# CHAPTER II

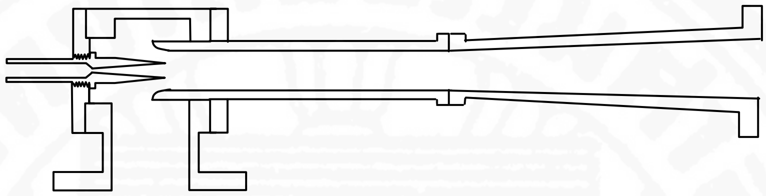
# LITERATURE REVIEW

As mentioned in the introduction, ejectors and their applications in refrigeration system have been researched and developed continuously over the decades. This chapter provides a literature review of the ejectors background and past researches on improvement to the performance of the ejectors, highlighting their application in refrigeration systems.

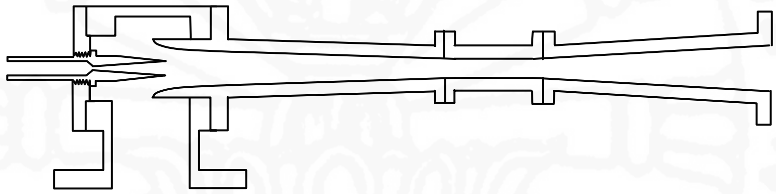
## 2.1 Background of Ejector

An ejector was first invented by Sir Charles Parsons around 1901 for removing air from the condenser of a steam engine [23]. Over the decades, ejectors have been applied for many industrial applications. For example, it was used as a thermo-compressor, a desuperheater and a vacuum generator. It was also used as a jet-conveyer in particulate solid transportation. For refrigeration purposes, an ejector was used to replace the role of a conventional mechanical-drive compressor with addition of a vapour-generator which provides thermal energy.

A typical ejector is composed of two major components, a primary nozzle and a mixing chamber. The design theory of ejectors can be classified into two theories based on the shapes of the mixing chamber, *"constant-pressure mixing ejector"* and *"constant-area mixing ejector"*. A *"constant-area mixing ejector"* is an ejector whose primary nozzle exit is placed within the constant-area section of the mixing chamber (Figure 2.1a) [24~26]. For a *"constant-pressure mixing ejector"* (Figure 2.1b), an ejector which has its nozzle exit position placed in a convergent chamber upstream of the constant-area section [27], the static pressure through the mixing process was assumed to be constant. Both types of ejector have been extensively tested experimentally and theoretically [24~27]. It was found that the constant-pressure mixing ejector had a better performance than the constant-area one. Therefore, after that, almost all studies have been focused on the constant-pressure mixing ejector.



a) “Constant-Area Mixing” Ejector



b) “Constant-Pressure Mixing” Ejector

**Figure 2.1**. Configurations of typical ejectors.

Conventional ejectors were designed and analyzed base on one-dimensional analysis. The design method based on one-dimensional analysis for compressible-gas flow in ejector using the models of stream mixing at constant pressure was first proposed by Keenan and Neumann [27]which was later become a classical theory. The analysis was based on the ideal gas assumption combined with the principles of mass, momentum, and energy conservation. Eames et al. [28] proposed a set of the 1-D equation in designing the ejector based on Keenan and Neumann’s theory [27]. The loss coefficient at the primary nozzle, the mixing chamber and the diffuser were accounted. The mixing of the two streams is able to start at any point from the exit of the nozzle plane to the exit of the constant area section. The equation of pressure ratio across the normal shock was expressed. Discussion on choke at the entrained flow was not given. Huang et al. [29] developed the 1-D analysis based on Manday and Bagster's theory [30] with assumption that no mixing occurs before choking at the hypothetical throat. The mixing of the two streams begins at some point inside the constant area section. The equation of pressure ratio across the shock expressed by Huang et al. [30] is derived from the mixing section to the exit of the constant area section. His results show only a small error in the values of entrainment ratio compared to the experiment results. The one-dimensional analysis, however, can be used to predict the performance when the ejector is operated at its design condition (at critical back pressure) only. Moreover, effects of the ejector's geometries were not included.

