NUMERICAL INVESTIGATION OF JET EJECTORS

Pratik P. Bhatt[1] Prof. Dr. Gajendra Asthana[2]
[1]P.G. Student [2]Associate Professor
[1, 2] Mechanical Engineering Department
[1, 2] LJIT, Sarkhej , Ahmedabad, Gujarat, India.

Abstract--- Jet ejectors are the simplest devices among all compressors and vacuum pumps. They do not contain any moving parts, lubricants or seals; therefore, they are highly reliable devices with low capital and maintenance costs and also energy saving device. Furthermore, most jet ejectors use steam or compressed air as the motive fluid, which are easily found in chemical plants. Due to their simplicity and high reliability, they are widely used in chemical industrial processes; however, jet ejectors have a low efficiency. In this paper available standard manufacturer design and experiment data of jet ejector system is used and mathematical model for jet ejector design is solved with solution algorithm. The outcomes of this mathematical model is in the form of discharge pressure of diffuser, throat dia. of nozzle , exit dia. of nozzle and throat dia. of diffuser and this is compared with available design and experiment data. So we can check reliability of this mathematical model for jet ejector design.

Key word: Primary nozzle, diffuser, motive fluid, Mach no. , throat.

I. INTRODUCTION

Applications of jet ejectors include refrigeration, air conditioning, removal of non-condensable gases, transport of solids and gas recovery. The function of the jet ejector differs considerably in these processes. For example, in refrigeration and air conditioning cycles, the ejector compresses the entrained vapour to higher pressure, which allows for condensation at a higher temperature. Also, the ejector entrainment process sustains the low pressure on the evaporator side, which allows evaporation at low temperature. As a result, the cold evaporator fluid can be used for refrigeration and cooling functions. As for the removal of non-condensable gases in heat transfer units, the ejector entrainment process prevents their accumulation within condensers or evaporators. The presence of non-condensable gases in heat exchange units reduces the heat transfer efficiency and increases the condensation temperature because of their low thermal conductivity. Also, the presence of these gases enhances corrosion reactions. However, the ejector cycle for cooling and refrigeration has lower efficiency than the MVC units, but their merits are manifested upon the use of low grade energy that has limited effect on the environment and lower cooling and heating unit cost.

Although the construction and operation principles of jet ejectors are well known, the following sections provide a brief summary of the major features of ejectors. This is necessary in order to follow the discussion and analysis that follow. The conventional steam jet ejector has three main parts: (1) the nozzle; (2) the suction chamber; an (3) the diffuser (Fig. 1).The nozzle and the diffuser have the geometry of converging/diverging venturi. The diameters and lengths of various parts forming the nozzle, the diffuser and the suction chamber, together with the stream flow rate and properties, define the ejector capacity and performance. The ejector capacity is defined in terms of the flow rates of the motive steam and the entrained vapour. The sum of the motive and entrained vapour mass flow rates gives the mass flow rate of the compressed vapour. As for the ejector performance, it is defined in terms of entrainment, expansion and compression ratios. The entrainment ratio (w) is the flow rate of the entrained vapour and divided by

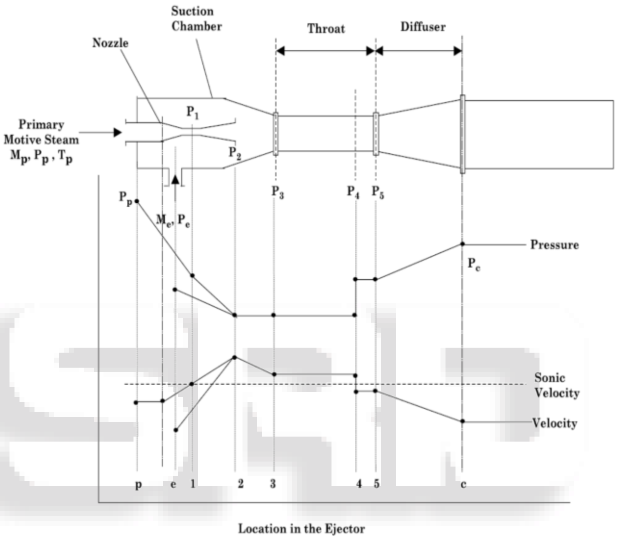

Fig. 1: Variation in stream pressure and velocity as a function of location along the ejector.

