

Feasibility Study of Replacing Steam Ejector with Liquid Ring Vacuum Pump (LRVP) in 210 MW Plant of Vijayawada Thermal Power Station (V.T.P.S)

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Abstract: Steam jet ejectors are an essential part in many industries like process, chemical, petroleum refining, petrochemical and refrigeration & air conditioning. In this study, ejector mathematical models have been presented based on basic thermodynamic relations. In the present study a Main-air-ejector which is used in Vijayawada Thermal Power Station of 210MW power plant at UNIT-1 in STAGE-1 is considered. The model based on integration equations momentum as well as energy for different parts of ejectors, using special mathematical methods to solve and finally showing the mathematical results are high accurate to the Main-air-ejector which we have considered. Also in continuation, using algorithms designed the ejector and performance of ejector. With this we find how much the ejector is accurate in the performance to produce vacuum. And also studied about replacing Liquid Ring Vacuum Pump with steam ejector for saving the consumption of steam and also the maximum ratio of Return on Investment and the minimum initial investment will be needed.

Keywords: steam jet ejectors, modelling, and liquid ring vacuum pump.

I. INTRODUCTION

The primary application of vacuum systems in the power generation industry is for the evacuation of air and other non-condensable gases from the shell side and the water-box side of a steam surface condenser. On the shell side, the vacuum equipment is used for two purposes they are hogging mode and holding mode. The removal of air and other non-condensable gases from the condenser shell side is required for proper heat transfer from steam to cooling water in the condenser and, thus, to maintain high vacuum in the condenser. This, in turn, enhances the amount of energy extracted from the steam exhausted from the steam turbine and increases the plant's energy production. Without a vacuum system, air and other non-condensable gases would severely reduce the heat transfer in the condenser, and the plant would require a condenser with significantly more surface area for the same thermal load.

II. DESIGN AND PERFORMANCE OF STEAM AIR EJECTOR:

2.1 EJECTOR:

Ejector is a device which is used to create vacuum. Though it is having a relatively low efficiency, many industries and power plants use them to produce vacuum. Because of its simple design and as there are no moving parts in system, installation costs and a little maintenance is required and therefore is easily used in the industry. Vacuum production in the ejector takes place by the dynamic stimulus with high pressure, which is usually water steam. The basis, is the conversion of pressure energy into kinetic energy and vice versa in a way that the steam entering the high pressure nozzle reduced in level, also velocity and pressure increases until the nozzle throat quickly reaches the speed of sound passing through the throat and continuance to increase rapidly as the pressure finally reveals to the output at the end. We will see in the nozzle exit the highest speed and lowest pressure. But the major defects of ejectors, is large size versus their relatively little efficiency and production of noise pollution and high consumption of high pressure steam. In the present study different parts of ejector has been modeled. For this modeling design of ejector from V.T.P.S is taken into consideration.

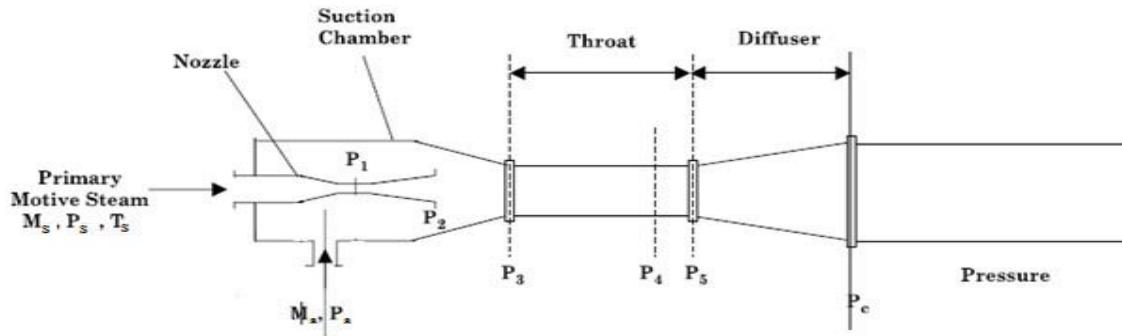


Fig 1: Ejector and its parts

2.2 Mathematical Model:

There are basically two approaches for the modeling of ejectors. These include mixing of motive steam and entrained vapour, either at constant pressure or at constant area. Between these two constant pressures is preferred most because the performance of the ejectors designed by this method are more superior. In this study the design and performance of the ejector is done using constant pressure method.

