.

[15] A. Ophir and J. Weinberg. Multi–Effect Distillation – A Solution to Water Problem, McGraw-Hill, New York, (1997), pp. 1–62.

[16] F. Pepp. The Vertical Multi–Effect Distillation Process, Addison Wesley, Boston, (1997), pp. 9–47.

[17] A. M. Hassan. A New Approach to Membranes and Thermal Seawater Desalination Processes – Volume 1, VCH, New York, (1998), pp. 53–59.

[18] A. M. Hassan. A New Approach to Membranes and Thermal Seawater Desalination Processes – Volume 2, VCH, New York, (1998), pp. 39–45.

[19] K. A. Faller. Reverse Osmosis and Nanofiltration, McGraw-Hill, New York, (1999), pp. 46–87.

[20] P. Gagliardo, S. Adham, R. Trussel, and A. Olivieri. Desalination: Water Purification via Reverse Osmosis, Van Nostrand Reinhold, New York, (1998), pp. 73–78.

[21] D. H. Furukawa. A Review of Seawater Reverse Osmosis, Marcel Dekker INC., Chicago, (1997), pp. 1–36.

[22] M. Thampy. Desalination using Electrodialysis, McGraw-Hill, New York, (1999), pp. 45–49.

[23] K. Wangnick. Desalination, Addison Wesley, Boston, (1996), pp. 1–32.

[24] O.K. Buros. The desalting ABCs, McGraw-Hill, New York, (1990), pp. 1–16.

[25] H.M. Ettouney. Understand Thermal Desalination, Chemical Engineering Progress, 95 (1999), pp. 43–57.

[26] E.E. Ludwig, Applied Process Design for Chemical and Petrochemical Plants, Vol. 1, McGraw-Hill, New York, second ed, (1977).

[27] H.T. El-Dessouky. Single Effect Thermal Vapor-Compression Desalination Process: Thermal Analysis, Heat Trans. Eng. 20 (1999), pp. 52–68.

[28] D. Birgenheier. Designing Steam Jet Vacuum Systems, Marcel Dekker INC., Chicago, (1993), pp. 1–7.

[29] J.H. Keenan. A Simple Air Ejector, J. Appl. Mech. 64 (1942), pp. 84–91.

[30] Artisan Industries, Ejector Principle-Effective Pumping action without moving parts. (2001), pp. 1–3.

[31] F.C. Chen. Performance of Ejector Heat Pumps, Energy Res. 11 (1987), pp. 289–300.

[32] H.G. Arnold. Steam Ejector as an Industrial Heat Pump, ASHRAE Trans. 88 (1982), pp. 845–857.

[33] H. El-Dessouky. Evaluation of Steam Jet Ejectors, Chemical Engineering and Processing 41 (2002), pp. 551–561.

[34] M.T. Holtzapple, "High-Efficiency Jet Ejector for Thermocompression Evaporator," Proposal, Department of Chemical Engineering, Texas A&M University, College Station, April 2003.

[35] M.T. Holtzapple, "Ultrahigh-Efficiency Jet Ejector," Disclosure of Invention, Department of Chemical Engineering, Texas A&M University, College Station, August 2003.

[36] M.T. Holtzapple, G. Noyes, and A. Rabroker, "Improved Design for Jet Ejector," Disclosure of Invention, Department of Chemical Engineering, Texas A&M University, College Station, August 2003.

[37] M.T. Holtzapple, G. Noyes, "Improved Jet Ejector Evaporator," Disclosure of Invention, Department of Chemical Engineering, Texas A&M University, College Station, September 2003.

[38] M.T. Holtzapple, "Alternative Vapor-Compression Evaporator Systems," Disclosure of Invention, Department of Chemical Engineering, Texas A&M University, College Station, September 2003.

[39] S.K. Gupta. A Comparative Parametric Study of Two Theoretical Models of a Single-stage Single-fluid, Steam Jet Ejector, Chem. Eng. J. 18 (1979), pp. 81–85.

[40] Allis-Chalmers Company, "Axial Compressors," Bulletin No. B 8863, http://www.allis-chalmers.com accessed December, 2003.

[41] E.I. Ewoldsen. "Seawater Entrainment in Low Temperature Flash Evaporators," Sea Water Conversion Laboratory Report No. 64-3, WRC Contribution No. 90, University of California, Berkeley, December 1964.

[42] M. Tribus. "Thermodynamic and Economic Considerations in the Preparation of Fresh Water from the Sea," Dept. of Eng. Report No. 59-34, University of California, Los Angeles, September 1960.

[43] J.T. Chambers. "Series Staging of Vapor-Compression Distillation," Issue No. 20, Sea Water Conversion Laboratory, University of California, Berkeley, May 1960.

[44] W.H. McAdams, Heat Transmission, McGraw-Hill Book Company, New York, 3rd ed., (1954), pp. 219.

[45] Penberthy Bulletin 1100, Section 1000, Penberthy Division of Stanwich Industries, Inc., May 1987, http://www.stanwichind.com accessed on June 2003.

[46] "Ejectors and Their Applications," AMETEK, Schutte & Koerting Division, 1981, http://www.ametek.com accessed June, 2003.

[47] B.R. Power, Steam Jet Ejectors for Process Industries, McGraw-Hill, New York (1994), pp. 27–65.

[48] K. Wangnick, A Global Overview of Water Desalination Technology and the Perspectives, http://www.wangnick.com accessed June, 2003.

APPENDIX A

The schematic presentation of the experimental setup of jet ejector with different number of mixing vanes and for various pinch valve closing is shown. Also, the photos of experimental setup and the desalination process are shown.

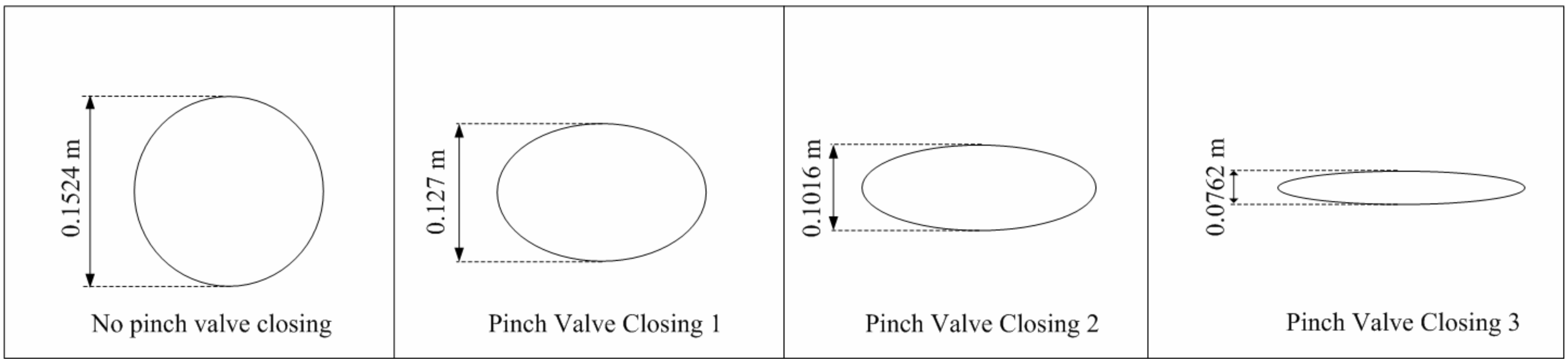

Figure A.1 A schematic representation of pinch valve closings during the jet ejector experiment. The tube of 6 in (0.1524 m) was closed inch-by-inch (5 in = 0.127 m, 4 in = 0.1016 m, 3 in = 0.0762 m) each time to create back pressure in the system.

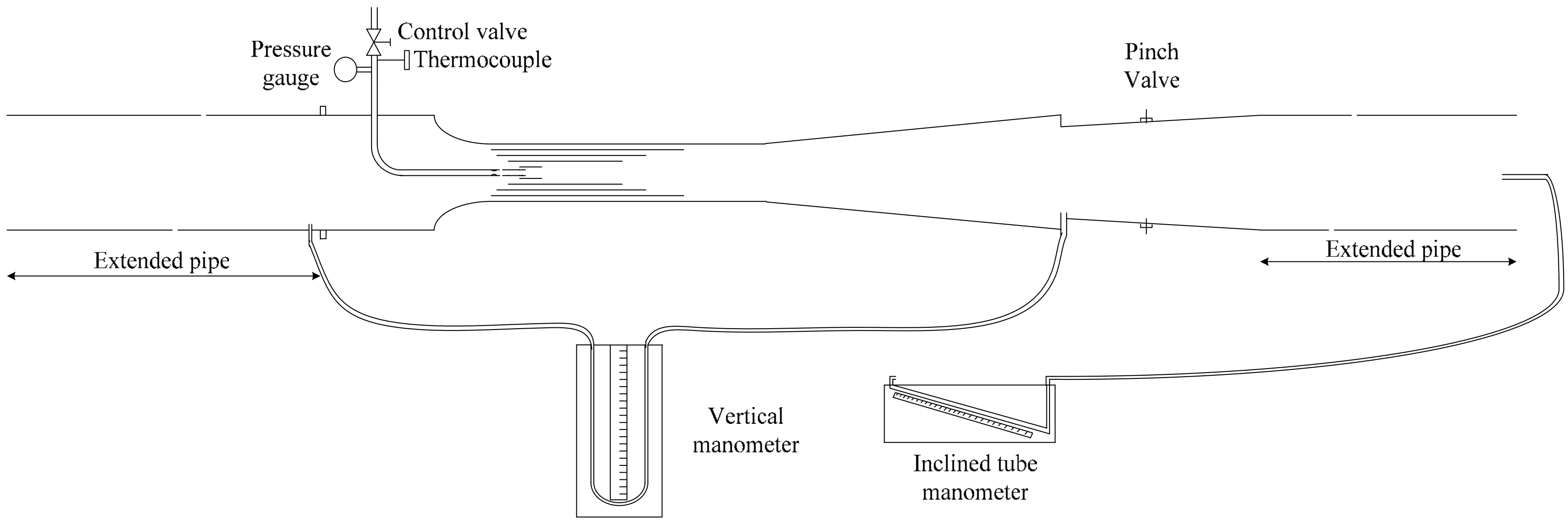

Figure A.2 Experimental setup of jet ejector with all the mixing vanes and no pinch valve closing.

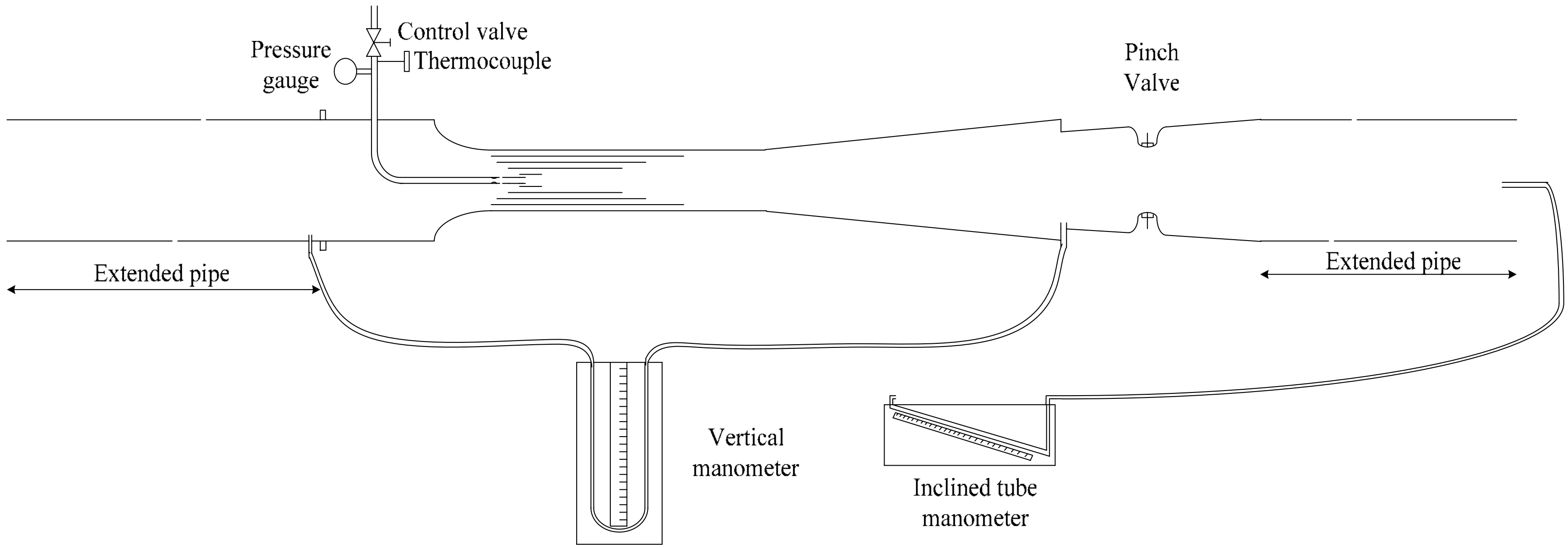

Figure A.3 Experimental setup of jet ejector with all the mixing vanes and Pinch Valve Closing 1.

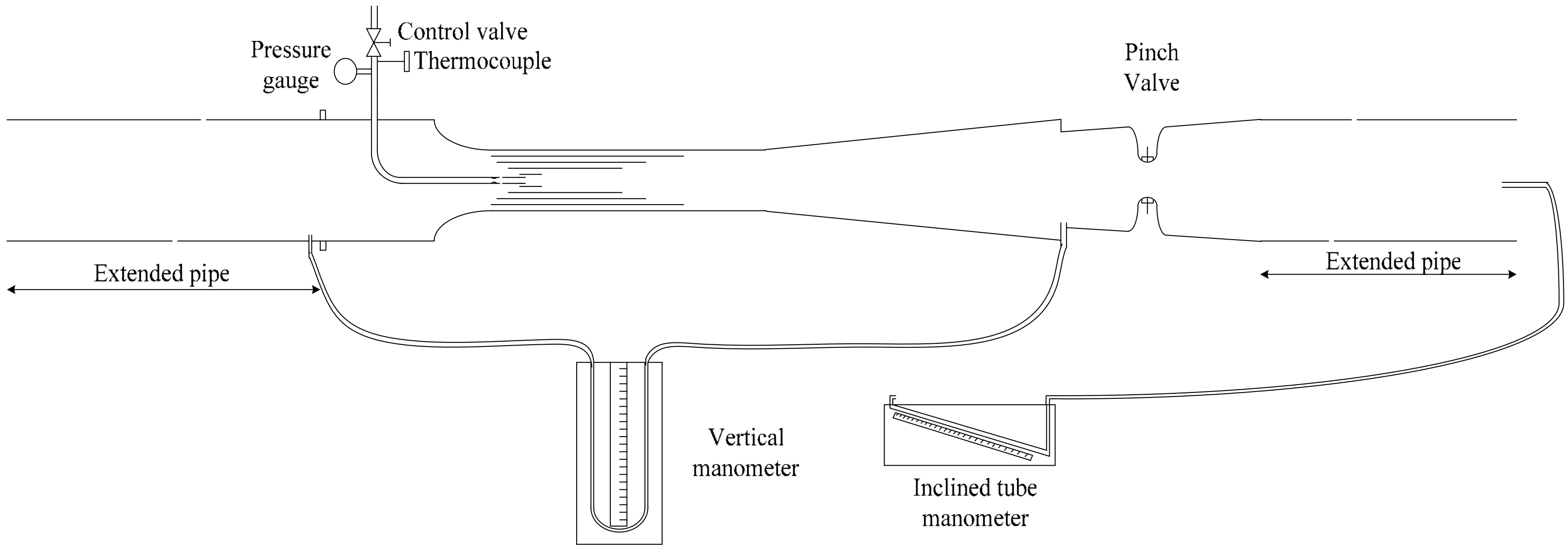

Figure A.4 Experimental setup of jet ejector with all the mixing vanes and Pinch Valve Closing 2.

