iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 7 **Issue:** III **Month of publication:** March 2019

DOI: http://doi.org/10.22214/ijraset.2019.3066

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 6.887
Volume 7 Issue III, Mar 2019- Available at www.ijraset.com

Augmenting the Capacity of Air Evacuation System of Condensers in 210 MW LMW Turbines by Replacing Main Ejectors and Starting Ejectors by Liquid Ring Vacuum Pump and CFD Analysis of Sealing in the Liquid Ring Vacuum Pump

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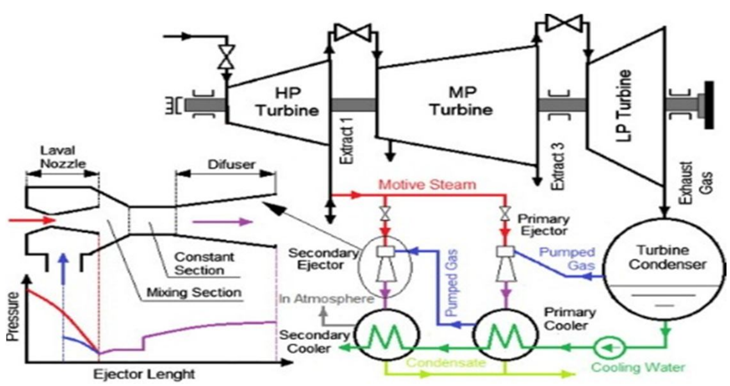
Abstract: In India 60 % of the power plants are coal based thermal power plant. In which steam turbines plays an important role in energy conversion cycle. The conventional method of creating vacuum in the condenser is done by the main ejector and starting ejector systems. 85% of 210 MW power plant units are installed with steam ejectors, which uses 10 % of super-heated steam from the boiler, which acts as a motive fluid in the main and starting ejectors. By replacing the ejector systems with the vacuum pump step up, the motive steam being utilized for the ejectors can be avoided and increase in level of vacuum in the condenser will increase the heat rate of the steam input to the turbine, which in turn reduce the coal consumption for steam production due to reduced coal consumption the monetary gain will be enormous. The financial commitments made in using vacuum pumps instead of ejectors along with the further improvement that can be made in the proposed liquid ring vacuum pump set up is analysed.

Keywords: Turbine, condenser, steam ejectors, Liquid ring vacuum pump, efficiency improvement, financial commitments

I. INTRODUCTION

The ejectors are operated through motive steam from De-aerator or Auxiliary Header. Normally the Ejector would be operating during hogging and for holding operation, starting ejectors is switched off and one main ejector is kept in operation, the one being standby. For effective evacuation of air and non-condensable gases from the system, starting ejector is also kept in service up to the reach of full load instead of cutting out after synchronization. In a thermal power plant condenser vacuum plays vital role which decides the heat rate of the unit fuel economy. The air ingress in the system in the course of running the unit is expelled by ejector thereby maintaining the optimum level of condenser vacuum. The existing main ejectors are not efficient to expel the increased quantity of air ingress in the system. In practice both the ejectors are kept in service instead of keeping one ejector that too with the seam pressure of 9.980 bar as against the rated 4.5 bar.



1.1 Layout of steam ejectors in thermal Power Plant

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II. CONVENTIONAL VACUUM CREATING METHOD

A. Ejectors

An ejector is a device used to suck the gas or vapour from the desired vessel or system. An ejector is similar to a vacuum pump or compressor. The major difference between the ejector and the vacuum pump or compressor is it had no moving parts. Hence it is relatively low cost and easy to operate and maintenance free equipment.

B. Principle of Ejectors

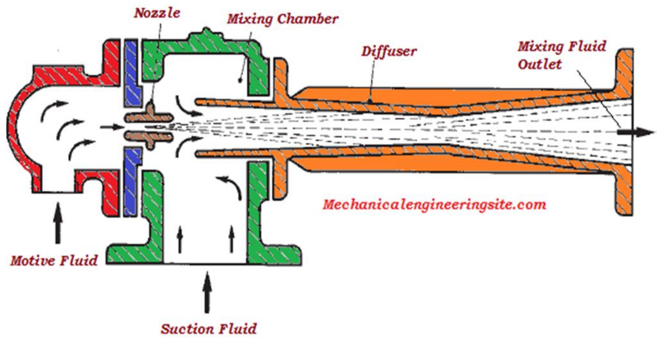


Figure 1.2 Principle of ejectors

The operating principle of the ejector is the pressure energy in the motive fluid is converted to velocity energy by an adiabatic expansion in the converging diverging nozzle. Due to the pressure drop of the motive fluid, it will create a low-pressure zone before the mixing chamber. Due to the low-pressure zone, the suction fluid will start to move to toward it and mix with motive fluid in the mixing chamber. When the mixed fluid enters the diverging portion of the ejector where its velocity energy is converted into pressure energy.