The flow phenomena in ejectors are very complicated, and thus, cannot be explained easily. In the past, therefore, the analyses of the ejector were usually done based on one dimensional (1-D) analysis. A schematic view of a typical steam ejector based on one-dimensional theory [31] is shown in Figure 2.2. As the high pressure steam, known as "a primary fluid", expands and accelerates through the primary nozzle (1), it fans out with supersonic speed to create a very low pressure region at the nozzle exit plane (2′) and subsequently in the mixing chamber (2″). This means "a secondary fluid" can be entrained into the mixing chamber. The primary fluid's expanded wave was thought to flow and form a converging duct without mixing with the secondary fluid. At some cross-section along this duct, the speed of the secondary fluid rises to sonic value (3) and chokes [30]. Then the mixing process begins after the secondary flow chokes. This mixing causes the primary flow to be retarded whilst secondary flow is accelerated. By the end of the mixing chamber, the two streams are completely mixed and the static pressure was assumed to remain constant until it reaches the throat section (4). Due to a high pressure region downstream of the mixing chamber's throat, a normal shock of essentially zero thickness is induced (5-6). This shock causes a major compression effect and a sudden drop in the flow speed from supersonic to subsonic. A further compression of the flow is achieved (7) as it is brought to stagnation through a subsonic diffuser until it reaches a desired discharged pressure (b).

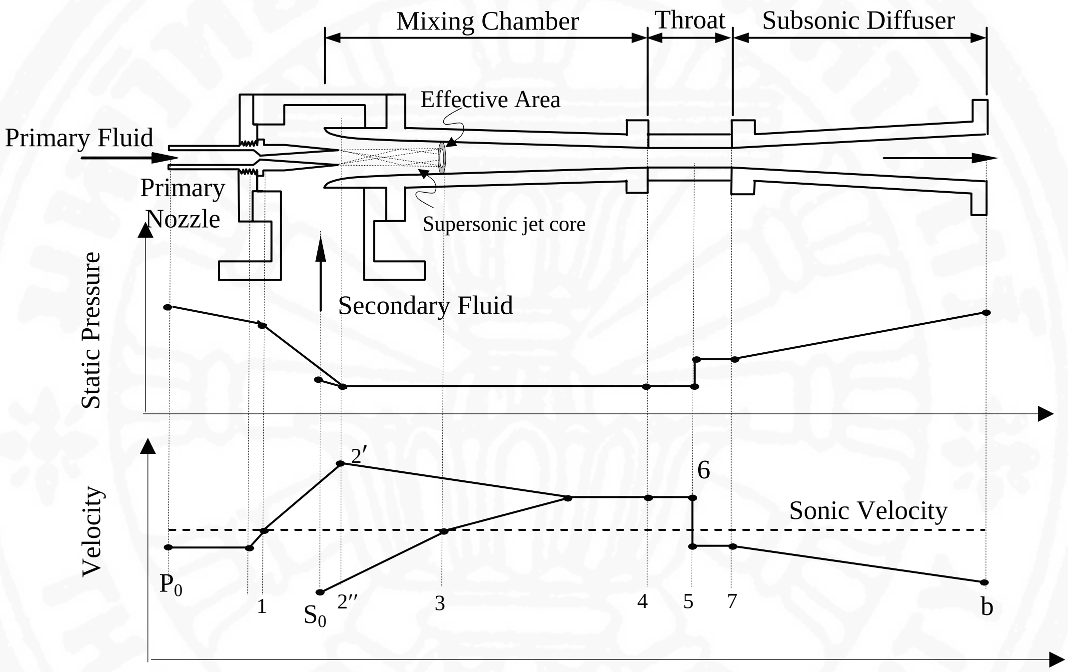



**Figure 2.2** Variation of stream pressure and velocity as a function of location along a steam ejector [31].

Matsuo et al. [32] study the flow in a rectangular supersonic ejector using the schlieren photograph technique. An example of schlieren photographs taken in a rectangular supersonic ejector is reproduced in Figure 2.3. In contrast to the 1-D analysis, the major compression effect of the flow in the ejector was found to be caused by a bifurcated shock plus a series of repeated shocks (pseudo shock followed by shock train) instead of a single normal shock. It was also concluded that the pseudo-shock occurs in the deceleration process of the flow in the ejector (downstream of the ejector's throat).

