SINGLE PHASE STEAM EJECTOR INVESTIGATION: EFFECT OF DIFFERENT AREA RATIO THROAT TO ENTRAINMENT RATIO

Stefan Mardikus and Gregorius Bryan H.R.

Mechanical Engineering Department, Faculty of Science and Technology, Sanata Dharma University, Indonesia
(E-mail: stefan@usd.ac.id, gregoriusbryan92@gmail.com,)

ABSTRACT

The utilization of waste and low-grade thermal energy has become an interest to researchers ever since this type of energy is available from sources, such as industrial processing waste, solar collectors, and emission from automobile. Steam ejector refrigeration system is an application, which is economically feasible and environment-friendly as it can operate with waste heat and a harmless refrigerant such as water. This refrigeration system has many advantages such as high reliability, structural simplicity, long life span, low cost, relatively flexible in terms of refrigerant use, easy to maintain and can be used with water which is the most environment friendly refrigerant. Ejector application in air-conditioning or refrigeration system is either to totally replace the compressor or is used for cycle optimization. The aim of this experiment is to investigate the entrainment behaviour and performance of steam ejector. Through enlarging the designed mixing chamber by replaceable throats, optimum area ratio throat of mixing chamber is studied experimentally. A small scale steam ejector refrigeration system was designed and manufactured. This ejector setup consist of an open loop configuration and the boiler operates in the pressure range of Pb = 100 to 400 kPa. The typical evaporator temperatures operates from Te = 50 to 80 degree Celsius, while the condenser temperature fixed at Tc = 27 degree Celsius. The mixing chamber with 8 mm diameter and three length configurations (50 mm, 100 mm, 150 mm) are tested with 2 mm nozzle diameter. With variable area ratio throat of mixing chamber, this experiment shows that the optimum entrainment ratio is obtained by throat area ratio 18.75 at 100 kPa primary pressure and 80 degree Celsius secondary temperature at 1.00.

Keywords: Area Ratio Throat; Entrainment Ratio; Steam Ejector

1. INTRODUCTION

Waste heat is a type of energy that available from sources such as industrial process waste, solar collectors, and exhausts with temperature between 80°C - 200°C (Chandra & Ahmed, 2014). Based on U.S. Department of Energy, 20 – 50% energy losses on manufacture process were waste heat, where this type of energy is potentially can be reused again. Richard Law (2015) noted that utilization of waste heat on manufactures in U.S may produce 14 TWh, which is equal to £100 million per year. According to this potential advantage, waste heat can be utilized as main source of energy in absorption chiller, electrical heat pump, absorption heat pump, and non-mechanical refrigeration system (Meyer et al., 2008).

Steam ejector refrigeration system is one of non-mechanical refrigeration system that has been researched in decades. This refrigeration system is first discovered by Le Blanc and Parson on 1901 and has many advantages over the other type of systems such as high reliability, structural simplicity, long life span, low cost, relatively flexible in terms of refrigerant use, easy to maintain and can be used with water which is the most environment friendly refrigerant. Ejector application in air-conditioning or refrigeration system is either to totally replace the compressor or is used for cycle optimization. Ejectors are used in aerospace engineering for thrust augmentation, exhaust noise suppression and mixing of exhaust gases with fresh air to reduce the thermal effect. In process industries, ejectors are noted to be used widely for entraining and pumping corrosive liquids and other type of gasses which is difficult to handle (Chandra & Ahmed, 2014).

