CHAPTER 2
LITERATURE REVIEW & THEORY

2.1 JET EJECTOR

Jet Ejectors (JEs) are considered the simplest devices among all the vacuum pumps in the present day (Watanawanavet, 2008 & Mohamad J., 1990) [2][8]. They are lubricant free equipment; do not contain any moving parts such as pistons, rotors or valves. In addition of absence of seals in JE's assembly, eventually, they are promoted to be the most mechanically reliable vacuum pump with low capital and maintenance costs. The easiness in the operation and maintenance of Jet Ejectors enabled them to have a long span life and to be widely incorporated in most of the chemical plant's configuration (Mohamad J., 1990) [8]. Additionally, they are easily adjusted to suit the exact results required (Mains and Richenberg, 1967) [9].

On the other hand, the major disadvantages of jet ejectors are as follows:

- ❖ The efficiency of jet ejector is limited according to their design parameters. The efficiency will drastically decrease if the operating parameters are set beyond the capability of the jet ejector.

- ❖ A single jet ejector has a limited compression ratio due its limitation in the process gas load for a single ejector, which is usually about 8:1 (Mohamad J., 1990) [8]. The compression ratio (Cr) is the ratio of the discharge pressure to the suction pressure. If higher compression ratio is needed, then two or more jet ejectors can be arranged in series to lower down the compression ratio at each stage.

- According to Heat Exchanger standards (2000) [10], the jet ejector deals with a fixed volume of gas and depends on the physical proportions of the ejector's diffuser. To handle with variable volumes, one or more ejector needed to be arranged in parallel in a single or multistage configuration; knocking-off a certain amount of volume at each stage to lower the volume, of steam and non-condensing gases as in our case, below the design parameters of each Jet Ejector.

2.2 JET EJECTOR MAIN COMPONENTS

After Martin (1997) [5], the main ejector components are with reference to figure 2.1:

1. **Steam nozzle:** where the motive fluid (primary fluid) is ejected at high velocity.

2. **Mixing chamber / Steam chest:** where the induced fluid (secondary) enters the ejector then to be mixed fully with the primary stream .

3. **Diffuser:** where a discharge pressure will form.

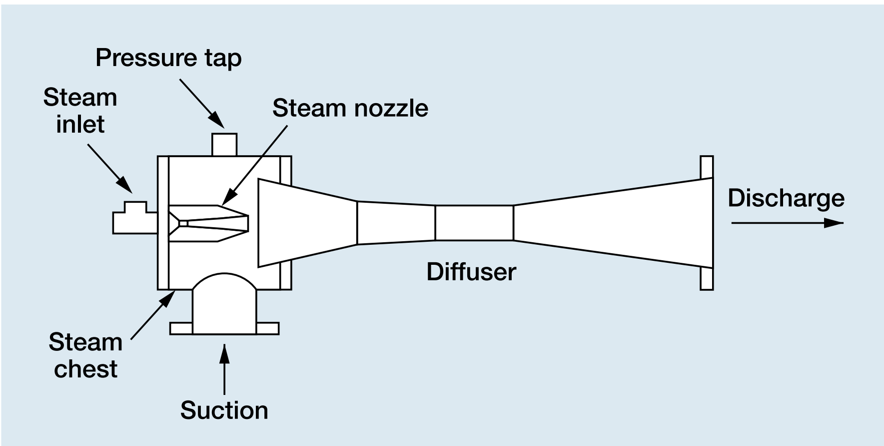

FIGURE 2.1 after Martin (1997) [7] shows the ejector main components

2.3 OPERATING PRINCIPLE OF A JET EJECTOR

Jet ejectors are supersonic flow induction devices that are employed for the generation of a vacuum for compressing a fluid (McGovern et al. 2012) [4]. To achieve this, there are two types of fluid in the jet ejector. Primary fluid, also known as the motive stream and secondary fluid also referred as the propelled stream. According to Watanawanavet (2008) [2], most of the jet ejectors use fully saturated steam as their motive fluid due to their moderate investment, ease of operation, reasonable maintenance requirement, and dependability. While secondary fluid varies according to the application in which the jet ejector has been used.

Figure B3 as per the appendix B, after K. Chunnanond et al (2006) [11] shows the pressure and velocity change inside each component of the jet ejector.