C. Working of Ejector

The suction line of ejector is connected to the vessel which is to be kept under low pressure. With reference below figure, high - pressure motivating fluid enters at “A” and expands through the converging-diverging nozzle to “B”. The motive fluid will create a vacuum in the mixing chamber refer the pressure curve where the pressure is decreased and the velocity is increased. Due to this suction fluid “C” (air or gas) from the connected vessel is moved toward the mixing chamber “D”. When the suction fluid starts mix with the motive fluid in the mixing chamber. The velocity of the fluid at the mixing chamber is approximately 600 to 900 metres per seconds.

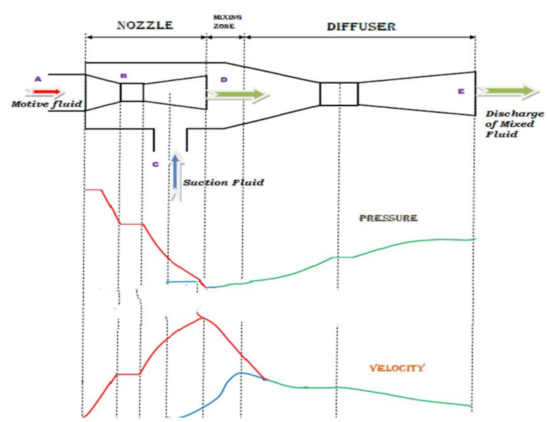


Figure 1.3 Working of stem ejectors

Then the mixture travels through the diffuser “E”, its velocity energy is converted into pressure energy. There by the mixture gained higher pressure send to the atmosphere or some closed system. Normally the discharge pressure will be 10 to 15 times of the suction pressure.

D. Functions of Ejector

The main function of the ejector is to extract air and non-condensate gases from a closed system. It removes air from the condenser and provide vacuum. The amount of air extracted at the time of starting is more as compared to running unit.

E. Parts Of Ejector

It generally consists of

1) Converging nozzle
2) Diverging nozzle
3) Diffuser throat
4) Inlet and outlet pipes
5) Rotameter for measurement of air flow
6) Cells with tube for regeneration heat transfer
7) Steam traps for drip control.

F. Hogging Or Starting Ejector

This ejector is known as starting ejector which is used to pull the gases at the time of starting of system It has high capacity of air extraction. This ejector operates in parallel with the running ejector till the vacuum reaches 500 to 600 mm of Hg column, then the hogger ejector is switched off and main ejector will remain in service. The main disadvantages of the ejector is the steam escaped to atmosphere and cannot reuse.

G. Main ejector

This is also known as running ejector which evacuate the air continuously at the system running condition. This is a multi-stage type ejector.

The high velocity air water mixture enters to the shell and cooled in the 1st stage of the shell by condensate. Thus the steam condensate and the steam air mixture volume is reduced and allowed to 2nd stage of nozzle. In the second stage the mixture is completely condensed and the air is vented to the atmosphere. The drains are provided with loops are siphoned to prevent ingress of air from the atmosphere. Here the condensate steam is again recovered in condenser and reused.

III. PROPOSED TYPE OF VACUUM PUMP

Vacuum pumps are used in condenser units / condensing cum extraction turbine to maintain vacuum inside the condenser. It actually cools the water, which helps in creating vacuum inside condenser. Exhaust steam changes the phase by giving away its heat, thereby creating a lot of empty space. If cooling is insufficient/poor, the phase change will not happen properly and vacuum starts dropping inside the condenser.

A. Liquid Ring Vacuum Pump (LVRP)

It has a cylindrical body of the pump, a sealant fluid under centrifugal force forms a ring against the inside of the casing. The source of that force is a multi-blade impeller whose shaft is mounted eccentric to the ring of liquid. Because of this eccentricity, the pockets bounded by adjacent impeller blades (also called buckets) and the ring increase in size on the inlet side of the pump, and the resulting suction continually draws gas out of the vessel being evacuated.

As the blades rotate toward the discharge side of the pump, the pockets decrease in size, and the evacuated gas is compressed, enabling its discharge.

A continuous flow of fresh sealing liquid is supplied to the pump via the sealing-liquid inlet.

In the case of the two-stage liquid ring pump, the discharge from the first stage does not discharge to atmosphere. Instead, the first stage discharges through the manifold leading to the second stage as well as through a discharge port located in the intermediate plate between the first and second stage impellers. The process repeats itself allowing deeper vacuum and finally discharges into the atmosphere. The ring of liquid not only acts as a seal; it also absorbs the heat of compression, friction and condensation.

