International Engineering Research Journal

Effect of primary nozzle diameter and primary steam pressure on performance of steam ejector in steam jet refrigeration system

Sagar R. Bhagat†, Dr. P.A. Patil‡

†Post graduate student, Department of Mechanical Engineering, JSPM's JSCOE, Pune, Maharashtra, India
‡Head of department, Department of Mechanical Engineering, JSPM's JSCOE, Pune, Maharashtra, India

Abstract

COP of steam jet refrigeration is dependent on theperformance of steam ejector. Primary nozzle throat diameter and primary steam pressure plays an important role for obtaining better entrainment ratio of steam ejector. The performance of steam ejector depends upon the geometric parameter of primary nozzle, primary steam pressure, evaporator side (suction) pressure and condenser side pressure. CFD technique was used to study effects ofdifferent types of parameter on performance of steam ejector. CFD simulation was conducted for two different diameters of primary nozzles, having a throat diameter of 1.4 mm and 1.7 mm respectively. Evaporator side temperature and condenser pressure is kept constant at 7.5°c and 30 mbar respectively providing that ejector body dimension is same for all cases. Primary steam pressure is varied from 5 bar to 10 bar. From results it is found that secondary mass flow rate increases with increase in primary nozzle diameter and primary steam pressure which increases entrainment ratio of ejector but if superheated steam is used instead of saturation steam at same pressure then mass flow rate of primary steam and secondary vapor decreases with increase of degree of superheat and there is small decrease in entrainment ratio.

Keywords:*steam ejector, entrainment ratio, nozzle diameter, primary steam pressure.*

1. Introduction

In mostindustrial processes, an amount of waste heat is rejected to the surrounding. By using heat powered refrigeration systems, electricity purchased from companies for conventional refrigeration cycles can be reducedif this waste unless we convert heat to useful refrigeration.Absorption refrigeration and jet refrigeration cycle are most widely used refrigeration cycles.

These heat powered refrigeration cycles are nothing but used waste thermal energy with small quantity of electricity required to circulate their working fluids and to control the system. The absorption refrigeration system has a better COP value than that of the jet refrigeration system. But the jet refrigeration is comparatively simple to construct, operate, and control. The only refrigeration system that can use water is jet refrigeration system providing that it is one of the most environmentally friendly and cheapest refrigerant, as its working fluid.

The performance of steam jet refrigeration cycle is mainly dependent on steam ejector geometry and operating parameters. Steam ejector consist of primary motive fluid nozzle and ejector body. In steam ejector motive fluid used is steam from boiler and secondary fluid is vapor from evaporator. Ejector body has a converging section, constant area throat and diverging diffuser outlet for production of pressure variation inside ejector body. Converging section acts as mixing chamber for primary and secondary fluid.

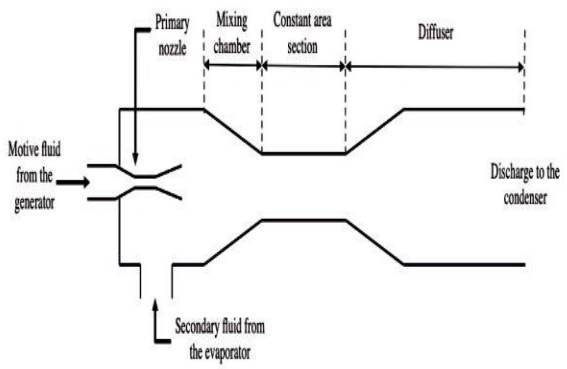

Fig1. Steam ejector

In this research the effect of primary nozzle diameter and primary steam pressure on the performance steam ejector in terms of entrainment ratio is studied with CFD software. Performance of steam jet refrigeration is defined in terms of the coefficient of performance,

COP=Rm× ((hg_evap–hf_con)÷(hg_boiler – hf_con)

COP=Rm× [(Hfg)_sec. fluid ÷ (Hfg)_primary fluid]…(a)

Where, Rm= (M1÷M2)
M1=mass flow of secondary fluid.
M2=mass flow of primary fluid.