Figure 1 shows a schematic diagram of an ejector refrigeration system. This cycle is similar to the conventional vapor compression system except that the compressor is replaced by a liquid circulation pump, boiler and ejector. Briefly, as heat is added to the boiler, the evaporated refrigerant is evolved at high temperature and pressure (2). This high pressure refrigerant, which can be called either ‘‘primary fluid’’ or ‘‘motive fluid’’, expands through the primary nozzle in an ejector and produces a very low pressure region at the primary nozzle exit plane (3). This low pressure allows a liquid refrigerant in the evaporator to vaporize at low temperature to create the refrigeration effect. Heat used to vaporize this refrigerant is the cooling load of the system. The evaporated ‘‘secondary fluid’’ will be entrained from the evaporator and mixed with the primary fluid in a mixing chamber of the ejector. The mixed stream is discharged via the diffuser to a condenser (4), where the vapor is condensed (5). The accumulated liquid refrigerant in the condenser is returned back to the boiler by the feed pump (1) whilst the remainder is expanded through the throttling valve to the evaporator (6), to complete the cycle (Sriveerakul et al., 2006).

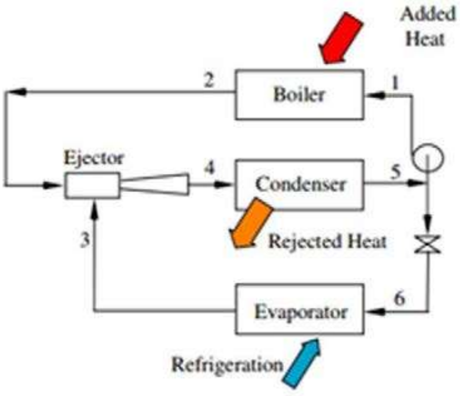

Figure 1 Schematic diagram of ejector refrigeration system

Figure 2 shows the schematic diagram of a typical steam ejector. According to Sriveerakul, a steam ejector consists of four principal parts, which are the primary nozzle, the mixing chamber, the ejector throat and the subsonic diffuser. Moreover, the diagram describes the operating characteristic of an ejector. The high pressure primary steam (P) starts to accelerate as it enters a convergent section of the nozzle and reaches the sonic level at the nozzle throat (i). The speed of primary flow is further increased while expanding through a divergent section of the nozzle. At the exit plane, the primary fluid expands out with supersonic speed and results the low pressure region (ii). This expanded wave (jet core) of the motive steam entrains and draws the secondary fluid into the mixing chamber (S), where the secondary steam is accelerated and completely mixed with the primary steam (iii). A normal shock wave is then induced in the ejector throat (iv), creating a compression effect, and the flow speed suddenly drops to subsonic value. Further compression is achieved when the mixed stream passes through the subsonic diffuser (B).

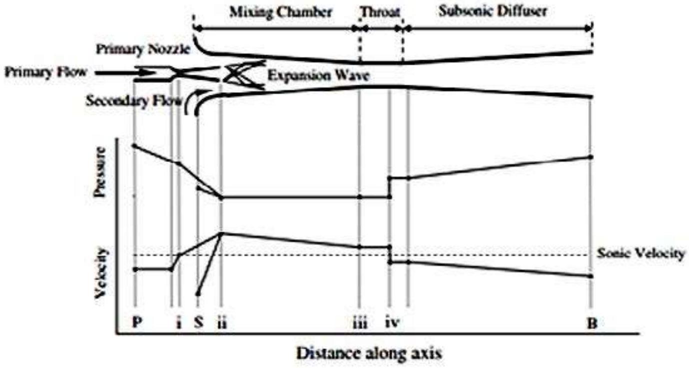

Figure 2 Schematic diagram of typical steam ejector and flow characteristic

2. METHODOLOGY

The schematic diagram and photograph of an experimental steam ejector refrigerator is shown in Figure 3. In this paper, the ejector was designed to operate with a boiler pressure of 100 – 400 kPa, while the temperature of evaporator operated at 50 – 80 °C with water as the refrigerant. The boiler was constructed using 8” diameter mild steel pipe with thickness 10 mm and used two 2 kW electric heaters which is attached the bottom plate. The evaporator also had same construction with boiler, but it equipped with 1 kW electric heater. The rubber gaskets and sealant were used to avoid any leakage. The condenser operates at constant temperature 27 °C and constructed from 150 mm diameter aluminum with maximum volume 20 L.