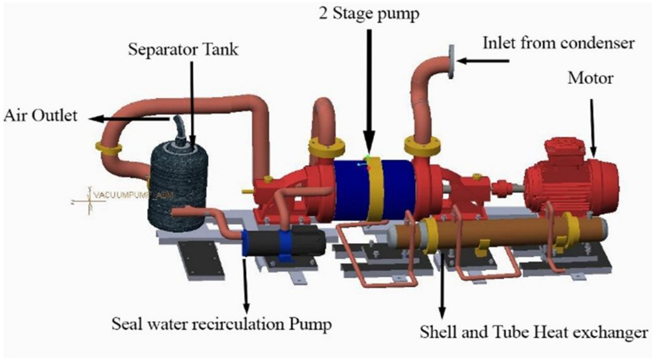


Figure 1.4 Multistage Liquid Ring Vacuum Pump

B. Part of Liquid Ring Vacuum Pump:

1) *Motor:* The motor forms the prime mover of the impeller that is fixed on shaft of the vacuum pump. A 150 hp motor is used in running the vacuum pump.

Figure 1.5 Motor

2) *Double Stage Impeller*: Multi-blade impeller whose shaft is mounted eccentric to the ring of liquid. Because of this eccentricity, the pockets bounded by adjacent impeller blades (also called buckets) and the ring increase in size on the inlet side of the pump, and the resulting suction continually draws gas out of the vessel being evacuated.

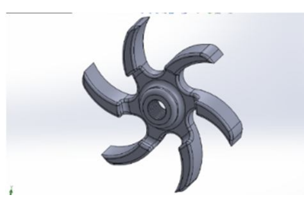


Figure 1.6 Impeller

3) *Shell and Tube Heat Exchanger*: A shell and tube heat exchanger is a class of heat exchanger design. It is the most common type of heat exchanger in oil refineries and other large chemical processes, and is suited for higher pressure applications here one fluid runs through the tubes, and another fluid flows over the tubes to transfer heat between the two fluids.

Figure 1.7 Shell and Tube Heat exchanger

4) *Seal water Recirculation Pump*: Circulator pump or circulating pump is a specific type of pump used to circulate gases, liquids, or slurries in a closed circuit. They are commonly found circulating water in a hydronic heating or cooling system. Because they only circulate liquid within a closed circuit, they only need to overcome the friction of a piping system

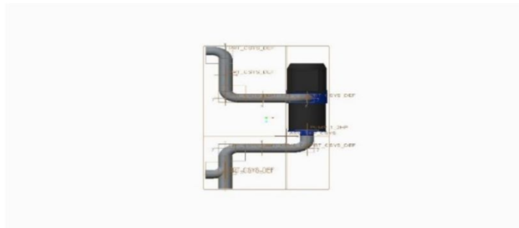


Figure 1.8 Recirculation pump

5) *Separator Tank:* A separator eliminate air quickly and efficiently from closed loop heating and cooling systems. Water enters and exits through unique tangential pipe connections, which promote a low velocity swirling vortex

Figure 1.9 Separator tank

C. Working Principle of Liquid Ring Vacuum Pump

The vacuum pump consisting an impeller which is located eccentric to the cylinder body. Vacuum is created in the vacuum pump by using a liquid seal. The most commonly used liquid sealant is water. The other liquids sealants used in the vacuum pump are oil and water methanol mixture. Before starting the vacuum pump, the liquid is filled the minimum of ¼ of the cylinder volume. In vacuum pump, the impeller is placed between two port plates. The port plates act as suction and discharge of vacuum pump, which has shaped holes cut into them called ports. When the impeller starts to rotate, the liquid is starts move outward by centrifugal force. Due to this an area of void space is created without liquid and the liquid form a ring shape.

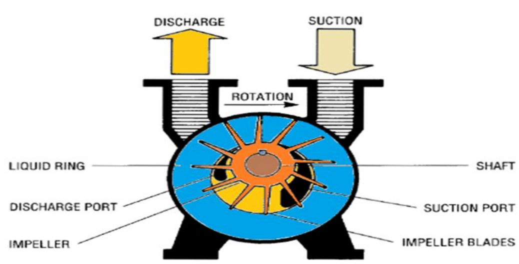


Figure 1.9 Principle of vacuum pump

The portion between the impeller vane and the liquid is called “impeller cell”. Let us consider an impeller cell at the top of the vacuum pump and the impeller rotates in clockwise direction. At the top of an impeller, the cell filled with seal liquid. Due to the impeller rotation, the liquid recedes from the impeller cell. Due to this air or gas/vapour is drawn from the vessel which is to be maintained at the sides of the impeller. After impeller cell passes the sealant liquid is forced back toward the centre hub of the impeller, creating the compression step. As the impeller cell near to the discharge port, the compression is at its highest, and the gases, along with some of the liquid sealant are exhausted through the discharge port to atmosphere. Although the diagrams show a very smooth ring of liquid, in actually, the liquid sealant is highly turbulent, which is why some of the liquid sealants are discharged with the gases. Again the cycle is repeated.