2.3 Assumptions for constant pressure method:

- The motive steam expands isentropically in the nozzle and the mixture of the motive steam and the entrained vapour compresses isentropically in the diffuser.
- The motive steam and the entrained vapour are saturated and their velocities are negligible.
- Velocity of the compressed mixture leaving the ejector is insignificant.
- Constant isentropic expansion exponent and the ideal gas behavior.
- The flow is adiabatic.
- Friction losses are defined in terms of the isentropic efficiencies in the nozzle, diffuser and mixing chamber.
- The motive steam and the entrained vapour have the same molecular weight and specific heat ratio.
- The ejector flow is one-dimensional and at steady state conditions.

2.4 Calculation:

2.4.1 Mathematical equations:

For design of an ejector and calculating performance of the ejector, we use some basic mathematical model equations. And finding Mach numbers and pressure required at different points s, a, 1, 2, 3, 4, 5 and c.

Overall mass balance:

$$m_s + m_a = m_c \quad (1)$$

Entrainment ratio:

$$E = m_a / m_s \quad (2)$$

Compression ratio:

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

Expansion ratio:

$$ER = P_s / P_a \quad (4)$$

At point 2, we have to find out the Mach number; here in nozzle isentropically expansion of primary fluid takes place. So, we find Mach number of the primary fluid at the nozzle outlet plane.

$$M_{p2} = \sqrt{\frac{2 \eta_n \left[\left(\frac{P_2}{P_2^*} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right]}{\gamma - 1}} \quad (5)$$

Where,

M is the Mach number.

P is the pressure.

γ is the isentropic expansion coefficient.

η_n is the nozzle efficiency.

Here at point 2 we find the equation for Mach number of the primary fluid. Now, we have to find the entrained vapour Mach number at this same point. Which is also takes place isentropically. Mach number of the entrained fluid at the nozzle exit plane is.

$$M_{p2} = \sqrt{\frac{2 \left[\left(\frac{P_2}{P_2^*} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right]}{\gamma - 1}} \quad (6)$$

After the point 2, mixing of the motive fluid and entrained vapour takes place. So, the mixing process is modelled by one- dimensional continuity, energy and momentum equations. Combination of these equations is used to define the critical Mach number of the mixture at point 5 in terms of the critical Mach number for the entrained fluid and primary fluid at point 2.

$$M_4^* = \frac{M_{s2}^* + \epsilon M_{s2}^* \sqrt{\frac{T_2}{T_2^*}}}{\sqrt{(1+\epsilon) \left(1 + \epsilon \frac{T_2}{T_2^*} \right)}} \quad (7)$$

The relation between Mach number and critical Mach number at any point in the ejector is given by the following equation.

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

From the above equation (8a) we find Mach number M

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

Hence by using equation (8a) we can calculate the critical Mach numbers of the entrained vapour and motive fluid at point 2 (M_{a2}^* , M_{s2}^*) and Mach number at point 4.

Now we have to find out the Mach number at the point 5. Mach number of the mixed flow after the shock wave is.

$$M_5 = \frac{M_4^* + \frac{\epsilon}{\gamma} \frac{M_{s2}^*}{\gamma}}{\sqrt{(\gamma - 1) M_4^{*2} + 1}} \quad (9)$$

Now we have pressure increase across the shock wave at point 4

$$\frac{P_2}{P_3} = \frac{1 + \gamma M_2^2}{1 + \gamma M_3^2} \quad (10)$$

Here we use constant pressure mathematical model. So, the constant pressure assumption implies that the pressure between point 2 and 4 remains same. Therefore, $P_2 = P_3 = P_4$.

Pressure rise in the diffuser outlet is given by following equation.

$$\frac{P_2}{P_3} = \left[\frac{\gamma_2 (\gamma - 1) M_2^2}{2} + 1 \right]^{(\gamma / (\gamma - 1))} \quad (11)$$

Now, calculation of areas.

The area of nozzle throat is given by the following equation.

$$A_t = \frac{m_2}{P_2} \sqrt{\frac{RT_2}{\gamma}} \left(\frac{\gamma + 1}{2} \right)^{(\gamma + 1) / (\gamma - 1)} \quad (12)$$

Area ratio of the nozzle throat to the nozzle outlet is.

$$\frac{A_t}{A_2} = \sqrt{\frac{1}{M_2^2} \left(\frac{2}{\gamma + 1} \left(1 + \frac{(\gamma - 1) M_2^2}{2} \right) \right)^{(\gamma + 1) / (\gamma - 1)}} \quad (13)$$

The area ratio of the nozzle throat to the diffuser constant area is.

$$\frac{A_t}{A_3} = \frac{P_2}{P_3} \sqrt{\frac{1}{(1 + \gamma) \left(1 + \frac{\gamma}{2} \left(\frac{P_2}{P_3} \right)^2 \right)}} \times \frac{\left(\frac{P_2}{P_3} \right)^{1/\gamma} \left(\sqrt{1 - \left(\frac{P_2}{P_3} \right)^{(\gamma - 1) / \gamma}} \right)}{\left(\frac{2}{\gamma + 1} \right)^{1/(\gamma - 1)} \left(\sqrt{1 - \frac{2}{\gamma + 1}} \right)} \quad (14)$$

The temperature correlation is given by

$$T = \left(42.6776 - \frac{3892.7}{(10(P/1000) - 3.48334)} \right) \quad (15)$$

2.5 Solution methods:

There are two solution algorithms for the considered model. First algorithm is used for system (ejector) design and the second algorithm is used for the performance evaluation.

