Exhaust to Energy: Waste Heat Recovery in Alumina Digesters

Santunu Pathy[1], Kausikisaran Misra[2], S. Sasi Kumar[3] and Uttam Kumar Giri[4]
1. AGM – Operations
4. Head Operations
Hindalco – Utkal Refinery, Doraguda, India
2. Head Projects
Hindalco – Aditya Refinery, Kansariguda, India
3. Plant Head
Hindalco – Mahan Smelter, Mahan, India
corresponding author: santunu.pathy@adityabirla.com
https://doi.org/10.71659/icsoba2024-aa004

Abstract

Waste heat recovery is a crucial aspect of sustainable industrial processes, offering both environmental and economic benefits. This study investigates the potential to recover energy from waste/ low quality heat that is released to exhaust in an alumina refinery. Alumina refining process involves digestion of bauxite ore at high temperatures and pressure. After digestion, pressure is released using a series of flash vessels and the evaporative flash steam is optimally used for regenerative heating of caustic liquor. The blow-off slurry still possess temperature of about 104 °C, i.e., above boiling point. Thereby, produces flash steam which is generally unutilized for its relative low energy content and vent through the relief tanks. In alumina refineries, steam is the major source of energy used in digestion (46 %) and any efforts to recover waste heat and utilize for other applications will be of great scope to reduce steam consumption.

Utkal Alumina International Ltd. (UAIL) Refinery being a modern alumina plant operates with 3 low temperature digestion circuits to support overall production requirement. The digestion circuit consumes steam at a rate of 75 t/h. Blow off slurry remains at ~104 °C approximately 6 t/h per train of vapor (waste heat) is being released to relief tank at atmospheric pressure and about 100 °C. Venturi condenser technology was applied to assess its feasibility and effectiveness for waste heat recovery. With this system, it is demonstrated to recover 1.24 MJ/day of waste heat that can be able to reduce 15 t/h of low-pressure (LP) steam from wash water heating in mud wash circuit ultimately saves 430 m^3/day of water from vaporization. Waste heat recovery emerges as a viable and sustainable solution for improving energy efficiency and reducing environmental impact in alumina refining processes.

Keywords: Energy efficiency, Waste heat recovery, Venturi condenser.

1. List of Abbreviations

SNL	Supernatant Liquor
BOT	Blow Off Tank
WHR	Waste heat recovery
PFD	Process Flow Diagram
PID	Piping and Instrumentation Diagram
BOP	Blow Off Pump
CP	Effluent/Caustic Pond
Lv	Latent Heat of Vaporization
Cp	Specific Heat at Constant pressure
Kpa	Kilopascal
RMP	Red Mud Pond
t/h	Tonnes per hour
M	Mass Flow Rate
MOL	Milk Of Lime (Lime Plant)

CFD	Computational Fluid Dynamics
LTD	Low Temperature Digestion
CCL	Caustic Cleaning Liquor
ID	Induced Draft

2. Introduction

The alumina digestion process is a pivotal stage in the production of aluminum, where the transformation of raw bauxite ore into valuable alumina occurs. Aluminum manufacturing itself is an energy consuming process, where 27 % of the energy [1] is being consumed in alumina refining process. and out of 27 % in the refinery the energy consumption pattern seems 46 % (Figure 1) of the total steam energy is consumed in Digestion area and 36 % is used in Evaporation area while 12 % of the miscellaneous steam is being utilized in other areas like lime plant (MOL), mud wash, caustic cleaning liquor (CCL) heating etc. The major challenge is to reduce the miscellaneous steam consumption and waste heat recovery could be a possible alternative.

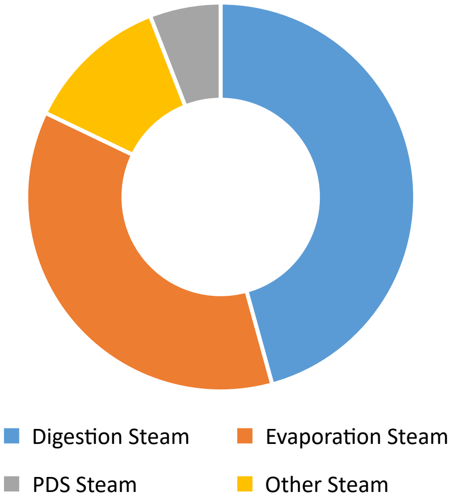

Figure 1. Typical steam consumption in a low-temperature alumina refinery.