D. Liquid ring vacuum pump specification (Double stage impeller)

1) Vacuum Pump

No of stage	- 2
Pump rated speed	- 640 rpm
Rotor vane tip speed	- 17.28 m/s

2) Seal Water Heat Exchanger

Type	- Shell and tube
a) At pump design point	
i) Heat transfer area	- 4.86 m^2
ii) Total heat load	- 100268 Kcal/hr
iii) Cooling water inlet	- 13℃
iv) Cooling water outlet	- 20℃
v) Seal water inlet	- 23.90℃
vi) Seal water outlet	- 16.50℃
b) At pump operating point	
i) Heat transfer area	- 4.86 m^2
ii) Pump heat load	- 109172 Kcal/hr
iii) Cooling water inlet	- 32℃
iv) Cooling water outlet	- 40℃
v) At seal water inlet	- 43.1℃
vi) At seal water outlet	- 35℃
Operating pressure seal side	- 2 bar G
Operating pressure cooling water Side	- 4 bar G
Design pressure	- 6 bar G
Hydrostatic pressure	- 9 bar G

3) Seal Water Recirculation Pump

Design capacity	- 13.6 m^3/hr
Total developed head at design	- 33.2 m
Shut off head	- 36 m
Power absorbed	- 1.87 kW
Motor rating	- 2.2 kW

E. Capacity Of Liquid Ring Vacuum Pump (Double Stage Impeller)

Since the existing ejector system is operating with the steam pressure of 9.86 bar as against 4.41 bar (design), it is not possible to measure the exact value of air quantity expelled from the system. However the level of vacuum in the condenser about 60kg/hr are adequate. Available capacity of existing main ejector is also 60kg/hr.

IV. CFD (COMPUTATIONAL FLUID DYNAMICS) ANALYSIS OF SEALING IN LIQUID RING VACUUM PUMP

1) Computational fluid dynamics (CFD) is a branch of fluid mechanics that uses numerical analysis and data structures to analyze and solve problems that involve fluid flows.
2) Computers are used to perform the calculations required to simulate the free-stream flow of the fluid, and the interaction of the fluid with surfaces defined by boundary conditions.
3) Engineering fields where CFD analyses are frequently used are aerodynamics and hydrodynamics, where quantities such as lift and drag or field properties like pressures and velocities are obtained.
4) Fluid dynamics is involved with physical laws in the form of partial differential equations.
5) Steps involved in CFD:
a) Preprocessing (Problem statement to computer model)
b) Simulation (Computations by solver)
c) Post processing (Results are visualized and analyzed)

A. Finite volume method

1) In the finite volume method, the governing partial differential equations (typically the Navier-Stokes equations, the mass and energy conservation equations, and the turbulence equations) are recast in a conservative form, and then solved over discrete control volumes.
2) This discretization guarantees the conservation of fluxes through a particular control volume.
3) In finite volume method, the object is first divided into very small but finite sized elements of geometrically simple shapes.
4) Here the finely sized elements are termed as cells.
5) The finite volume method is based on the fact that many physical laws are conservation laws which describes what goes into one cell on one side needs to leave the same cell on the other side.
6) This method has been very successful in solving fluid flow problems with increased accuracy, as it performs flux evaluation for the cell boundaries.

B. Mesh sizing and Time step:

1) The Mesh quality effects the solution progress, thus the accuracy of the simulation results.
2) In addition, the inconsistent mesh distribution increases the calculations time or halts the whole simulation process.
3) The total number of cells in the meshing process and their orientation with their size within the geometry are important to achieve a reasonable result.
4) For unsteady flow conditions, where the properties of flow changes with time, time step are used which specifies the time between each iterative solution.
5) Time derivatives are approximated by finite differences in time.
6) The Time step is the incremental change in time for which the governing equations are being solved.