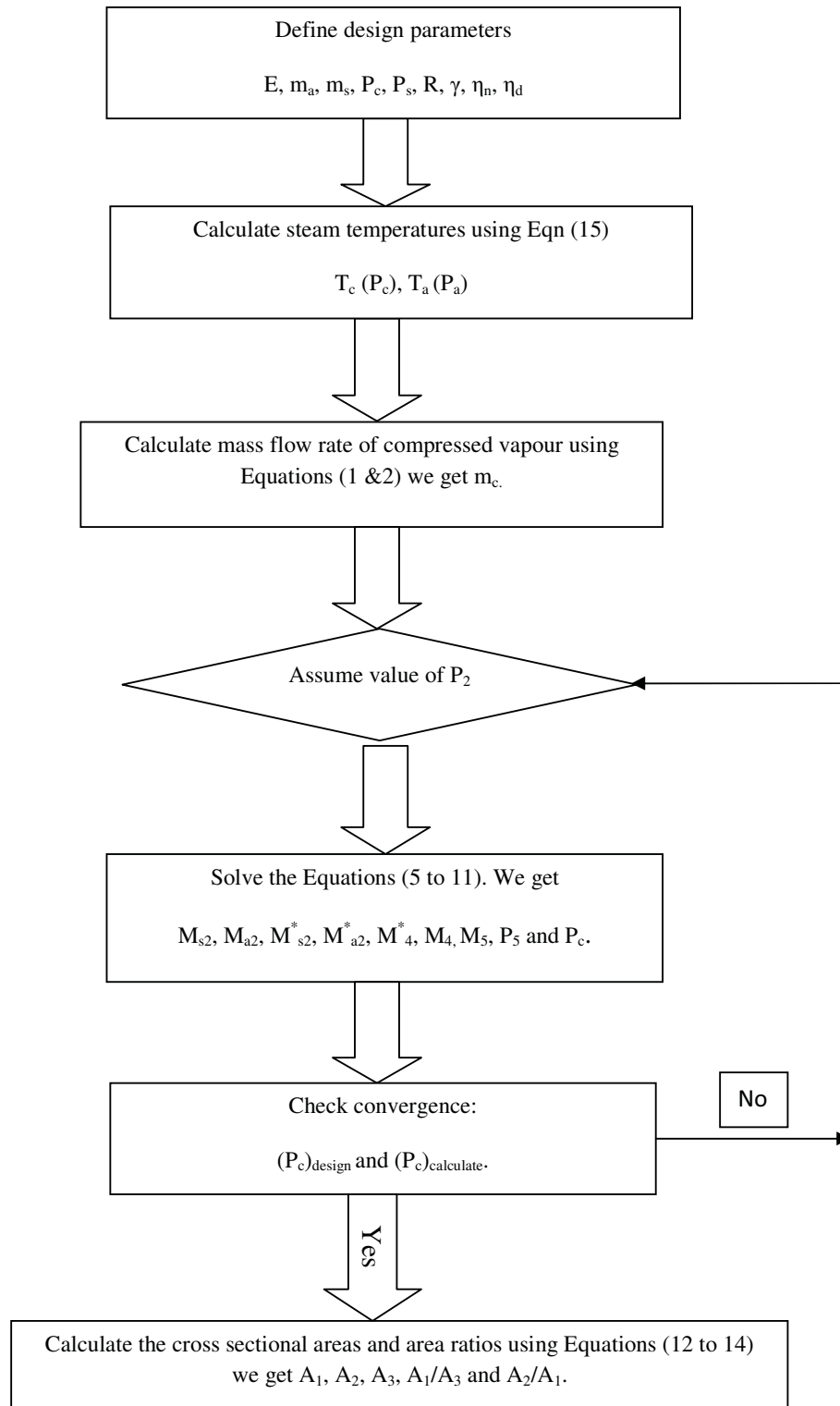
The two algorithms are explained in detail.

2.5.1 First algorithm:

This algorithm is used for system design, where the system pressures and the entrainment ratios are defined. Here iterations are made to determine the pressure of motive steam at the nozzle outlet means at point 2, (P_2). This P_2 values gives the same back pressure P_c .