In the digestion process the mixture of ground bauxite and sodium hydroxide solution is fed into the digesters, where it undergoes high-temperature and high-pressure digestion. Typically, the digestion process occurs at temperatures ranging from 140 °C to 280 °C and pressures ranging from 172 to 345 kPa (25 to 50 psi). The elevated temperature and pressure enhance the dissolution of gibbsite/boehmite present in the bauxite into the sodium hydroxide solution, forming sodium aluminate.

The dissolution reaction is an endothermic reaction [2] that consumes major steam energy in the refining process. Utkal Alumina International Limited (Utkal) being a modern alumina plant operates with 3 low temperature (LT) digestion trains to produce 2.47 million tonnes of alumina per annum. The digestion circuit consumes 225 tonnes of steam per hour. The blow off slurry remains at the temperature of 104 °C produces flash steam (Figure 2) which used to vent through the relief tanks.

Waste heat recovery is a crucial aspect of sustainable industrial processes, offering both environmental and economic benefits. This process demonstrates and investigates the potential for waste heat recovery in alumina refinery digestion process through the implementation of a venturi condensing system. The parameters such as heat transfer efficiency, energy savings, and environmental impacts are evaluated, alongside economic considerations. The findings highlight the potential of venturi condenser-based waste heat recovery to optimize specific steam consumption to improve profitability of alumina refining operations.

Figure 2. Vapor from relief tank.

3. Scope for Waste Heat Recovery and Utilization

The digestion operation is carried out by feed liquor heating and mixing of bauxite slurry with the heated liquor, digestion of bauxite and flash cooling of the digested slurry. Strong feed liquor is first heated in a string of four process heat exchangers in series, utilizing process steam from the corresponding flash tanks. Bauxite slurry is mixed with the heated strong feed liquor prior to entering the first digester. The digestion temperature of 145 °C is maintained by injecting steam to the first online digester. The digested slurry containing the dissolved alumina and the residual solids is flash cooled to near its atmospheric boiling point in a series of four flash tanks. The process steam, generated in each flash tank is used in the corresponding process heat exchanger. The digester slurry leaving the last flash tank is further cooled to slightly below its atmospheric boiling point with the addition of first mud washer overflow (dilution stream) at the entry to the blowoff tank.

At Utkal, the blow off tank operates at ~104 °C and generates flash vapor that vents through the relief tank. The relief tank operates at atmospheric pressure; hence the vapor exits at the said pressure only. Hence, waste heat recovery from flash vapor was a challenge. Further an induced draft fan can also be considered, but as per the study it will create the negative draft in the blow off tank that will reduce the temperature in BOP so as the supersaturation.

3.1 Waste Heat Quantification

The vapor from the relief tanks is released at ~102 °C from the stack. The inlet temperature to the Blow off tank (BOT) is ~106 °C while the outlet temperature of the BOT is ~104 °C (Figure 3).

The calculation shows approximately 6 t/h (first items of the Appendix) of vapor is generating from the blow off tank. Ultimately 18 t/h of vapor is being released to relief tank at atmospheric pressure and being cooled down to ~102 °C temperature.

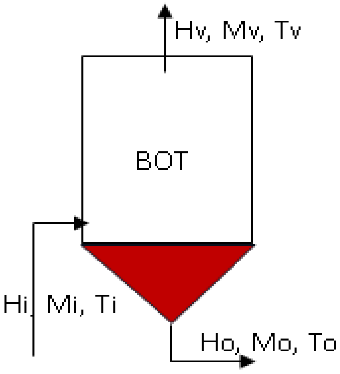

Figure 3. Vapor from BOT.

3.2 Feasibility of Waste Heat Recovery

There are few opportunities to utilize the waste heat like CCL heating circuit, PDS slurry heating circuit, wash water heating, spent liquor heating, lime slurry heating.

The flash steam of 18 t/h is available at atmospheric pressure and at ~102 °C temperature. The major challenges for waste heat recoveries from the flash steam was vapor flowability (being at low pressure), low enthalpy (low temperature ~102 °C), transporting of vapor to the desired place requires high capital investment (usage of thermo-compressors).

Out of 12 % of the miscellaneous steam, 68 % is being used in washer area for wash water heating. As per design the direct steam is injected to achieve the desired temperature for washing. Hence, focus had been given to reduce direct steam usage by using the waste heat in the mud washing circuit.