Time step size	= 0.0002seconds
Number of time steps	= 100
Number of iterations/time step	= 85
Time Considered	=0.02 seconds

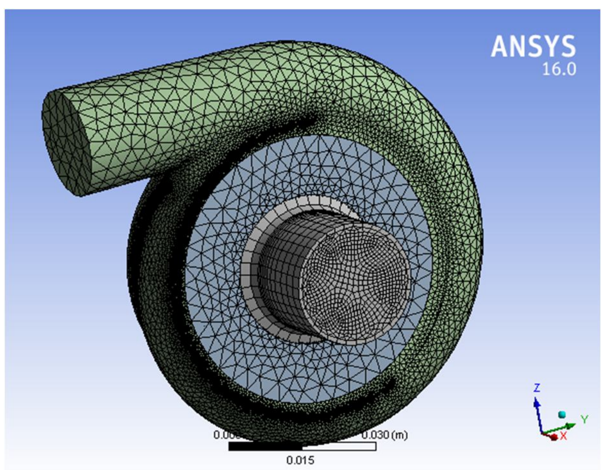


Figure 1.10 Meshing of segments

C. Governing equations for CFD analysis:

1) *Conservation Of Mass*

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}) = 0 \longrightarrow \frac{D\rho}{Dt} + \rho \nabla \cdot \boldsymbol{u} = 0$$

2) *Navier – Stokes Equation (Conservation Of Momentum)*

$$\frac{\partial \rho u}{\partial t} + \nabla \cdot \rho u u = \rho f + \nabla \cdot \mathbf{T}$$

$$\rightarrow \quad \rho \frac{\partial u}{\partial t} + \rho u \nabla u = -\nabla p + \rho f_b + \nabla \cdot \mu\left(\nabla u + \nabla^T u\right)$$

3) *Work With The Finite Volume Approximation*

$$\frac{\partial}{\partial t}\int \rho u\, dv + \oint \rho u(u \cdot n)\, ds = \int \rho f\, dv + \oint \mu\left(\nabla u + \nabla^T u\right) n\, ds + \int_V \sigma \kappa n \delta(n)\, dv$$

4) *Temporary Velocity Advection And Diffusion Equation*

$$\mathbf{u}_{i,j}^{n+1} = \mathbf{u}_{i,j}^{tmp} - \frac{\Delta t}{\rho^n}\nabla_h p_{i,j} \qquad \mathbf{u}_{i,j}^{tmp} = \mathbf{u}_{i,j}^{n} + \Delta t\left(-\mathbf{A}_{i,j}^{n} + \mathbf{f}_b^n + \frac{1}{\rho^n}\left(\mathbf{D}_{i,j}^n + \mathbf{f}_\sigma^n\right)\right)$$

5) *Pressure – velocity*

$$\nabla_h \cdot \left(\frac{1}{\rho^n}\nabla_h p_{i,j}\right) = \frac{1}{\Delta t}\nabla_h \cdot \mathbf{u}_{i,j}^{tmp}$$

D. *Analysis Of Sealing In Vacuum Pump*

1) *Trail No. I:* Taking the below mentioned parameters as operating conditions, the level of Low pressure (vacuum) generated within the liquid sealing is analysed and the results are obtained.

a) Heat transfer area = 4.86 m^2
b) Pump heat load = 109172 Kcal/hr
c) Cooling water inlet = 32°C
d) Cooling water outlet = 40°C
e) At seal water inlet = 43.1°C
f) At seal water outlet = 35°C
g) Speed of Impeller = 620 rpm
h) Velocity of air inlet = 0.3 m/s

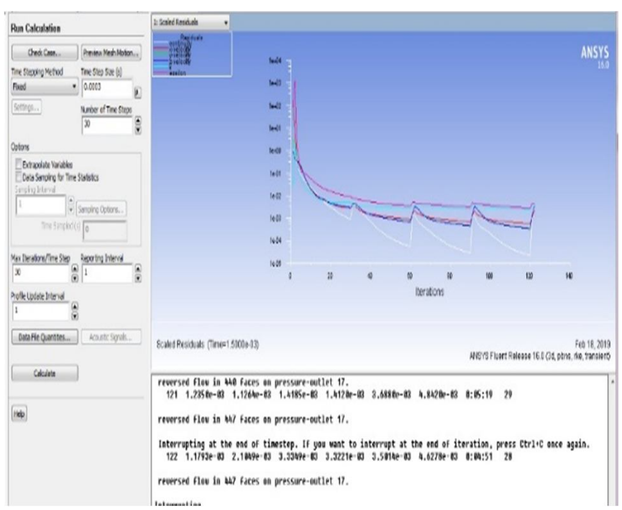


Figure 1.10 Iteration Process (a)

i) Results of Trial No. 1

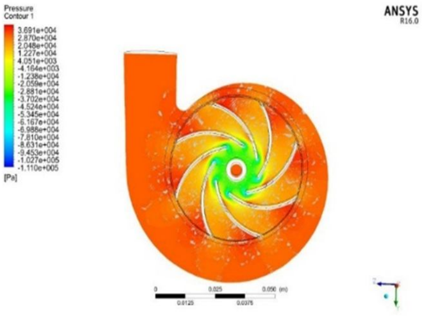


Figure 1.11 Heat distribution in sealing (a)