The operating principles for a single jet ejector is explained as follows:

1. **Flow of the motive steam:** A high velocity-pressurized stream of motive fluid enters the jet ejector through the Nozzle. The motive fluid can be also referred as the primary fluid [8]. Initially, the primary fluid has a subsonic velocity but with the aid of the nozzle, the stream's pressure will be converted into kinetic energy; leaving the nozzle with a subsonic velocity. The primary fluid then enters the low pressurized converging suction chamber. Then, it passes to the nozzle where the velocity decreases to sonic velocity [2]. Then it is diverged through a diffuser to be discharged with high velocity but lower than the velocity of injection to avoid the formation of backpressure.

2. **Flow of the propelled gases:** The propelled induced fluid, also referred by Secondary fluid, enters the Jet ejector through the suction chamber. It flows to the mixing chamber through a converging nozzle .The secondary fluid's speed increases and pressure decreases. The secondary's fluid velocity will continually increase; according to Munday (1977) [7], until it reaches the sonic value then chokes. Refer to (point iii) on the graph of appendix A1.

3. After choking, secondary fluid will have an intimate contact with the high velocity jet stream (primary fluid). Mixing is completed before the entrance of the throat area. Therefore, the primary velocity will retard meanwhile the secondary fluid will accelerate.

4. Due to the high pressure at the downstream of the mixing chamber, a shock wave is formed causing a sudden drop in the velocity from supersonic to subsonic (point v) on Chunnanondet's graph. [11] (refer to appendix A1)

5. Then more compression will occur before discharging the mixture of the primary and the secondary fluid through the nozzle. The discharged mixture will be having a lower velocity and pressure than of that the initial speed and pressure of the motive fluid. The reason behind it, to avoid any backpressure.

In a nutshell, the kinetic energy of the primary fluid is transferred to the secondary fluid. Thus, to optimize the efficiency of the jet ejector, the difference in the kinetic energy (K.E) between both fluids should be minimized.

2.4 FLOW REGIMES OF EJECTOR OPERATION

According to McGovern [4], one of the most important aspects in the analysis and design of jet ejectors is the variety of flow regimes, depending on the operating conditions and the ejector's geometry. According to Watanawanavet [2], the ejector has two types of geometry a constant-pressure (varying area geometry) jet ejector and a constant area (fixed geometry) jet ejector. They were classified according to the dimensions of the convergence section. The difference between both can be viewed in figure B1 as per appendix B. Since, it was crucial to understand the favorable flow regime, therefore, in the upcoming section it will be explaining, firstly, the effect of the ejector geometry upon the entrainment ratio of a jet ejector with fixed operating conditions and secondly the effect of the operating conditions upon a jet ejector of constant area / fixed geometry jet ejector.

2.4.1 Flow regimes within an ejector with fixed operating conditions

McGovern et al. (2012) [4] have agreed with Nahdi et al (1993) [12] and Lu et al. (1987) [13] about their conclusion regarding their study of the flow regimes within an ejector with fixed operating conditions. They have identified three regimes dependable on the variance of the jet ejector's geometry with a fixed inlet fluid states and a fixed discharged pressure. The fixed inlet fluid states and a fixed discharged pressure is the method for fixing the operating conditions. The three flow regimes are [4]:

1. Over Expanded flow: where the motive and the entrained fluid are choked at the motive nozzle throat and in the mixing chamber. The ratio of chamber to the nozzle throat, ϕ, is significantly small such that the motive nozzle over expanded.

2. Perfectly Expanded flow: The value of ϕ is reduced causing a higher entrainment ratio. The nozzle will be perfectly expanded leading to weaken the compression shocks of the motive fluid in the downstream of the ejector until they cease to exist. The downstream of the ejector is at the beginning of the diffuser. McGovern (2012) [4] agreed with Nahdi et al (1993) [12] that ϕ at this point is considered as the optimal area ratio for a given set of inlet conditions and discharged pressure. The entrainment ratio is considered maximum, as the static pressure of the motive stream and the secondary fluid are equal at the point of meeting.

3. Under expanded flow: The value of ϕ is very much reduce below optimal, causing a decrease in the entrainment ratio. The under expanded motive fluid will spread onset its exit from the nozzle, restricting the flow area of the entrained fluid. The flow regime takes the flow structure as per figure 2.2 after [4].