3.3 The Objective

The objective of the project is to reduce the amount of steam being consumed for the heating of wash water from the waste heat of digestion area. Presently the wash water in the washing circuit being mixed with different streams having different temperature conditions. The purpose can be solved with two possibilities. Primarily separating higher temperature streams like condensates with different temperatures from cold streams. Secondary, heating of cold stream to the desired temperature.

3.4 Stream 1: Condensate Stream

Two condensate streams, namely process condensate from digestion area available at ~100 °C and high-quality condensate at ~60 °C are being mixed at plant tank farm area and are being pumped to the wash water tank.

3.5 Stream 2: SNL and Caustic Pond Stream

The SNL and filtrate at ~44 °C and caustic pond at ~25 °C are the second source of the wash water. Heating up this stream independently can reduce the subsequent amount of heat load at the wash water tank.

3.6 Waste Heat Utilization

A heat absorbing equipment [3] has been designed in view of direct contact of the SNL with the process vapor from the relief tank. The process vapor will lose energy by the direct contact with SNL. And can be utilized directly at the wash water tank. The heat load on the equipment can be calculated from following heat balance (second item of the Appendix) [4]. As per the calculation, we can be able to achieve the temperature by splitting the flow and heating the colder one with the waste heat available.

From the calculation it was found that the with the utilization of waste heat streams the wash water outlet temperature can be able to achieve the desired temperature of 70 °C. Hence there will be no requirement of any additional steam for the heating.

4. Process Development

To mitigate all the challenges, the following process has been developed. The process is identical for three digestion trains. The vapor from the blow off tank has been diverted to the venturi condenser. Inside the condenser the heat will be transferred to the SNL (cooling media) [3]. The hot SNL after heat transfer is collecting at an atmospheric tank. A hot water pump will be engaged to discharge the hot water after mixing the process condensate from digestion to the mud wash water tank. After a detailed study the PFD (Figure 4) and P&ID for the process has been developed. The simplified diagram is demonstrated below.

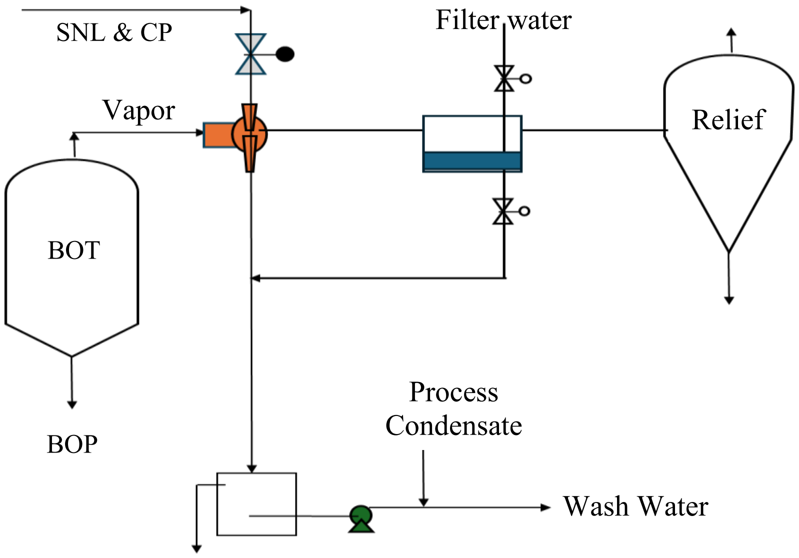

Figure 4. Simplified flow diagram of the process.

4.1 Equipment Selection

Selecting equipment for such a waste heat recovery system involves several crucial considerations to ensure efficiency, reliability, and cost-effectiveness. Waste heat recovery systems need to capture and utilize excess heat energy generated.

4.2 Vapor Seal Pot

The vapor generated in the blow off tank is available at atmospheric pressure since it is connected to the atmospheric relief tank. The vapor flow will be always to the natural vent of relief tank. For collecting the vapor from the blow off tank (BOT), we need to put an induced draft (ID) fan or some vacuum mechanism. Putting any of the options may affect the blow off temperature so as the supersaturation of the blow off slurry.

Hence, we have designed a vapor seal pot (Figure 5), that can be able to restrict the vapor flow to the relief tank. The seal pot is designed in such a way that in can handle any abnormal conditions of the downstream like BOT level and pressures.

