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Modelling and Optimization of Double Choking Ejectors for Refrigeration Systems

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Abstract:
The aim of the work was to investigate effect of pressure difference of primary and secondary flow of double choking system on the system performance by analytically using MATLAB tools. The geometrical variable such as mixing chamber diameter, length of mixing chamber and other geometrical parameter were varied to vary the pressure difference of primary and secondary flow. Analytical results show that nozzle exit conditions influence the mixing chamber, primary exit, and secondary flow of the fluid. Varying condenser pressure and geometrical parameters had a large impact on entrainment ratio and thus performance of ejector refrigeration. If the length of the convergent section of the ejector is lesser than the value calculated for the deflected primary flow, the primary flow will hit the wall of the convergent section and create a barrier for the secondary flow. Ejector refrigeration system can replace the conventional vapour compression refrigeration systems as it is more environmental friendly and uses less power.

Keywords: *Double choking, Ejector, Analytical, MATLAB.*

I. Introduction

The world population increasing day by day and the energy demand for cooling / air conditioning is expected to grow exponentialy due to more requirement comfort for civilians. Hence there is lot of potential scope for improving the cooling capacity of ejection cycle. Air-condition, medical and food preservation field are more promising areas to require more ejector cooling system. Ejector cooling system is replacing other cooling system due to its reliability, ruggedness, long life and low initial and operating costs. One dimensional analysis of ejector was investigated at constant pressure and mixing area of both primary and secondary streams, which is concluded that constant pressure mixing leads to optimum performance of ejectors[1]. The effective area of the secondary vapour at choke conditions is not constant for a jet-pump but it varies with operating conditions.

Operating conditions are maintained at evaporator saturation temperature at 7.5°C and boiler saturation temperature between 110°C and 150°C. The effect on performance due to change in throat diameter is analysed and experimental results show that geometry of primary nozzle has great effects on ejector performance and thereby, the COP of the system[2]. Steam ejector for multi-effect distillation system showed largest entrainment ratio, there is an optimum range of mixing chamber length and also an optimum convergence angle[3]. Munday and Bagster[4] formulated a new theory for ejector performance specifically for steam jet refrigerator performance at eh Mach number of 1 at critical section. Many researchers [5-8] developed thermodynamic models for the ejector refrigeration system, which is assumed to formation hypothetical throat area to the mixing area [9]. Scott et al [10,11] presented the results of computational fluid dynamics (CFD) simulations using R245fa as working fluid. The impact of varying geometrical parameters of ejectors performance was analysed. However the most of the work is concentrated on experimental analysis of ejector but only few works investigate on double choked ejector analytically. The main objective work was to analyse the effect of nozzle exit conditions along with geometric parameters and operating conditions

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2. MATHEMATICAL MODEL

One-dimensional analysis used to determine the dimensions of critical flow passages, which are the primary nozzle throat and exit diameters and the diffuser throat and exit diameters. The one-dimensional analysis described by Eames et al[12] with developments by this author were used throughout this design analysis. The analysis is based on steady state and steady flow equations of energy, momentum and continuity which, are applied through all critical points of flow passages. The nomenclature used in this analysis is shown in Figure 1.

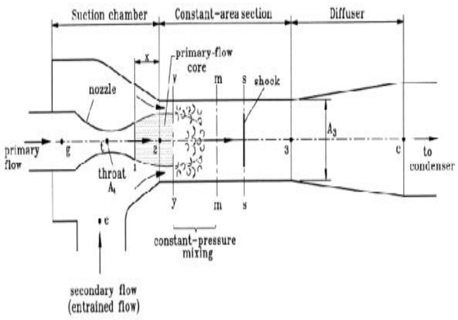

Figure 1.Aschematic representation of

The exit conditions of the nozzle are initially determined for an ideal gas using the following equations. The initial conditions of the nozzle are known based on the cooling capacity of ejector refrigeration system and the geometry of the ejector[13].

$$\frac{P_g}{P_{p1}} = \left(1 + \frac{\gamma - 1}{2} M_{p1}^2\right)^{\frac{\gamma}{\gamma-1}} \qquad (1)$$

For outlet pressure:

$$\frac{T_g}{T_{p1}} = \left(1 + \frac{\gamma - 1}{2} M_{p1}^2\right) \qquad (2)$$

In a similar manner the condition of the secondary flow at the same section x-x (throat corresponds to exit of the primary nozzle) is computed. There is a difference in these two pressures which leads to expansion fan at the exit of the nozzle shown in Figure 2.