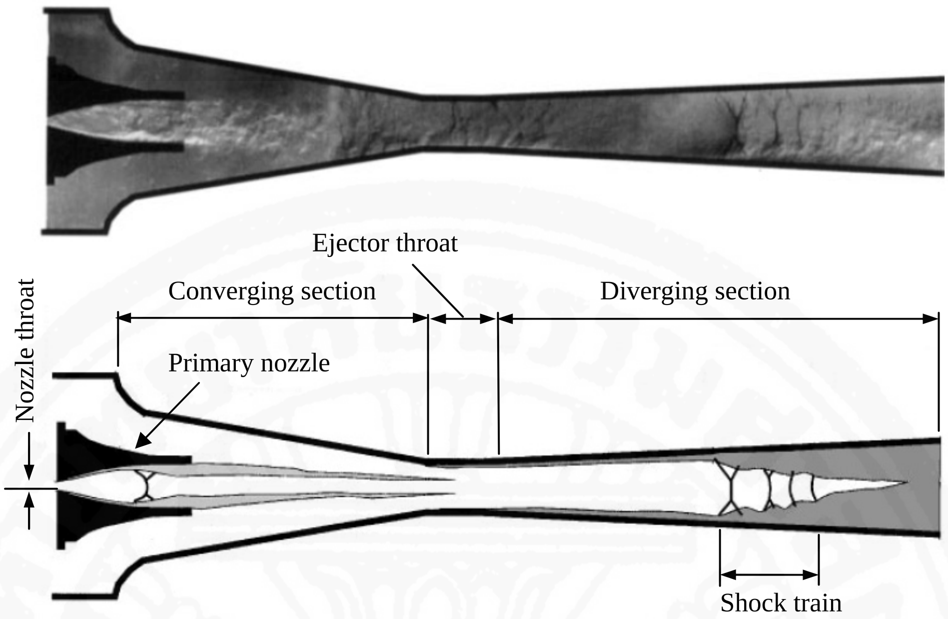



**Figure 2.3** An example of Schlieren photograph of flow in an air ejector (Source: Matsuo et al. [32]).

The difference in pressure jump across the pseudo-shock to that obtained from the normal shock was discussed using Figure 2.4, an illustration of the shock train (a series of repeated shocks) and the corresponding static pressure distributions at the wall and at the centerline of the constant-area duct, based on experimental data provided by Tamaki et al., [33]. As shown in this figure, if only a single normal shock occurs, the pressure across the shock jumps suddenly. With existence of a series of repeated shocks, pressure at downstream of the shocks increases continuously at the wall, but fluctuates at the centerline of the duct till the shocks disappear.

With rapid development in computer technology and numerical solution method, some researchers attempted to apply Computational Fluid Dynamics (CFD) in modeling the flow within ejectors [26 and 34~40]. Early of the 90S, the CFD technique was applied to analyze the mixing behavior only for some specific parts of the ejector [34~36]. The use of CFD to study the flow processes in a whole ejector assembly was still incomplete.