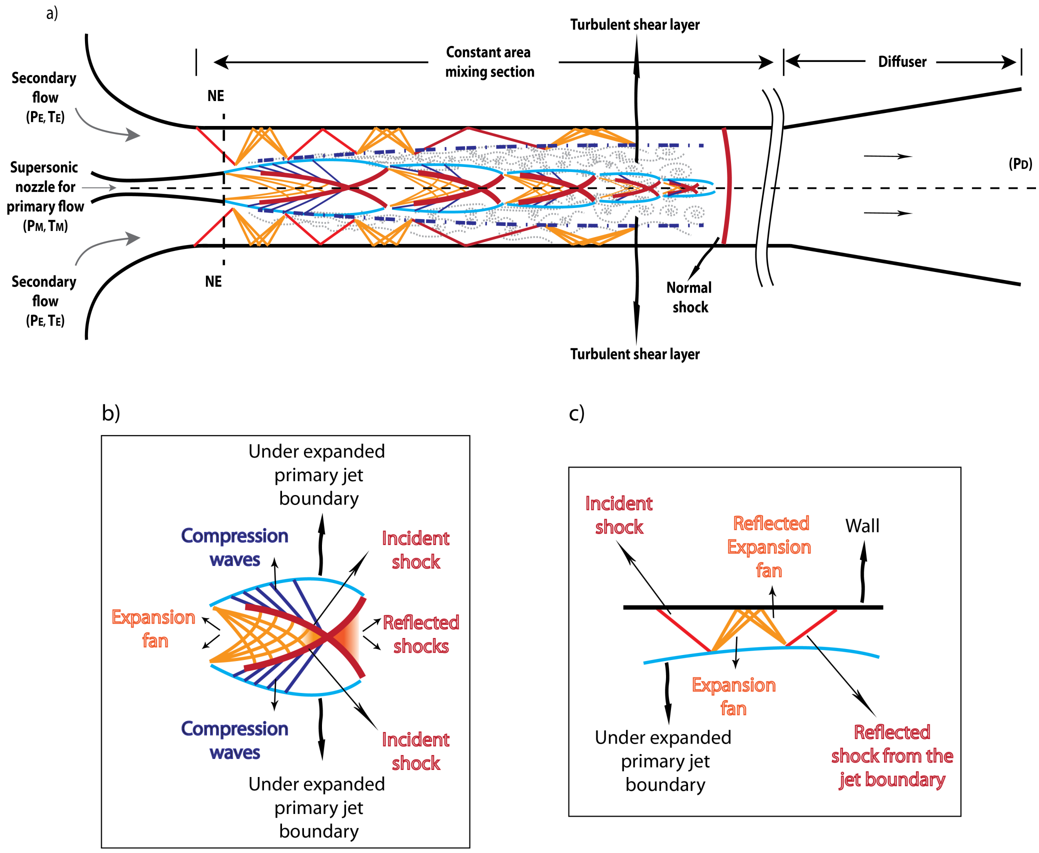

FIGURE 2.2 after McGovern et al (2012) shows the flow structure of an under expanded primary fluid flow and choked secondary fluid flow

2.4.2 Flow regimes within an ejector of fixed geometry

The explanation of flow regimes within an ejector of fixed geometry revolves around the concept of critical discharge pressure, P_D^* (McGovern et al., 2013)[4]. The description of critical discharge pressure was illustrated clearly by Sriveerakul et al (2007) [14] through using a computational fluid dynamic analysis and Bartosiewicz et al (2005) [15] through using experimental data. The motive fluid area, the chamber area and the inlet primary and secondary fluid states at the inlet to the jet ejector are fixed. According to McGovern et al (2012) [4] the flow regimes are, with reference to figure 1.1 after Scot et al (2008) [6] under section 1.1.4:

1. Reversed flow region – the back pressure is to the right of point A as in figure 1.1 after Scot et al (2008) [6] on the x-axis and the discharged pressure is too high to allow entrainment. According to Bartosiewicz et al [15] the primary flow through the nozzle is over expanded, resulting in compression shocks. Primary fluid partially flows back through the entrained fluid inlet.

2. Un choked entrainment – The discharge pressure drops to point A as in figure 1.1 after Scot et al (2008) [6]. The compression shocks of the motive fluid will be weaken allowing the mixing pressure to be lower thus evoking entrainment.

3. Critical operation - The discharge pressure is equal to the critical backpressure thus causing the secondary fluid to accelerate to the sonic speed within the mixing chamber.