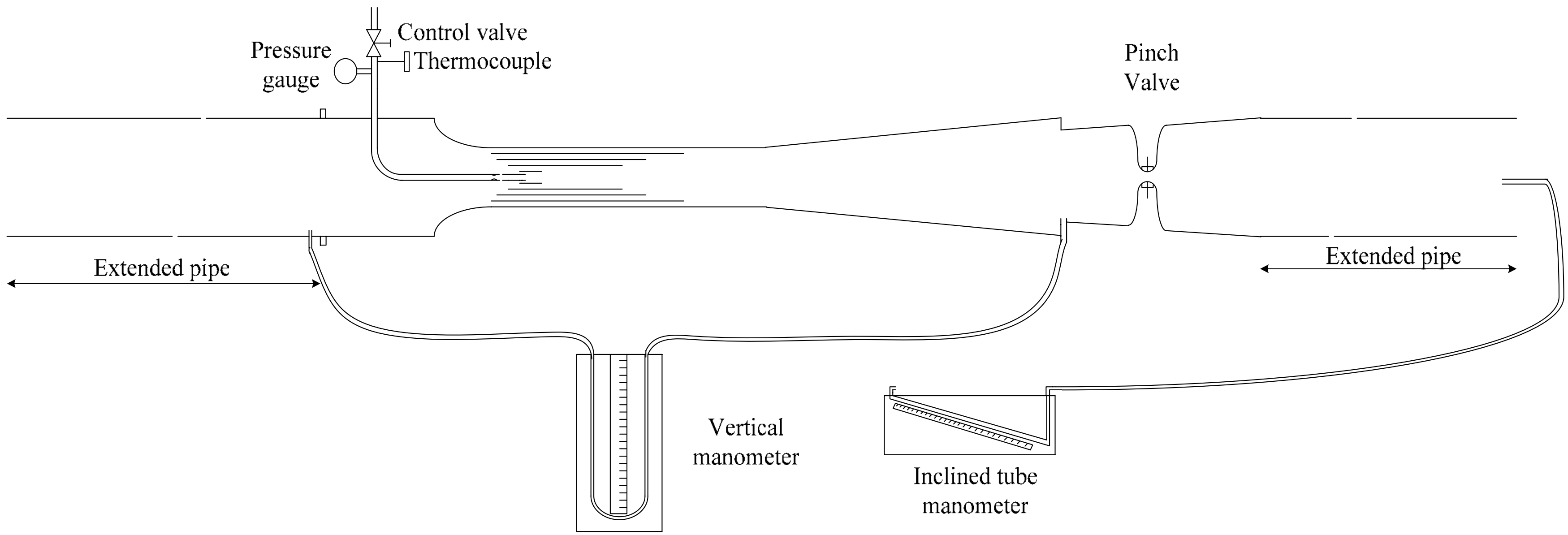

Figure A.5 Experimental setup of jet ejector with all the mixing vanes and Pinch Valve Closing 3.

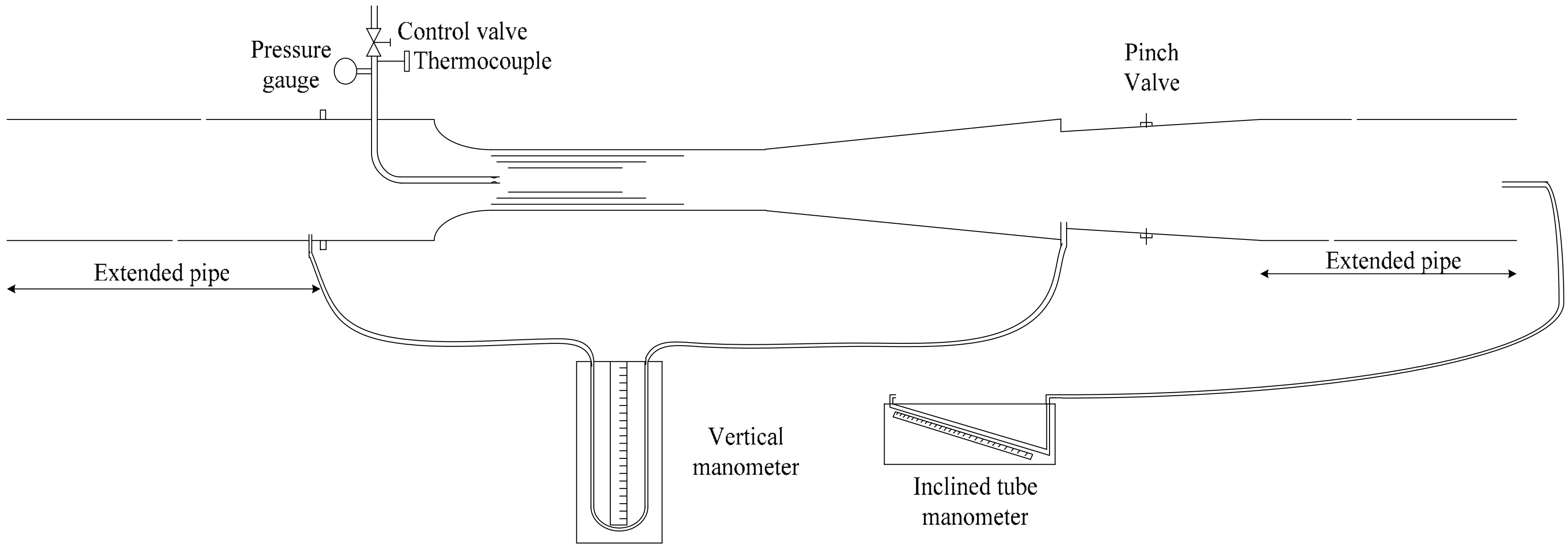

Figure A.6 Experimental setup of jet ejector with three mixing vanes and no pinch valve closing.

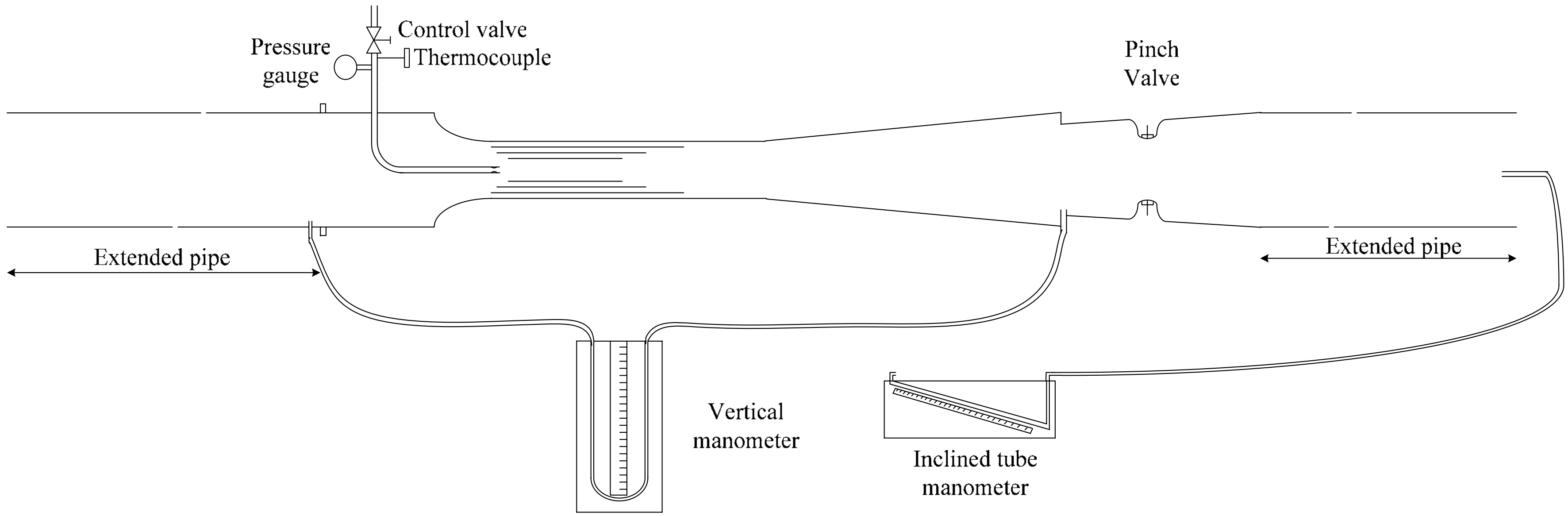

Figure A.7 Experimental setup of jet ejector with three mixing vanes and Pinch Valve Closing 1.

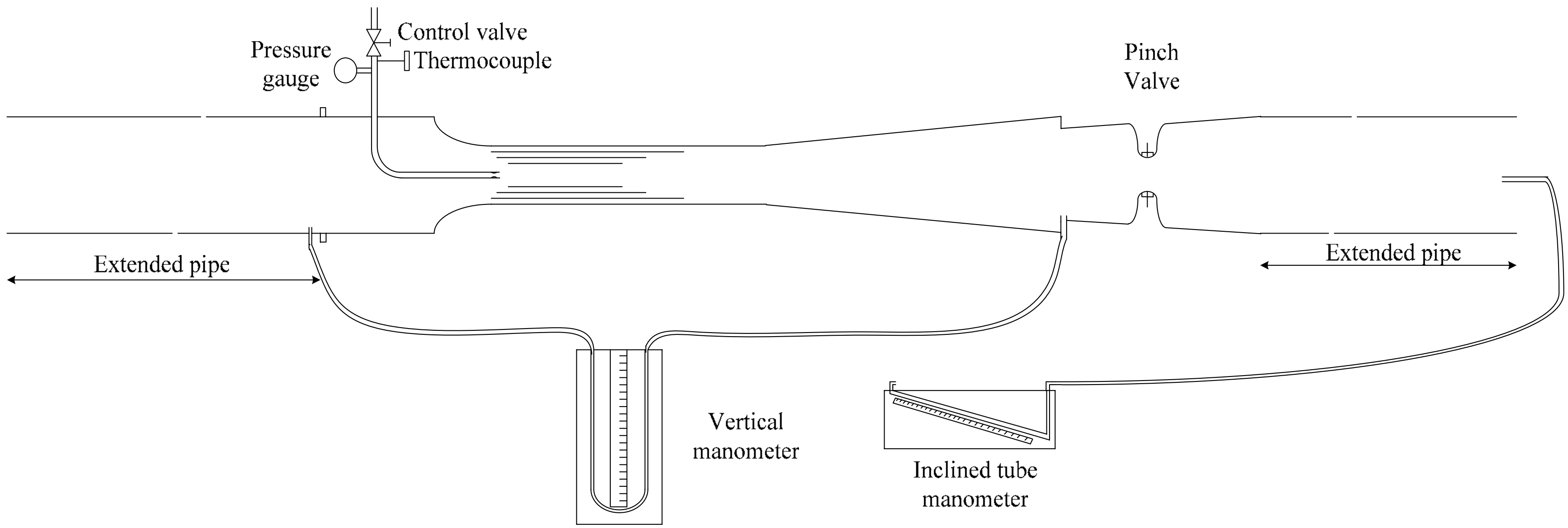

Figure A.8 Experimental setup of jet ejector with three mixing vanes and Pinch Valve Closing 2.

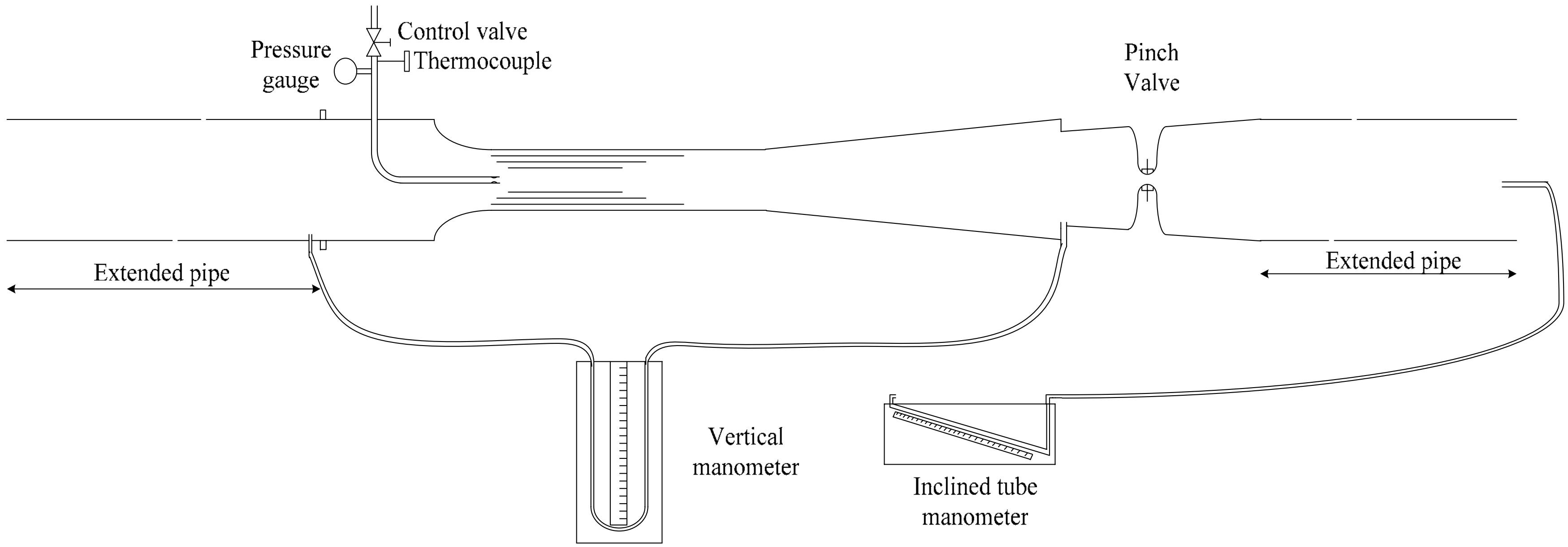

Figure A.9 Experimental setup of jet ejector with three mixing vanes and Pinch Valve Closing 3.

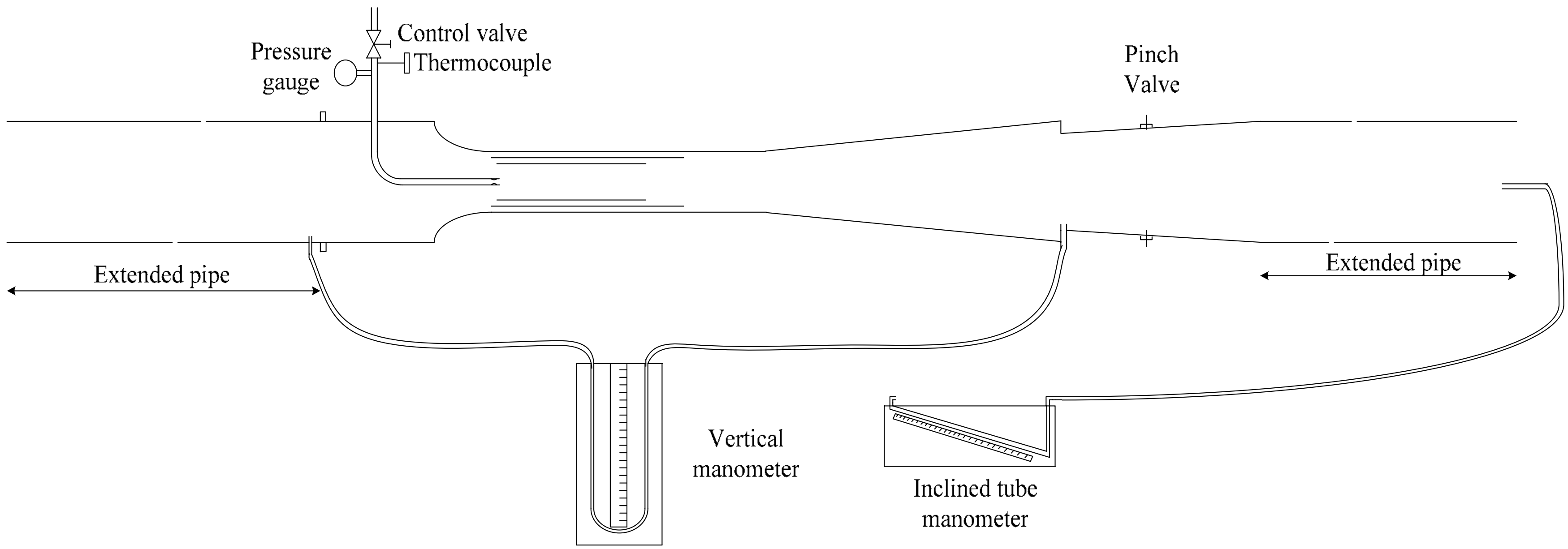

Figure A.10 Experimental setup of jet ejector with two mixing vanes and no pinch valve closing.