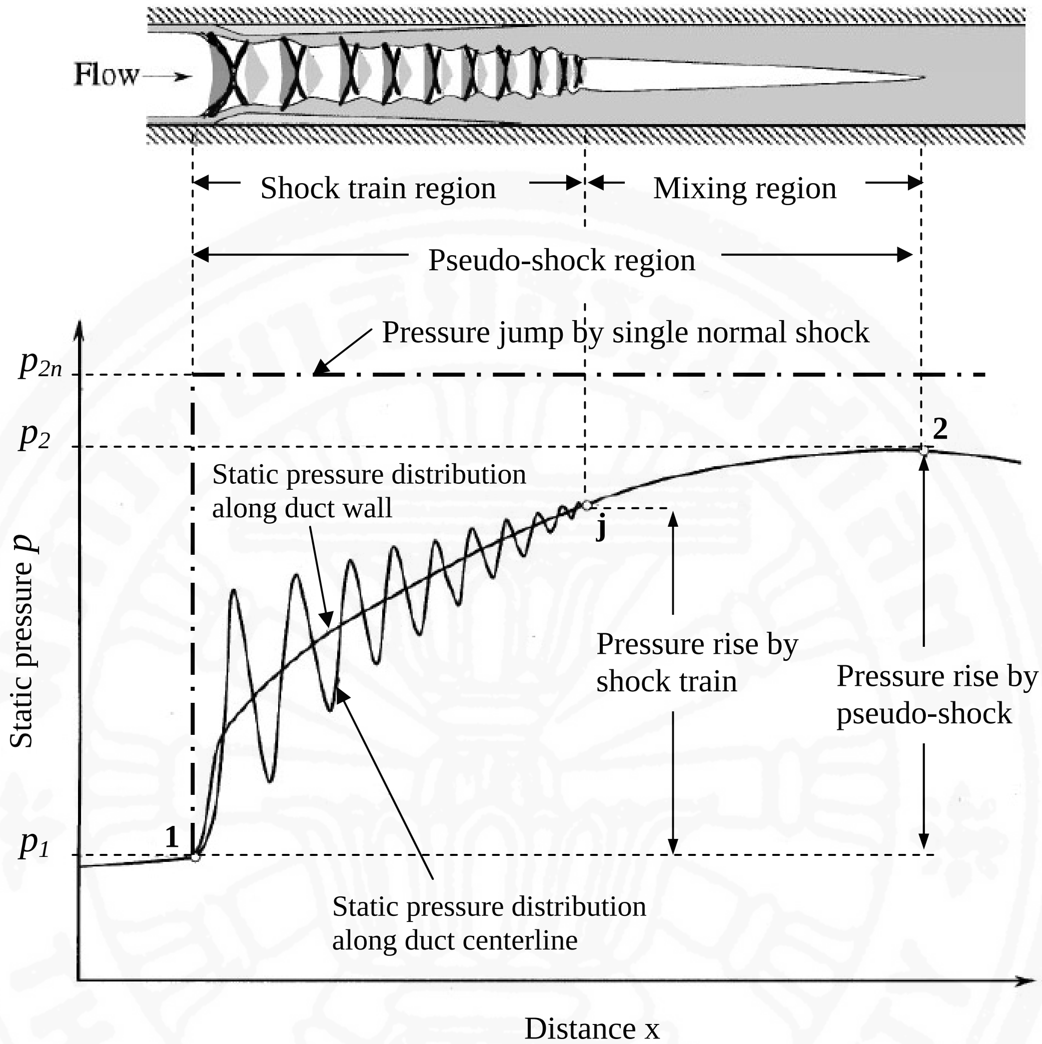



**Figure 2.4** Static pressure distribution along duct centerline and wall surface in constant-area duct [33].

In 1996, Riffat et al. [37] employed the CFD method to analyze the performance of ejectors when operating with various types of working fluids and with various shapes of primary nozzles. The three dimensional ejector was modeled and meshed with a grid size of around 37,000 elements. The fluid was assumed as incompressible fluid to avoid convergence difficulty with compressible fluid. This contradicts to the fact that high speed fluid is compressible. Moreover, using the incompressible flow assumption, the effects of shock associated with supersonic were discounted.

Riffat and Omer [38] used the 2 dimensional CFD results to obtain the optimum shape of the methanol driven ejector with the coefficient of performance (COP) between 0.2 and 0.4. The results show that higher entrainment ratio would be obtained by positioning the primary nozzle exit at least 0.21 the length of the mixing chamber. Unfortunately, the calculated results were not validated through any experimental data.

Rusly et al. [26] analyzed the flow through an ejector using CFD technique. The method of simulation is different from others since the real gas model was used instead of the ideal gas model and the geometry of the ejector was chosen as the 2-dimensional constant area-mixing ejector. The results indicate the presence of oblique shock in the constant area section. The CFD's results were validated with experimental data provided by others. Most of the previous studies including the above CFD studies have generally focused on the prediction of the maximum performance and the flow when the discharge pressure of the ejectors were lower than the critical back pressure.

Sriveerakul et al. [39 and 40] reported the use of CFD to simulate the flow within a constant pressure mixing-steam ejector along with validation data from experiments. Using helpful functions available in the CFD package, the flow characteristics within the steam ejector were explained and also the performances of the steam ejector, when its operating conditions and geometries were varied, were predicted. It was shown that CFD predictions could satisfactorily predict the entrainment ratio and the critical back pressure under the choked flow mode, but provided large error in the prediction under the unchoked flow mode.