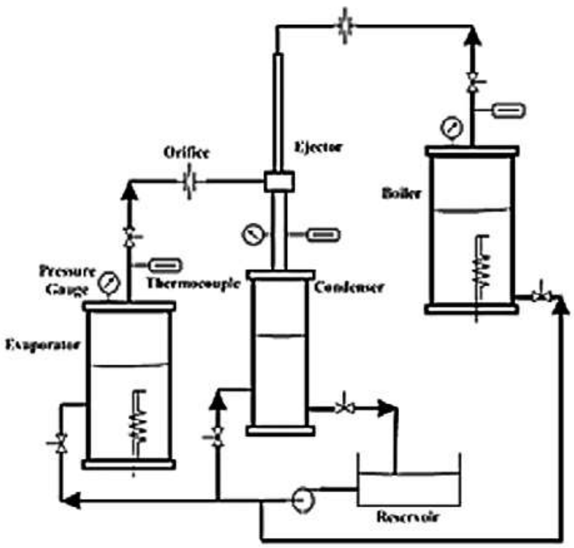

Figure 3 Experimental Steam Ejector Refrigeration System

The experimental are executed in batches. Before each test run the boiler and evaporator were filled with water up to 10 liter. The next step is switch the boiler and evaporator electric heaters on. While the boiler and evaporator heat up until designed operating condition, the condenser was filled with water up to 15 liter and remained at constant temperature 27 °C. After boiler and evaporator reached the designated pressure and temperature, both valves were opened for about 10 seconds at a time. The mass flow rate of boiler, evaporator, and outlet ejector were measured by orifice flow meter and recorded at the same time. Next, the boiler and evaporator valve remained open until all vapor removed from the system at atmospheric pressure in both vessels. Water in boiler, evaporator, and condenser then removed from vessel using a vacuum pump. The procedure was repeated again with different operating condition of boiler and evaporator, for 3 different replaceable throats that shown in Table 1.

Geometries of experimental ejector described in Figure 4. The ejector was designed based on the methods provided in literature (Sriveerakul et al., 2006). There were three throats constructed three different throat length, for the purpose of examining influence of mixing chamber throat on ejector performance. These throats had the same diameter 8 mm. The significant geometries of the experiment throat were listed in Table 1.

Table 1 Mixing Chamber's Throat Variable Geometries

Throat Diameter, x (mm)	Throat Length, y (mm)	Area Ratio Throat (L/D)
8	50	6.25
8	100	12.5
8	150	18.75

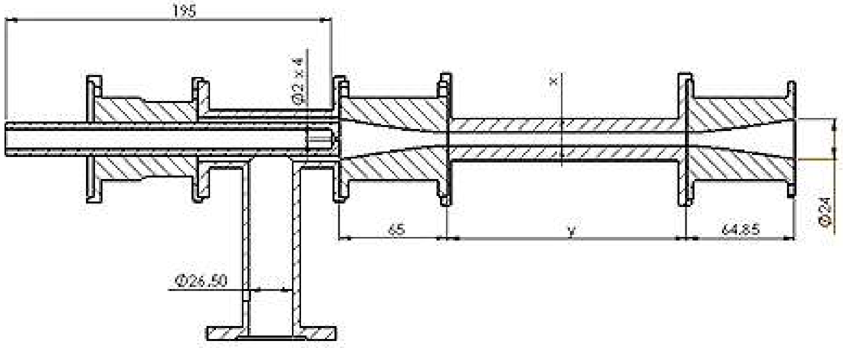

Figure 4 Experimental ejector geometries

3. RESULTS AND DISCUSSION

Based on measurements of ejector primary fluid and secondary fluid mass flow rates, the ejector entrainment ratio which is used to determine optimum throat area ratio can be defined as

$$\omega = m_s / m_p \qquad (1)$$

where ω is the entrainment ratio of the ejector, is m_s the mass flow rate of the secondary fluid in kg/s, and m_p is the mass flow rate of the primary fluid in kg/s (Chandra & Ahmed, 2014).