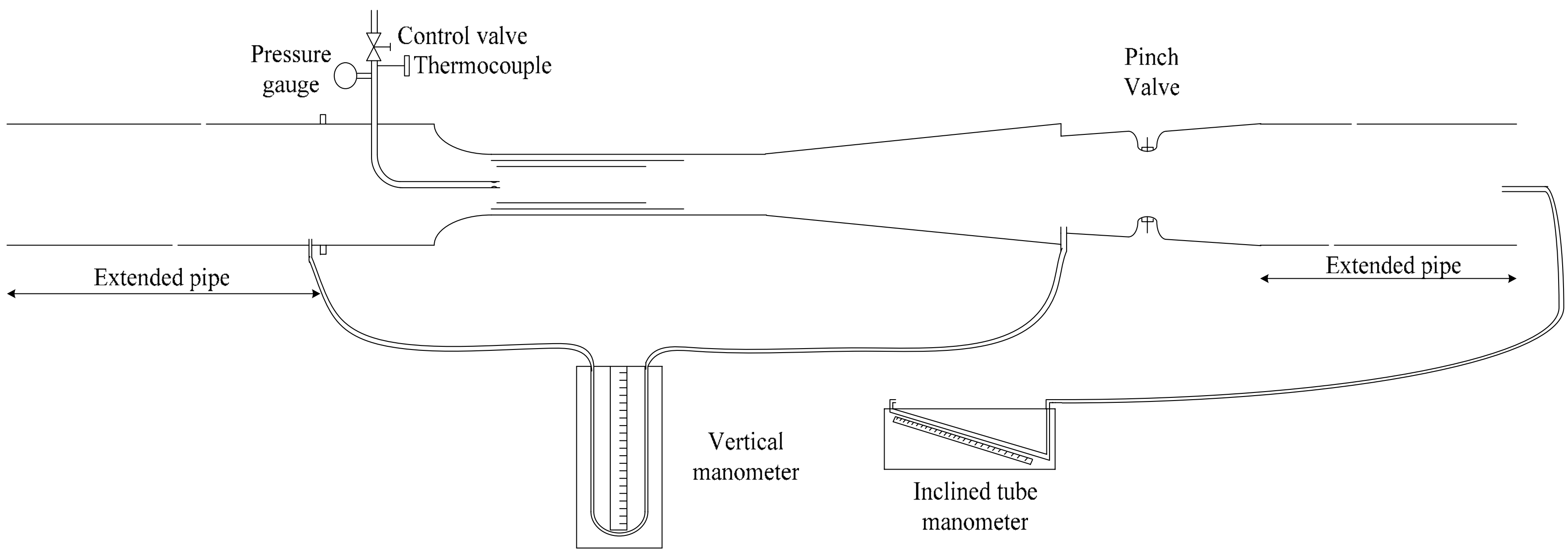

Figure A.11 Experimental setup of jet ejector with two mixing vanes and Pinch Valve Closing 1.

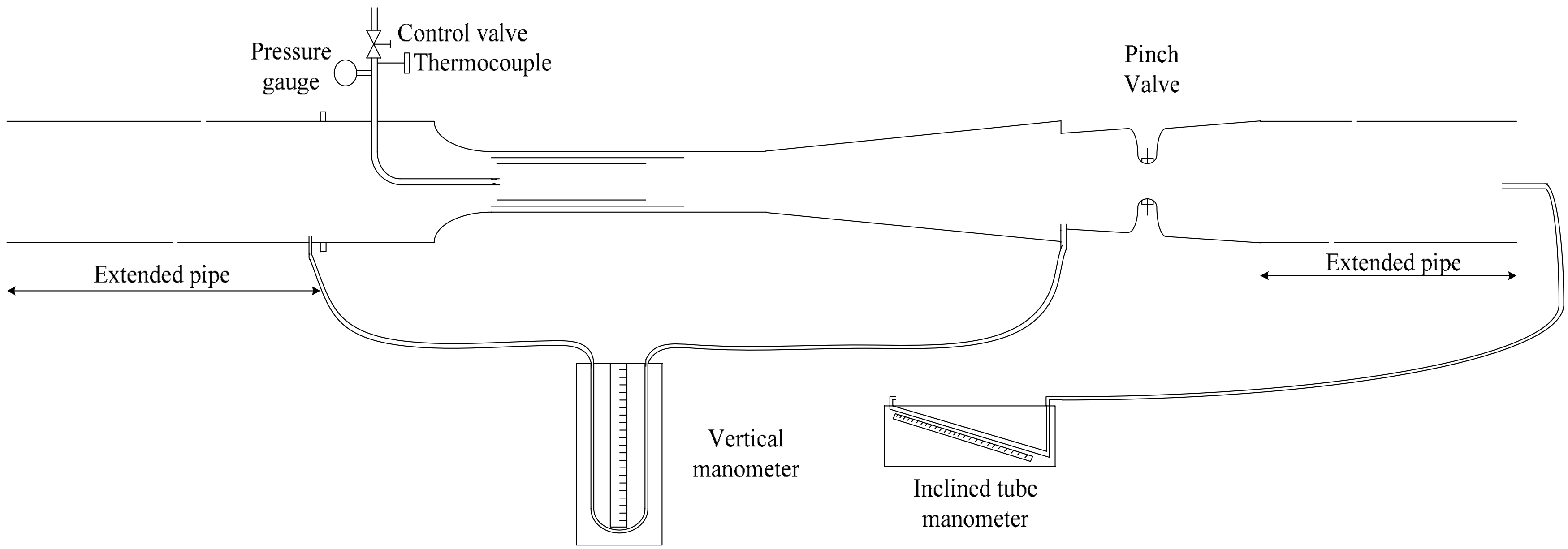

Figure A.12 Experimental setup of jet ejectors with two mixing vanes and Pinch Valve Closing 2.

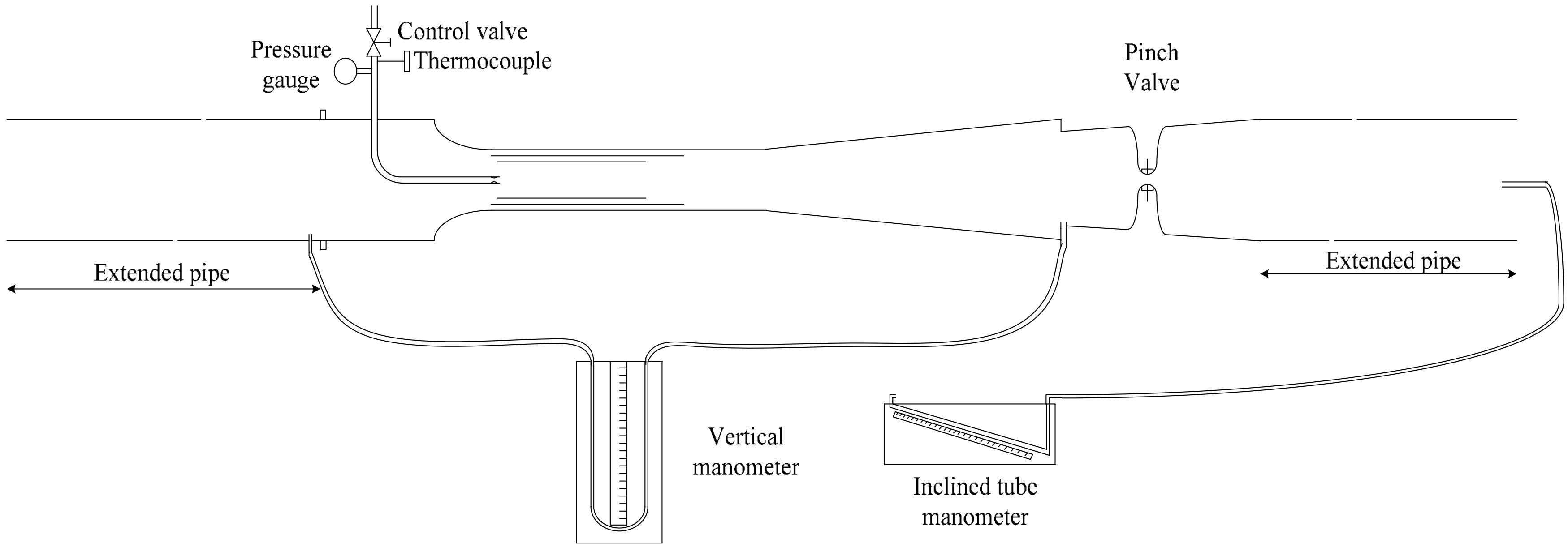

Figure A.13 Experimental setup of jet ejector with two mixing vanes and Pinch Valve Closing 3.

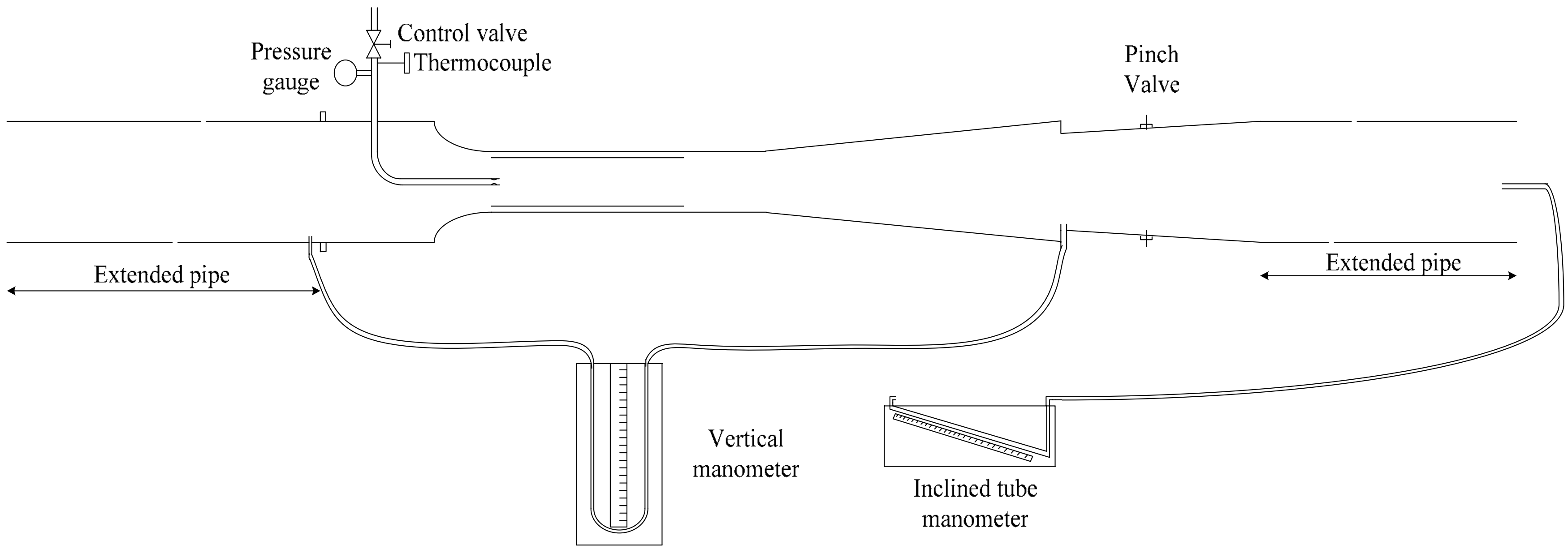

Figure A.14 Experimental setup of jet ejector with one mixing vane and no pinch valve closing.

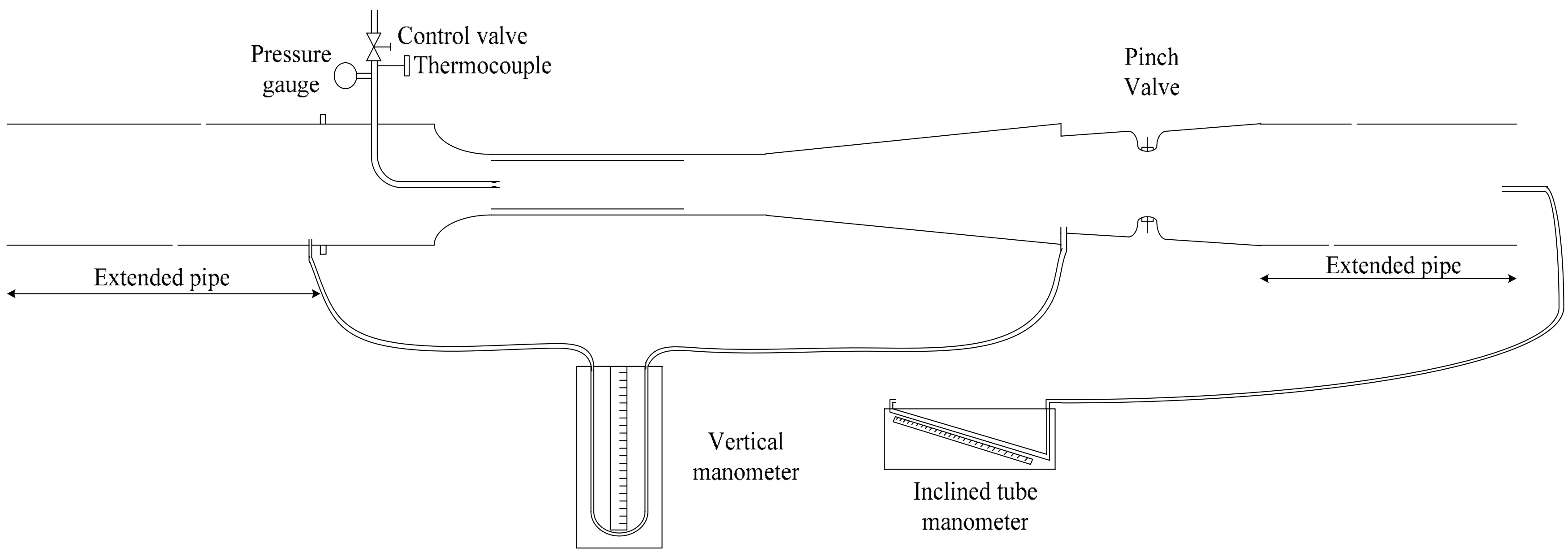

Figure A.15 Experimental setup of jet ejector with one mixing vane and Pinch Valve Closing 1.

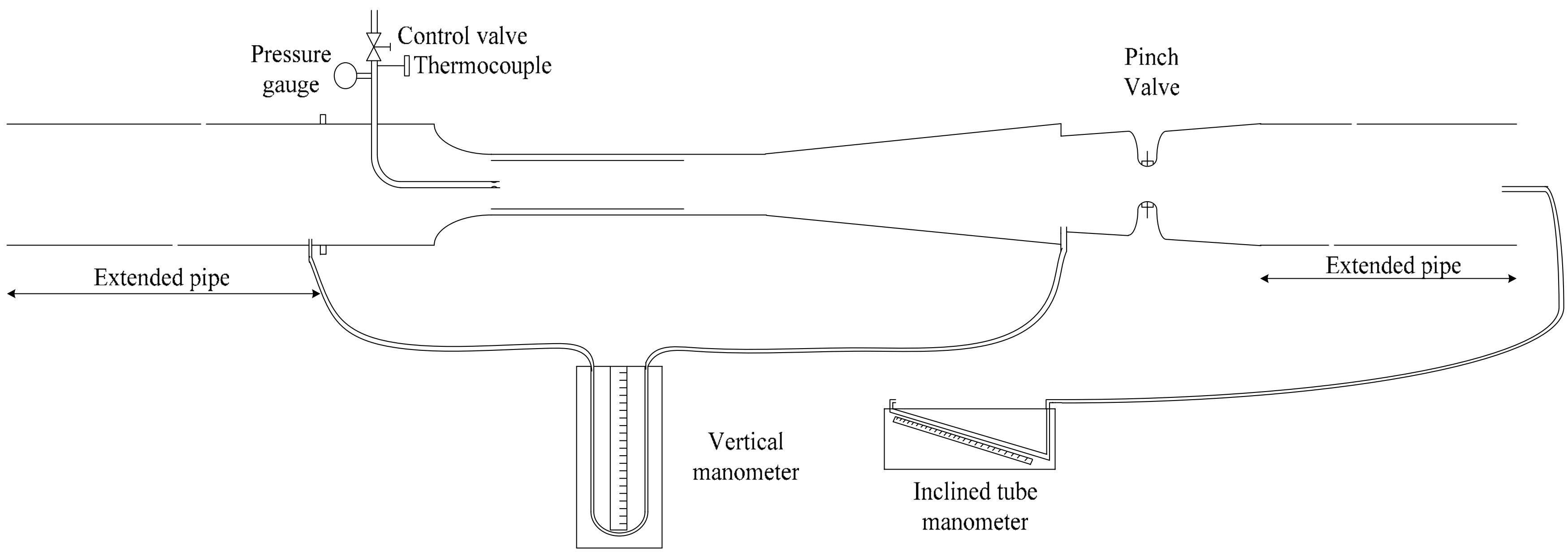

Figure A.16 Experimental setup of jet ejector with one mixing vane and Pinch Valve Closing 2.

