Comparison between Heat Pipes based condenser and Conventional condenser of Power Plant

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Abstract This paper explores the feasibility of using heat pipes for steam condensation and heat pipe based condenser. The concept of heat pipes for steam condensation is newly proposed and studied herewith. CFD analysis and Experimental studies carried on the single heat pipe for steam condensation. Experimental setup and results of heat pipes based steam condenser presented. Properties like Effectiveness, heat transfer surface area, exergy analysis for the conventional condenser made of simple copper tubes and heat pipe based condenser are compared.

1. INTRODUCTION

Improving the energy efficiency and miniaturization are continual processes in industrial world and power sector has no exception. At present, the major of dependence for electric power is on thermal power generation. Nevertheless, as compared to other industrial sectors, especially electronic industry the miniaturization of major subcomponents of thermal power station is minimal. Reports on improvement in thermodynamic energy efficiency and exergy efficiency among thermal power generation components like boiler, turbine, condenser etc. are very little. In this work, the design modification of condenser has been proposed and also the advantages of the proposed condenser has been compared with the conventional condenser. The proposal of condenser modification is presented with the help of a case study which is described below.

2. Case Study

A 210 MW thermal power plant operating in India was considered. This plant is a base load plant, operates on Rankine cycle with reheating. The plant is equipped with different sub components like Boiler (consisting of pulverized coal firing burners, super heater, re heater, economizer etc.), 3 stage Steam turbine (High pressure turbine, Intermediate Pressure Turbine, Low Pressure Turbine), Condenser etc. Feed water is pumped by Boiler feed pump into the boiler and the boiler converts this water into super-heated steam and streams this super-heated steam into the turbine. The steam exhaust of the turbine will be dumped into condenser. Condenser converts this steam into water which again fed into the boiler as feed water.

Condenser converts the steam into water with help of cooling water flowing through the condenser tubes. During this process, the heat energy from the steam transfers from the steam to cooling water due to which there will be temperature rise in the cooling water. This visible temperature rise indicates that, the heat transfer mechanism, employed for the purpose condensing the steam is single phase mechanism. Because of this single phase mechanism a large heat transfer area is required to handle the steam exited from the turbine resulting large number of condenser tubes.

This paper describes the technology for improvement of efficiency and the miniaturization of this condenser by improving the heat transfer mechanism. It is proposed a two phase heat transfer mechanism in condenser which enhances the heat transfer capability and improves the effectiveness of condenser. The introduction of this two phase heat transfer mechanism is achieved by using heat pipes in place of conventional condenser tubes.

3. Description of Heat Pipe

Heat pipe is a man-made heat transfer device which transports large quantities of heat with minimum temperature gradient without any additional power between the two temperatures limits [1]. It consists of three different sections namely evaporator, adiabatic and condenser and a working fluid inside the heat pipe. The heat energy to be transferred will be
streamed on the evaporator section of heat pipe. The working fluid present in the heat pipes will absorb the heat energy and converts into vapour (change of phase). This vapour will migrate from the hotter portion of heat pipe to the cooler section of heat pipe which is condenser portion of the heat pipe. In this section vapour condenses back to liquid by releasing absorbed heat energy to the cooling media present at peripheral area of condenser section of the heat pipe. The condensed heat pipe liquid drops back to vapour section by gravitational force or through wick. Due to the latent heat of evaporation of working fluid inside heat pipe, considerable quantities of heat energy will be transported by this heat pipe. The evaporator and condenser sections of a heat pipe function independently, needing only common liquid. Amir Faghri [2] reported in his text book the details of heat pipe and also wide applications of heat pipes. These heat pipes were utilized to upgrade the design of the condenser in thermal power plants.

3.a Literature Review on the Application of heat pipes
In 1981, Littwin and McCurely [3] reported that usage of HPHE (Heat exchanger made by heat pipes) for steam generation and for preheating of combustion air in fossil fuel fired power plants. Vasiliev et al (1984) [4] described the usage of HPHE for waste heat recovery systems. Hong Zhang, Jun Zhuang [5] in 2003 narrated the application of heat pipes for different industrial uages. L.L Vasiliev in 2005 [6] described the application of Heat pipes in modern heat exchangers and indicated the use of heat pipes in thermal power plants. But, the heat transfer Industries have not explored the condensation of steam using the heat pipes or heat pipe based condenser., in spite of excellent heat transfer capabilities of heat pipes. This paper address the usage of heat pipe for steam condensation and also heat pipe based condenser.