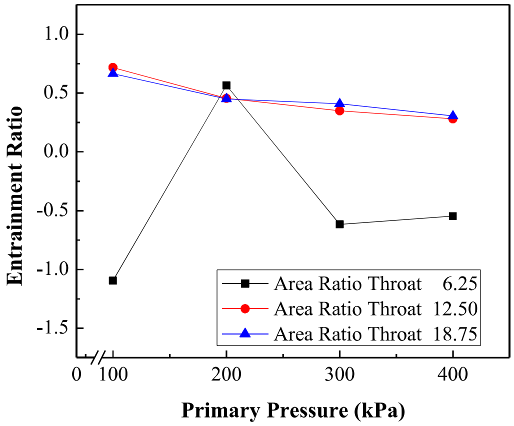

Figure 5 Variation of primary pressure with three area ratio throat (Te = 50°C).

Figure 5 shows the testing result for the three different area ratio throats (from 6.25 to 18.75) while the evaporator temperature fixed at 50 °C. It was observed when the secondary temperature fixed at 50 °C, the entrainment ratio decreased when the primary pressure increased. This phenomenon happened because higher primary pressure induced higher expansion angle from primary fluid flow from outlet nozzle. High expansion angle caused entrainment region in suction chamber decreased (Chandra & Ahmed, 2014). Furthermore, higher primary pressure caused mass flow rate of primary fluid increased. This behavior agreed well with the experimental result was published by Yan Jia (2011). Area ratio throat 6.25 didn't make any significant effect on entrainment ratio, meanwhile showed negative value of entrainment ratio because momentum transfer didn't intensively occur or the primary and secondary flow got inadequately mixed, for such cases the pressure recovery region in pseudo-shock became shorter and thus the ejector efficiency decreased dramatically (Li, 2010). The optimum entrainment ratio reached at 100 kPa primary pressure with area ratio throat 12.5, ω = 0.71. This phenomenon happened because the mixed flow in mixing chamber became fully developed due to adequate length of mixing chamber.

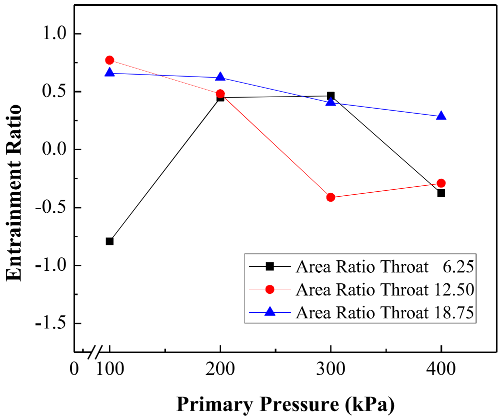

Figure 6 Variation of primary pressure with three area ratio throat (Te = 60°C).

Figure 6 showed the testing result for the three different area ratio throats at constant secondary temperature 60 °C. The overall experiment result showed same phenomenon as previous evaporator temperature condition. The optimum entrainment ratio happened at 100 kPa with area ratio throat 12.5, ω = 0.77. The entrainment ratio showed positive value for area ratio throat 18.75 in any operating primary pressure. This phenomenon occurred because mixed fluid that flow through constant area throat became fully developed. The fully developed flow produced smaller shock wave, therefore momentum transfer between primary and secondary fluids were better (Li, 2010).

Figure 7 and Figure 8 showed the testing result for the three different area ratio throats at constant secondary temperature 70 °C and 80 °C respectively. The experiment result showed same phenomenon with previous work, the entrainment ratio decreased as the primary pressure increased. Optimum entrainment ratio for secondary temperature 60 °C reached at 100 kPa pressure with area ratio throat 12.5, with ω = 0.91. Meanwhile, the maximum entrainment ratio of this experiment was 1.00 at operating condition of secondary temperature 80 °C and 100 kPa primary pressure with area ratio throat 18.75. Based on four different secondary temperatures, the result showed entrainment increased as evaporator temperature increased. This phenomenon occurred because higher secondary temperature caused back pressure increased (Li, 2010 and Jia, 2011). Moreover, higher secondary temperature caused density of secondary fluid decreased (Meyer et al., 2008).