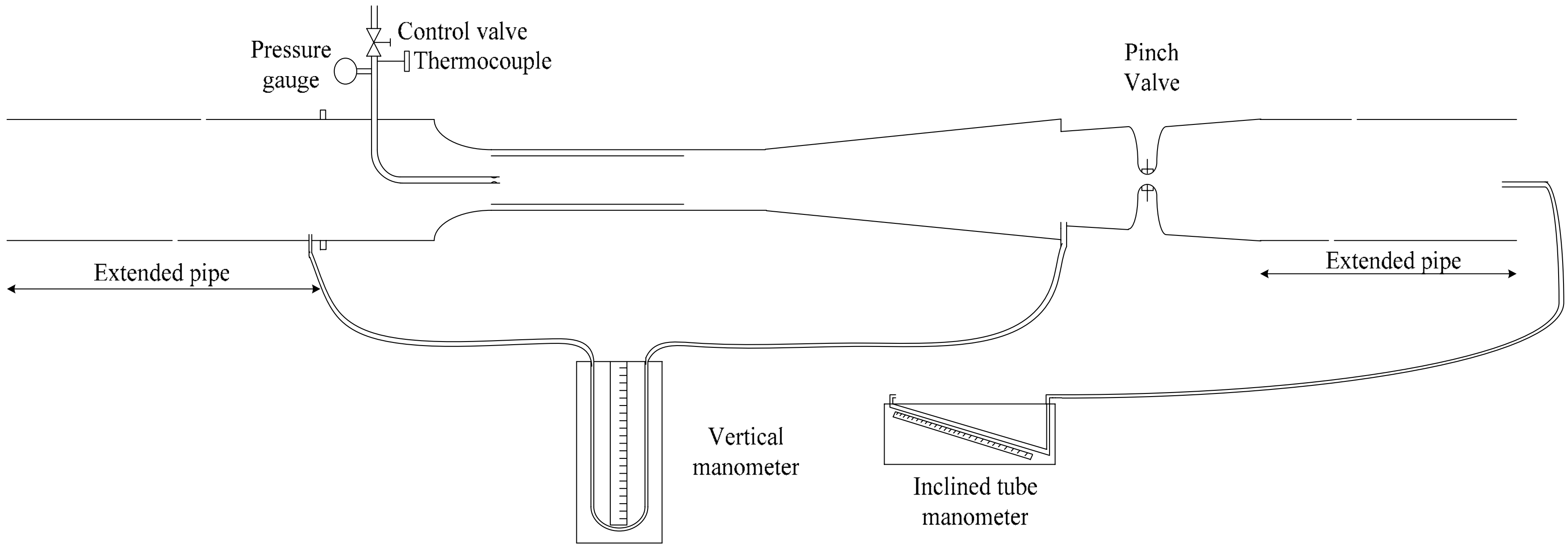

Figure A.17 Experimental setup of jet ejector with one mixing vane and Pinch Valve Closing 3.

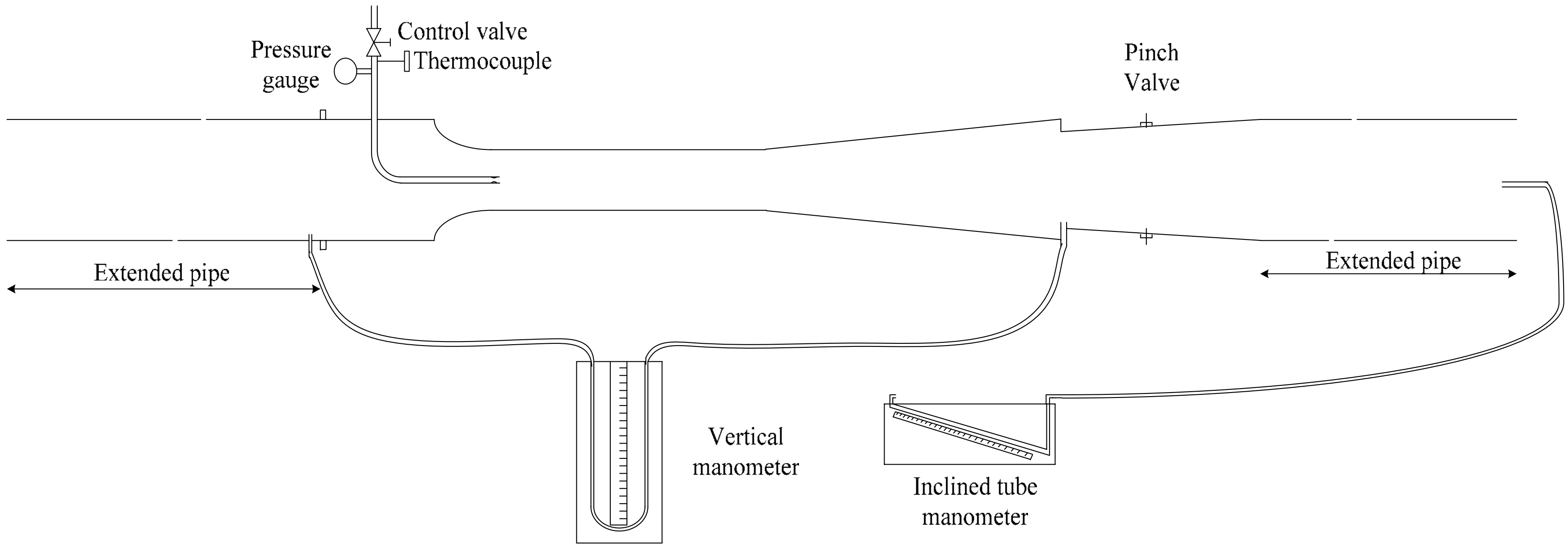

Figure A.18 Experimental setup of jet ejector with no mixing vanes and no pinch valve closing.

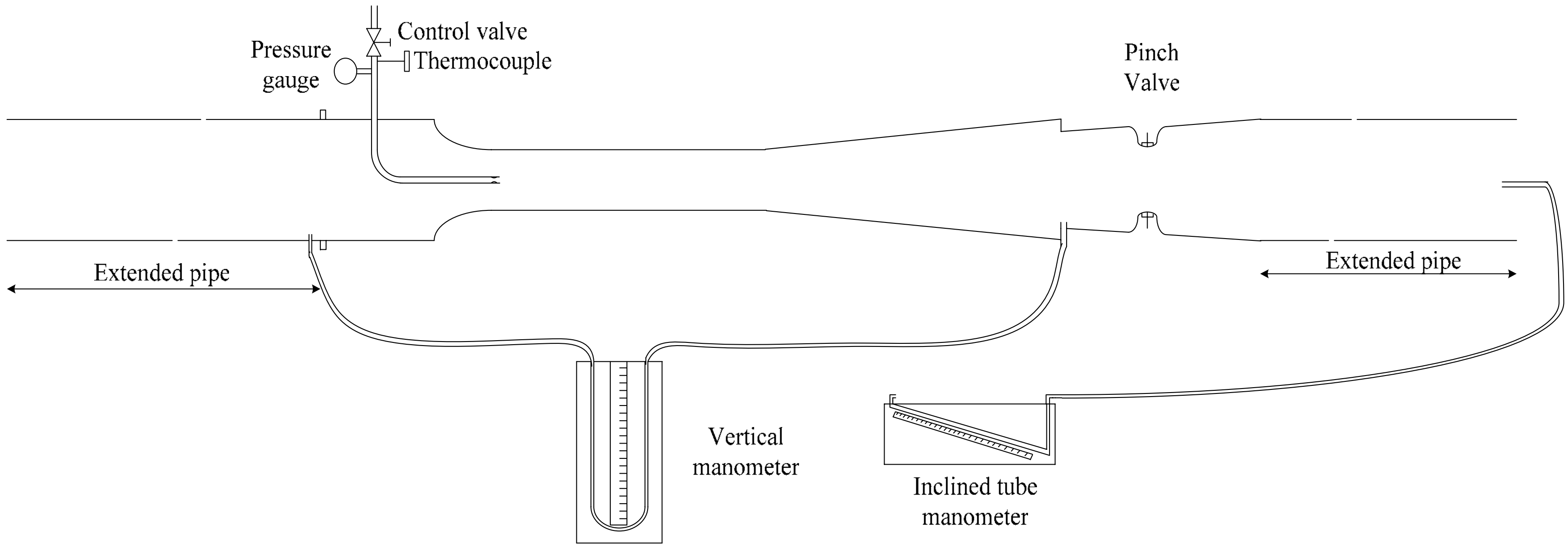

Figure A.19 Experimental setup of jet ejector with no mixing vanes and Pinch Valve Closing 1.

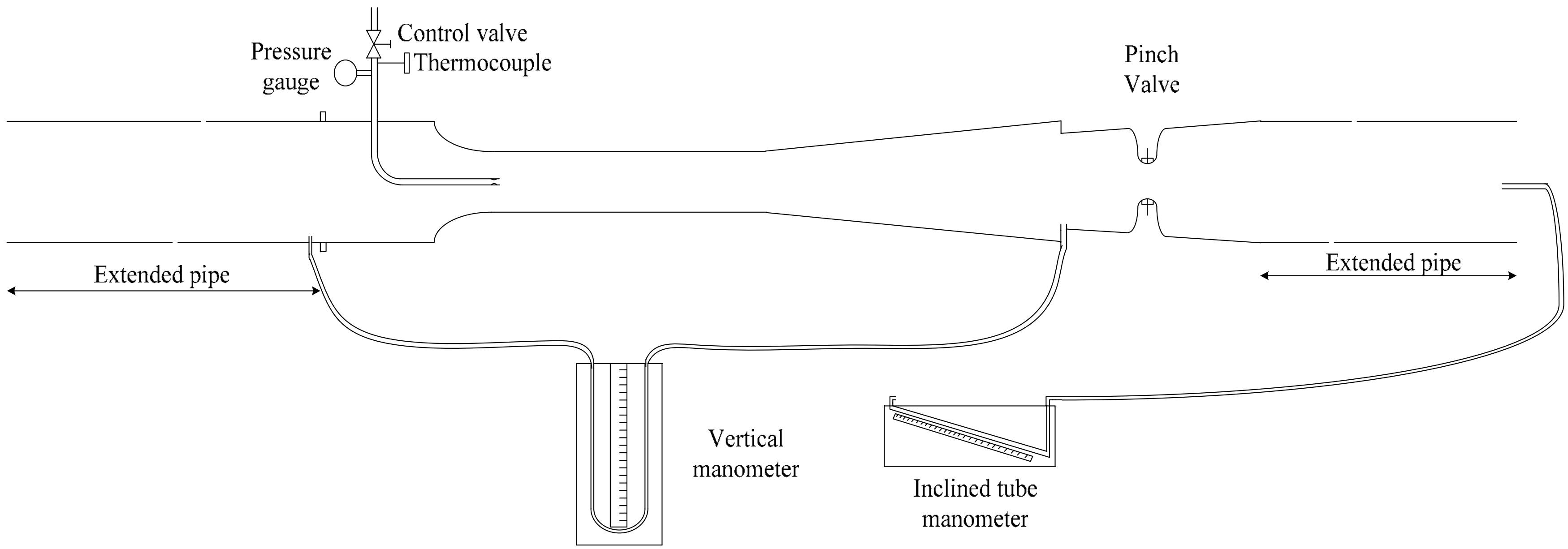

Figure A.20 Experimental setup of jet ejector with no mixing vanes and Pinch Valve Closing 2.

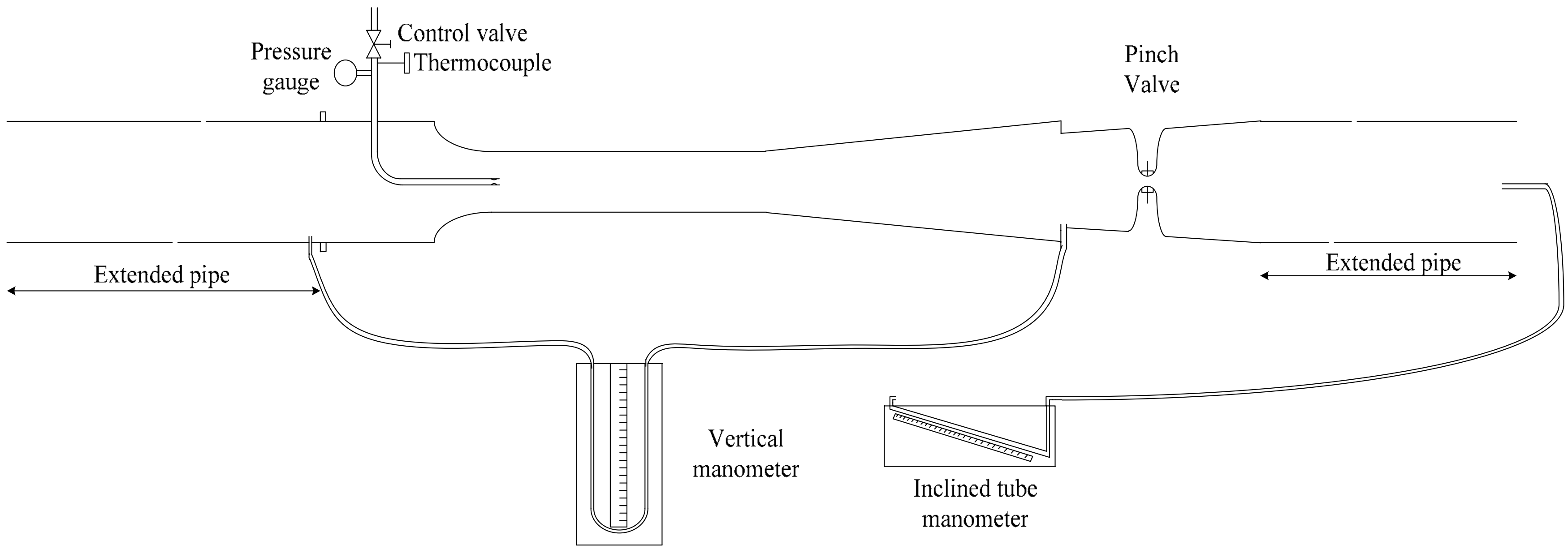

Figure A.21 Experimental setup of jet ejector with no mixing vanes and Pinch Valve Closing 3.

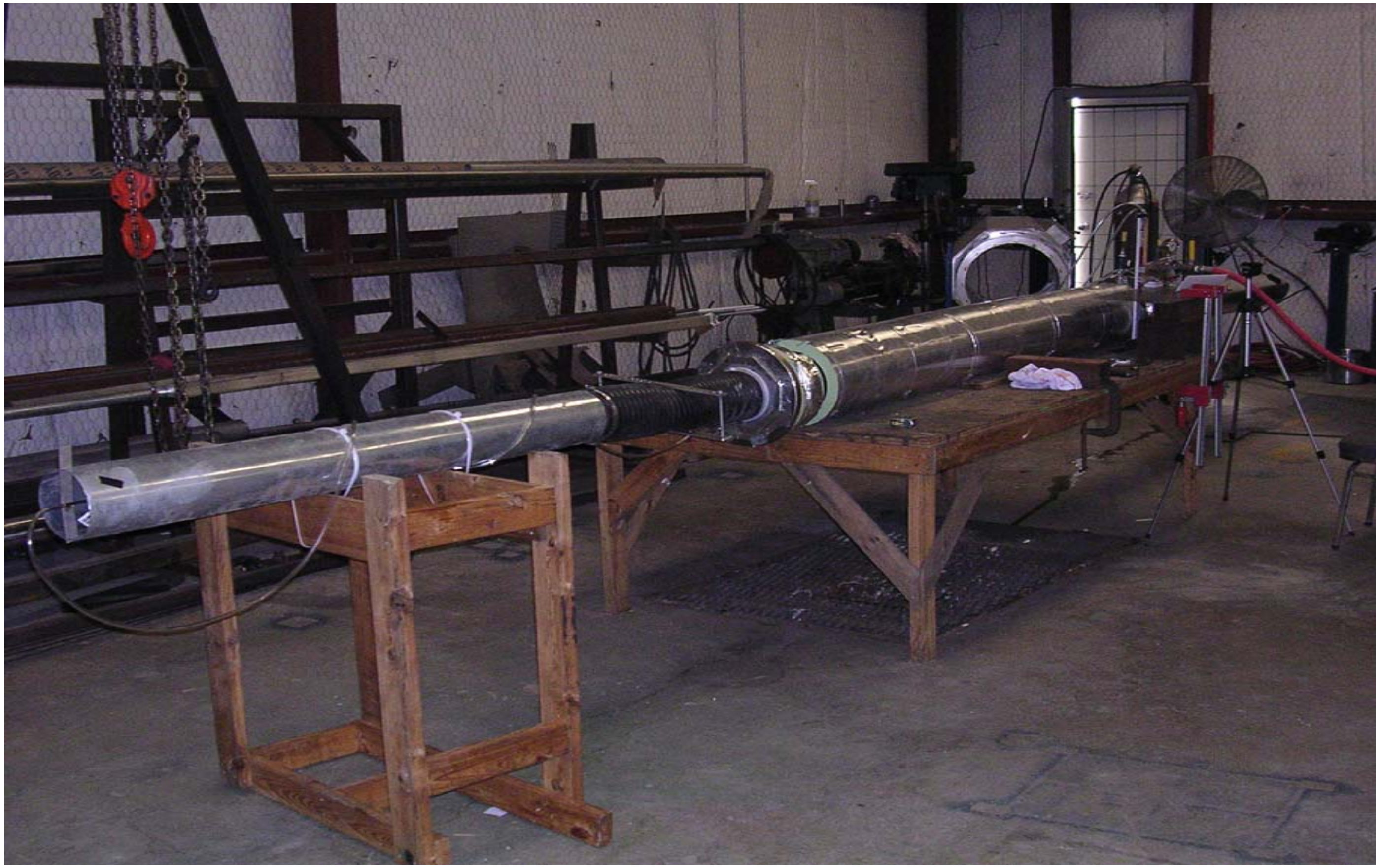

Figure A.22 The experimental setup showing jet ejector and the extension at the outlet along with the pinch valve.