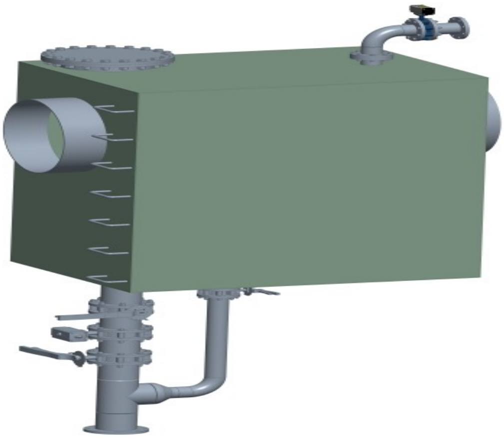

Figure 5. Vapor seal pot.

Fresh water input line was provided and the vapor from blow off pipeline was submerged into the water containing in it. According to the pressure of the blow off vessel the water level will be maintained. The water level in the pot is automatically controlled through the inlet and outlet automatic valves. During the abnormal situation of upstream process, the water will drain automatically, and the vapor will pass to the natural vent of relief tank.

4.3 Hot Water Tank

A hot water tank has been designed to collect the hot water coming from the venturi condenser. Followed by a pump to deliver the hot water to the designated wash water tank.

4.4 Venturi Condenser

The condenser was designed to capture all the vapor from blow off tank to the recovery system through a self-created draft for condensation. The venturi condenser was designed with the help of a local vendor. As per the calculations we found the amount of water to be heated and amount of vapor to be condensed. The calculations are done with reference to Bernoulli's principle [3, 5] and the pressure gradients are calculated at different points on the venturi condenser.

The model was prepared and tested through CFD (Figure 6) for maximum velocity and pressure for the cooling water flow for. The CFD model was established to handle 100 m^3/h. of cooling water to condense 7 t/h (max.) of vapor per train of operation.

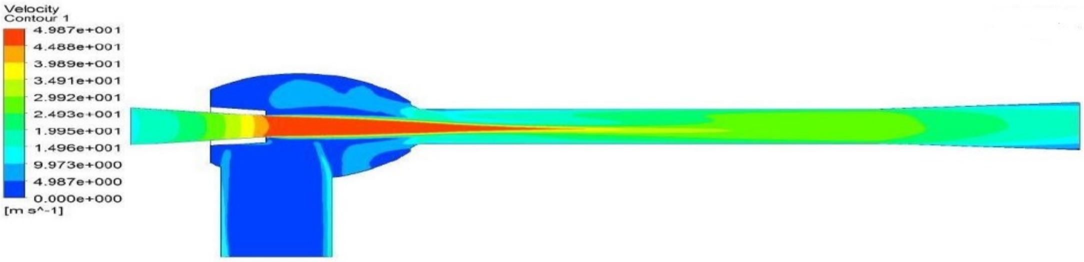

Figure 6. CFD analysis of venturi condenser.

5. Results and Discussion

After getting the CFD results a pilot study had been carried out, to check the condensation efficiency with the designed venturi condenser.

5.1 Pilot Study

According to the CFD results and calculations of venturi a pilot project (Figure 7) has been made ready with a scale of 1:10 at the fabrication site by the vendor. The test carried at different pressure conditions for steam (flash vapor was not available at the fabrication site) starting from 1 bar absolute to 1 bar gauge and similarly by varying the cooling water flow and pressure the effect of condensation. After carrying out the tests for some time it was confirmed the condensation efficiency by the pilot scale was 98 %.

After pilot study following results were predicted and on that basis venturi model was prepared by the vendor. The pilot study carried out for establishing the condensation efficiency and it was found that the condensation efficiency was 98 % with +/- 0.5 % variance and outlet temperatures were ~67 °C.

Figure 7. Pilot study setup.

The detailed calculation can be referred in the third section of the Appendix.

The pilot study carried out with available fresh water (Table 1); hence the temperature of the inlet stream is varied from 25 to 27 °C. The condensation depends on the inlet temperature hence the condensation efficiency recorded highest with 25 °C cold water at 99.2 %.

Table 1. Pilot study results.

