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Numerical Investigation of Ejectors for Ejector Refrigeration System

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Abstract:- This paper presents the numerical analysis performed on ejectors to optimize operating conditions like evaporator temperature, condenser temperature and generator temperature. R245fa was the working fluid used. Parametric analysis was performed to study the effect of mixing chamber geometry on ejector performance which has direct impact on coefficient of performance of ejector refrigeration cycles. Results show that operating conditions and geometric parameters have a value or range of values for which entrainment ratio of ejector is maximum.

Keywords:- *Ejector, entrainment ratio, CFD, ANSYS, optimization, operating conditions .*

I. INTRODUCTION

The jet refrigeration cycle is like conventional refrigeration cycle; all the basic system components are the same except that the compressor is replaced by a sub-system made up from a liquid feed-pump, a vapour generator, and the ejector. The ejector is used to compress refrigerant vapour from the evaporator pressure to the condenser pressure. The generator is used to produce high pressure vapour to drive the ejector and the feed-pump is used to return liquid refrigerant coming from the condenser to the vapour generator.

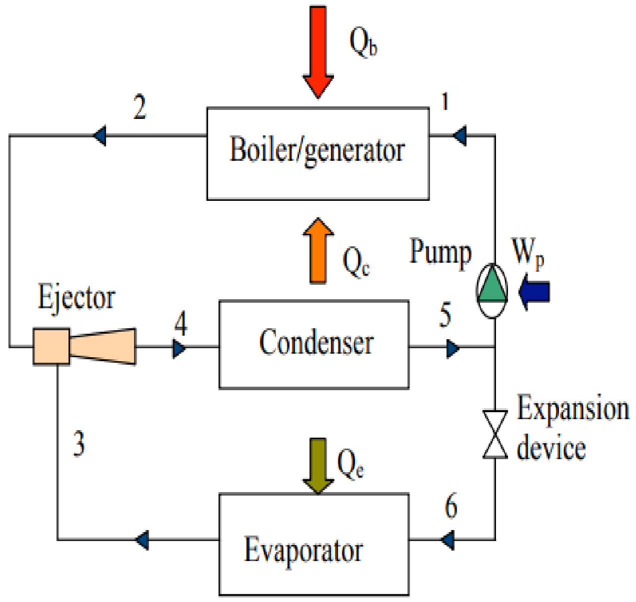

Fig 1:- A schematic representation of ejector refrigeration System

Figures 1. and 2. provide schematic representations of an ejector refrigeration system and of the ejector, respectively.

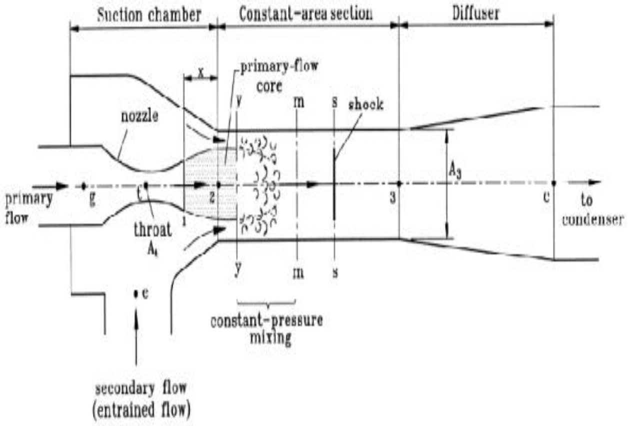

Fig 2:- A schematic representation of an ejector

Referring to Figure 1, the ejector refrigerator operates as follows: heat is absorbed by the generator and this causes liquid refrigerant to be vaporised at a high pressure. This vapor (m_p) is fed to the primary nozzle of the ejector, (shown in Figure 2), through which it is accelerated to supersonic velocity. At the nozzle exit, a jet is formed, which entrains the suction or secondary stream (m_s) coming from the evaporator. The primary and secondary streams combine within the mixing section. The kinetic energy of this combined stream is transformed into pressure energy in the diffuser section of the ejector from where the combined vapor stream is fed to the condenser [Eames et al (1995b)]. The heat of condensation is rejected to the environment via the condenser and part of the resulting condensate is fed back to the generator via feed-pump whilst the remainder is expanded, via a throttling valve, to the evaporator where it absorbs heat at low temperature, causing it to vaporise and produce the desired refrigeration effect.