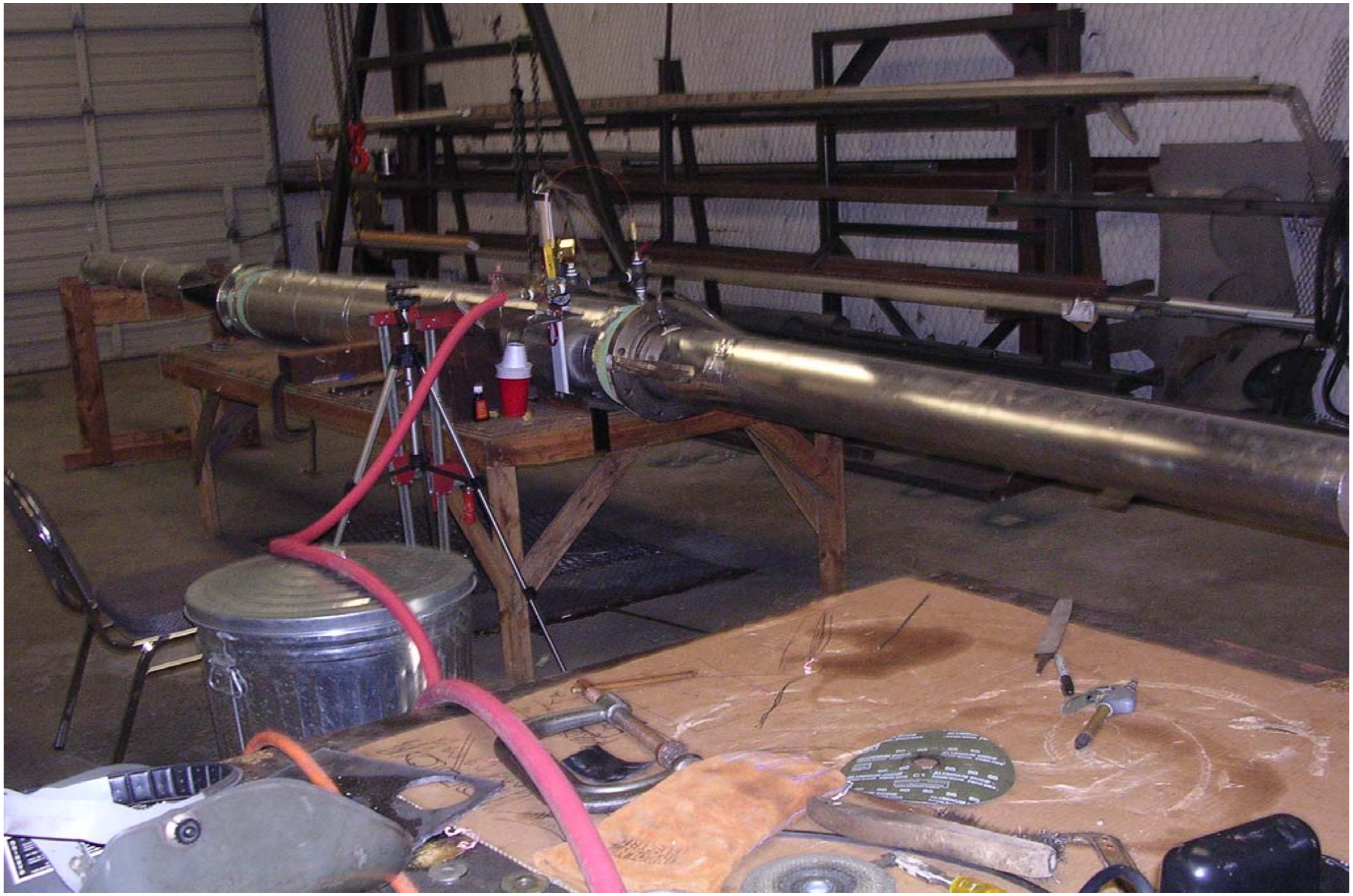

Figure A.23 The experimental setup showing jet ejector and the extension at the inlet to obtain a narrow flow of propelled stream before mixing with motive stream.

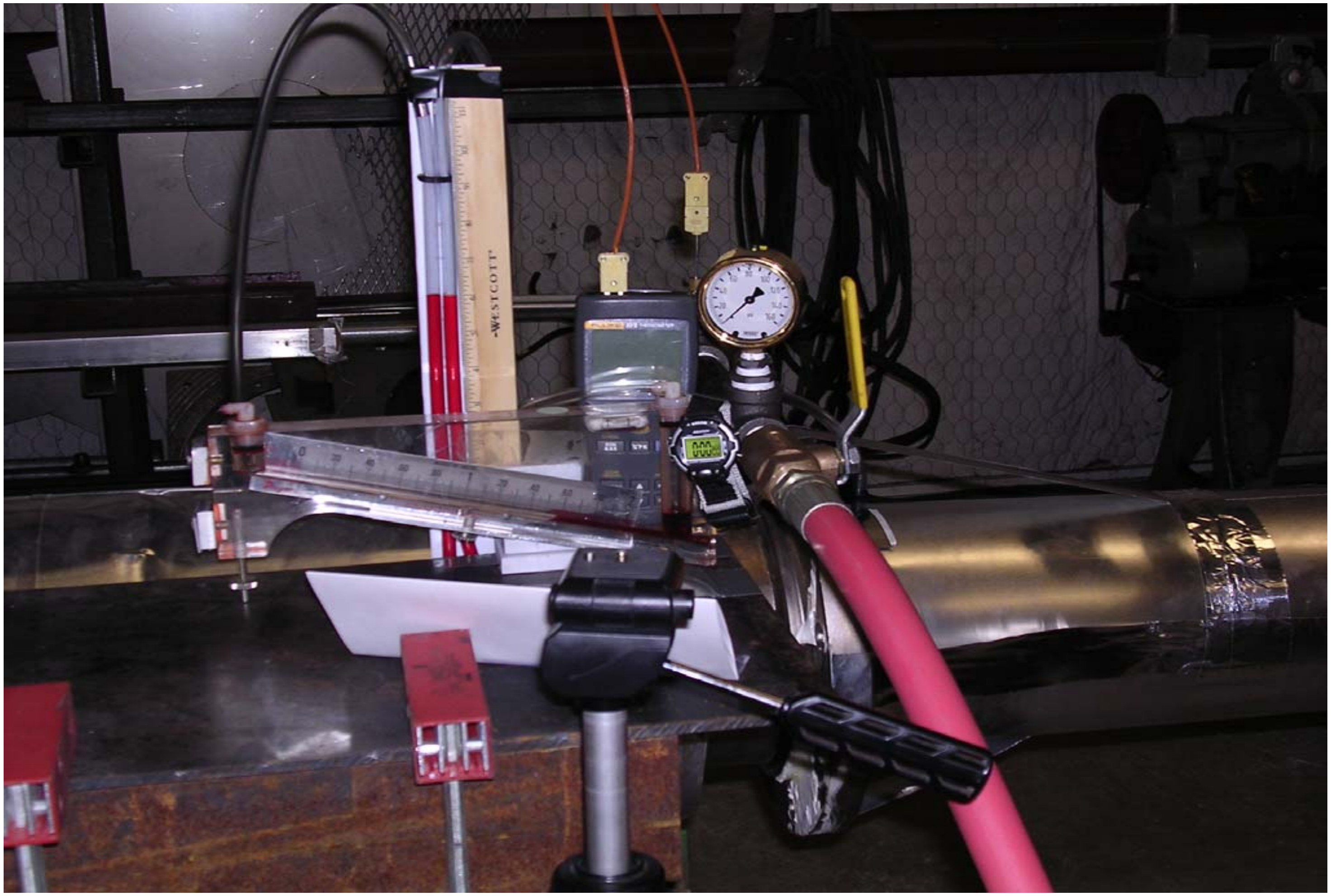

Figure A.24 The experimental setup showing the measuring instruments used to measure inlet pressure, inlet temperature, pressure rise across the jet ejector, and dynamic pressure at the outlet.

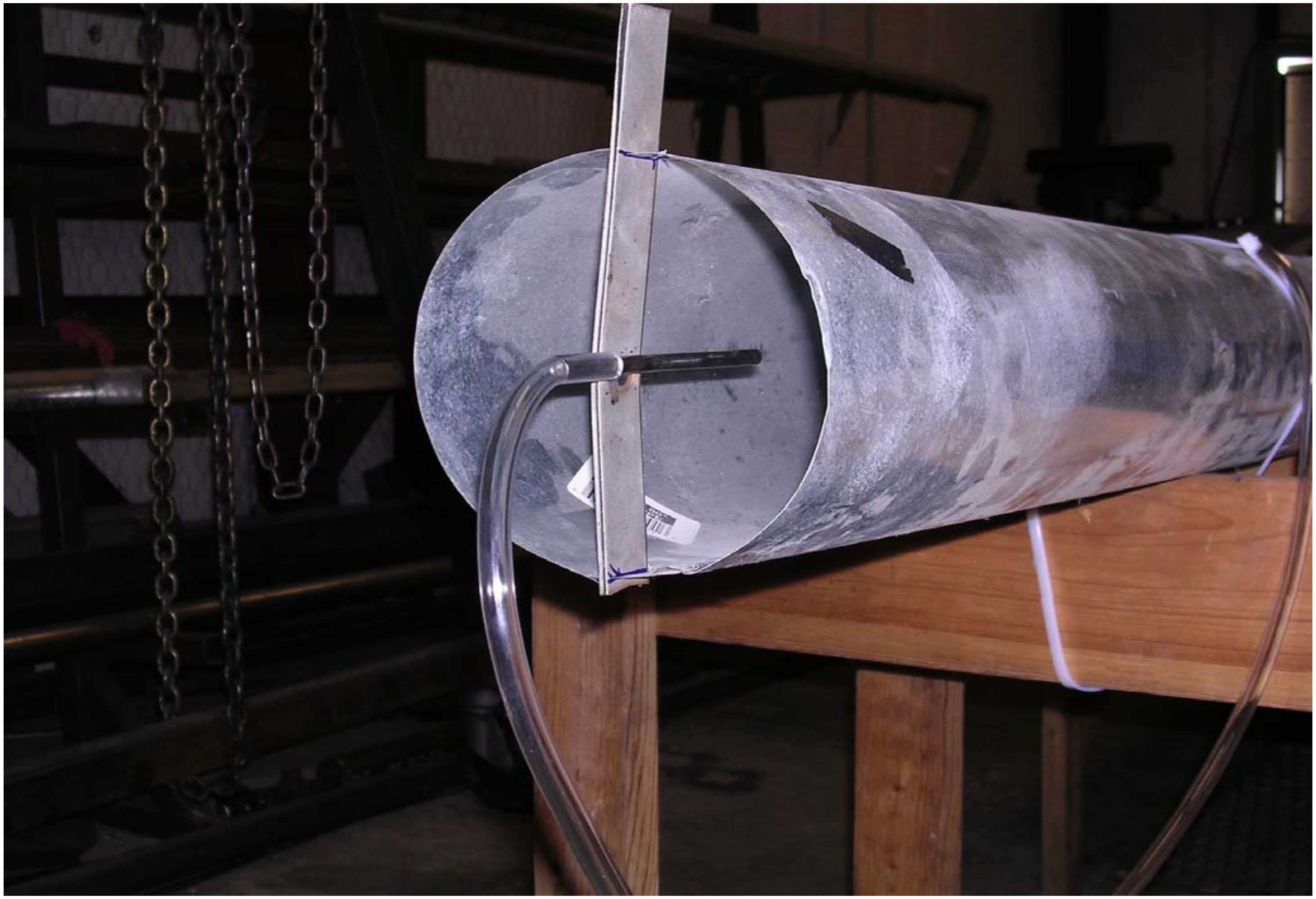

Figure A.25 The experimental setup showing the pitot-tube placed at the outlet of the jet ejector to measure the dynamic pressure.

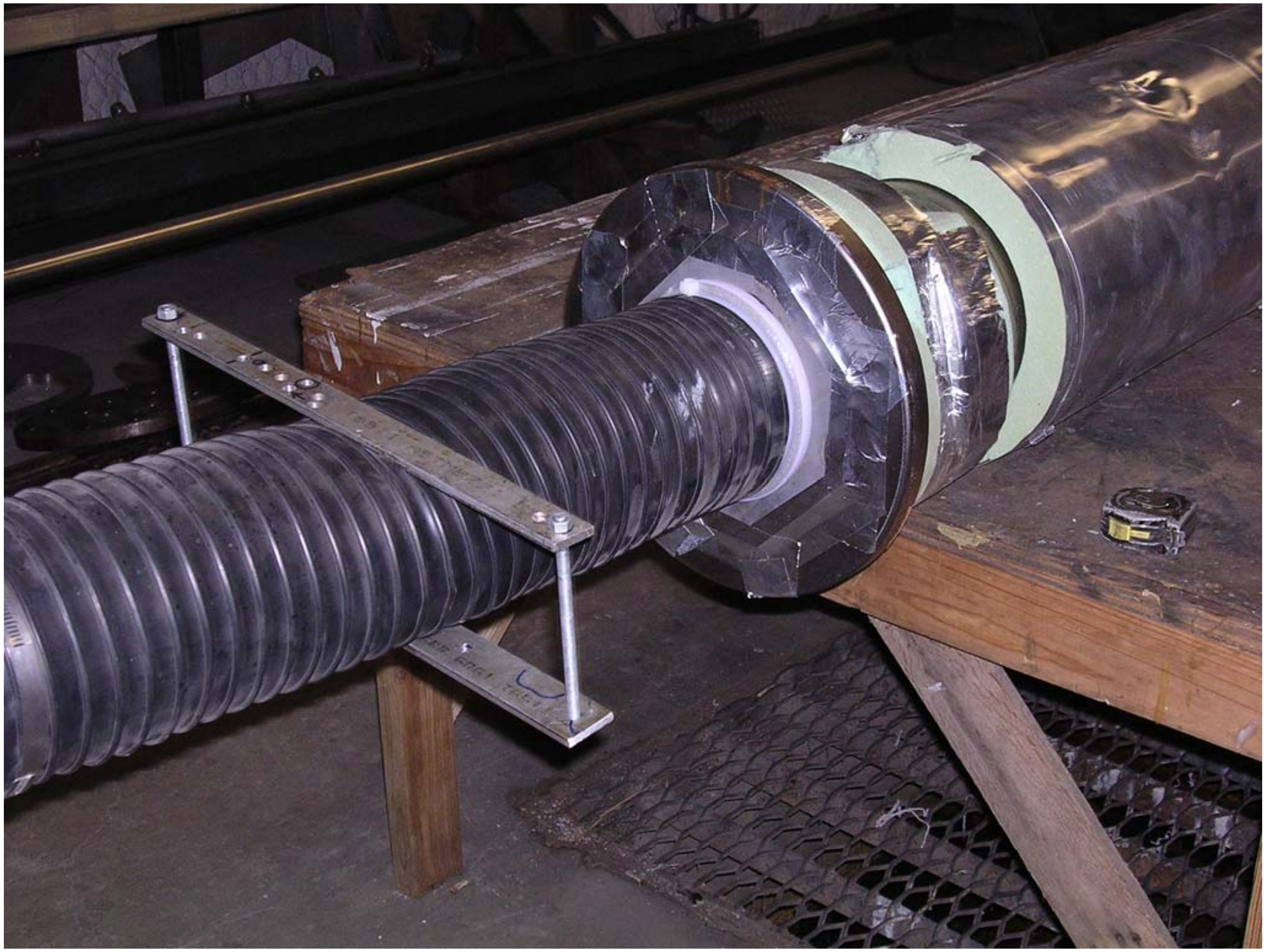

Figure A.26 A closer look of the pinch valve located at the outlet of the jet ejector, which is used to create back pressure inside the system.

Figure A.27 The inside view of the jet ejector showing the mixing vanes and the nozzle. (a) The left picture shows the nozzle pointing towards the diffuser is placed at the center of the mixing vanes. (b) The right picture shows the three internal mixing vanes located in the diffuser section of the jet ejector for proper mixing of motive and propelled streams.