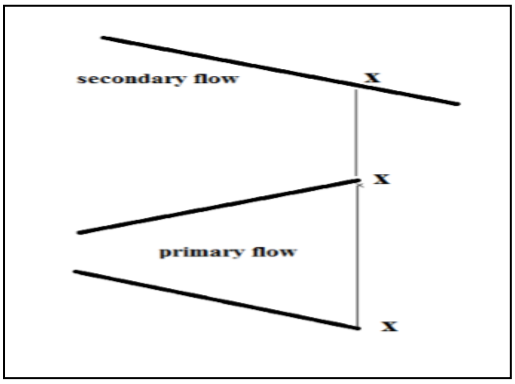

Figure 2.The flow section of x-x of the ejector

3.1 Angle of Deflection for Ideal Gas

The angle of deflection is calculated using equation (6). The quantity on the left-hand side of Equation (6) is referred to as the "Prandtl Meyer Function' as mentioned in the theory of expansion developed by Prandtl and Meyer shown in Figure 3.

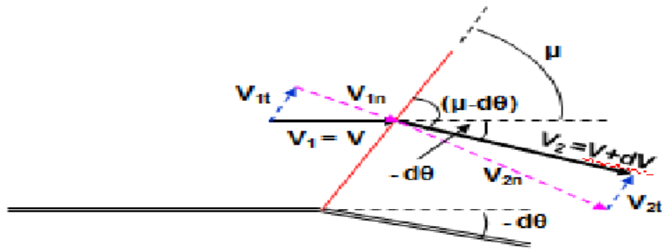

Figure 3. Deflection of flow due to Mach line

The governing equation for Prandtl Meyer flow is

$$d\theta = \sqrt{M^2 - 1}\frac{dV}{V} \qquad (3)$$

This equation is applicable for all kinds of gases. M is the Mach number and V is the velocity. It gives the infinitesimal angle of deflection d□ for a dV change in velocity. For ideal gas assumption, dV/V is given by,

$$\int_{\theta_1}^{\theta_2} d\theta = \int_{M_1}^{M_2} \frac{\sqrt{M^2 - 1}}{1 + \frac{\gamma - 1}{2} M^2} \frac{dM}{M} \qquad (4)$$

From this integration the Prandtl Meyer function is obtained. This Prandtl Meyer function is used to calculate the totaldeflectionof the flow, as mentioned in equation (5)

$$\nu(M) = \sqrt{\frac{\gamma + 1}{\gamma - 1}} \tan^{-1} \sqrt{\frac{\gamma - 1}{\gamma + 1}(M^2 - 1)} - \tan^{-1}\sqrt{M^2 - 1} \qquad (5)$$

Where □ is the isentropic exponent and M is the Mach number.

$$\theta_2 - \theta_1 = \nu(M_1) - \nu(M_2) \qquad (6)$$

Equation [4-6] gives the difference in θwhich gives the angle of deflection of the primary flow from its initial path.

3.2 The Secondary Flow

The variation in the angle of deflection of the primary flow greatly affects the characteristics of the secondary flow. In Huang, Chang [14], the assumption is made that the angle of the nozzle is retained even after the exit of the primary flow from the nozzle. When constant pressure mixing theory is considered, the mixing of the two flows start when the pressures of the two flows are equal. If angle is assumed to be retained, the pressures become equal in the constant area section and the analysis is further resumed based on this result. However, the deflection of the primary flow due to Prandtl Meyer expansion varies the pressure of the secondary flow. As shown in Fig. 4, the deflection of the primary flow constricts the area available for secondary flow. Now, the area is lesser than the area that would be available for the secondary flow had the angle been retained. With lesser area, the increase in velocity occurs rather rapidly which leads to decrease of pressure at a much 'faster' rate. The faster rate of pressure decrease will subsequently lead to the primary and secondary pressures becoming equal at a point in the convergent section itself. The flows get mixed even before reaching the constant area section. This will have a great impact on the ejector performance. Thus, the expansion factor has to be considered to design the ejector for optimum performance.