Hfg=Latent heat of vaporization.
As primary and secondary fluids are same hence latent heat of vaporization is equal, hence equation (a) is reduced to,
Rm= COP.

2. Literature Review

1.Natthawut ruangtrakoon, et al. in their paper acclaimed after having experimental studies of a steam jet refrigeration system "Effect of the primary nozzle geometries to system performance'' apparently they studied steam ejector with eight different nozzles experimentally and concluded that, geometries of the primary nozzle have bold effects on ejector performance and precisely on the system COP.

2.Natthawut ruangtrakoon et al. in their paper "CFD simulation on the effect of primary nozzle geometries for a steam ejector in refrigeration cycle" using CFD technique to investigate the effect of primary nozzle geometry, primary fluid pressure on the performance of an ejector used in the refrigeration system. It was found that two series of shock waves were found. First shock wave immediately appeared at the primary nozzle's exit plane and second shock wave appeared with in the ejector throat and subsonic diffuser section. Shock's position of the mixed fluid and the expansion angle of the primary fluid jet stream within the mixing chamber played a very important role in the ejector performance.

3. Alejandro Gutierrez et al. in their work on "conceptual development and CFD evaluation of a high efficiency variable geometry ejector for use in refrigeration application": An ejector that implements variable geometry mechanisms is proposed and evaluated using CFD simulations. It states that the resulting ejector operates more efficiently than current designs while maintaining a constant efficiency when subjecting to variable operating conditions.

4.T.Sriveerakul et al. in their paper "Performance prediction of steam ejector using computational dynamics: part2. Flow structure of a steam ejector which is influenced by operating pressures and geometries." Analyze the flow phenomenon inside the steam ejector when it's geometries and operating conditions were varied using the CFD.

5. Kavous Ariafar et al. in their paper, "Mixing layer effect on the entrainment ratio in steam ejectors through ideal gas computational simulations." investigated the flow in a representative steam ejector to specify the contribution of mixing and pressure-driven effects to the overall ejector entrainment ratio under various operating conditions.

6. Ali Hakkaki-Fard et al.in their paper, "A computational methodology for ejector design and performance maximization." Increase the entrainment ratio of ejector without much more affecting critical pressure by shaping primary nozzle and its position. Entrainment ratio results in increasing performance of ejector and hence cycle efficiency increases.

By studying above reference paper it is clear that researchers have studied effect of primary nozzle geometry on performance of ejector and also studied flow phenomenon inside ejector body. Geometric parameter is main area of focus in all above papers. Along the geometric parameter we can study the effect of operating parameter and condition of steam on performance of steam ejector by computational fluid dynamics technique.

3. CFD Model Setup

The CFD model used for this project is 2-dimensional which is created in ansys workbench 15. This model was divided as grid elements using a fluent 15. The meshing used for grid element generation is quadrilateral type. The grid element are generated about 0.6mm size. For solving the equations the commercial CFD software, FLUENT 15was used, to solve mathematical model in the defined planar domain.
All dimensions of steam ejector are shown in figure 2.and listed in table 1. [2]

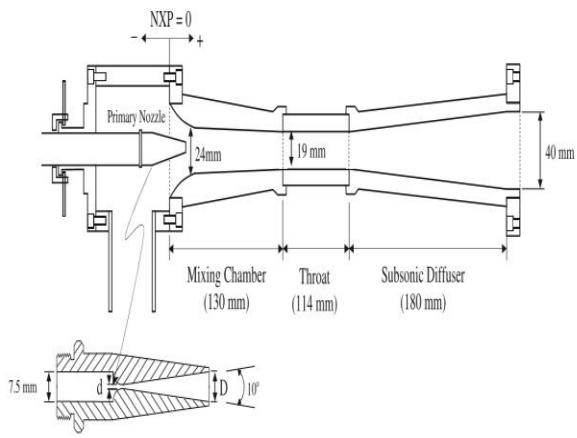

Fig 2. The steam ejector[2]