A. Description of Ejectors

Fig 2 shows a schematic structure of an ejector. The high-pressure gaseous working fluid is sent to ejector and pass through the nozzle section. While passing, the gas is accelerated and expands with decreasing pressure. The supersonic primary flow becomes supersonic. As the pressure of the primary flow is lower than the pressure in evaporator, the working fluid in the evaporator flows as the secondary flow at supersonic speeds.

In the suction chamber of ejector, the primary and secondary flows begin mixing and in the mixing section the two flows are mixed completely. In the diffuser, this mixed flow raises its own pressure with a transverse shockwave, and enter into condenser. In condenser, the working fluid changes from gaseous state to liquid state. The liquid is sent to generator by pump. Power consumption by pump is small, which can be provided by photovoltaic cells. Some of the liquid is sent to evaporator through expansion valve.

In evaporator, the liquid working fluid evaporates at lower pressure and absorbs heat from the ambient. Advantage of this cycle is that the cycle is activated by heat input, even if low grade thermal energy at about 60^0C. Therefore, heat resources such as solar thermal energy, geothermal energy and exhaust heat from factories etc. can be effectively utilized. And, ejector itself is simple, so this cycle would require only light maintenance.

B. Ejector performance

Eames et al (1995b) defined the coefficient of performance (COP) of a jet-pump refrigerator as:

$$COP = \frac{refrigeration\ effect\ at\ the\ evaporator}{heat\ rate\ at\ the\ generator + power\ consumed\ by\ the\ pump}$$

[1-1]

$$COP = \frac{Q_e}{Q_b + W_p}$$

The power absorbed by the circulation pump is typically less than 1% of the heat supplied to the generator and thus it is usually ignored to simplify thermodynamics calculation. Therefore, for the calculation of overall system performance, COP, equation [1-3] is used:

$$COP = \frac{\dot{m}_s(h_3 - h_1)}{\dot{m}_p(h_2 - h_5)} \qquad [1-2]$$

$$COP = R_m \frac{\Delta h_{evap}}{\Delta h_{generator}} \qquad [1-3]$$

Where R_m is the entrainment ratio of the jet-pump defined as:

$$R_m = \frac{\dot{m}_s}{\dot{m}_p} \qquad [1\text{-}4]$$

Entrainment ratio is a function of jet-pump geometry and operating conditions; thus, the corresponding COP of the system will vary dependently. However, for fixed jet-pump geometry, designed for specific refrigerator operating conditions, the maximum COP of the system is obtained at the maximum value Of R_m.

II. CFD METHODOLOGY

A. Geometric modelling

3 D surface modelling of ejector was modelled using SolidWorks CAD package due to easy commercial availability. However, for Computational simulations 2D planar and axisymmetric modelling was considered. Simulations were performed using both 2D planar and axisymmetric models for couple of operating conditions. It was seen that both type of models provided almost same results. Hence, 2D axisymmetric model was used for rest of the simulations for lesser memory requirements and less computational time