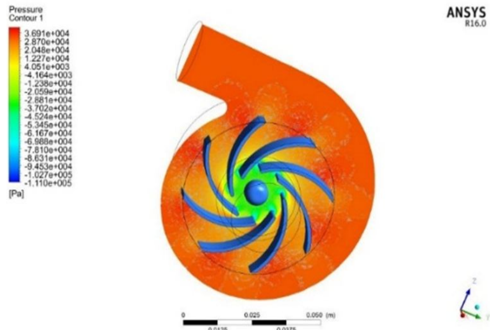


Figure 1.12 Pressure around the impeller (a)

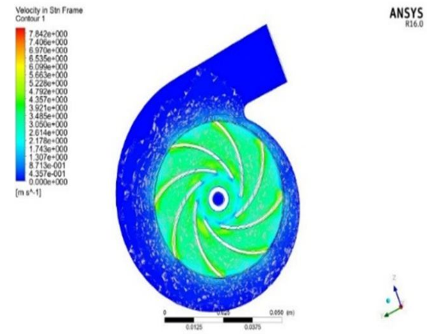


Figure 1.13 Velocity in std Frame (a)

ii) *Result (CFD):* From the pressure contour value the level of low pressure generated with the sealing is obtained.
Low pressure (Vacuum) generated = - 685mm of Hg

2) Trail No. II: Taking the below mentioned parameters as operating conditions, the level of Low pressure (vacuum) generated within the liquid sealing is analysed and the results are obtained.

a) Heat transfer area = 4.86 m^2
b) Pump heat load = 109172 Kcal/hr
c) Cooling water inlet = 30 °C
d) Cooling water outlet = 35 °C
e) At seal water inlet = 35 °C
f) At seal water outlet = 28 °C
g) Speed of Impeller = 620 rpm
h) Velocity of air inlet = 0.3 m/s

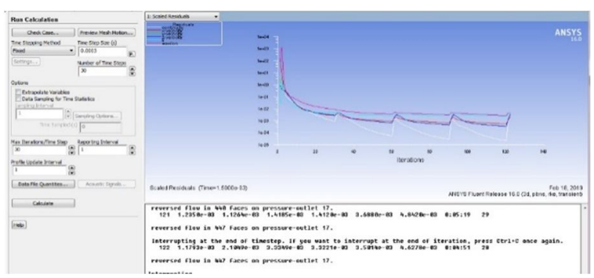


Figure 1.14 Iteration Process (b)

i) Results for Trial No. 2

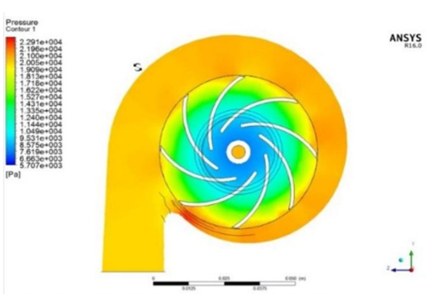


Figure 1.15 Heat distribution in sealing (b)

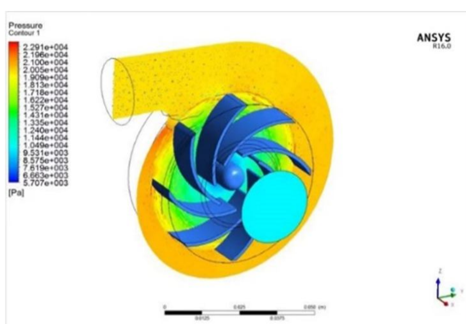


Figure 1.16 Pressure around the impeller (b)

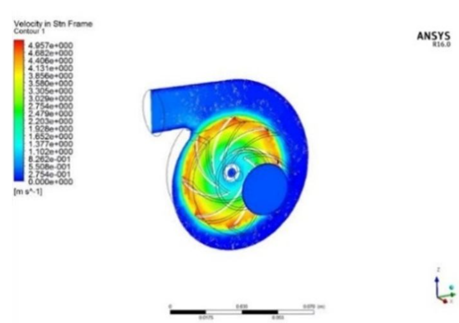


Figure 1.17 Velocity in stn Frame (b)

ii) *Result (CFD):* From the pressure contour value, the level of low pressure generated with the sealing is obtained.
Low pressure (Vacuum) generated = - 690mm of Hg

E. *Effect of improvement of vacuum:*

The heat rate will be improved as explained below. If a better sealing is provided around the eccentrically placed impeller of vacuum pump, the level of vacuum in the condenser would certainly improve by nearly 2mm to 5 mm of Hg. For 1mm increase in condenser vacuum, heat rate will be improved by 2 kcals/ kWhr. The internal efficiency of turbine will improve which in turn will improve the heat rate by above 2%. By providing better sealing in the vacuum pump which will get an increased level of vacuum by about 5%.