Sr. no	Diameter of nozzle throat (d)mm	Area ratio $(D:d)^2$	Nozzle exit diameter (D) mm
1.	1.4	20:1	6.26
2.	1.7	20:1	7.6

Table 1. Dimensions of primary nozzle[2]

3.1. Solver setup

The ansys software, FLUENT 15, employed the finite volume method to convert all governing equations to algebraic form so that those governing equations can be solved numerically. This technique discretizes all

governing equations by first dividing the physical space into a number of quadrilateral control volume grid elements. Due to the fact that the flow inside the ejector was thought to be in a supersonic flow field, it is assumed to correspond to turbulent compressible flow. Based on this hypothesis, the governing equations had to be composed of a conservative form of mass, momentum and energy equation.

In present work, the density-based implicit solver was chosen to solve the governing equations which is best suitable for a supersonic flow field and the flow was set based on steady-state. The convective terms were discretized with a second order upwind scheme. Shear -stress-transportation k-w (k-w-sst) turbulence viscosity model were selected. These turbulence models have been extensively used in the field of the supersonic flow field.

The grid structure of ejector domain is shown in fig.3

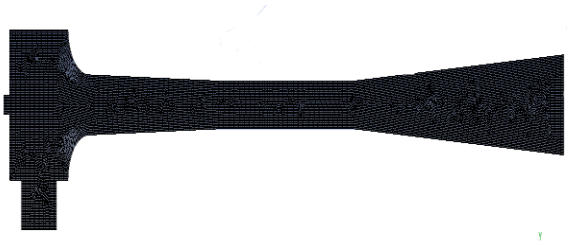

Fig .3. Grid structure of an ejector domain

3.2. Working fluid properties and boundary conditions

Water vapor is used as working fluid which is assumed as an ideal gas because steam ejector was operated at relatively small absolute pressure in mixing chamber. In this case real steam behavior is close to ideal gas therefor ideal gas assumption is acceptable.

Primary fluid inlet and secondary fluid inlet upstream conditions are set as a pressure inlet type, downstream outlet of ejector is set as pressure outlet type. All surfaces of steam ejector are set as adiabatic wall which means that heat transfer across any surface wall is zero.

The properties of steam used during simulation is tabulated in table2.

Sr. No.	properties	Value
1	Viscosity(kg/m.s)	1.34×10-5
2	Thermal conductivity(W/mk)	0.0261
3	Specific heat(J/kg k)	2014
4	Molecular weight (kg/kmol)	18.015

Table 2. Working fluid properties

Problem statement:

The aim of project is to study and analyze effect of geometric parameter of primary nozzle and operating conditions on steam ejector performance by using CFD software to improve the efficiency of steam ejector.

Objectives:

1. Investigate the performance of specific requirement steam jet ejector using computational technique under various operating conditions.
2. Comparison of computational research with theoretical results from previous paper for validation of computational model.
3. Computational investigation of performance of steam jet ejector for various geometric parameter under various operating conditions.
4. Investigate the effect of geometric and operating parameter on performance of ejector system.

Aim and scope for future study:

The entrainment ratio and suction mass flow rate from evaporator for different nozzle diameter and operating conditions have been studied to know which nozzle diameter is far better than others. It helps us to increase suction mass flow rate as well as entrainment ratio and hence efficiency of steam jet refrigeration can be improved. If efficiency of steam jet refrigeration system get increase then environment friendly and less costly water is used in refrigeration. It also reduces energy consumption and utilizes waste heat.

4. Results and discussion:

Results are obtained from the CFD simulation technique using ansys 15. Effects of primary nozzle diameter and primary steam pressure on performance steam ejector are discussed below:

Following are some parameters which are kept constant during entire simulation.