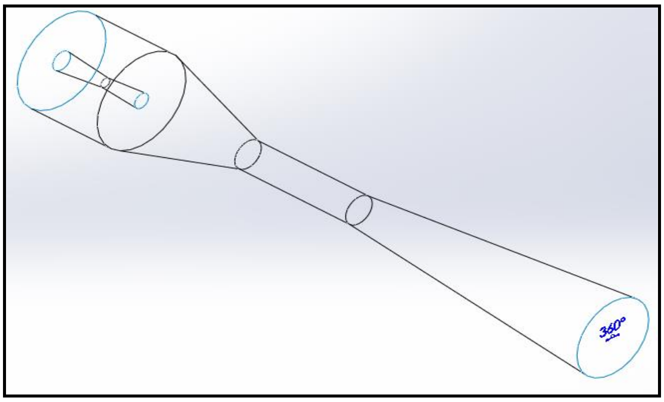

Fig 3:- 3D ejector model, modeled in Solidworks

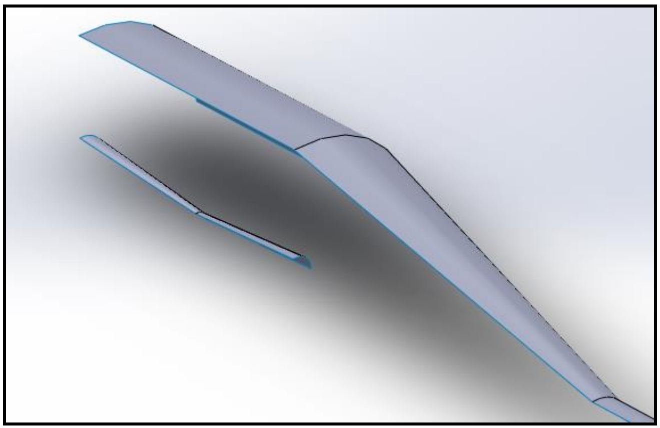

Fig 4:- 1/4th symmetry model of ejector

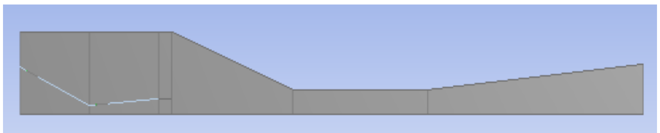

Fig 5:- Axisymmetric model of ejector

Ejector geometrical specifications (dimensions)

Geometry was borrowed from literature work of Huang, Chang [2]. The geometrical dimensions/specifications of ejector are presented below in table 1.

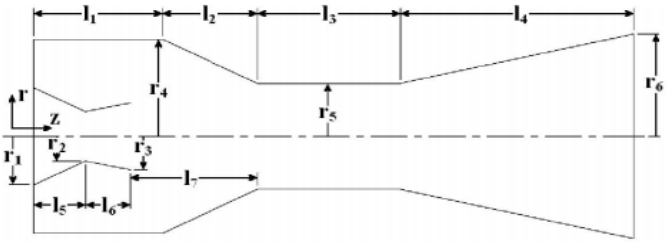

Fig 6:- Geometry of ejector

Length	Dimensions (mm)	Radii	Dimensions(mm)
L_1	40	r_1	6.65
L_2	32.24	r_2	1.32
L_3	35.6	r_3	2.25
L_4	56.94	r_4	11.55
L_5	18.32	r_5	3.49
L_6	18.32	r_6	7.04

Table 1. Geometric parameters of an ejector

B. *CFD Setup*

ANSYS Fluent is used for computational simulations because due to reasons like commercial licensed version of software available. Technically, ANSYS works using Finite Volume method (FVM) unlike other packages like COSMOS use Finite element method (FEM) which saves computation time. ANSYS also captures shocks due to FVM technique. Along with this, ANSYS is used to capture both far-field and boundary characteristics.

- *Mesh generation*

Meshing is highly important in CFD approach as whole entity is broken down into small 2-D or 3-D elements and properties are calculated at nodes. Face meshing with edge sizing along inlet and axis is employed. The element size is defined as 0.4mm for axis and 0.5 mm for inlet. It is a quad element with 4 nodes