Pianthong et al. [41] simulated a flow within a steam ejector using a 2-dimensional axisymmetric model and a 3-dimensional model. The results obtained from both models were almost the same. However, due to the larger number of grid elements of the 3-

dimensional model than that of the 2-dimensional axisymmetric model, the more computational time to obtain a converged solution was required.

## 2.2 Performance Characteristics of the Ejector

For refrigeration applications, the most two significant parameters used to describe the performance of an ejector are *"an entrainment ratio"* and *"a pressure lift ratio"* [42]:

$$\text{entrainment ratio, } Rm = \frac{\text{mass of secondary flow}}{\text{mass of primary flow}} = \frac{\dot{m}_s}{\dot{m}_p} \tag{2.1}$$

$$\text{pressure ratio, } Pr = \frac{\text{static pressure at diffuser exit}}{\text{static pressure secondary flow}} = \frac{P_b}{P_s} \tag{2.2}$$

The entrainment ratio relates to the energy efficiency of a refrigeration cycle, the COP, while the pressure ratio limits a temperature at which the mixed stream can be rejected [1]. Therefore, there is no doubt that an ejector, which operates at the given operating conditions with the highest entrainment ratio and maintains the highest possible discharged pressure, is the most desirable ejector.

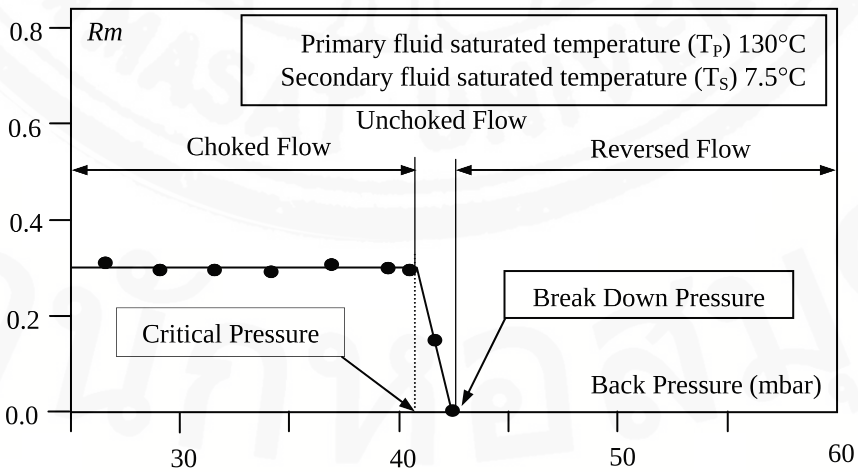



**Figure 2.5** Performance characteristics of a steam ejector based on experimental data provided by Eames and Aphornratana [2].

Experimental investigations of ejectors and their application in refrigeration have been conducted. Those provided similar results in term of performance characteristic curves of ejectors [1, 2, 28, 39, 40, and 43~46]. Consider a typical performance curve of a steam ejector for the specified primary and secondary flow pressures as shown in Figure 2.5. There are three operating regions distinguished by the critical back pressure and the breakdown back pressure: the choked flow, the unchoked flow, and the reversed flow of secondary fluid. In the "choked flow" region, where the back pressures are below the "critical value", the secondary flow choking in the mixing chamber causes the ejector to entrain the same amount of secondary fluid. This causes the entrainment ratio to remain constant all over this region. This essential character is called "constant-capacity characteristic" of an ejector. In this "choked flow" region, a transverse shock, which creates a compression effect, was thought to appear in either the throat or diffuser section. The location of the shock process varies with the back pressure. If the back pressure is increased, the shock will move upstream into the ejector throat without disturbing the mixing process.