Evaporator (suction) temperature= 7.5°c

Evaporator pressure=10.37 mbar

Condenser pressure= 30mbar

Result table-

Case4.1. Primary nozzle diameter=d=1.4 mm

Exit nozzle diameter=D=6.26 mm

Steam press-ure (bar)	Satura-tionte mpe-rature (°c)	Primary steam flow (kg/s)	Vapor flow (kg/s)	Entrain-ment ratio
5	151.8	0.001052	0.00017404	0.1654
6	158.8	0.001244	0.000343	0.2757
8	170.4	0.001580	0.0006107	0.3865

10	179.9	0.001922	0.0007791	0.4054

Table 3. Result table for d=1.4 mm

A. The plot of primary steam pressure vs. entrainment ratio for d=1.4 mm.

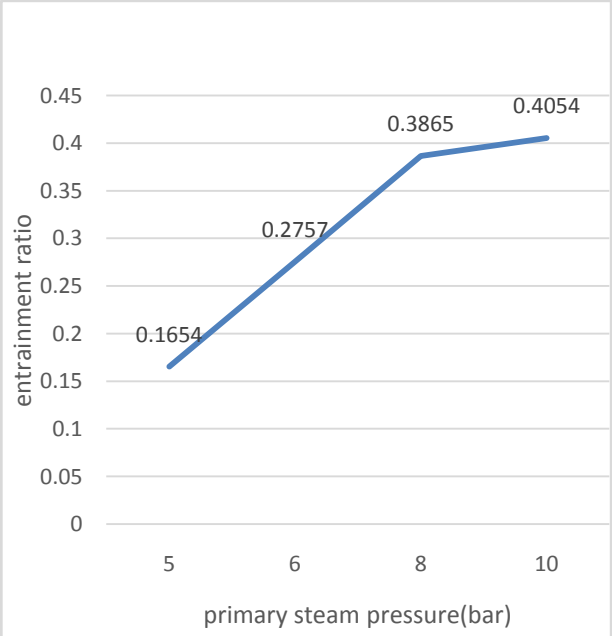

Fig 4.
Effect of primary steam pressure on entrainment ratio

B. The plot of primary steam pressure vs. vapor flow rate for d=1.4 mm.

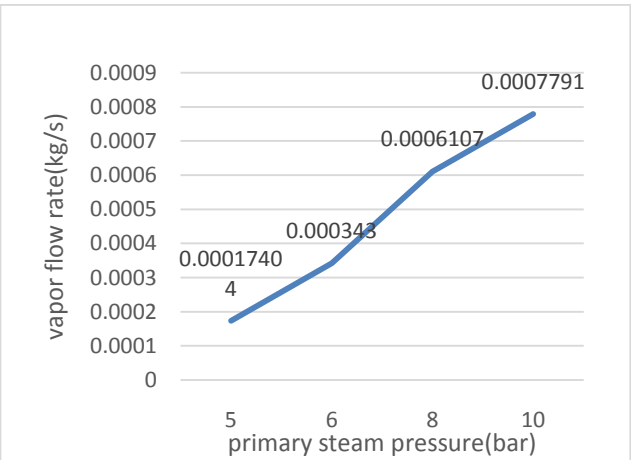

Fig 5.
Effect of primary steam pressure on vapor flow rate.

Case 4.2. Primary nozzle diameter=d=1.7mm
Exit nozzle diameter=D=7.6 mm

Steam press-ure (bar)	Satura-tionte mpe-rature (°c)	Primary steam flow (kg/s)	Vapor flow (kg/s)	Entrain-ment ratio
5	151.8	0.001288	0.00026056	0.2023
6	158.8	0.001502	0.000421	0.2803
8	170.4	0.001923	0.0006495	0.3377
10	179.9	0.002337	0.0007906	0.3383