The iteration sequence of the first algorithm steps are shown below.

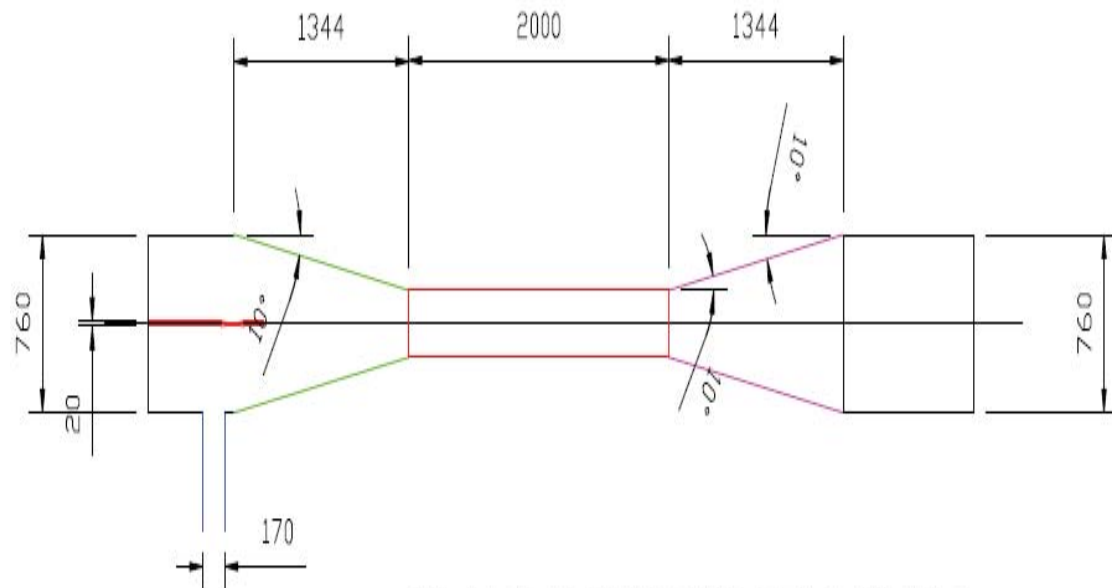
Design procedure to calculate area ratios:



Description:

1. Define the design parameters, which include mass flow rate of motive steam (m_s), mass flow rate of entrained vapour (m_a), entrainment ratio (E) and the pressures of entrained vapour, motive fluid and compressed vapour mixture (P_a , P_s and P_c). And also define efficiencies of nozzle and diffuser (η_n and η_d). Assume the universal gas constant (R) and specific heat ratio (γ) for steam are 0.462 and 1.33.
2. Calculate the steam temperatures with the help of Eqn (15) using corresponding pressures. Here in this step we get T_c , T_a and T_s .
3. Calculate the mass flow rate of the compressed vapour mixture (m_c) using Eqn (1-2).
4. At point 2, a value of pressure (P_2) is estimated.
5. Then by using estimated value of P_2 solve the equations from 5 to 11. By solving these equations we get pressure of the compressed vapour mixture (P_c).
6. Now compare the designed value of P_c to the calculated value of P_c . if it comes approximately nearer to the designed value, then estimated value of P_2 is acceptable to calculate cross sectional areas and area ratios of the ejector using Equations (12 to 14).
7. If the calculated value is not nearer to the designed value, then repeat the step 5.

DESIGN OF A STEAM EJECTOR:



ALL DIMENSIONS ARE IN MM

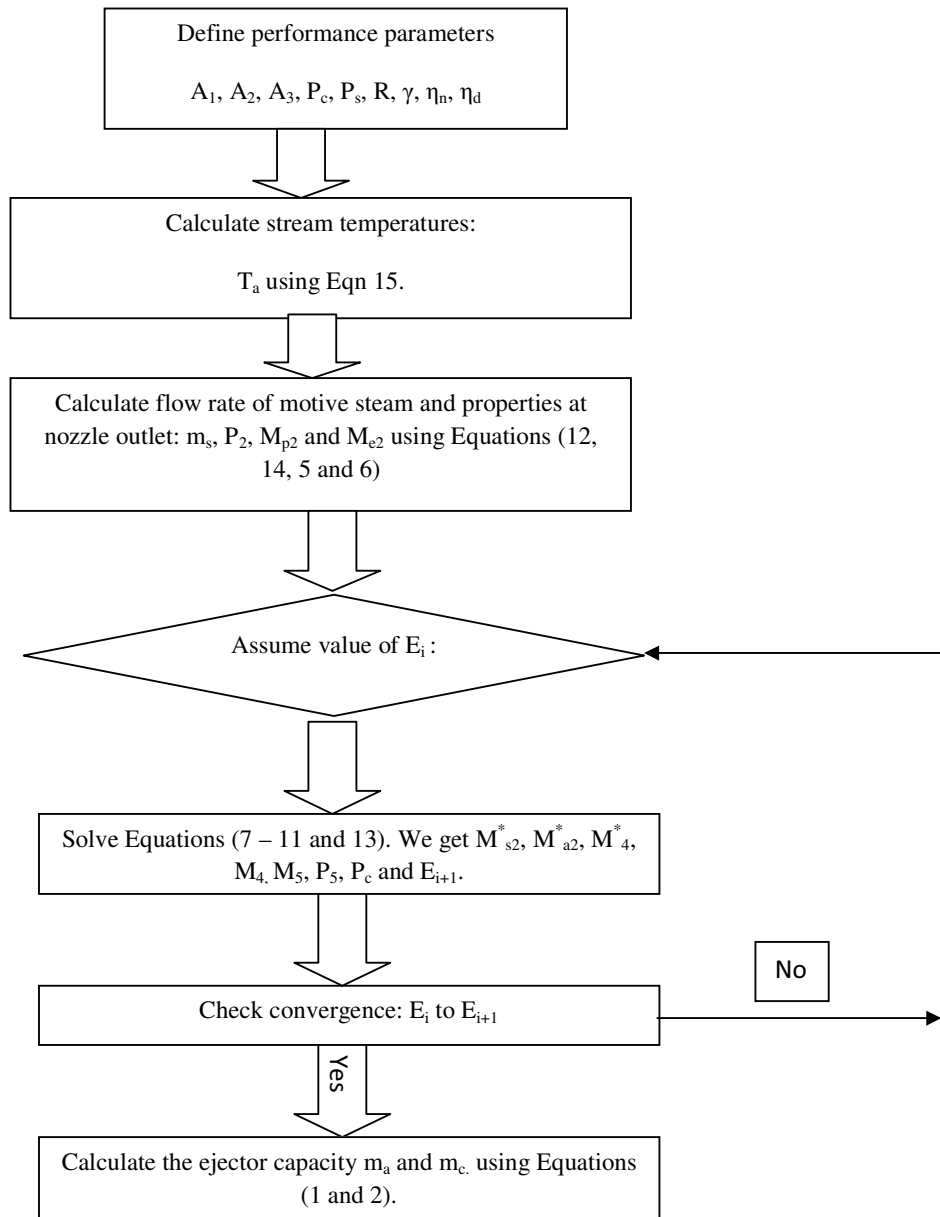
Fig 2 steam ejector

2.5.2 Second algorithm:

This algorithm is used for performance evaluation of the ejector, where cross section areas and entrainment and motive steam pressures are the values taken from the first algorithm. Here we use the first algorithm to calculate area values, by keeping them constant we find the performance of the ejector by changing the entrainment ratio (E). Here iterations are made to determine the entrainment ratio.

The iteration sequence of the second algorithm steps are shown below.

Performance evaluation of the ejector by varying entrainment ratio (E):



Description:

1. Define the performance parameters, which include cross sectional areas (A_1 , A_2 and A_3), and also the pressure values of entrained vapour and primary steam (P_a and P_s) and temperature of the motive steam (T_s). Define the efficiencies of nozzle and diffuser. Assume universal gas constant and specific heat ratio for steam are 0.462 and 1.33.
2. Calculate the stream temperature using Eqn (15) corresponding to pressure value. Here we get T_a .
3. Calculate the mass flow rate of motive steam (m_s), and the properties at nozzle outlet (P_2 , M_{a2} and M_{s2}) using Equations 12, 14 5 and 6.
4. Estimate a value of entrainment ratio (E) and solve the equations (7 to 11) and find the other system parameters, which include M_{s2}^* , M_{a2}^* , M_4^* , M_4 , M_5 , P_5 , P_c .
5. After finding all the parameter values of the ejector. From Eqn 14 we get a new value of E by using constant physical properties.

6. If the assumed value and the calculated value of entrainment ratios are nearer, then we can find capacity of ejector include flow rate of compressed vapour mixture and entrained vapour values using equations 1 and 2.
7. If the values are not nearer, then a new value of E is assumed. This is will done by iterations and step 4 is repeated.

2.6 Input parameters:

Desired parameter values of the ejector are listed below.

Mass flow rate of motive fluid (steam) $m_s = 0.4167$ Kg/sec.

Mass flow rate of entrained vapour (air) $m_a = 0.0056$ Kg/sec.