Study No.	Cold Water Flow	Cold Water Pressure (bar, g)	Steam Pressure (bar, g)	Steam Flow (kg/h)	Inlet Temperature (T1)	Outlet Temperature (T2)	Condensation Efficiency (%)
1	10	4.0	0.1	500	25	64.6	99.2
2	10	4.0	0.1	500	26	66.7	98.6
3	10	4.0	0.1	500	26	67.3	98.6
4	10	4.0	0.1	500	27	68.3	98.1
5	10	4.0	0.1	500	27	69.6	98.1

With reference to the pilot study a model of the venturi condenser was prepared, and fabrication was started at the site. With the model we can be able to achieve the following:

- ✓ The vapor can condense without a separate vacuum system and can easily suck all the vapor with
- ✓ the mild draft.
- ✓ This system can heat the cold water itself in a way so that it can create a suction draft of ~100 mm WC.
- ✓ The induced draft will suck the entire vapor from the system for heating the cooling media to the desired temperature.
- ✓ Inline mixing process condensate with the hot liquor outlet from the condenser.

At the time of writing this article, the project setup installation was under construction (Figures 8 and 9), and it was planned to commission the waste heat recovery project from the first week of June.

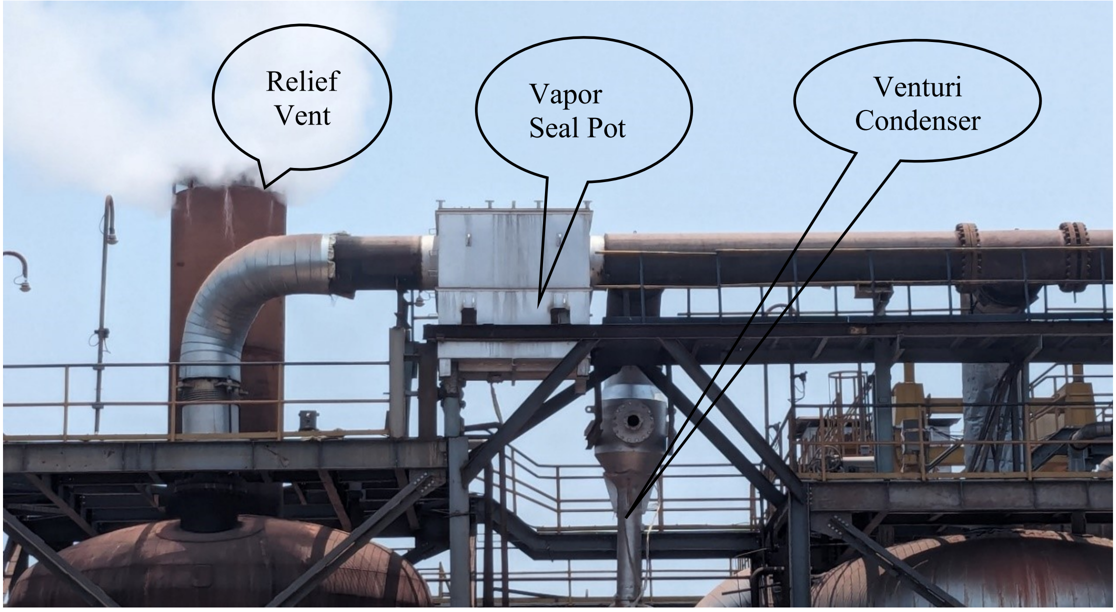

Figure 8. Vapor seal pot and venturi condenser installation at site.

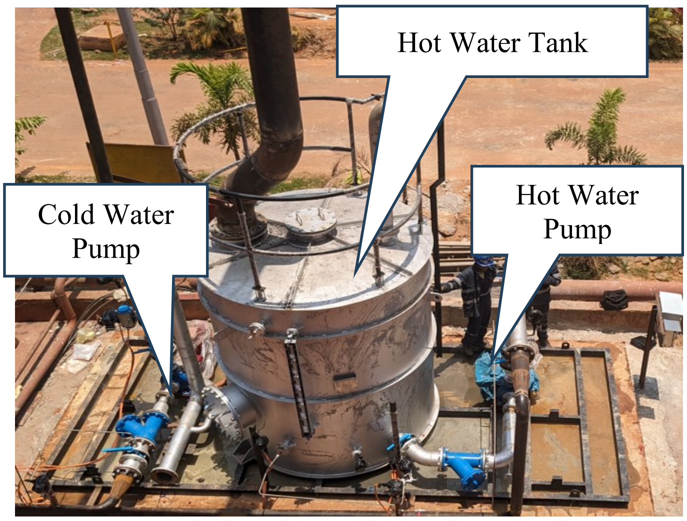

Figure 9. Hot water tank and pump.