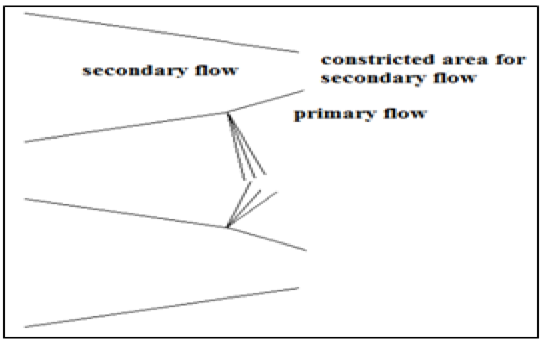

Figure 4.Change in area available for secondary flow

The ejector considered is a double choking ejector. So, both the primary and secondary flows have to choke before they are mixed. The choking of the primary flow occurs at the throat of the primary nozzle. The case is slightly different for the secondary nozzle.

The entrainment ratio (the ratio of the primary and the secondary mass flow rates) of the ejector is fixed. Therefore, there is a necessity for the secondary flow to choke at the point the primary and secondary flows become equal. That is the section of minimum area for the secondary flow. If the choking occurs before the section of minimum area, the entrainment ratio will change, thus defeating the purpose of the ejector itself. It is required that the secondary flow choke at the minimum area itself. This is brought about by the change in the dimensions of the ejector. As it can be seen from the equations mentioned below, the Pressure of the secondary flow, the angle of deflection of the primary flow are all dependent on the initial area of the ejector.For the secondary flow, from the known initial conditions of the ejector, the variables Pressure, temperature, Entropy and velocity are known.

P1s, T1s, m1s, V1s, S1s are known.

Isentropic conditions are assumed.

S1s=S2s (7)

A2s is known from the deflection angle calculated in primary flow calculations.

The mass conservation equation, the secondary mass flow rate is known from the primary mass flow rate and the fixed entrainment ratio.

m2s = m1s* Rm(8)

The energy conservation equation

$$h_{1s} + \frac{V_{1s}^2}{2} = h_{2s} + \frac{V_{2s}^2}{2} \tag{9}$$

$$V = f(P, S) \tag{10}$$

$$h = f(P, S) \tag{11}$$

With four equations and four variables, the pressure at the next section is calculated. The iterations proceed till the primary and secondary pressures become equal. This is the point where the expansion fan ceases to exist. Once the primary and secondary flow pressures become equal, the mixing

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of the flows starts according to the constant pressure mixing theory. The secondary flow is subsonic at section x –x. With decreasing area, the velocity of the secondary flow increases, consequently increasing the mach number of the flow.

Thus, the pressure of the secondary flow decreases as the velocity increases. At any section of the convergent section of the ejector, the primary and the secondary flow pressures become equal. This is the section where mixing of the two flows start, according to the constant pressure mixing theory.

3.3 Formulation of MATLAB Code

MATLAB code was formulated to study the effect of exit nozzle conditions on the ejector design and the performance. The algorithm below shows the steps used for coding and flow chart are drawn in Fig. . The entire code is GUI (Graphic user interface) supported. The algorithm shows the simple steps highlighting the technical concepts used.

Nozzle inlet Pressure, Nozzle outlet pressure, and Nozzle geometry is given as inputs

- Input inlet pressure, outlet pressure, nozzle geometry.
- Compute Pressure and Mach number at all nodes [for i=1: dx: nozzle length] using the continuity equation.
- Assuming Mach number at inlet is very less, take it as Min=0.2.
- Based on the Mach number, various cases can be considered as shown below

Case 1: Mt<1, Flow is not choked. Subsonic flow everywhere

Case 2: Mt = 1 & Me<1, Subsonic and choked. Isentropic.