Pressure of primary fluid (steam) $P_s = 0.932$ MPa.

Pressure of entrained vapour (air) $P_a = 0.007$ MPa

Universal gas constant for steam $R = 0.462$ Kj/Kg K.

Specific heat ratio for steam $\gamma = 1.33$.

Efficiencies of nozzle and diffuser $\eta_n = 0.9$ and $\eta_d = 0.8$.

Temperature value of motive steam $T_s = 473.15$ K

Designed value of compressed vapour mixture pressure $(P_c)_{design} = 0.008$ MPa.

By using the first algorithm and using the equations from 1 to 15 we design the ejector with the help of desired parameters and the results are tabulated in the table 1.

Table 1: Values of parameters from first algorithm at the value of pressure $(P_2) = 0.000056$ MPa are

Parameter	Value
Flow rate of compressed vapour mixture (m_c)	0.4223 Kg/sec
Temperature of entrained vapour (T_a)	312.0987 K
M_{p2}	7.442
M_{e2}	3.745
M_{p2}^*	2.523
M_{e2}^*	2.220
M_4^*	2.519
M_4	10.365
M_5	0.131
P_5	0.0079 MPa
$(P_c)_{calculates}$	0.00795 MPa
A_1	$3.276 * 10^{-4} \text{ m}^2$
A_2	0.09137 m^2
A_3	0.4531 m^2
A_2/A_1	278.9
A_1/A_3	$7.2302 * 10^{-4}$

2.7 Liquid ring vacuum pump:

Next to the ejectors, liquid ring vacuum pumps are the most used vacuum-producing devices in power industries. Simple arrangement of a vacuum pump is shown below.

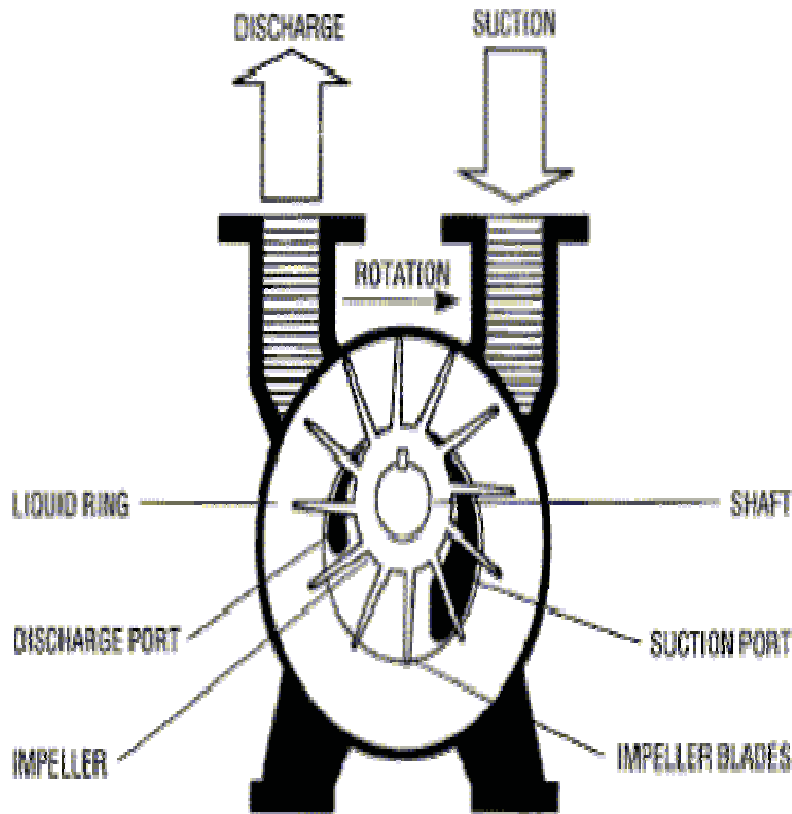


Fig 3: vacuum pump.

Vacuum pump operating principle is that the only moving part is an eccentrically mounted impeller with a ring of liquid. Pump action is created by increasing and decreasing spaces between the impeller blades and liquid ring. Process gases enter and leave these spaces through adjacent ports in side plates next to the impeller.

2.7.1 Applications:

Vacuum pumps are used in many industries instead of steam ejectors, which include refining industry for crude oil vacuum distillation, lube oil dryers, in power industries to evacuate steam surface condensers, chemical industries, pharmaceuticals, hospitals, pulp & paper etc. uses liquid ring vacuum pumps extensively.

In VTPS, except stage-I all remaining stages are uses vacuum pump; these stages are worked on the modern techniques. First any unit create vacuum in condenser with the help of steam ejector only, after the unit synchronization vacuum pumps are work by closing the steam ejector valves.