Table 4. Result table for d=1.7mm

A. The plot of primary steam pressure vs. entrainment ratio for d=1.7 mm.

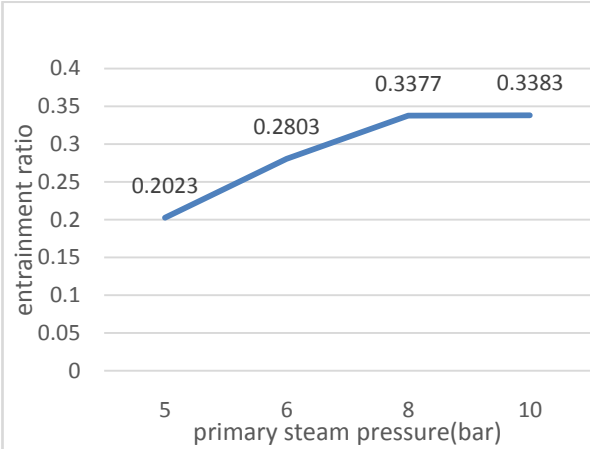

Fig 6.
Effect of primary steam pressure on entrainment ratio

4.2. B. The plot of primary steam pressure vs. vapor flow rate for d=1.7 mm.

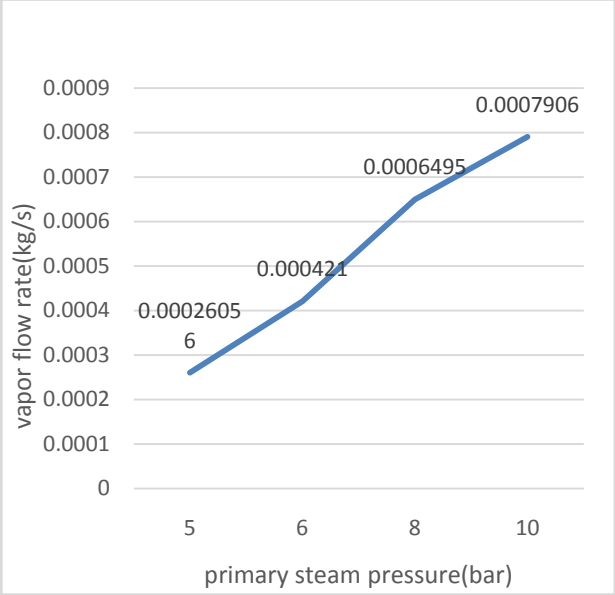

Fig 7.
Effect of primary steam pressure on vapor flow rate.

Outputs from the results table and graphs it is clear that entrainment ratio is increased with rise in primary steam pressure for both cases. The rate of increase of entrainment ratio for rise in primary pressure is higher for d=1.4 mm than d=1.7 mm nozzle. Up to 8 bar pressure entrainment ratio increases linearly but above that pressure rate the linear increase in entrainment ratio is raised with lesser rate.

Vapor flow rate increases linearly for both cases with increase in primary steam pressure.

4.3. Effect of superheated steam on performance of steam ejector.

Primary steam used is superheated to analyze the effect of superheat of steam on performance of steam ejector.
All conditions are kept same at evaporator and condenser side like an above cases.

For this case we selected primary nozzle diameter of 1.7 mm and primary steam pressure of 6bar and 8 bar. Primary steam is superheat from 10 °cto 30 °cfor analysis.
Temperature of superheated steam is summation of saturation temperature of primary steam pressure and superheat temperature.

Table 5. Result table for various steam condition at 8 bar.

Condition of steam	Steam pressure (bar)	Primary steam temperature (°c)	Steam flow rate (kg/s)	Vapor flow rate (kg/s)	Entrainment ratio
Saturated steam	8 bar	170.4	0.001923	0.0006495	0.3377
Superheated by 10°c	8 bar	180.4	0.0019012	0.0006413	0.3373
Superheated by 20°c	8 bar	190.4	0.00188	0.0006331	0.3368
Superheated by 30°c	8 bar	200.4	0.00186	0.000625	0.3360

Condition of steam	Steam pressure (bar)	Primary steam temperature (°c)	Steam flow rate (kg/s)	Vapor flow rate (kg/s)	Entrainment ratio
Saturated steam	6bar	158.8	0.0015021	0.000421	0.2803
Superheated by 10°c	6 bar	168.8	0.001484	0.0004097	0.2761
Superheated by 20°c	6 bar	178.8	0.001467	0.0003996	0.2724
Superheated by 30°c	6 bar	188.8	0.00145	0.000389	0.2683

Table 6. Result table for various steam condition at 6 bar.