4. Choked flow - For values of discharge pressure below the critical backpressure the entrainment remain constant where the primary and the secondary flow are choked in the mixing region.

As summary with the aid of figure 1.1 after Scot et al (2008)[6] that the entrainment ratio is constant as the discharge pressure is lower than the critical discharge pressure. Munday and Bagster (1977) [7] have concluded in their theory that the secondary fluid pressure is held constant at the inlet this can only mean that the cross sectional area or the capacity of the ejector is constant as previously highlighted under section 1.1.4.

In conclusion of regimes of ejector operation, Nahdi et al. (1993) [12] was able to recognize experimentally that the entrainment ratio of an ejector was maximized when the primary nozzle was perfectly expanded and the entrained fluid reaches a choked condition. McGovern [4] and Watanawanavet [2] have used Nahdi's [12] work as the basis for the mathematical modeling of their analysis of jet ejector. Both McGovern et al (2012) [4] and Watanawanvet (2008) [2] used simulation and computational fluid dynamics in validating their work. All concluded that their results were promising.

2.5 PROCESS GAS LOAD OF EJECTOR

Ejector system process gas load affects the ejector suction pressure [5]. As seen in figure 2.3 after Martin (1998) [5], higher gas load increases ejector inlet pressure and reduced gas load decreases ejector inlet pressure. Watanawanavet (2008) [2] has simplified the concept of the process gas load of ejector and has defined it as the maximum capacity of the ejector can withstand.

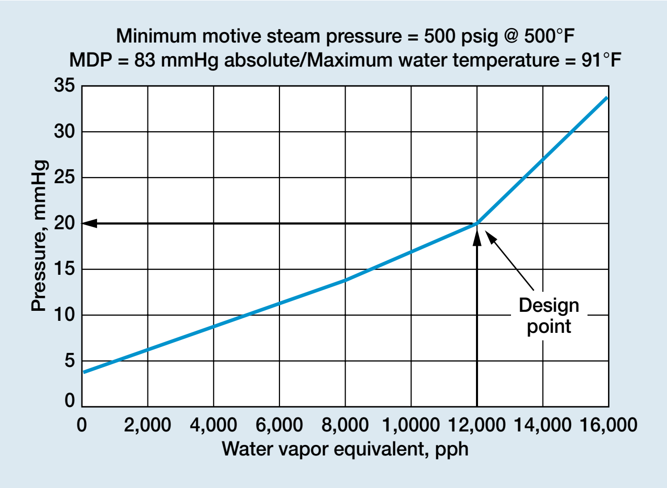

FIGURE 2.3 after Martin (1998) shows an ejector performance curve

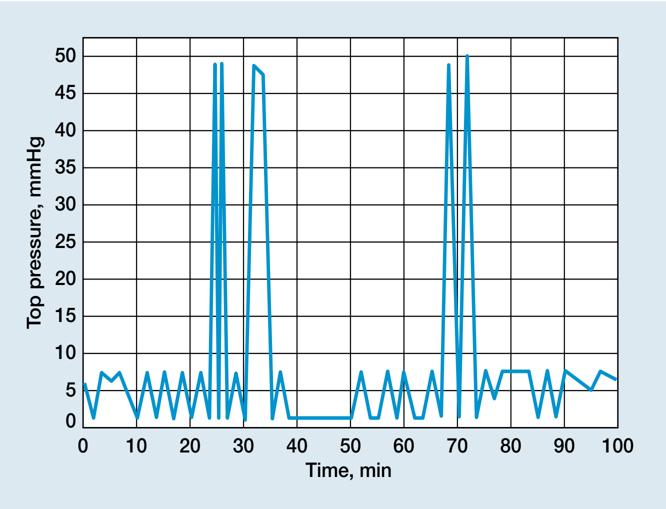

FIGURE 2.4 after Martin (1998) shows “Breaking” vacuum ejector

The ejectors operates based on the their performance curve, refer to figure 2.3, however when a downstream ejector inlet pressure increases above the endurance of the ejector's maximum discharge pressure, the ejector will operate on a "broken" curve, which is unknown as appear in figure 2.4 after [5].