2.8 Draw backs of steam ejectors:

- Steam ejectors have low efficiency.
- Auxiliary power consumption is more.
- Annual cost is more.
- Steam consumption is also more i.e. not utilizing the heat in steam.

III. RESULTS AND DISCUSSION

In this present study feasibility study of replacing steam ejector with LRVP in V.T.P.S is done. From first and second algorithm the obtained results are tabulated in the tables 2 and 3.

Table 2: The values of pressure of motive fluid by varying entrainment ratio are listed below

Entrainment ratio (E)	Pressure of motive fluid (steam) P_s	Temperature of motive fluid (steam) T_s
0.0134	0.926	176.57
0.0149	0.925	176.52
0.01	0.928	176.66
0.02	0.921	176.33
0.03	0.913	175.94
0.04	0.906	175.64
0.05	0.899	175.31
0.06	0.892	174.98
0.07	0.885	174.65
0.08	0.878	174.31
0.09	0.871	173.98
0.10	0.864	173.64

Table 3: The values of pressure of the compressed vapour mixture by varying entrainment ratios are listed below:

Entrainment ratio (E)	Pressure of compressed vapour mixture (P_c)
0.01	0.0081
0.0119	0.00814
0.0134	0.008
0.0149	0.0082
0.02	0.00832
0.03	0.00852
0.04	0.00879
0.05	0.00903
0.06	0.00926
0.07	0.00952
0.08	0.00978
0.09	0.01004
0.10	0.0103

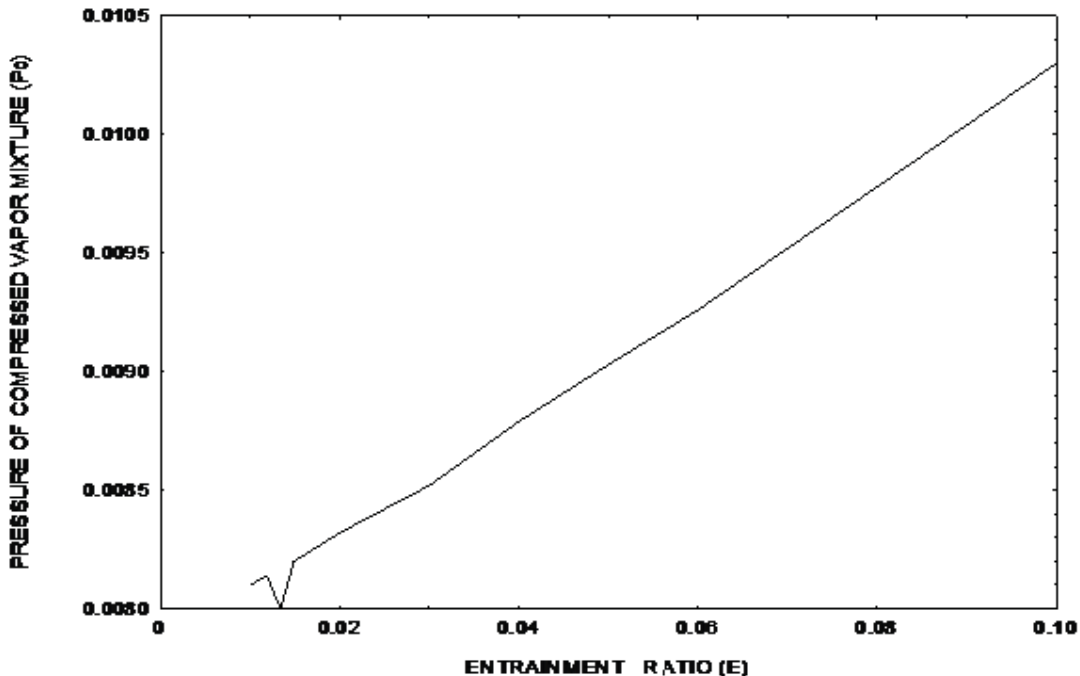


Fig 4 shows the variation of compression vapour mixture with the entrainment ratio.