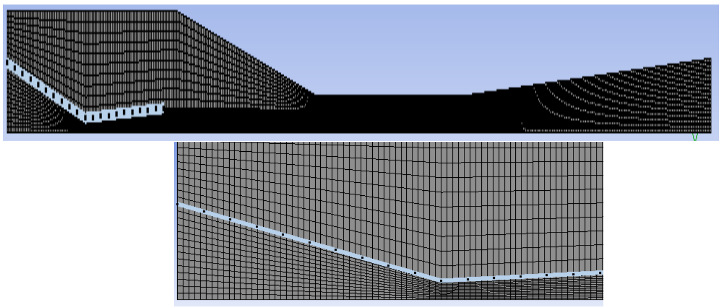

Fig 7:- Meshing of ejector

- *Mesh attributes*

The table 2 shows the mesh attributes or important characteristics of a mesh. Mesh quality is defined by these mesh attributes. Skewness of the mesh is a measure of how close the element shape is to the equilateral shape (0 being best and 1 being worst). Orthogonality relates how close the angles between adjacent element faces are to some optimal angle. (For ex, 90^0 for quad element). Aspect ratio is defined as ratio of largest edge length to shortest edge length.

$$skewness=\frac{optimal\ cell\ size-cell\ size}{optimal\ cell\ size}$$

Mesh attribute	value
Orthogonal quality	0.95
Skewness	0.05
Aspect ratio	4.8
No. of nodes	10396
No. of elements	9946

Table 2. Mesh Attributes

- *Grid Independence Test*

Determining the minimum number of elements or nodes required to get converging and accurate result is important to optimise the computational power and time required. The graph of entrainment ratio Vs no of elements is plotted in figure 8.

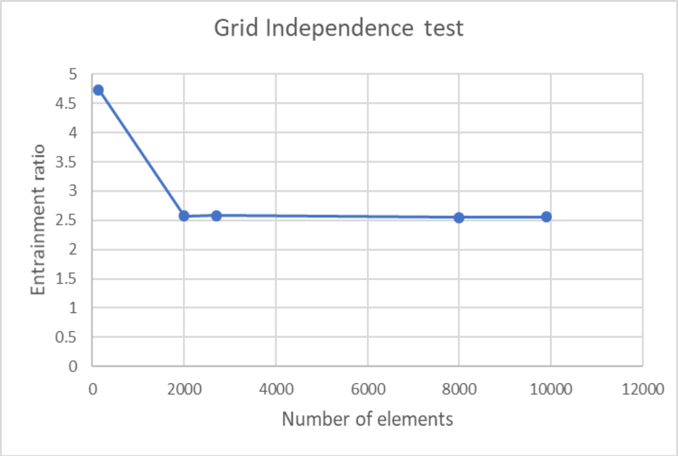

Fig 8:- Graph of Entrainment Ratio Vs Number of elements (Grid Independence test)

- *Boundary conditions*

From the experimental data in ICER lab, the boundary conditions are showed in table 3. Certain properties like condenser pressure is varied to note determine the effect of variation of operating conditions.

Pressure at inlet 1	0.4MPa
Pressure at inlet 2	0.04MPa
Pressure at outlet	0.06MPa

Table 3. Boundary Conditions

Refprop is used to determine temperature and other thermal properties.

- *FLUENT Setup*

There are different types of turbulent models: k-omega [5 – 1] model, k-epsilon model, k-omega SST model. K-omega SST model is used as it captures both far field and boundary characteristics. All of these turbulence models are based on RANS (Reynold's Averaged Navier Stokes) Equation. Pressure based steady state axisymmetric solver is used.

K-omega SST model is a two-equation eddy viscosity model which is given by the below equations.