the flow rate of the motive steam. As for the expansion ratio (Er), it is defined as the ratio of the motive steam pressure to the entrained vapour pressure. The compression ratio (Cr) gives the pressure ratio the compressed vapour to the entrained vapour. Variations in the stream velocity and pressure as a function of location inside the ejector, which are shown in Fig. 1, are explained below: The motive steam enters the ejector at point (p) with a subsonic velocity. As the stream flows in the converging part of the ejector, its pressure is reduced and its velocity increases. The stream reaches sonic velocity at the nozzle throat, where its Mach number is equal to one. The increase in the cross section area in the diverging part of the nozzle results in a decrease of the shock wave pressure and an increase in its velocity to supersonic conditions. At the nozzle outlet plane, point (2), the motive steam pressure becomes lower than the entrained vapour pressure and its velocity ranges between 900 and 1200 m/s. The entrained vapour at point (e) enters the ejector, where its velocity increases and its pressure decreases to that of point (3).The motive steam and entrained vapour streams may mix within the suction chamber and the converging section of the diffuser or it may flow as two separate streams as it enters the constant cross section area of the diffuser, where mixing occurs. In either case, the mixture goes through a shock inside the constant cross section area of the diffuser. The shock is associated with an increase in the mixture pressure and reduction of the mixture velocity to subsonic conditions, point (4). The shock occurs because of the back pressure resistance of the condenser.

As the subsonic mixture emerges from the constant cross section area of the diffuser, further pressure increase occurs in the diverging section of the diffuser, where part of the kinetic energy of the mixture is converted into pressure. The pressure of the emerging fluid is slightly higher than the condenser pressure, point (*c*).

Summary for a number of literature studies on ejector The following outlines the main findings of these studies: Optimum ejector operation occurs at the critical condition. The condenser pressure controls the location of the shock wave, where an increase in the condenser pressure above the critical point results in a rapid decline of the ejector entrainment ratio, since the shock wave moves towards the nozzle exit. Operating at pressures below the critical points has negligible effect on the ejector entrainment ratio.

At the critical condition, the ejector entrainment ratio increases at lower pressure for the boiler and condenser. Also, higher temperature for the evaporator increases the entrainment ratio. Use of a variable position nozzle can maintain the optimum conditions for ejector operation. As a result, the ejector can be maintained at critical conditions even if the operating conditions are varied. Multi-ejector system increases the operating range and improves the overall system efficiency.

II. MATHAMATICAL MODAL

The review by Sun and Eames outlined the developments in mathematical modelling and design of jet ejectors. The review shows that there are two basic approaches for ejector analysis. These include mixing of the motive steam and entrained vapour, either at constant pressure or at constant area. Design models of stream mixing at constant pressure are more common in literature because the performance of the ejectors designed by this method is more superior to the constant area method and it compares favourably against experimental data.The basis for modelling the constant pressure design procedure was initially developed by Keenan. Subsequently, several investigators have used the model for design and performance evaluation of various types of jet ejectors. This involved a number of modifications in the model, especially losses within the ejector and mixing of the primary and secondary streams. In this section, the constant pressure ejector model is developed. The developed model is based on a number of literature studies.

The constant pressure model is based on the following assumptions:

(1) The motive steam expands isentropically in the nozzle. Also, the mixture of the motive steam and the entrained vapour compresses isentropically in the diffuser.
(2) The motive steam and the entrained vapour are saturated and their velocities are negligible.
(3) Velocity of the compressed mixture leaving the ejector is insignificant.
(4) Constant isentropic expansion exponent and the ideal gas behavior.
(5) The mixing of motive steam and the entrained vapour takes place in the suction chamber.
(6) The flow is adiabatic.
(7) Friction losses are defined in terms of the isentropic efficiencies in the nozzle, diffuser and mixing chamber.
(8) The motive steam and the entrained vapour have the same molecular weight and specific heat ratio.
(9) The ejector flow is one-dimensional and at steady state conditions.

The model equations include the following:

-Overall material balance

$$m_p + m_e = m_c \quad (1)$$

-where *m* is the mass flow rate and the subscripts c, e and p, define the compressed vapor mixture, the entrained vapor and the motive steam or primary stream.