Figure A.28 MixAlco biomass pilot plant located at Texas A&M University, College Station campus.

Figure A.29 The steam produced from the boiler was superheated using the super-heater before entering the jet ejector as motive stream.

Figure A.30 A closer look of the desalination unit, showing the three jet ejectors connected in series.

Figure A.31 A closer look at the primary and secondary heat exchangers connected to the jet ejectors, which are used to distill water.

Figure A.32 The TVC method was supplemented with the Roots Blower to improve the performance. The Roots Blower was used to mechanically compress vapor before entering the jet ejector.

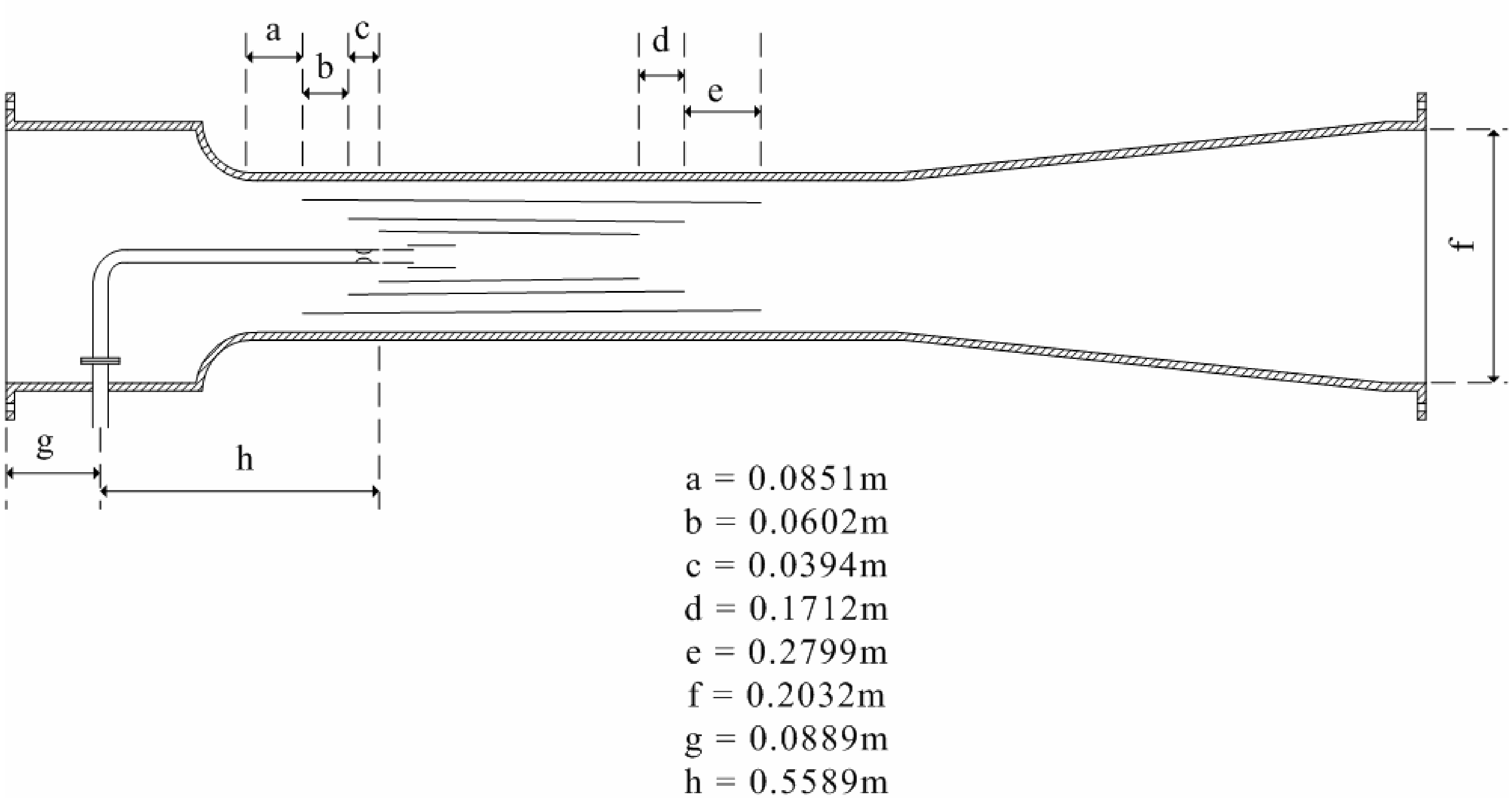

Figure A.33 Diagram of a high-efficiency jet ejector representing position of mixing vanes and nozzle.

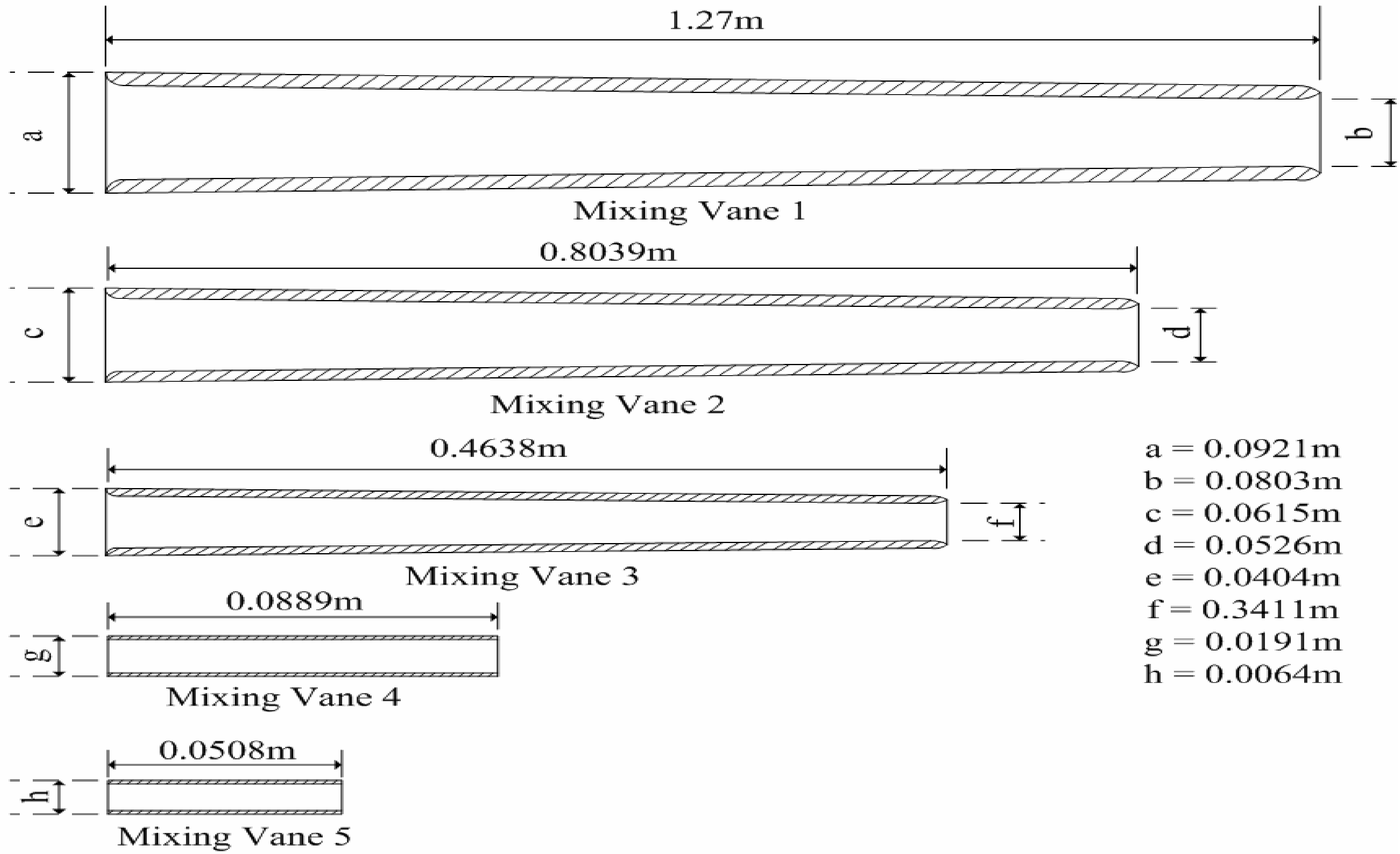

Figure A.34 Diagram of mixing vanes used in a high-efficiency jet ejector operated desalination process.

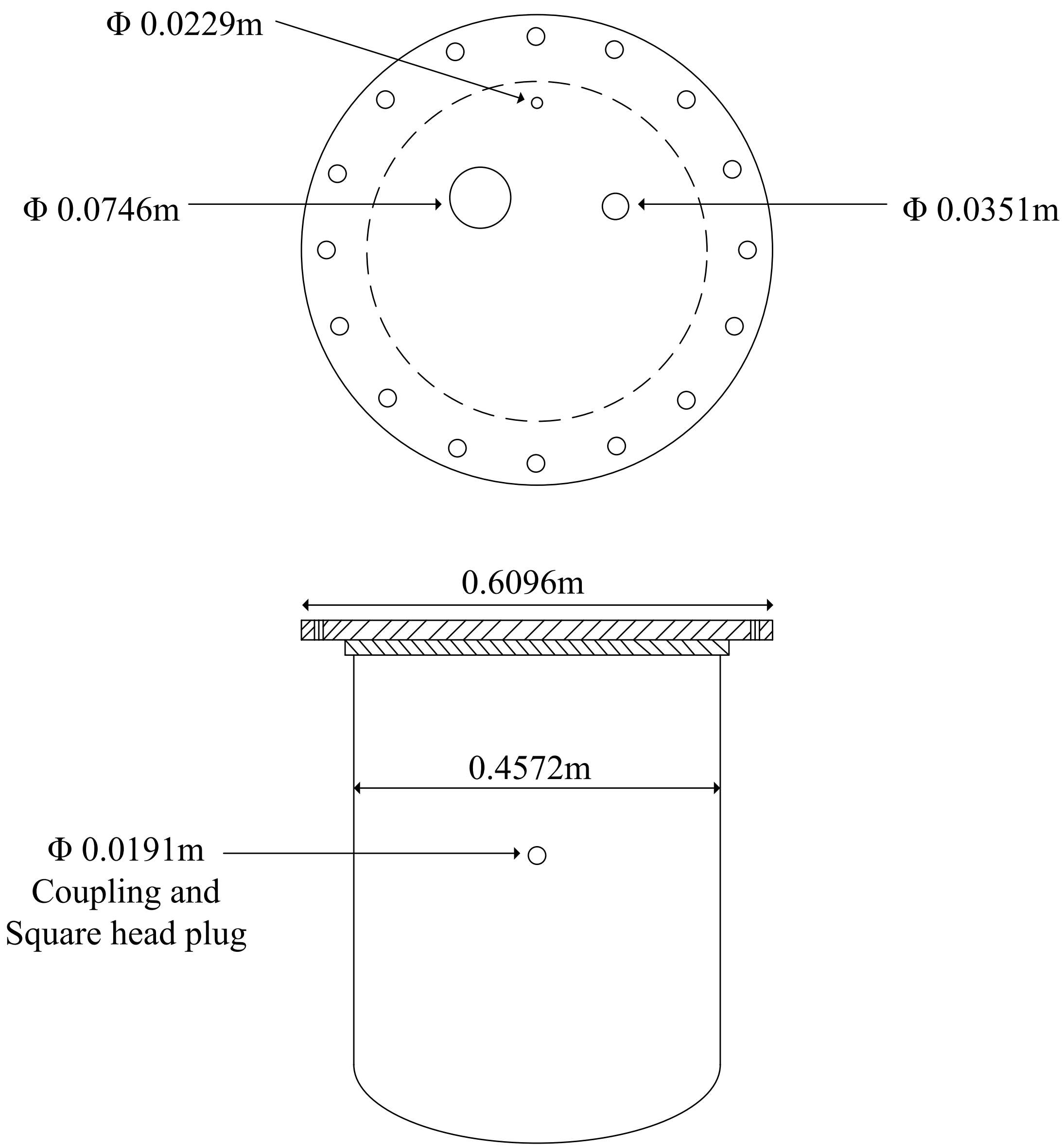

Figure A.35 Diagram of a product water tank used in a high-efficiency jet ejector operated desalination process.

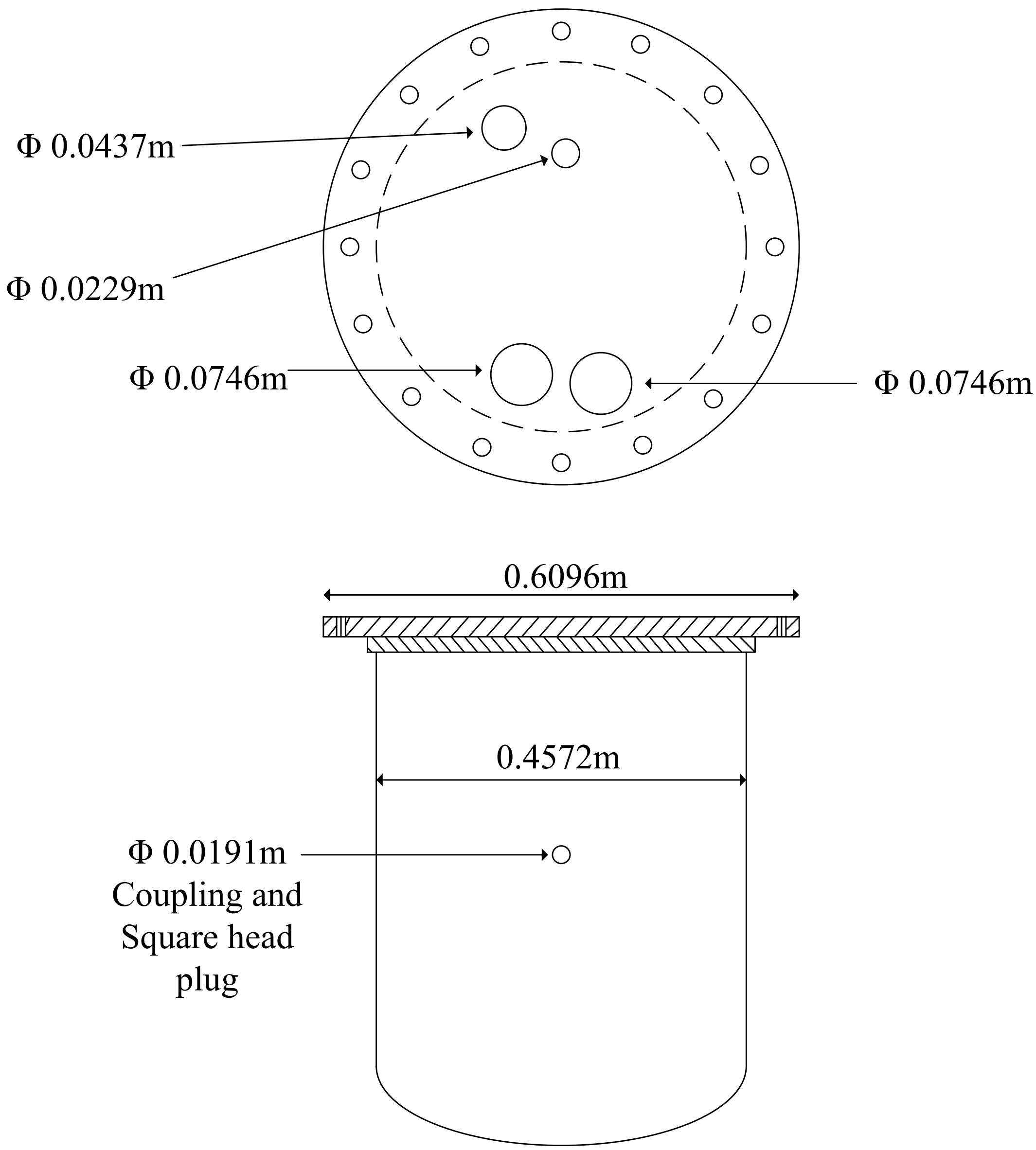

Figure A.36 Diagram of a level control tank used in a high-efficiency jet ejector operated desalination process.