From above table it is clear that at same pressure, if superheated steam is used instead of saturated steam then mass flow rate of steam and vapor decreases with degree of superheat increases, also decreases entrainment ratio of steam ejector.

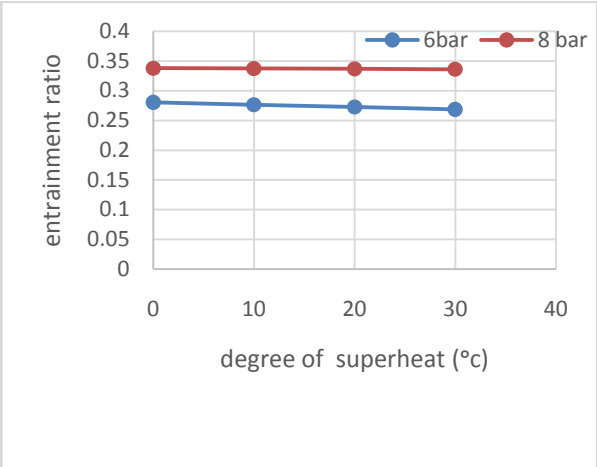

Fig 8.
Effect of superheated steam on entrainment ratio.

From above graph it is clear that entrainment ratio decreases slowly with increase of degree of superheat. Rate of Decrease in entrainment ratio is greater for primary steam pressure of 6 bar than 8 bar.

Conclusions

From the CFD simulation it is found that with constant evaporator pressure and condenser pressure the vapor flow rate is higher in primary nozzle diameter of d=1.7 mm than d=1.4 mm.
i)Vapor flow rate is increases with increase in primary nozzle diameter at constant primary steam pressure and evaporator pressure.
ii) Entrainment ratio is increases as primary steam pressure increases for same diameter primary nozzle.
iii) Entrainment ratio is increase more with increase in primary steam pressure than increase in nozzle diameter.
iv) For higher pressure entrainment ratio is greater for nozzle diameter of d=1.4 mm than d=1.7mm.
v) From the results obtained from CFD simulation it is clear that primary nozzle diameter d=1.4 and P=10 bar is more accurate combination for obtaining highest entrainment ratio.
Vi) At same pressure, if superheated steam is used instead of saturated steam then mass flow rate of steam and vapor decreases with degree of superheat increases, which decreases entrainment ratio of steam ejector. Entrainment ratio decreases slowly with increase of degree of superheat. Rate of Decrease in entrainment ratio is greater for primary steam pressure of 6 bar than 8 bar.

References

1. Natthawut ruangtrakoon et al. (2011)"Experimental studies of a steam jet refrigeration cycleEffect of the primary nozzle geometries to system performance', experimental thermal and fluid science 35,676-683.

2. Natthawut ruangtrakoon et al. (2013) "CFD simulation on the effect of primary nozzle geometries for a steam ejector in refrigeration cycle", International journal of thermal sciences 63,133-145.

3.Alejandro Gutierrez et al. (2014) "Conceptual development and CFD evaluation of a high efficiency variable geometry ejector for use in refrigeration application", energy procedia 57, 2544-2553.

4.T.Sriveerakul et al. (2007) "Performance prediction of steam ejector using computational dynamics: part2. Flow structure of a steam ejector influenced by operating pressures and geometries", international journal of thermal science 46,823-833.

5.Kavous Ariafar (2016) "Mixing layer effect on the entrainment ratio in steam ejectors through ideal gas computational simulations", energy 95,380-392.

6.Ali Hakkaki-Fard et al.(2015) "A computational methodology for ejector design and performance maximization", energy conservation and management 105, 1291-1302.