-Entrainment ratio

$$w = m_e/m_p \quad (2)$$

- Compression ratio

$$Cr = P_c/P_e \quad (3)$$

- Expansion ratio

$$Er = P_p/P_e \quad (4)$$

- Isentropic expansion of the primary fluid in the nozzle is expressed in terms of the Mach number of the primary fluid at the nozzle outlet plane

$$M_{p_2} = \sqrt{\frac{2\eta_n}{\gamma - 1}\left[\left(\frac{P_p}{P_2}\right)^{(\gamma - 1/\gamma)} - 1\right]} \quad (5)$$

- where *M* is the Mach number, *P* is the pressure and γ is the isentropic expansion coefficient. In the above equation, n_n is the nozzle efficiency and is defined as the ratio between the actual enthalpy change and the enthalpy change undergone during an isentropic process.

- Isentropic expansion of the entrained fluid in the suction chamber is expressed in terms of the Mach number of the entrained fluid at the nozzle exit plane.

$$M_{e_2} = \sqrt{\frac{2}{\gamma - 1}\left[\left(\frac{P_e}{P_2}\right)^{(\gamma - 1/\gamma)} - 1\right]} \quad (6)$$

- The mixing process is modelled by one-dimensional continuity, momentum and energy equations. These equations are combined to define the critical Mach number of the mixture at point 5 in terms of the critical Mach number for the primary and entrained fluids at point 2. where w is the entrainment ratio and M^* is the ratio

$$M_4^* = \frac{M_{p2}^* + wM_{e2}^*\sqrt{T_e/T_p}}{\sqrt{(1+w)(1+wT_e/T_p)}} \quad (7)$$

between the local fluid velocity to the velocity of sound at critical conditions.

- The relationship between M and M * at any point in the ejector is given by this equation

$$M^* = \sqrt{\frac{M^2(\gamma+1)}{M^2(\gamma-1)+2}} \quad (8)$$

-Eq. (8) is used to calculate M_{e2}*, M_{p2}*, M_4

$$M_5 = \frac{M_4^2 + \frac{2}{(\gamma-1)}}{\frac{2\gamma}{(\gamma-1)}M_4^2 - 1} \quad (9)$$

- Pressure increase across the shock wave at point 4

$$\frac{P_5}{P_4} = \frac{1+\gamma M_4^2}{1+\gamma M_5^2} \quad (10)$$

- In Eq. (10) the constant pressure assumption implies that the pressure between points 2 and 4 remains constant. Therefore, the following equality con- straint applies $P_2 = P_3 = P_4$.

- Pressure lift in the diffuser

$$\frac{P_c}{P_5} = \left[\frac{\eta_d(\gamma-1)}{2}M_5^2 + 1\right]^{(\gamma/\gamma-1)} \quad (11)$$

-where n_d is the diffuser efficiency.The area of the nozzle throat

$$A_1 = \frac{m_p}{P_p}\sqrt{\frac{RT_p}{\gamma\eta_n}\left(\frac{\gamma+1}{2}\right)^{(\gamma+1)/(\gamma-1)}} \quad (12)$$

-The area ratio of the nozzle throat and diffuser constant area

$$\frac{A_1}{A_3} = \frac{P_c}{P_p}\left(\frac{1}{(1+w)(1+w(T_e/T_p))}\right)^{1/2} \frac{\left(\frac{P_2}{P_c}\right)^{1/\gamma}\left(1-\left(\frac{P_2}{P_c}\right)^{(\gamma-1)/\gamma}\right)^{1/2}}{\left(\frac{2}{\gamma+1}\right)^{1/(\gamma-1)}\left(1-\frac{2}{\gamma+1}\right)^{1/2}} \quad (13)$$

The area ratio of the nozzle throat and the nozzle outlet

$$\frac{A_2}{A_1} = \sqrt{\frac{1}{M_{p_2}^2}\left(\frac{2}{(\gamma+1}\left(1+\frac{(\gamma-1)}{2}M_{p_2}^2\right)\right)^{(\gamma+1)/(\gamma-1)}} \quad (14)$$