Turbulence Kinetic energy (k):

$$\frac{\partial k}{\partial t}+U_j\frac{\partial k}{\partial x_j}=P_k-\beta^* k\omega+\frac{\partial}{\partial x_j}\left[(\nu+\sigma_k\nu_T)\frac{\partial k}{\partial x_j}\right]$$

Specific dissipation rate (omega):

$$\frac{\partial\omega}{\partial t}+U_j\frac{\partial\omega}{\partial x_j}=\alpha S^2-\beta\omega^2+\frac{\partial}{\partial x_j}\left[(\nu+\sigma_\omega\nu_T)\frac{\partial\omega}{\partial x_j}\right]+2(1-F_1)\sigma_{\omega 2}\frac{1}{\omega}\frac{\partial k}{\partial x_i}\frac{\partial\omega}{\partial x_i}$$

Solver Type	Pressure based solver- steady-axisymmetric
Wall	Ideal-Stationary
Navier Stokes Activated	Energy-on: K-omega SST Turbulence model
Material	R245fa refrigerant

Table 4. FLUENT Setup

- *Solution Setup*

Gradients of solution variables are required in order to evaluate diffusive fluxes, velocity derivatives, and for higher-order discretization schemes.

$$\frac{\partial(\rho\phi)}{\partial t}V+\sum_{f}^{N_{\text{faces}}}\rho_f\,\mathbf{V}_f\,\phi_f\cdot\mathbf{A}_f=\boxed{\sum_{f}^{N_{\text{faces}}}\Gamma_\phi\,\nabla\phi_f\cdot\mathbf{A}_f}+S_\phi V$$

Green-gauss cell based, Green-gauss node based, least square cell based are three different gradient solving techniques. Least square cell based is preferred in this case as it best suits polyhedral meshes (in this case, quad mesh) while Green-gauss node method is suitable for tri/tet meshes. SIMPLE algorithm is used as pressure-velocity coupling algorithm because of the faster convergence achieved.

Initialization	Hybrid
Conditions computed from	Inlet
Modelling	Implicit
Gradient solving	Least square cell based
Upwind scheme	Second order upwind

Table 5. Solution Setup

III. RESULTS

Computational simulations carried out for different conditions and different geometry profiles. For each computation, Mach contours and entrainment ratios are recorded. Mach contours of all the conditions looks the same and hence one such contour is shown in figure 9.

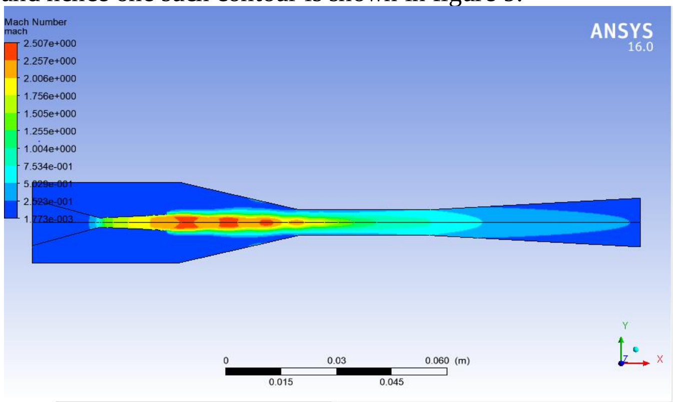

Fig 9:- Mach contour (ANSYS 16.0)

A. *Effect of operating conditions on ejector performance*

Effect of generator temperature on ejector entrainment ratio is studied. Simulations for primary inlet temperature (generator temperature) from 80^{0}C to 100^{0}C with constant evaporator temperature of 8^{0}C and condenser temperature of 28^{0}C was performed. The result was plotted as graph is shown in figure 10. The plot shows one value of Tg for which E.R is maximum.

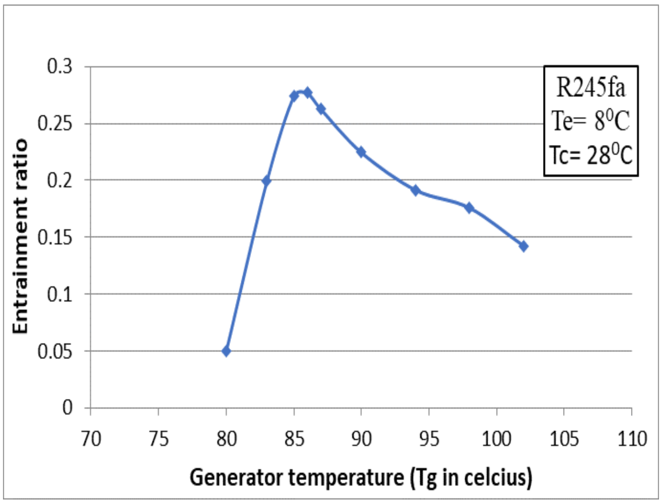

Fig 10:- Predicted effect of Generator temperature/ pressure (Tg, Pg) on ejector performance