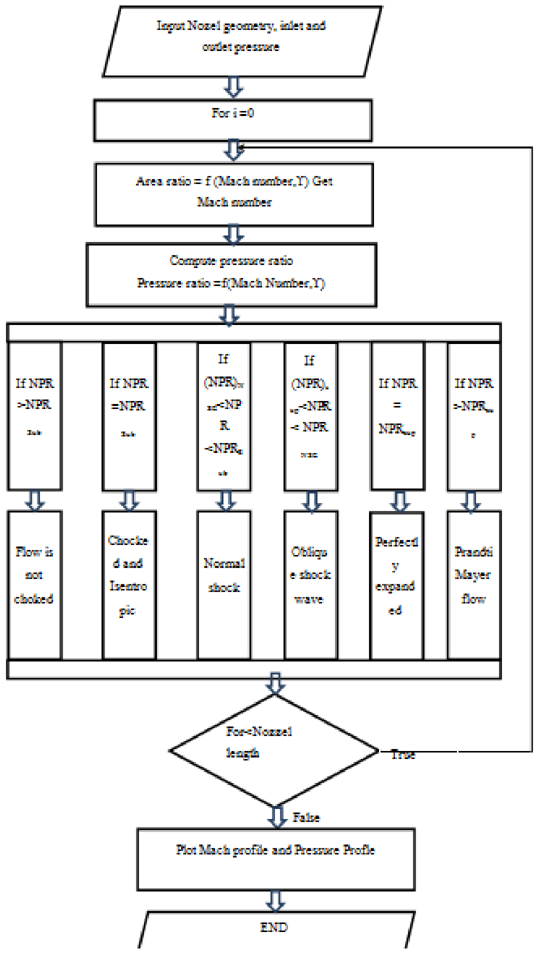
Case 3: NPR is between subsonic and supersonic solution

- Either a normal shock exists inside the nozzle, or an oblique shock exists outside the nozzle.
- If a normal shock is found inside the nozzle, determine the position of normal shock inside the nozzle. Draw the location of the shock.
- If an oblique shock exists outside the nozzle, draw the orientation of the shock depending on how close the pressure ratio is to the supersonic solution. Also, compute oblique shock angle

Case 4: Perfectly expanded

Case 5: Under-expanded jet. Draw Expansion fans outside the nozzle. Pressure and Mach number outside the nozzle change according to Prandtl Meyer expansion formula

- Plot the graph: Pressure profile and nozzle geometry. Cubic smooth curve is used to show the variation. The abrupt jump in pressure indicates the point of discontinuity i.e., shocks



4. RESULT AND DISCUSSION

4.1 Effect of Operating Conditions on Ejector Performance

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Effect of generator temperature on ejector entrainment ratio is studied. Simulations for primary inlet temperature (generator temperature) from 800C to 1000C with constant evaporator temperature of 80C and condenser temperature of 280C was performed. The result was plotted as graph is shown in Figure 6. The plot shows one value of Tg for which E.R is maximum.

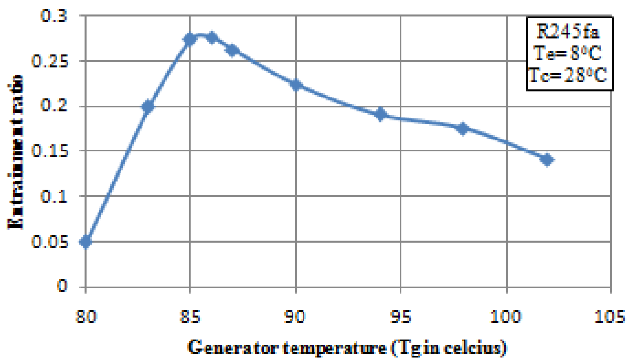

Figure 6. Predicted effect of Generator temperature/ pressure (Tg, Pg) on ejector performance

The optimum value of generator temperature is obtained at 860C. With Tg = 860C and Te= 80C and 120C, simulations were performed to determine critical condenser temperature. Critical condenser pressure/ temperature is a characteristic after which entrainment ratio starts varying. If condenser temperature is maintained below critical temperature, entrainment ratio is maintained constant and also both primary and secondary flow is choked. For Te= 80C, critical condenser temperature is 280C and for Te= 120C, critical condenser temperature is 310C

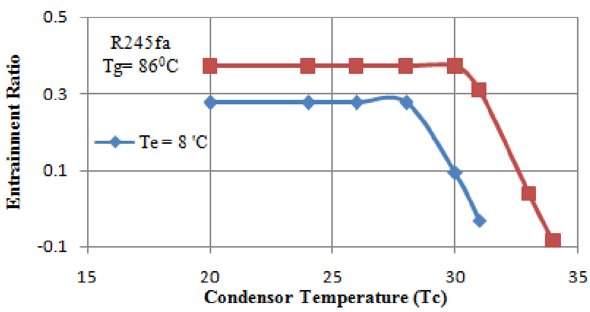

Figure 7. Predicted effect of Condenser temperature/ pressure (Tc, Pc) on ejector performance

Using optimum values of both condenser temperature and generator temperature, the variation of entrainment ratio with evaporator temperature is determined and shown in Figure 8. It is seen that entrainment ratio increases with increase in evaporator temperature. But due to certain limitations, it can't be increased beyond certain value.