So, with the effect of increased level of vacuum in the condenser, heat rate in the turbine, will be considerably reduced and it would be well below with the CEA (Central Electricity Authority) norms.

LMW Turbine Design specifications

Turbine (Design Heat rate)	= 2404 kcal/kWhr
Present Heat rate	= 2690 kcal/kWhr
Heat rate gained by improving vacuum in condenser	= 40 kcal/kWhr
Heat rate gained by improvement in Turbine (2% of 2232.7) efficiency 2%	= 44.65 kcal/kWhr
Turbine Heat rate would be	= 2232.7 – 40 - 44.65
	= 2148.05 kcal/kWhr
Unit Heat rate	$= \frac{\text{Turbine Heat rate}}{\text{Boiler Efficiency}}$
	$= \frac{2148.05}{0.83}$
	= 2557 kcal/kWhr
% Variation after improved vacuum condition	= 6.4 %

F. *Cost benefit analysis for one unit*

1) *Expenditure – steam Ejector Systems*

P = 9.980bar

V = Specific volume at 9.980 bar and 240^{0}c is $0.2374 m^3/kg$

$Q = 464.736 \times \sqrt{9.980/0.2374} = 464.736 \times 6.483$ = 3012kg

	= 3.012 T/Hr.
For 2 ejectors 'Q' = 3.016 T/hr x 2	= 6.028 T/Hr.
Specific Enthalpy of steam at 9.980 bar /240^{o} C	= 702.4kcal /kg
Heat gained by the feed water and through the drips to the condenser from the motive steam of 0.8 bar @45^{o} C	= 50kcal /kg
Total Energy spent towards motive steam	= 702.4-50
Boiler Efficiency (n)	= 83% (for the month of September 2017)
Total Energy required	= Q X 652.4 /n
	= 6.028 x652.4 /0.83
	= 4738.15
Actual Coal Calorific Value	= 3600kcal /kg
Quantity of coal required	= 4738.15/3600
	= 1.316 T /Hr.
Per day requirement of coal	= 31.584 T

Considering cost of Blended Coal is Rs 3947/ Ton (Weight average coal cost as on September 2016)

Expenditure towards Ejector Steam is	= 31.584T x 3947
	= Rs.1, 24,662/-

G. *Expenditure – Liquid ring Vacuum Pump System*

Vacuum pump power rating	= 150Hp x 0.786 = 117.9 kWh

Energy consumption per day	= 117.9 x 24 = 2829.6Kwh
Energy cost (@Rs. 4.33/KWh	= 2829.6 x 4.33
(for the month of September 2017)	= Rs. 12,252/-
Difference in expenditure per day	= Rs. 1, 24,662 – 12,252
	= Rs. 1, 12,410/-
Cost towards the savings for one year	
(Assuming 330 working days in a year)	= 1, 12,410 x 330
	= Rs. 3, 70, 95,300
Total investments should be made for erecetion of vacuum pump and testing is assumed to be	= Rs. 3, 80, 60,000
The payback period for one unit	= $\frac{\text{Rs. 3, 80, 60,000}}{\text{Rs. 3, 70, 95,300}}$
	= 1.03 years