The optimum value of generator temperature is obtained at 86^{0}C. With T_g = 86^{0}C and T_e= 8^{0}C and 12^{0}C, 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 T_e= 8^{0}C, critical condenser temperature is 28^{0}C and for T_e= 12^{0}C, critical condenser temperature is 31^{0}C.

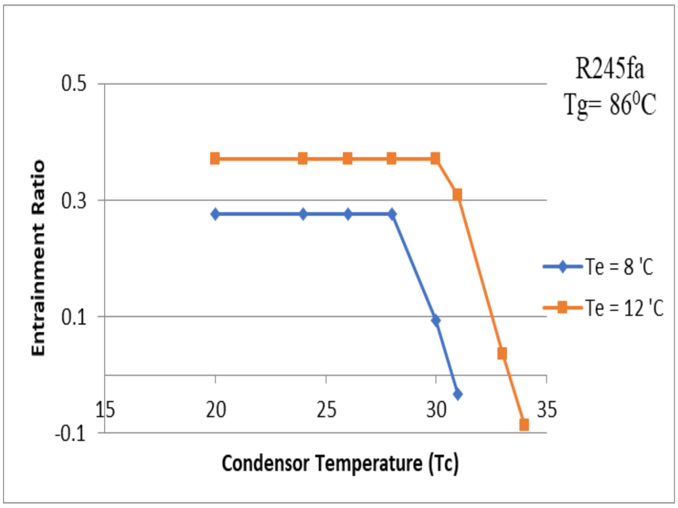

Fig 11:- Predicted effect of Condenser temperature/ pressure (Tc, Pc) on ejector performance

Using optimum values of both condenser temperature and generator temperature, the variation of entrainment ratio with evaporator temperature is determined and shown in figure 12. 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.

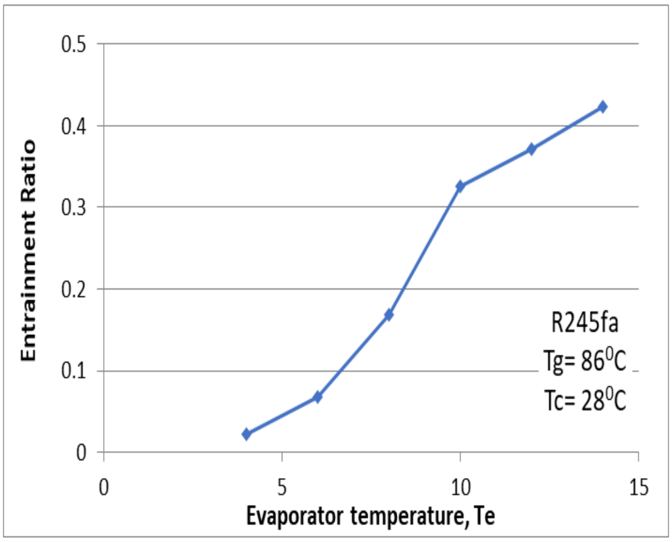

Fig 12:- Predicted effect of Evaporator temperature/ pressure (Tc, Pc) on ejector performance