6. Conclusion

The use of venturi condenser for waste heat recovery from digestion circuit of alumina refinery is a novel process improvement idea. Through this design intervention “low quality steam” can optimally be used for heating of any cold stream, selected SNL for Utkal circuit and miscellaneous steam consumption can be reduced. The facility is under erection and commissioning stage during the paper submission. However, pilot study and working erections from other chemical industries confirm its successful operation.

The implementation of the waste heat recovery project in Utkal refinery has a saving potential of 1.24 MJ/day of waste heat that can be able to reduce 15 t/h of low-pressure steam (which is 68 % of the total miscellaneous steam requirement at Utkal) from wash water heating in mud wash circuit ultimately saving 360 m^3/day of water in the boiler and 430 m^3/day of condensate from relief vapor. Overall, from the project we not only save heat but also 790 m^3/day of water to the circuit. It represents a significant milestone in the pursuit of energy efficiency and sustainability within the industrial sector.

The lessons learned from this project can serve as a blueprint for other alumina refineries across any alumina refinery for sustainable future initiatives aimed at maximizing energy efficiency and minimizing environmental impact across the industrial landscape and can lead to a sustainable business of “Greener, Stronger, Smarter”.

7. Appendix

1) The net heat energy loss from the slurry can be calculated as:

Net Heat loss = Q = Inlet energy – Outlet Energy [6]
= M × Cp × (Ti – To) with Cp = 2.071 kJ/kg
= 13 668 kJ
Mass of vapor generated = Mv = Heat Loss/ Enthalpy of steam)
= 6 tph Per Train

2) Amount of heat lost (Ql) = Amount of heat gained (Qg)

(Ql) = Mass of vapor × Enthalpy of steam + Mass of liquid × Enthalpy of liquid
= 20 046 kJ

Considering 5 % energy losses through non-condensable, the net energy is 19 043 kJ

Enthalpy of the vapor at this temperature = 2 676 kJ/kg·°C [Steam Table]

Enthalpy of liquid at this temperature = 419.1 kJ/kg·°C

As per energy balance, if we can heat up the SNL of ~ 42 °C (T1) then the energy balance can be written as:

Heat gain by SNL = Heat loss by vapor

The final temperature of the hot SNL after heating can be calculated as:

M × Cp × (T1-T2) = 19 043 kJ
T2 = 70 °C

[The nominal calculations are shown based on 100 m^3/h cold stream, SNL flow]

3) Condensate Efficiency = $= \frac{T2-T1}{T3-T1} \times 100$ [7]

Or

$$\eta = \frac{M_{out}}{M_{in}} \times 100$$

Where:

T1 = Cooling Water Inlet Temperature
T2 = Hot water temperature from venturi
T3 = Temperature with respect to vacuum inside condenser
M_{in} = The mass of steam input to the condenser.
M_{out} = The mass of steam condensed.

8. References

1. Katerina Kermeli et al., Energy efficiency improvement and GHG abatement in the global production of primary aluminium, *Energy Efficiency*, Springer Netherlands, Vol. 8 issue 4, 2015, 629–666.
2. Gary Gerard & P. T. Stroup, *Volume 1, Alumina; Chapter 1, Discussion of Heat Balance in the Digestion Process of Bauxite*, JW & Sons Publication, pp.73-75, 77.

3. Herman Charles Krannert; *A Digest of the Rules for the Design of Condensers and Air Pumps*, 1912, Chapter 2, Cooling Water for Jet Condensers, pp.5-6.
4. P. J. Marto, *Handbook of Heat Transfer, 3rd Edition*, 1998, Chapter-14, Condensation, pp.14.33, 14.42, 14.43.
5. Bernard Massey, Revised by John Ward-Smith, The Principle Governing Fluids in Motion*, Mechanics of Fluid, Eighth Edition,* 2005; Chapter 3, p. 95.
6. Warren McCabe, Julian Smith and Peter Harriott, Unit Operations of Chemical Engineering, Chapter 11, *Enthalpy Balance in Heat Exchangers*, pp. 319-320, McGraw-Hill.
7. K. Shruthi et al., Increasing the Efficiency of Surface Condenser under Various Load Climatic Conditions by Reducing Subcooling, *International Research Journal of Engineering and Technology (IRJET)*, Volume: 07 Issue: 06 | June 2020, p.3/4069.