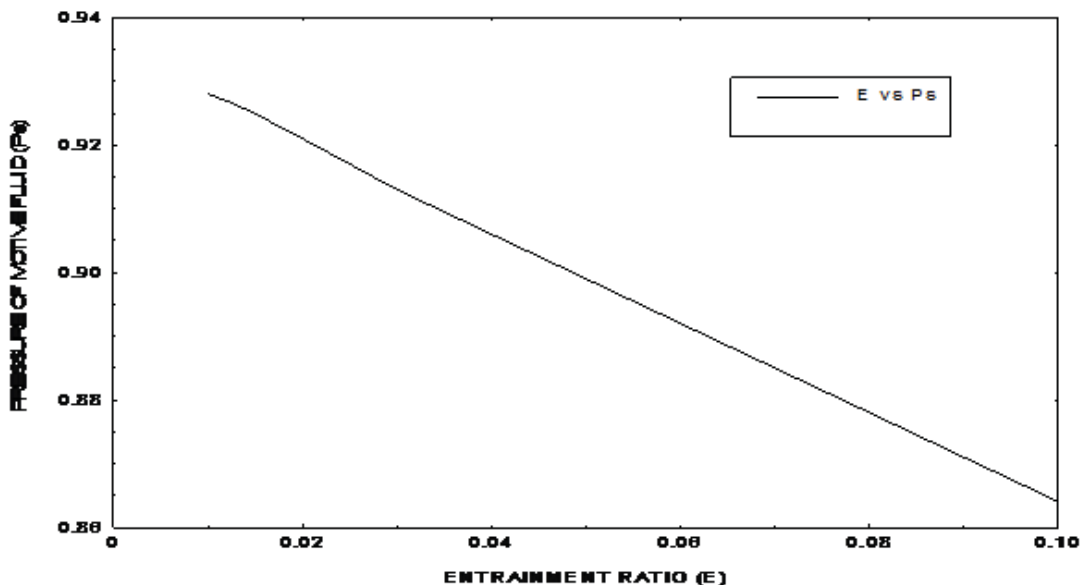


Fig 5 shows the variation of motive fluid pressure with the entrainment ratio

From figure 4 it is observed that the increase in entrainment ratio increases the ejector output i.e. compressed vapour mixture pressure. From figure 5 it is observed that increase of entrainment ratio decreases the pressure of motive fluid. As a result the pressure of the compressed vapour mixture decreases .because of this the vacuum creation will be less. So, in order to have good amount of vacuum creation we need to maintain low entrainment ratios.

IV. ANNUAL COST OF STEAM EJECTOR & LIQUID RING VACUUM PUMP (LRVP) FOR PAYBACK PERIOD ONE YEAR FOR A UNIT IN VTPS 210 MW

Steam ejector:

Input parameters of ejector....

Pressure: 9.5 kg/cm²

Temperature: 200 deg C

Steam flow (m_s): 1.5TPH

Enthalpy of input steam (at 9.5 kg/cm² and 200 deg C) from steam tables (h): 2832 Kj/Kg

Energy input to the ejector (Q_s)

$$Q = h \cdot m_s = 2832 \cdot 1.5 \cdot 1000 / 3600 = 1180 \text{ KW}$$

For two numbers of ejector = 1180*2 = 2360 KW

Condensate temperature gain in ejector = 1.86 deg C

Condensate flow (m_c) = 484 TPH

$$\text{Energy gain (Q}_g) = 1.86 \cdot 484 \cdot 1000 \cdot 4.18 / 3600 = 1046 \text{ KW}$$

Net energy input to the steam ejector (Q) = Q_s - Q_g

$$= 2360 - 1046$$

$$= 1314 \text{ KW}$$

Annual cost to the ejector = 1314*24*365*2.5 = 2.87 Cr.

Vacuum pump:

Energy input to the vacuum pump= 100 KW

Annual income = 100*24*365*2.5 = Rs 2190000

Net savings = 28776600-2190000 = 2.65 crores per annum

Cost of LRVP package per each unit = 1.75 Cr (consisting of two vacuum pumps)

V. CONCLUSIONS

In the present study feasibility study of replacing steam ejector with LRVP in V.T.P.S is done. In this steam ejector is designed and its performance is evaluated. It is observed that at lower entrainment ratios the amount of air sucking is high which shows that the vacuum creation will be appropriate which indicates the condenser performance and also the cost analysis is done for ejector and LRVP. From the cost benefit analysis it is observed that there is a chance to replace the steam ejector with LRVP.

VI. NOMENCLATURE

A= cross section area (m²)

Cr= compression ratio defined as pressure of compressed vapor to pressure of entrained vapor

ER=expansion ratio defined as pressure of compressed vapor to pressure of entrained vapor

m= mass flow rate (kg/s)

M= Mach number, ratio of fluid velocity to speed of sound

M* =critical Mach number, ratio of fluid velocity to speed of sound

P= pressure (N/m²)

R= universal gas constant (J/kg K)

T= temperature (K)

E=entrainment ratio, mass flow rate of entrained vapor to mass flow rate of motive steam

γ=compressibility ratio

η =ejector efficiency

Subscripts:

1-5: Location inside the ejector

s= motive fluid (steam)

a= sucked air

c= compressed vapor mixture

n= nozzle

d= diffuser

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