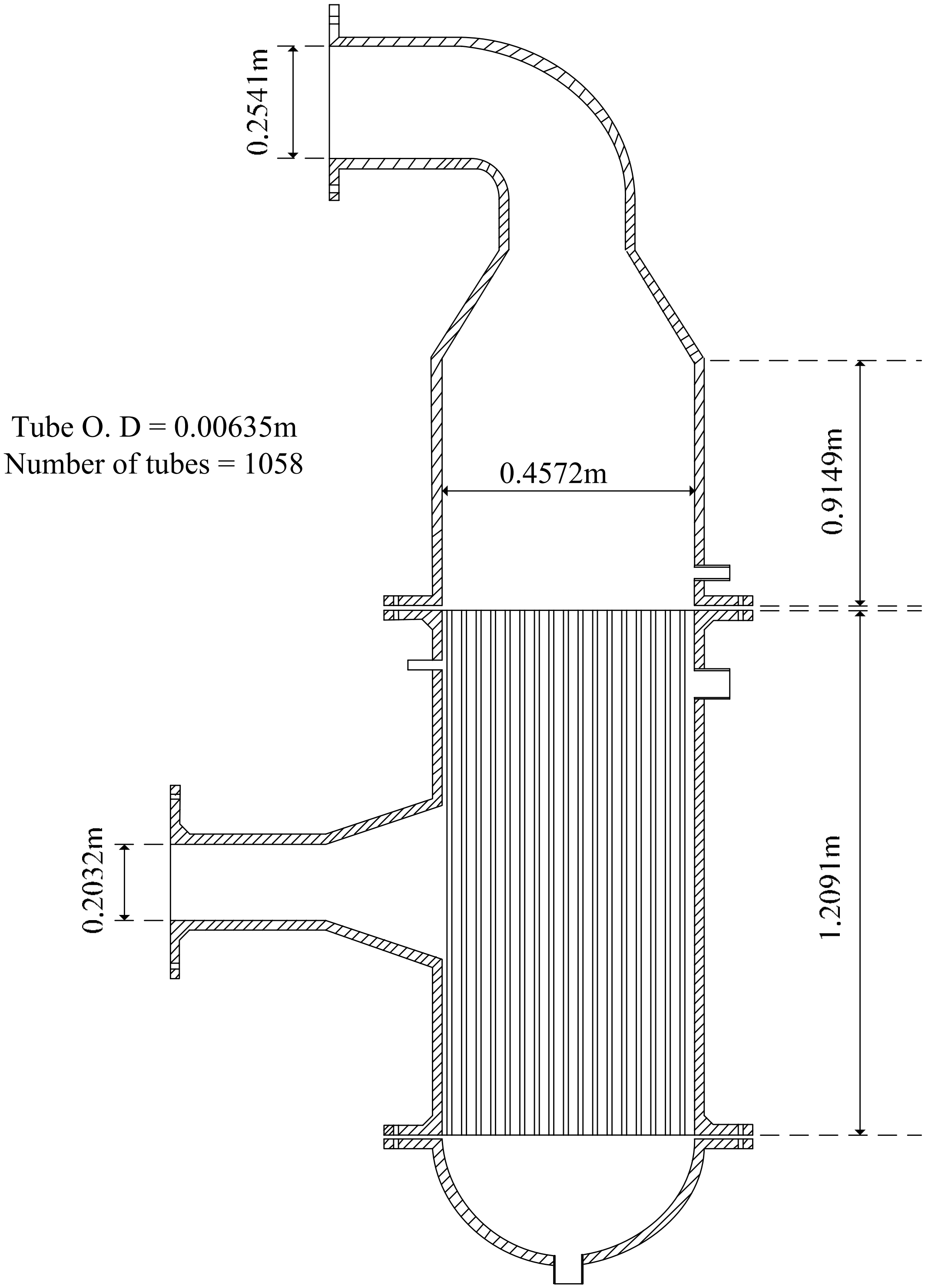

Figure A.37 Diagram of a primary heat exchanger used in a high-efficiency jet ejector operated desalination process.

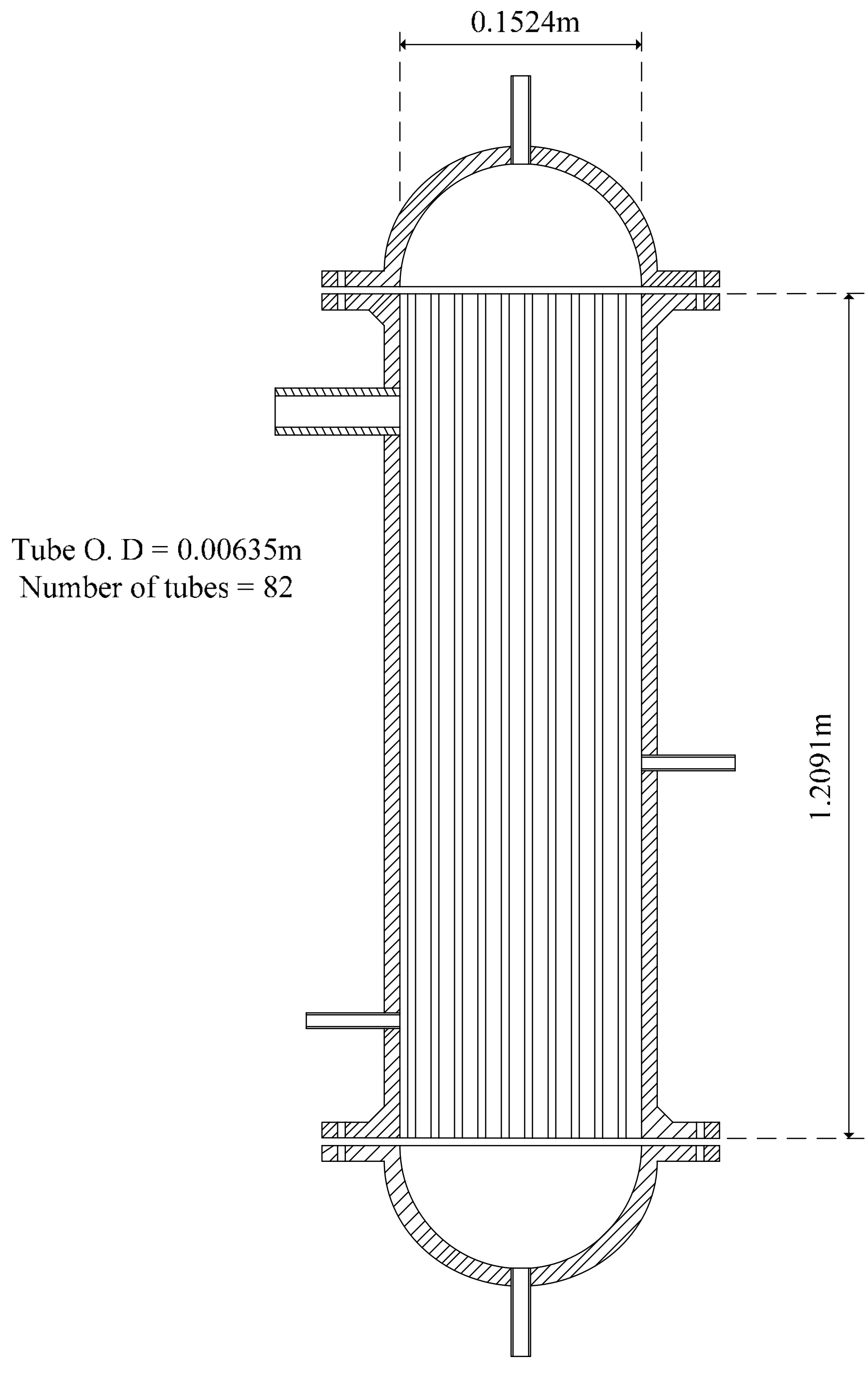

Figure A.38 Diagram of a secondary heat exchanger used in a high-efficiency jet ejector operated desalination process.

APPENDIX B

The static pressures at jet ejector inlet (P_p), nozzle outlet (P_m), and jet ejector outlet (P_t) were obtained using CFD simulation software. The above values for various motive and total mass flow rate, different number of mixing vanes, and various back pressures are noted below (Tables B.1 to B.6).

Table B.1 Static pressures with five mixing vanes (Figures A.2 to A.5) for various pinch valve closings (back pressures).

P_m (Pa)	P_p (Pa)	P_t (Pa)
No pinch valve closing		
102481.56	103694.32	101328.60
102477.24	103505.60	101328.50
102472.86	103321.70	101328.50
102432.17	101763.25	101327.30
102370.20	102832.50	101327.40
Pinch Valve Closing 1		
102477.20	103505.60	101328.50
102459.10	103103.60	101328.20
102442.20	102904.40	101327.90
102401.00	102853.70	101327.60
102370.20	102832.50	101327.40
Pinch Valve Closing 2		
102472.90	103321.70	101328.50
102459.10	103103.60	101328.20
102442.20	102904.40	101327.90
102401.00	102853.70	101327.60
102370.20	102832.50	101327.40
Pinch Valve Closing 3		
102432.20	101763.30	101327.30
102423.50	101764.10	101327.20
102415.00	101768.30	101327.10
102372.70	101902.50	101326.90
102345.70	102028.60	101326.90

Table B.2 Static pressures with three mixing vanes (Figures A.6 to A.10) for various pinch valve closings (back pressures).

P_m (Pa)	P_p (Pa)	P_t (Pa)
No pinch valve closing		
102495.04	104293.40	101328.80
102475.66	103827.80	101328.50
102457.80	103588.40	101328.23
102412.20	103330.40	101327.70
102377.80	103136.70	101327.50
Pinch Valve Closing 1		
102490.45	104088.40	101328.00
102471.40	103638.80	101328.40
102453.90	103410.10	101328.20
102412.20	103330.40	101327.70
102377.80	103136.70	101327.50
Pinch Valve Closing 2		
102481.60	103694.30	101328.60
102463.20	103277.10	101328.30
102449.97	103236.60	101328.00
102408.50	103166.70	101327.70
102374.01	102982.30	101327.50
Pinch Valve Closing 3		
102440.12	102035.95	101327.55
102427.50	101894.00	101327.30
102418.60	102024.20	101327.30
102398.10	102157.90	101327.10
102354.20	102278.55	101327.10

Table B.3 Static pressures with two mixing vanes (Figures A.10 to A.13) for various pinch valve closings (back pressures).

P_m (Pa)	P_p (Pa)	P_t (Pa)
No pinch valve closing		
102676.70	104744.50	101330.30
102690.90	104255.82	101329.80
102702.75	103815.95	101329.40
102688.10	103553.00	101329.76
102690.90	104255.82	101329.80
Pinch Valve Closing 1		
102691.00	104323.30	101330.05
102705.90	103867.33	101329.60
102710.90	103634.70	101329.20
102702.75	103815.95	101329.40
102703.90	102897.90	101328.10
Pinch Valve Closing 2		
102698.10	104121.01	101329.90
102713.30	103680.80	101329.50
102718.30	103458.10	101329.10
102702.75	103815.95	101329.40
102703.90	102897.90	101328.10
Pinch Valve Closing 3		
102774.95	101938.50	101328.03
102781.01	101941.22	101327.90
102781.01	101946.50	101327.80
102783.12	102121.43	101327.50
102761.82	102218.60	101327.60

Table B.4 Static pressures with one mixing vane (Figures A.14 to A.17) for various pinch valve closings (back pressures).

P_m (Pa)	P_p (Pa)	P_t (Pa)
No pinch valve closing		
102593.91	104629.24	101331.60
102624.11	104010.00	101330.90
102638.21	103628.30	101330.35
102623.12	103260.90	101329.60
102676.44	102933.20	101328.30
Pinch Valve Closing 1		
102607.63	104435.50	101331.50
102638.66	103836.70	101330.70
102638.21	103628.30	101330.35
102639.40	103118.60	101329.40
102676.44	102933.20	101328.30
Pinch Valve Closing 2		
102593.90	104629.20	101331.60
102667.34	103504.20	101330.40
102683.00	103162.90	101329.90
102671.75	102845.65	101329.10
102694.10	102807.55	101328.20
Pinch Valve Closing 3		
102887.34	101384.90	101328.24
102884.90	101411.80	101328.10
102878.20	101439.20	101327.90
102837.80	101593.90	101327.70
102800.04	101716.83	101327.63

Table B.5 Static pressures with no mixing vanes (Figures A.18 to A.21) for various pinch valve closings (back pressures).

P_m (Pa)	P_p (Pa)	P_t (Pa)
No pinch valve closing		
102345.60	102652.50	101329.10
102378.40	102275.10	101328.20
102417.67	101882.80	101327.30
102438.12	101676.40	101326.70
102491.50	101337.20	101326.10
Pinch Valve Closing 1		
102391.90	102146.20	101328.20
102425.80	101831.70	101327.50
102442.60	101693.20	101327.00
102477.04	101436.20	101326.30
102517.80	101202.60	101325.90
Pinch Valve Closing 2		
102438.60	101704.50	101327.40
102461.40	101535.60	101326.90
102479.50	101431.00	101326.60
102502.80	101288.40	101326.10
102530.10	101138.40	101325.80
Pinch Valve Closing 3		
102672.40	100167.76	101325.23
102674.20	100237.50	101325.30
102673.41	100379.20	101325.30
102653.77	100571.80	101325.30
102646.96	100642.20	101325.30

Table B.6 Data obtained at the inlet and outlet of the nozzle (Figure IV.1) in FPS units.

P_1 (psig)	T_1 (^{o}F)	P_2 (psig)	T_2 (^{o}F)
130.0	90.9	55.0	58.0
110.0	90.1	45.0	57.5
90.0	88.1	36.0	58.3
70.0	86.1	28.0	56.5
50.0	84.1	22.0	56.4

Table B.7 Data obtained at the inlet and outlet of the nozzle (Figure IV.1) in SI units.

P_1 (Pa)	T_1 (K)	P_2 (Pa)	T_2 (K)
896318.4	305.9	379211.6	287.6
758423.3	305.4	310264.1	287.3
620528.1	304.3	248211.3	287.8
482633.0	303.2	193053.2	286.8
344737.9	302.1	151684.7	286.7

Note: Pressures P_1 and P_2 are gauge pressures.

Table B.8 Data obtained at the outlet of the jet ejector with five mixing vanes (Figure A.2 to A.5) for various pinch valve closings in FPS units.

Jet ejector with five mixing vanes and with no pinch valve closing				
Time (s)	**Inlet Pr (psig)**	**Temp (^oF)**	**Dyn Pr (in H_2O)**	**Pr rise (in H_2O)**
12.9	130	86.4	1.09	1.06
28.5	110	85.7	0.99	0.94
48.0	90	84.4	0.89	0.81
74.3	70	82.5	0.79	0.69
109.7	50	80.7	0.69	0.50
Jet ejector with five mixing vanes and with Pinch Valve Closing 1				
Time (s)	**Inlet Pr (psig)**	**Temp (^oF)**	**Dyn Pr (in H_2O)**	**Pr rise (in H_2O)**
13.7	130	87.2	1.03	1.63
29.8	110	88.6	0.93	1.38
47.8	90	88.8	0.84	1.13
74.2	70	88.3	0.76	0.88
109.7	50	87.7	0.67	0.63
Jet ejector with five mixing vanes and with Pinch Valve Closing 2				
Time (s)	**Inlet Pr (psig)**	**Temp (^oF)**	**Dyn Pr (in H_2O)**	**Pr rise (in H_2O)**
10.2	130	84.3	0.99	2.38
28.2	110	85.4	0.93	2.00
45.4	90	85.5	0.84	1.75
72.6	70	85.0	0.76	1.38
108.1	50	84.5	0.67	1.00
Jet ejector with five mixing vanes and with Pinch Valve Closing 3				
Time (s)	**Inlet Pr (psig)**	**Temp (^oF)**	**Dyn Pr (in H_2O)**	**Pr rise (in H_2O)**
12.6	130	84.7	0.60	6.25
30.2	110	84.4	0.56	5.25
48.1	90	83.5	0.54	4.50
75.6	70	81.8	0.51	3.50
112.1	50	80.1	0.49	2.50

Table B.9 Data obtained at the outlet of the jet ejector with all the mixing vanes (Figure A.2 to A.5) for various pinch valve closings in SI units.

Jet ejector with five mixing vanes and with no pinch valve closing				
Time (s)	**Inlet Pr (Pa)**	**Temp (K)**	**Dyn Pr (Pa)**	**Pr rise (Pa)**
12.9	896318.4	303.37	271.49	234.02
28.5	758423.3	302.98	246.58	234.13
48.0	620528.1	302.26	221.68	201.75
74.3	482633.0	301.21	196.77	171.86
109.7	344737.9	300.21	171.86	124.54
Jet ejector with five mixing vanes and with Pinch Valve Closing 1				
Time (s)	**Inlet Pr (Pa)**	**Temp (K)**	**Dyn Pr (Pa)**	**Pr rise (Pa)**
13.7	896318.4	303.82	256.55	405.99
29.8	758423.3	304.59	231.64	343.73
47.8	620528.1	304.71	209.22	281.46
74.2	482633.0	304.43	189.29	219.18
109.7	344737.9	304.09	166.88	156.92
Jet ejector with five mixing vanes and with Pinch Valve Closing 2				
Time (s)	**Inlet Pr (Pa)**	**Temp (K)**	**Dyn Pr (Pa)**	**Pr rise (Pa)**
10.2	896318.4	302.21	246.58	592.79
28.2	758423.3	302.82	231.64	498.15
45.4	620528.1	302.87	209.22	435.88
72.6	482633.0	302.59	189.29	343.73
108.1	344737.9	302.32	166.88	249.07
Jet ejector with five mixing vanes and with Pinch Valve Closing 3				
Time (s)	**Inlet Pr (Pa)**	**Temp (K)**	**Dyn Pr (Pa)**	**Pr rise (Pa)**
12.6	896318.4	302.43	149.45	1556.72
30.2	758423.3	302.26	139.48	1307.65
48.1	620528.1	301.76	134.51	1120.84
75.6	482633.0	300.82	127.11	871.76
112.1	344737.9	299.87	122.11	622.69

Note: The inlet pressure is gauge pressure.