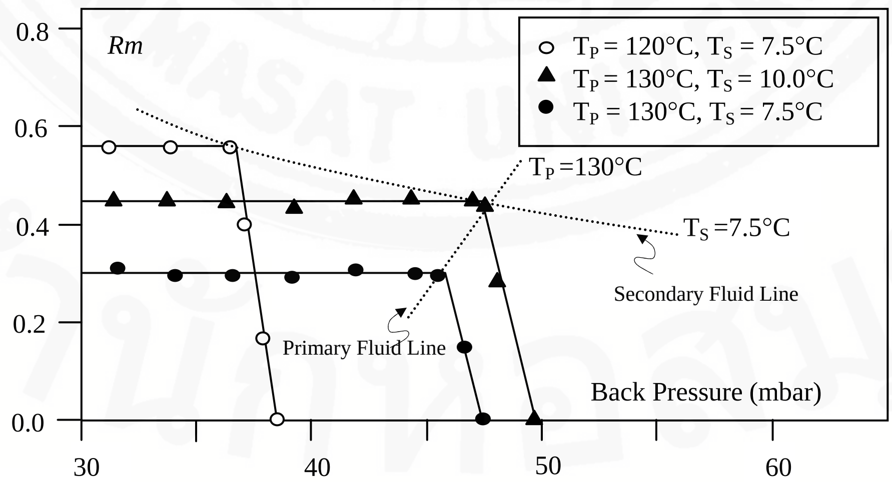



**Figure 2.6** Effect of operating pressures on performance of a steam jet refrigerator based on experimental data provided by Eames and Aphornratana [2].

In the “unchoked flow” region, where the back pressures are in excess of the critical value, there is no secondary flow choking. The entrained secondary fluid varies and the entrainment ratio begins to drop rapidly. The transverse shock was believed to move upstream into the mixing chamber and disturb the mixing between primary and secondary fluid. Further increase in the back pressure to the point called “break down” pressure (“reversed flow” region) causes the flow to reverse back to the secondary flow inlet and the ejector finally malfunctions.

Figure 2.6 shows the effect of operating pressures on the performance of a steam ejector based on experimental data provided by Eames and Aphornratana [2]. A decrease in the primary fluid saturated pressure causes the primary fluid mass flow to reduce. As the flow area in the mixing chamber is fixed, an increase in the secondary flow results. This causes the entrainment ratio of the ejector to rise. However, this causes the momentum of the mixed flow to drop. Thus, the critical pressure is reduced. On the other hand, an increase in the secondary fluid pressure, which is the ejector’s upstream pressure, will increase the critical pressure. This also increases the mass flow through the mixing chamber, which results in an increase of entrainment ratio.

Many past studies [3, 24, 27, 31, 39~40 and 46~47] show that, not only operating conditions, but ejector geometries also affect the ejector performance. The experimental studies of the effect of primary nozzle throat size and ejector geometry on system performance were conducted [47]. The influence of using a small primary nozzle throat diameter was similar to that of decreasing primary fluid pressure, whilst the influence of the primary nozzle exit diameter was not significant.

## 2.3 Conclusions

From the literature survey, the ejectors have significant impact on the performance of the jet refrigeration system. Even though the ejector was invented more than a century ago, very few of them focused on improving the performance of the ejector, especially, in the field of refrigeration application. Most researches were found to emphasize their objectives in improving the overall performance of the system only.

Since the complexity of the flow behavior and the mixing process within the ejectors, the use of 1-D assumption only may not be adequate to improve in the design of the ejector. Some past researches have been made to analyze the flow and the mixing process in the ejector in order to understand them clearly. Unfortunately, the very high-speed fluid flow, the shock behavior and the interaction between the primary and its surrounding fluid were not simple to experimentally investigate. There were very few studies made to reveal the flow characteristics in ejectors by various methods, i.e., the flow visualization, and the CFD (Computational Fluid Dynamics). However, their analytical results were not completed and some of them were out of experimental ranges and some were unable to be applied for the refrigeration applications.

To be concluded, a clear understanding of the performance characteristics, the nature of flow structure and the mixing process within an ejector is needed to improve the performance of an ejector, and thus, increase the COP of the jet refrigeration system. In this study, CFD software will be used to model the R141b ejector at various geometries and operating conditions. At specified operating conditions and geometries, the performance of the ejector can be predicted. Thanks to the advantage of the CFD software, the flow and mixing process within the ejectors can be explored graphically and numerically using the post function available within the software.