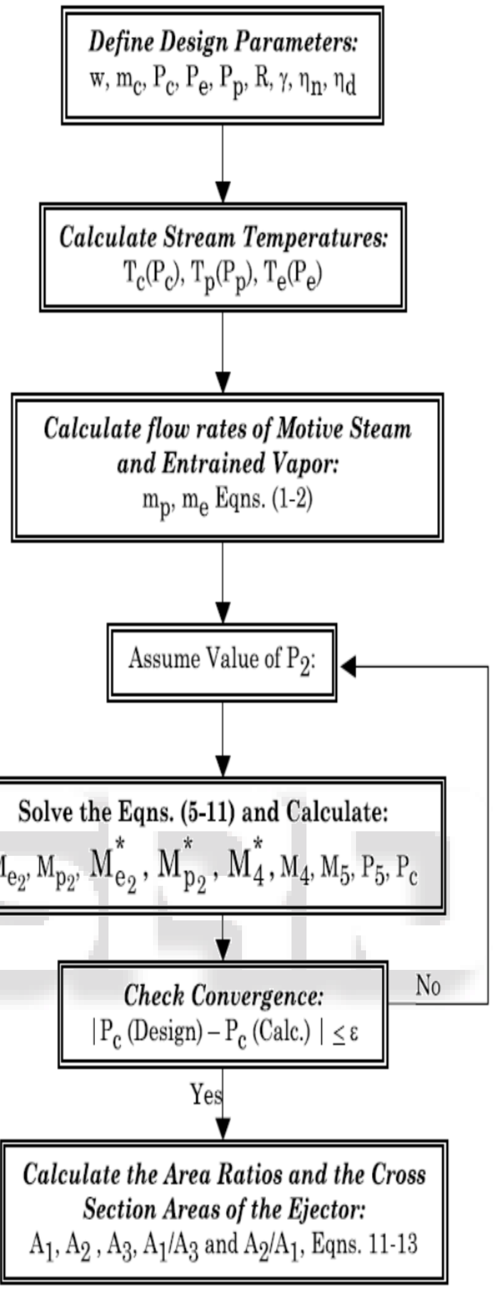

Fig. 2: Solution algorithms of the mathematical model

III. SOLUTION PROCEDURE

Procedure is used for system design, where the system pressures and the entrainment ratio is defined. Iterations are made to determine the pressure of the motive steam at the nozzle outlet (P_2) that gives the same back pressure (Pc). The iteration sequence for this procedure is shown in Fig. 2 and it includes the following steps.

(1) Define the design parameters, which include the entrainment ratio (w), the flow rate of the compressed vapor(m_c) and the pressures of the entrained vapor, compressed vapor and motive steam (Pe, Pp, Pc).
(2) Define the efficiencies of the nozzle and diffuser(n_n and n_d)

(3) Calculate the saturation temperatures for the compressed vapor, entrained vapor and motive steam, which include Tc, Tp, Te, using the saturation temperature.
(4) As for the universal gas constant and the specific heat ratio for steam, their values are taken as 0.462 and 1.3.
(5) The flow rates of the entrained vapor (m_e) and motive steam (m_p) are calculated from Eqs. (1) and (2).
(6) A value for the pressure at point 2 (P_2) is estimated and Eqs. (5)–(11) are solved sequentially to obtain the pressure of the compressed vapor (Pc).
(7) The calculated pressure of the compressed vapor is compared to the design value.
(8) A new value for $P2$ is estimated and the previous step is repeated until the desired value for the pressure of the compressed vapor is reached.
(9) The ejector cross section areas (A_1, A_2, A_3) and the area ratios (A_1/A_3 and A_2/A_1) are calculated from Eqs. (12)–(14).

IV. RESULT AND DISCUUSION

Primary fluid flow rate ,pressure ,tempereture and secondary fluid flow rate ,pressure ,temperature are known from available experiment data and based on calculation with above procedure solution we can therotically design ejector with outcomes of discharge pressure , throat dia. of nozzle,exit dia. of nozzle and throat dia of diffuser . Comparison between theoretical result and experiment result are tabulated in the form of Nozzle exit mach no. M1, diffuser exit pressure Pc , area ratio of nozzle exit and nozzle throat ,area ratio of diffuser throat and nozzle throat.

Table. 1: Comparasion between experimental and theoretical data

M_{p2}	$(P_c)_{th}$	$(P_C)_{exp}$	$\left(\frac{A_2}{A_1}\right)_{th}$	$\left(\frac{A_2}{A_1}\right)_{exp}$	$\left(\frac{A_3}{A_1}\right)_{th}$	$\left(\frac{A_3}{A_1}\right)_{exp}$
3	0.53 bar	0.47 bar	4.91	4.40	23.88	21.22
4	0.16 bar	0.15 bar	14.53	14.56	83.33	89.36

V. CONCLUSION

The available mathematical model is used for jet ejector design and the outcome of this results are good agreement the standard manufacturer design data. Here available two jet ejector model with nozzle exit Mach no. 3 and 4 is used for performance analysis.

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