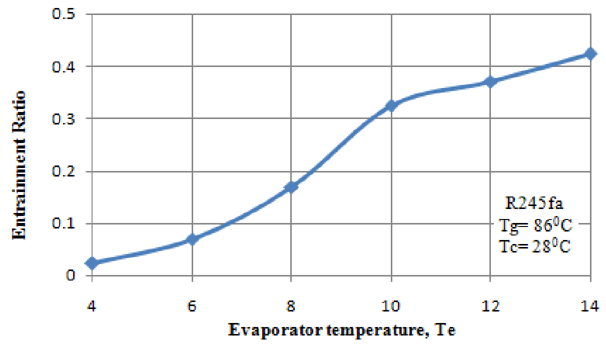

Figure8. Predicted effect of Evaporator temperature/ pressure (Tc, Pc) on ejector performance

Effect of Geometric Parameters on Ejector Performance (Parametric Analysis)

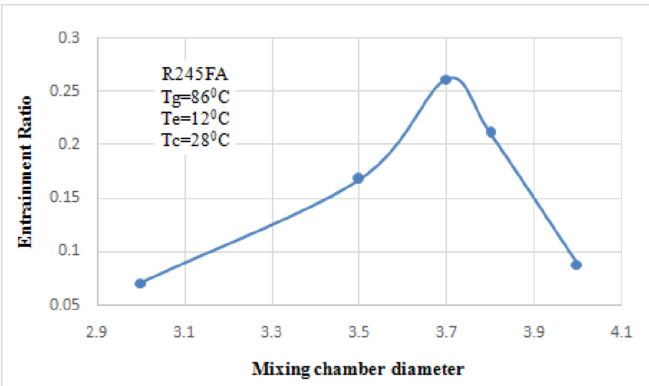

Figure 9. predicted effect of mixing chamber diameter on ejector performance

After determining the optimum operating conditions, these conditions are used to perform parametric analysis. Parametric analysis is very important to understand the importance of geometrical parameters of the ejector. Mixing of primary and secondary flow plays a major role in determining the performance of ejector. Hence, mixing chamber geometry is analyzed.

Effect of mixing chamber diameter and mixing chamber length is represented in Figure 9 and 10 respectively. It is seen that for one mixing chamber diameter of 3.7mm, the entrainment ratio is maximum. While, there is range of mixing chamber length for which entrainment ratio change is very small.

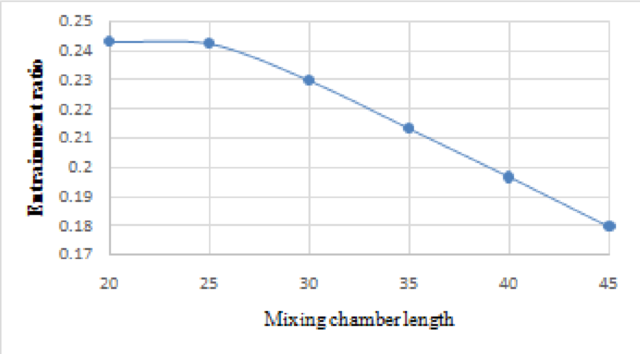

Figure 10. : predicted effect of mixing chamber length on ejector performance

5. CONCLUSION

The conclusions drawn from the present study is shown as follows:

- Primary nozzle design plays important role in determining overall ejector performance. If a primary nozzle is designed such that expansion fan occurs at the exit, then secondary choking occurs much before expected due to deflection of primary flow.
- If symmetry in shocks mentioned, then expansion fan is advantageous as it reduces the material and length of outer boundary.
- It is important to check the exit conditions exhibited by primary nozzle over the entire range of operating conditions. MATLAB code is formulated to determine nozzle exit conditions and deflection angle.
- The study of the deflection of the primary flow helps in the determining the design parameters of the ejector for optimum performance. It also helps to prevent dangerous consequences like stalling of the secondary flow and complete shut-down of the ejector refrigeration system.
- Ejector refrigeration system can replace the conventional Vapour Compression Refrigeration systems as it is more environmental friendly and uses less power. It would be very beneficial to increase the performance of the ejector refrigeration system and to make improvements to the existing system on a path towards a greener earth

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