More over, according to Scott et al. (2008) [6] , the excess of NCGs over the process gas load will result to choking in the throat of the ejector. Scott et al. [6] referred to Munday and Bagster's [7] theory to illustrate Martin's (1998) [5] "breaking" vacuum ejector theory. Scott et al explained that the constant capacity of an ejector is determined by the choking of the secondary fluid before it mixes with the primary fluid. Since both the primary and secondary flows are choked, the entrainment ratio will remain constant until the condenser vacuum pressure increases to a point that the secondary flow is no longer choked. But with the excess of NCGs in the condenser, the vacuum pressure will decrease leading to a choking effect in the jet ejector system and this will vitiate the ejector's performance.

Thus, according to G. R. Martin (1998) [5], has mentioned that it is very important that there is no excess in the NCGs over the process gas load of the ejector as it might lead to the failure of the ejector. Holtzapple (2001) [16], Watanawanavet (2008) [2] and McGrevon (2012) [4] have all agreed on G. R. Martin's (1998) [5] statement.

2.6 MULTI-STAGE EJECTOR

Due to the limitation of the process gas load, multi-stage ejectors have been used. Thus, to have a higher capacity more jet ejector stages are added hereby increasing the vacuum pressure as indicated in Figure (B4) (after Frumerman [17]). A satisfactory number of JE is being chosen to improve the work stability and to use the steam more economically. In other words, according to Mohamad J. (1990) [8] the number of stages required is dependent upon the vacuum required or the volume of gases must be evacuated [2]. Croll (1998) [18] validated Frumerman's [17] work. Croll (1998) [18] matched the suggested capacities and the operating range of multi-stage ejector to the need of the chemical engineering application. Croll (1998) [18] noted that most of the applications in chemical plants are covered in the rough vacuum region of a pressure range (101,325 Pa – 130 Pa). Figure B5 as per the appendix shows Berkeley's (1957) [19] work plotting a wide range of pressure that can be achieved by using various combinations of ejector and condensers with fixing the steam's consumption.

But due to the limitation in the capacity of a jet ejector, one must bear in mind the size of each and every ejector at every stage. For instance, when using a two-stage steam ejector, the second stage ejector has to be large enough in capacity to handle the initial suction load plus the motive steam from the first stage unless an inter-stage condenser is used (Mohamad J., 1990) [8]. Thus a multi stage ejector can be classified into condensing and non-condensing (Croll,1998) [18]. The condenser can be either surface condenser or a mixing condenser. Factors behind selecting the multi stage ejector were explained by Croll (1998) [18].

Most of the designs in petro-chemical industries, according to Mazda Corporation, India, utilize two stage ejectors. Steam Jet Ejector is found in a form of twin element; i.e. duplex design having two identical ejectors per stage, one of which being in operation at one time and the other as a standby. An inter-condenser usually incorporated as well as a hogger/start up ejector for faster pre-evacuation before the two stage holding ejectors take over.

2.7 OPERTING PARAMETERS AND MEASURING THE PERFORMANCE OF JET EJECTOR

Through, studies of [2], [4], [8], [16] all agreed that the critical operating parameters affecting the performance of the jet ejector, regardless the flow regime, are the compression ratio of the jet ejector defined as the ratio of the discharge pressure to the suction pressure. As well as, all respective parameters for primary and secondary fluid including pressure, temperature, velocity and mass flow rate. All these operating parameters contribute to the performance of the ejector.

According to Watanawanavet (2008) [2], two parameters measure the jet ejector performance, the efficiency and the entrainment ratio. Typically, efficiency involves a comparison of energy output to energy input but nevertheless, this ratio is of little value in the selection and design of ejectors (Watanawanavet, 2008) [2]. Since ejectors approach a theoretically isentropic process (Mohamad J., 1990) [8] , overall efficiency is expressed as a function of entrainment efficiency. The direct entrainment of a low velocity suction fluid by the motive fluid will result in an unavoidable loss of kinetic energy owing to impact and turbulence originally possessed by the motive fluid. This fraction that is successfully transmitted to the mixture through the exchange of momentum is called the entrainment efficiency. That proportion of the motive fluid energy, which is lost, is transferred into heat and is absorbed by the mixture, producing therein a corresponding increase in enthalpy. The entrainment ratio will be the ratio of the mass flow of the motive steam to the mass flow of the propelled stream.

$$\text{Entrainment ratio} = \frac{\mathrm{Mp}}{M_m}$$

where,

M_P the mass flow of the fluid at the exit of the diffuser

M_m the mass flow of the motive (primary) fluid