B. Effect of geometric parameters on ejector performance (Parametric Analysis)

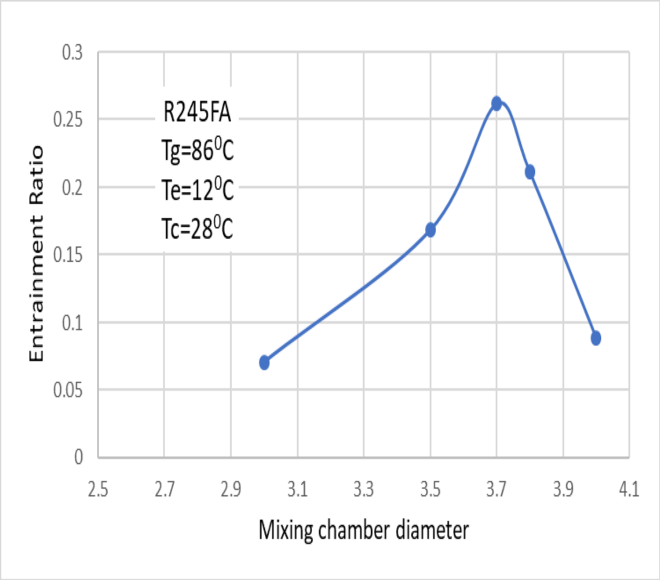

Fig 13:- predicted effect of mixing chamber diameter on ejector performance

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 13 and 14 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.

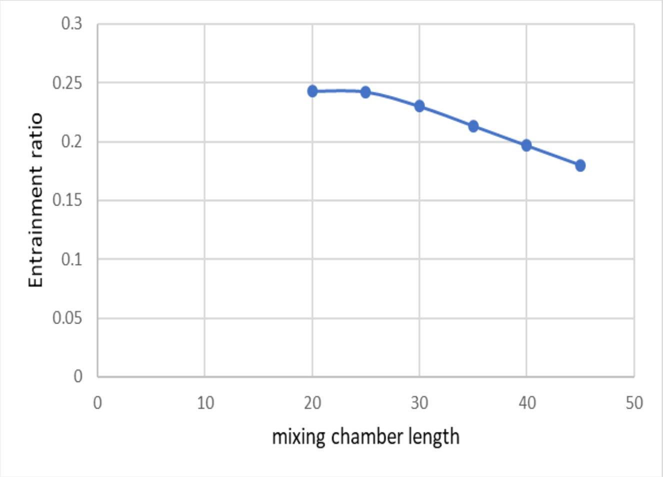

Fig 14:- predicted effect of mixing chamber length on ejector performance

C. Validation of CFD results

To validate the accuracy of CFD simulation results, a set of CFD simulations were run using operating conditions and geometry of nozzle identical to Haung, Chang [2] and Scott et al [10]. It was found that the results were close to the results obtained by Haung in one dimensional analysis of ejector and Scott's Computational simulations. The error was limited to ±5%. Hence, the same method was extended to other boundary conditions. Table containing boundary conditions, results and error is represented in the figure 15

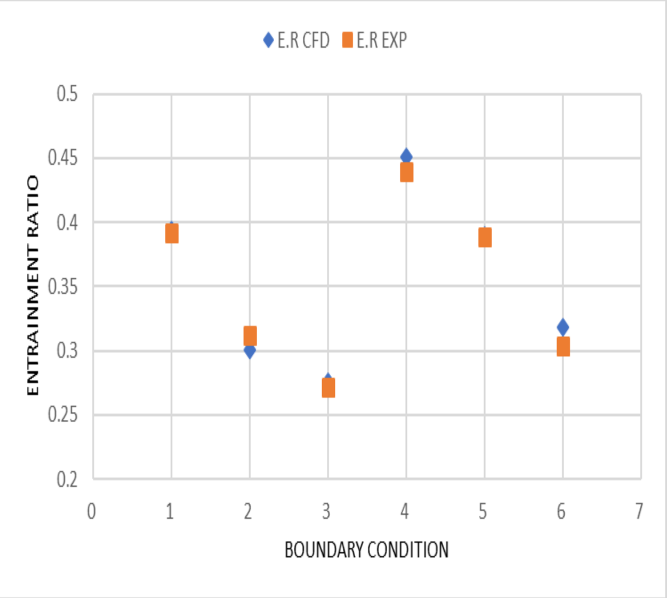

Fig 15:- Chart comparing experimental and numerical data

AB and AG represent two different geometries of ejector and are analysed for 3 different operating conditions maintaining the outlet pressure (condenser pressure) at 0.06 MPa. ANSYS fluent was used to run computational simulations. E.R CFD gives the entrainment ratio obtained by CFD simulations and E.R EXP is the experimentally determined entrainment ratio.