Table B.10 Data obtained at the outlet of the jet ejector with three mixing vanes (Figure A.6 to A.9) for various pinch valve closings in FPS units.

Jet ejector with three mixing vanes and with no pinch valve closing				
Time (s)	**Inlet Pr (psig)**	**Temp (^oF)**	**Dyn Pr (in H_2O)**	**Pr rise (in H_2O)**
11.0	130	91.4	1.23	1.250
26.5	110	90.8	1.12	1.125
47.1	90	89.5	1.01	0.937
74.3	70	87.7	0.87	0.813
111.2	50	86.2	0.74	0.563
Jet ejector with three mixing vanes and with Pinch Valve Closing 1				
Time (s)	**Inlet Pr (psig)**	**Temp (^oF)**	**Dyn Pr (in H_2O)**	**Pr rise (in H_2O)**
13.0	130	83.5	1.33	2.063
28.6	110	84.2	1.18	1.813
48.4	90	84.1	1.08	1.625
75.5	70	83.5	0.92	1.187
112.4	50	83.1	0.76	0.813
Jet ejector with three mixing vanes and with Pinch Valve Closing 2				
Time (s)	**Inlet Pr (psig)**	**Temp (^oF)**	**Dyn Pr (in H_2O)**	**Pr rise (in H_2O)**
12.5	130	87.4	1.27	3.5
28.4	110	88.1	1.12	3.0
47.4	90	87.9	1.02	2.563
75.1	70	87.5	0.88	2.063
110.5	50	87.1	0.74	1.437
Jet ejector with three mixing vanes and with Pinch Valve Closing 3				
Time (s)	**Inlet Pr (psig)**	**Temp (^oF)**	**Dyn Pr (in H_2O)**	**Pr rise (in H_2O)**
11.5	130	91.2	0.72	10.0
27.5	110	92.8	0.68	7.5
47.0	90	92.7	0.64	6.5
73.5	70	92.1	0.60	4.75
110.3	50	91.3	0.56	3.375

Table B.11 Data obtained at the outlet of the jet ejector with three mixing vanes (Figure A.6 to A.9) for various pinch valve closings in SI units.

Jet ejector with three mixing vanes and with no pinch valve closing				
Time (s)	**Inlet Pr (Pa)**	**Temp (K)**	**Dyn Pr (Pa)**	**Pr rise (Pa)**
11.0	896318.4	306.15	306.36	311.35
26.5	758423.3	305.82	278.96	281.45
47.1	620528.1	305.09	251.57	234.13
74.3	482633.0	304.09	216.69	201.75
111.2	344737.9	303.26	184.32	139.48
Jet ejector with three mixing vanes and with Pinch Valve Closing 1				
Time (s)	**Inlet Pr (Pa)**	**Temp (K)**	**Dyn Pr (Pa)**	**Pr rise (Pa)**
13.0	896318.4	305.76	293.91	420.94
28.6	758423.3	305.87	264.02	358.67
48.4	620528.1	305.54	241.61	326.29
75.5	482633.0	304.82	214.21	234.02
112.4	344737.9	304.21	184.32	171.86
Jet ejector with three mixing vanes and with Pinch Valve Closing 2				
Time (s)	**Inlet Pr (Pa)**	**Temp (K)**	**Dyn Pr (Pa)**	**Pr rise (Pa)**
12.5	896318.4	306.43	276.47	717.34
28.4	758423.3	306.87	244.09	607.75
47.4	620528.1	306.76	226.66	530.53
75.1	482633.0	306.48	204.24	388.56
110.5	344737.9	306.21	174.35	296.39
Jet ejector with three mixing vanes and with Pinch Valve Closing 3				
Time (s)	**Inlet Pr (Pa)**	**Temp (K)**	**Dyn Pr (Pa)**	**Pr rise (Pa)**
11.5	896318.4	307.71	166.88	1868.06
27.5	758423.3	308.09	154.43	1589.11
47.0	620528.1	308.09	149.45	1384.86
73.5	482633.0	307.93	139.48	1043.63
110.3	344737.9	307.65	132.01	717.34

Note: The inlet pressure is gauge pressure.

Table B.12 Data obtained at the outlet of the jet ejector with two mixing vanes (Figure A.10 to A.13) for various pinch valve closings in FPS units.

Jet ejector with two mixing vanes and with no pinch valve closing				
Time (s)	**Inlet Pr (psig)**	**Temp (^oF)**	**Dyn Pr (in H_2O)**	**Pr rise (in H_2O)**
7.1	130	80.7	1.41	1.375
22.4	110	81.9	1.25	1.25
40.1	90	81.5	1.15	1.063
66.5	70	80.6	0.97	0.875
102.2	50	79.6	0.79	0.625
Jet ejector with two mixing vanes and with Pinch Valve Closing 1				
Time (s)	**Inlet Pr (psig)**	**Temp (^oF)**	**Dyn Pr (in H_2O)**	**Pr rise (in H_2O)**
13.5	130	83.5	1.33	2.063
29.5	110	84.2	1.18	1.813
49.1	90	84.1	1.08	1.625
76.4	70	83.5	0.92	1.187
111.5	50	83.1	0.76	0.813
Jet ejector with two mixing vanes and with Pinch Valve Closing 2				
Time (s)	**Inlet Pr (psig)**	**Temp (^oF)**	**Dyn Pr (in H_2O)**	**Pr rise (in H_2O)**
18.2	130	87.4	1.27	3.5
33.3	110	88.1	1.12	3.0
52.1	90	87.9	1.02	2.563
79.2	70	87.5	0.88	2.063
115.4	50	87.1	0.74	1.437
Jet ejector with two mixing vanes and with Pinch Valve Closing 3				
Time (s)	**Inlet Pr (psig)**	**Temp (^oF)**	**Dyn Pr (in H_2O)**	**Pr rise (in H_2O)**
9.3	130	91.2	0.72	10.0
26.2	110	92.8	0.68	7.5
43.1	90	92.7	0.64	6.5
69.0	70	92.1	0.60	4.75
103.4	50	91.3	0.56	3.375

Table B.13 Data obtained at the outlet of the jet ejector with two mixing vanes (Figure A.10 to A.13) for various pinch valve closings in SI units.

Jet ejector with two mixing vanes and with no pinch valve closing				
Time (s)	**Inlet Pr (Pa)**	**Temp (K)**	**Dyn Pr (Pa)**	**Pr rise (Pa)**
7.1	896318.4	300.21	351.19	343.72
22.4	758423.3	300.87	311.34	311.34
40.1	620528.1	300.65	286.34	264.02
66.5	482633.0	300.15	241.61	219.18
102.2	344737.9	299.59	196.77	156.92
Jet ejector with two mixing vanes and with Pinch Valve Closing 1				
Time (s)	**Inlet Pr (Pa)**	**Temp (K)**	**Dyn Pr (Pa)**	**Pr rise (Pa)**
13.5	896318.4	301.76	331.27	513.09
29.5	758423.3	302.15	293.91	450.83
49.1	620528.1	302.09	269.00	405.99
76.4	482633.0	301.76	229.15	296.39
111.5	344737.9	301.54	189.29	201.75
Jet ejector with two mixing vanes and with Pinch Valve Closing 2				
Time (s)	**Inlet Pr (Pa)**	**Temp (K)**	**Dyn Pr (Pa)**	**Pr rise (Pa)**
18.2	896318.4	303.93	316.33	871.76
33.3	758423.3	304.32	278.96	747.23
52.1	620528.1	304.21	254.06	637.63
79.2	482633.0	303.98	219.18	513.09
115.4	344737.9	303.76	184.32	358.67
Jet ejector with two mixing vanes and with Pinch Valve Closing 3				
Time (s)	**Inlet Pr (Pa)**	**Temp (K)**	**Dyn Pr (Pa)**	**Pr rise (Pa)**
9.3	896318.4	306.04	179.33	2490.75
26.2	758423.3	306.93	169.37	1868.07
43.1	620528.1	306.87	159.41	1618.99
69.0	482633.0	306.54	149.45	1183.11
103.4	344737.9	306.09	139.48	841.87

Note: The inlet pressure is gauge pressure.

Table B.14 Data obtained at the outlet of the jet ejector with one mixing vane (Figure A.14 to A.17) for various pinch valve closings in FPS units.

Jet ejector with one mixing vane and with no pinch valve closing				
Time (s)	**Inlet Pr (psig)**	**Temp (^oF)**	**Dyn Pr (in H_2O)**	**Pr rise (in H_2O)**
16.1	130	85.8	1.64	2.125
33.4	110	83.3	1.43	1.75
54.3	90	81.1	1.26	1.563
82.2	70	79.7	1.08	1.187
119.3	50	77.5	0.87	0.813
Jet ejector with one mixing vane and with Pinch Valve Closing 1				
Time (s)	**Inlet Pr (psig)**	**Temp (^oF)**	**Dyn Pr (in H_2O)**	**Pr rise (in H_2O)**
11.3	130	87.8	1.56	2.687
28.4	110	86.0	1.38	2.25
45.4	90	84.0	1.24	2.0
77.2	70	81.7	1.02	1.437
113.5	50	80.3	0.84	1.063
Jet ejector with one mixing vane and with Pinch Valve Closing 2				
Time (s)	**Inlet Pr (psig)**	**Temp (^oF)**	**Dyn Pr (in H_2O)**	**Pr rise (in H_2O)**
15.3	130	88.3	1.65	4.063
32.0	110	88.4	1.27	3.25
51.5	90	87.9	1.13	3.0
78.4	70	87.1	0.96	2.313
115.0	50	86.0	0.79	1.563
Jet ejector with one mixing vane and with Pinch Valve Closing 3				
Time (s)	**Inlet Pr (psig)**	**Temp (^oF)**	**Dyn Pr (in H_2O)**	**Pr rise (in H_2O)**
16.4	130	92.3	0.63	10.5
30.5	110	92.9	0.60	9.0
50.5	90	92.7	0.57	7.375
78.3	70	92.3	0.55	5.5
114.2	50	91.9	0.53	3.75

Table B.15 Data obtained at the outlet of the jet ejector with one mixing vane (Figure A.14 to A.17) for various pinch valve closings in SI units.

Jet ejector with one mixing vane and with no pinch valve closing				
Time (s)	**Inlet Pr (Pa)**	**Temp (K)**	**Dyn Pr (Pa)**	**Pr rise (Pa)**
16.1	896318.4	303.04	408.48	530.53
33.4	758423.3	301.65	356.18	435.88
54.3	620528.1	300.43	313.84	388.56
82.2	482633.0	299.65	269.00	296.39
119.3	344737.9	298.43	216.69	201.75
Jet ejector with one mixing vane and with Pinch Valve Closing 1				
Time (s)	**Inlet Pr (Pa)**	**Temp (K)**	**Dyn Pr (Pa)**	**Pr rise (Pa)**
11.3	896318.4	304.15	388.56	670.13
28.4	758423.3	303.15	343.73	560.42
45.4	620528.1	302.04	308.85	498.15
77.2	482633.0	300.76	254.06	358.67
113.5	344737.9	299.98	209.22	364.02
Jet ejector with one mixing vane and with Pinch Valve Closing 2				
Time (s)	**Inlet Pr (Pa)**	**Temp (K)**	**Dyn Pr (Pa)**	**Pr rise (Pa)**
15.3	896318.4	304.43	410.97	1011.25
32.0	758423.3	304.48	316.33	809.49
51.5	620528.1	304.21	281.46	747.23
78.4	482633.0	303.76	239.11	575.36
115.0	344737.9	303.15	196.77	388.56
Jet ejector with one mixing vane and with Pinch Valve Closing 3				
Time (s)	**Inlet Pr (Pa)**	**Temp (K)**	**Dyn Pr (Pa)**	**Pr rise (Pa)**
16.4	896318.4	306.65	156.92	2615.29
30.5	758423.3	306.98	149.45	2241.68
50.5	620528.1	306.87	141.97	1838.17
78.3	482633.0	306.65	136.99	1369.92
114.2	344737.9	306.43	132.01	934.33

Note: The inlet pressure is gauge pressure.

Table B.16 Data obtained at the outlet of the jet ejector with no mixing vanes (Figure A.18 to A.21) for various pinch valve closings in FPS units.

Jet ejector with no mixing vanes and with no pinch valve closing				
Time (s)	**Inlet Pr (psig)**	**Temp (^oF)**	**Dyn Pr (in H_2O)**	**Pr rise (in H_2O)**
16.1	130	84.1	2.20	2.75
31.5	110	83.8	1.92	2.53
52.2	90	82.9	1.60	1.875
79.6	70	81.4	1.32	1.437
115.4	50	80.5	1.05	0.937
Jet ejector with no mixing vanes and with Pinch Valve Closing 1				
Time (s)	**Inlet Pr (psig)**	**Temp (^oF)**	**Dyn Pr (in H_2O)**	**Pr rise (in H_2O)**
14.4	130	86.3	1.94	3.437
30.0	110	86.7	1.68	2.937
50.1	90	86.4	1.44	2.437
77.1	70	85.8	1.19	1.875
113.5	50	85.3	0.93	1.313
Jet ejector with no mixing vanes and with Pinch Valve Closing 2				
Time (s)	**Inlet Pr (psig)**	**Temp (^oF)**	**Dyn Pr (in H_2O)**	**Pr rise (in H_2O)**
13.4	130	87.1	1.72	4.623
30.0	110	87.1	1.50	4.125
49.2	90	86.4	1.3	3.375
78.0	70	85.2	1.07	2.5
113.2	50	84.0	0.88	1.75
Jet ejector with no mixing vanes and with Pinch Valve Closing 3				
Time (s)	**Inlet Pr (psig)**	**Temp (^oF)**	**Dyn Pr (in H_2O)**	**Pr rise (in H_2O)**
84.	130	80.8	0.74	8.75
29.5	110	78.5	0.70	7.437
49.5	90	76.4	0.65	6.25
79.3	70	74.1	0.60	4.5
117.0	50	72.5	0.56	3.187

Table B.17 Data obtained at the outlet of the jet ejector with no mixing vanes (Figure A.18 to A.21) for various pinch valve closings in SI units.

Jet ejector with no mixing vanes and with no pinch valve closing				
Time (s)	**Inlet Pr (Pa)**	**Temp (K)**	**Dyn Pr (Pa)**	**Pr rise (Pa)**
16.1	896318.4	302.09	547.96	684.96
31.5	758423.3	301.93	478.22	637.63
52.2	620528.1	301.43	398.52	468.26
79.6	482633.0	300.59	328.78	358.67
115.4	344737.9	300.09	261.53	234.13
Jet ejector with no mixing vanes and with Pinch Valve Closing 1				
Time (s)	**Inlet Pr (Pa)**	**Temp (K)**	**Dyn Pr (Pa)**	**Pr rise (Pa)**
14.4	896318.4	303.32	483.21	856.82
30.0	758423.3	303.54	418.45	732.28
50.1	620528.1	303.37	358.67	607.75
77.1	482633.0	303.04	296.39	468.26
113.5	344737.9	302.76	231.64	326.28
Jet ejector with no mixing vanes and with Pinch Valve Closing 2				
Time (s)	**Inlet Pr (Pa)**	**Temp (K)**	**Dyn Pr (Pa)**	**Pr rise (Pa)**
13.4	896318.4	303.76	428.41	1153.22
30.0	758423.3	303.76	373.61	1028.68
49.2	620528.1	303.37	323.79	841.87
78.0	482633.0	302.71	266.51	622.69
113.2	344737.9	302.04	219.18	435.88
Jet ejector with no mixing vanes and with Pinch Valve Closing 3				
Time (s)	**Inlet Pr (Pa)**	**Temp (K)**	**Dyn Pr (Pa)**	**Pr rise (Pa)**
14.5	896318.4	300.26	184.32	2179.41
29.5	758423.3	298.98	174.35	1853.12
49.5	620528.1	297.82	161.89	1556.72
79.3	482633.0	296.54	149.45	1120.84
117.0	344737.9	296.54	139.48	794.55

Note: The inlet pressure is gauge pressure.

VITA

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