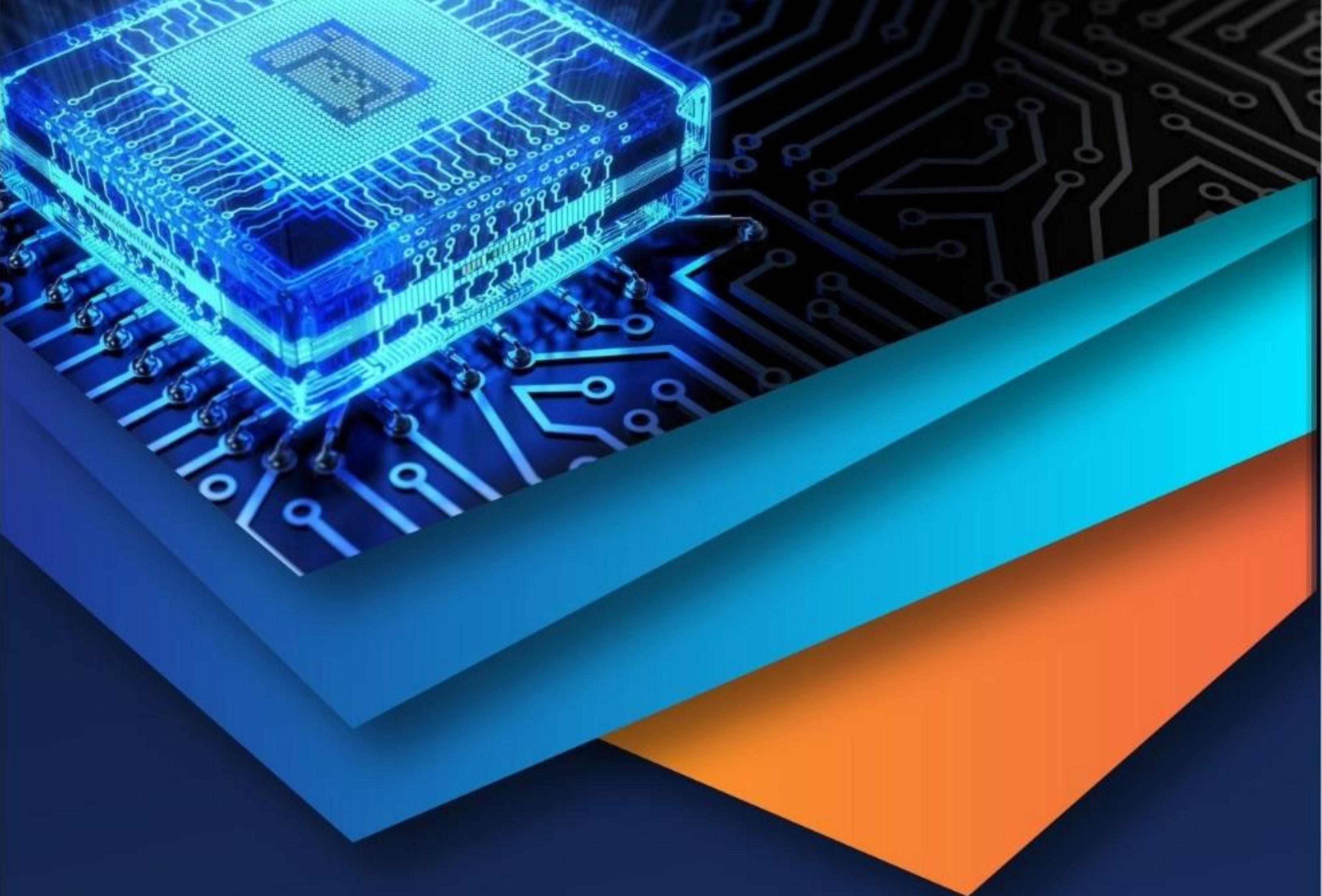
V. COST BENEFIT ANALYSIS OF IMPROVEMENT OF VACUUM IN CONDENSER

The Unit heat rate 2557 kcal/kWhr obtained by the increased level of vacuum in condenser is less than the value 2587 kcal /kWhr fixed by the CEA.

The coal savings towards reduction of heat rate is calculated for the calorific value of coal 3070 kcal (average) Heat rate (2690 – 2557) kcal	$= \frac{133 \times 5.04 \times 10^6}{3070}$
	= 218345 kcal
	= 218 Tonnes of coal
Cost of coal / Ton	= Rs. 4032.4
Cost savings towards coal /day (218 x 4032.4)	= Rs. 8, 79,063
Revenue gained per day by power production	= Rs. 7, 20,000
Total savings per day	= 8, 79,063 + 7, 20,000
	= Rs.15, 99,063
(Assuming 330 working days in a year)	= Rs.52, 76, 90,790
Cumulative savings can be obtained by above methods	= 52, 76, 90,790 + 1, 12, 410
	=Rs. 52, 78, 03,200

VI. CONCLUSION

In condenser, vacuum is being maintained by main ejector and starting ejector by utilizing steam as motivational medium. From the project it is clearly understood that, introducing vacuum pump in place of ejectors would certainly reduce in coal consumption by cutting out the motive steam used in ejectors. So the losses due to usage of steam will be averted and the total revenue gain from the power production will be around Rs. 52, 78, 03,200. This can be achieved by using double stage liquid ring vacuum pump and the improvement of vacuum in the condenser, by calculating the financial gain, this project is more beneficial to 210 MW thermal power plants.



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