The results of current study can also be validated comparing the results obtained numerically with analytical results. The graphs below show the variation of entrainment ratio with Condenser temperature numerically and analytical. Both the graphs have identical behaviour as shown in figure 16. and 17.

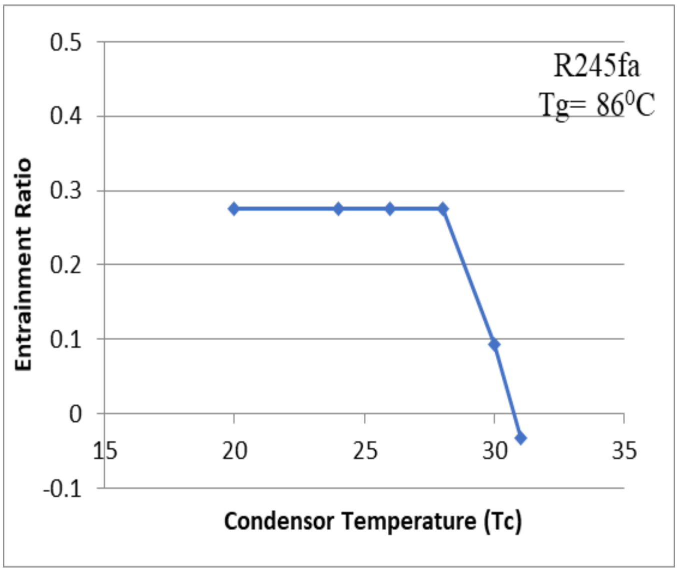

Fig 16:- Graph of Entrainment Ratio Vs Condenser Pressure obtained numerically

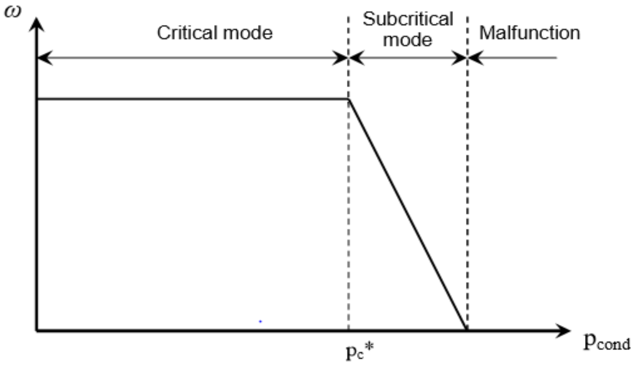

Fig 17:- Graph of Entrainment Ratio Vs Condenser Pressure (Analytical)

IV. CONCLUSION

The ejector cycle refrigeration is a green refrigeration technique. To improve the performance of the ejector refrigeration system, the understanding of the flow of the fluid in the ejector is very essential. In the present study, the flow of the primary fluid after the exit of the nozzle, subjected to a drastic pressure difference is investigated. The effect of the deflection of the primary flow on the secondary flow is determined. It can be observed from the results that due to the deflection of the primary flow, the choking of the secondary flow occurs much earlier than anticipated, thus causing the mixing to occur in the convergent section of the ejector itself. This has profound implications on the performance of the ejector as the pressure after mixing will not remain constant but will vary according to the variation in the area of the convergent section of the ejector. CFD simulations was performed to identify optimum geometry and optimum operating conditions. It was mostly observed that all properties had a bell curve with one optimum point and decreasing on either side

V. ACKNOWLEDGMENT

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