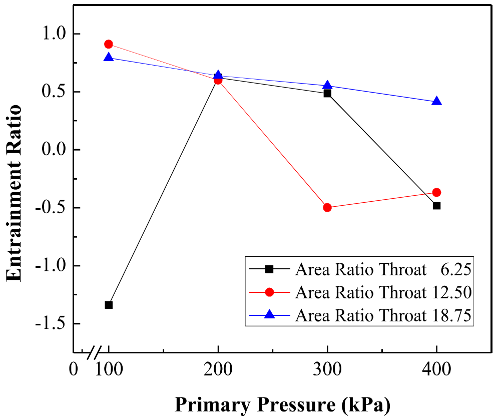

Figure 7 Variation of primary pressure with three area ratio throat (Te = 70°C).

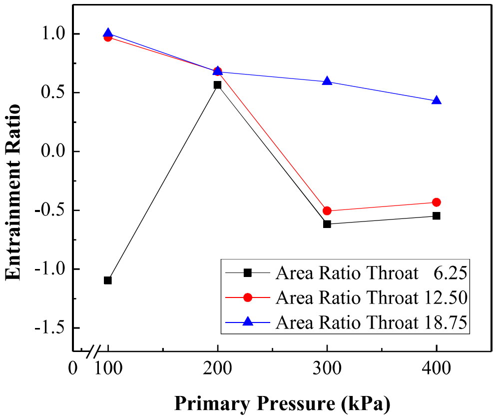

Figure 8 Variation of primary pressure with three area ratio throat (Te = 80°C).

4. CONCLUSION

Experimental investigation was performed on variable area ratio throat of mixing chamber in steam ejector refrigeration system. The experiment proved that the area ratio throat of mixing chamber was an important design parameter and can exert a remarkable influence on steam ejector performance. The area ratio throat optimum was 18.75. It caused the maximum entrainment ratio, which can be defined as the optimum length of throat that depends on the pseudo-shock. The operating conditions also had important influence due to back pressure value and formation of expansion angle in suction chamber. The maximum entrainment ratio for this experiment was 1.00 with area ratio throat 18.75, at 100 kPa primary pressure and 80 °C secondary temperature.

5. REFERENCES

A.J. Meyer, T.M. Harms, and R.T. Dobson (2008), "Steam jet ejector cooling powered by waste or solar heat," Renewable Energy, vol. 34, pp. 297-306.

C. Li and Y.Z. Li (2010), "Investigation of entrainment behavior and characteristics of gas–liquid ejectors based on CFD simulation," Chemical Engineering Science, vol. 66, pp. 405-416

Richard Law, Adam Harvey, and David Reay (2015), "A Knowledge-Based System for Low-Grade Waste Heat Recovery in The Process Industries," Applied Thermal Engineering, vol. 94, pp. 590-599.

T. Sriveerakul, S. Aphornatana, and K. Chunnanond (2006), "Performance prediction of steam ejector using computational fluid dynamics: Part 1. Validation of the CFD results," International Journal of Thermal Science, vol. 46, pp. 812-822.

U.S. Department of Energy (2008), "Waste heat recovery: Technology and Opportunities in The U.S. Industry," Industrial Technologies Program.

Vineet V. Chandra and M.R. Ahmed (2014), "Experimental and computational studies on a steam jet refrigeration system with constant area and variabel area ejectors," Energy Conversion and Management,vol. 79, pp. 377-386.

Yan Jia and Cai Wenjian (2011), "Area ratio effects to the performance of air-cooled ejector refrigeration cycle with R134a refrigerant," Energy Convervasion and Management, vol. 53, pp. 240-246.