4.0 CONCEPT OF THE PROPOSED HEAT PIPE BASED CONDENSER
The mechanism of steam condensation using heat pipe is presented in the Fig. 2. The steam incidents on the heat pipe evaporator surface at 46 °C. The evaporator will be heating the water (as working fluid inside the heat pipe) at a pressure of 0.07 bar. At this pressure the boiling temperature of the water is 39.02 °C. Therefore the ΔT will be (46–39.02) 6.98 °C. For 0.07 bar, ΔT<sub>cr</sub> is equal to 14 °C, which is greater than ΔT in the present case. Hence nucleate boiling will occur.

So the vapors from the evaporator regions enters the condenser portion of heat pipe. This portion is maintained at a surface temperature of 27 °C with the help of inlet cooling water. So, the vapors which reached the top portion of the heat pipe will condense on side surface of the heat pipe by releasing heat gained by evaporator section to the cooling water. The condensate will flow down due to gravity. The cycle repeats as the process go on.

4.a CFD Analysis of the proposed heat Pipe
Computational fluid dynamic analysis is carried out to know the working of the fluid inside heat pipe. For the analysis, exact boundary conditions similar to experimental set up are applied for CFD analysis. The analysis is carried out on a single heat pipe as shown in Fig 3.

Fig 3.0 The Heat pipes under analysis.
The CFD glimpses of the heat pipe under analysis are shown in Fig 4. And CFD results are shown in Table 1.

Fig 4. Heat pipe liquid changes inside heat pipe
Table 1: CFD Results

| Pressure in absolute bar | Steam Inlet temperature | Condensate temperature | Cold water outlet temperature |
|--------------------------|-------------------------|------------------------|-----------------------------|
| 0.080                    | 318.5 K                 | 317.7 K                | 308.4                       |
| 0.090                    | 317.8 K                 | 315.3 K                | 307.4 K                     |
| 0.10                     | 318.8 K                 | 317.5 K                | 308.3 K                     |

From the above it can be concluded steam Condensate temp is around 46°C and considering the input conditions, the outlet heat energy calculated is 36258.63 w. But the $h_f$ for this temperature and pressure is 2392.1 x 10³ w/kg. So, the quantity of Condensate = 36258.63/239100 = 0.015157 kg/hr = 0.909 lit/min.

The above designed heat pipe is experimented in the following case study.

5.0 Case Study

The details of Condenser chosen for this case study are presented in Table 2.

| Parameter                          | Value                        |
|------------------------------------|------------------------------|
| Plant Unit Load                    | Coal based thermal power plant, 210 MW (191 MW during the time of consideration) |
| Condenser type                     | Surface type, single pass    |
| Steam inlet temperature压                    | 46 °C & 0.09 bar             |
| Inlet and outlet cooling water Temp| 26.62 °C & 37.26 °C          |
| Total Condenser Tubes              | 19,208, Copper material     |
| Copper Tube OD & ID                | 25.4 & 24.0 mm               |
| Copper Tube Length                 | 11.28 m                     |
| Heat load                          | 221171743.8 Kcal/hr, 260 MW |
| Water Flow                         | 21033.95 t/hr, 5842.76 kg/s |
| Load on Each condenser tube and heat transfer rate per unit area | 13.5 kW and 15 kW/m² |

A suitable heat pipe is designed to suit the requirement and its specifications are presented in Table 3. The thermodynamics details of the designed heat pipe are presented in the Table 4.

| Parameter                          | Numerical value |
|------------------------------------|-----------------|
| Heat Pipe length                   | 4.3 m           |
| Heat Pipe material                 | Copper          |
| Heat Pipe vacuum                   | 0.07 bar        |
| Fluid inside heat pipe             | Distilled water |
| Saturation temperature of fluid    | 39.02 °C        |
| Wick material                      | Wickless heat pipe |

A condenser using the above designed heat pipe is proposed. The details of the proposed condenser using the specially designed heat pipes are presented in Table 4.

| Parameter                          | Value                        |
|------------------------------------|------------------------------|
| Total heat pipes                   | 9025                         |
| Arrangement of Heat pipes in HPHPE | Staggered, 95 x 95           |
| Load on each Heat Pipe and heat transfer rate per unit area | 28.8 kW = 30 kW and 84.73 kW/m² |

Table 5. Thermodynamic properties of designed heat pipe

| Parameters                          | Desired requirements of Heat Pipes in the proposed HPHE | Designed Heat pipes characteristics |
|-------------------------------------|--------------------------------------------------------|-------------------------------------|
| Maximum heat transfer limit from the Boiling point of view | 30 kW | 71 kW * |
| Maximum heat transfer limit from the Flooding point of view | 30 kW | 59.3 kW * |
| Overall heat transfer coefficient under prevailing conditions | 2447 * |

(* The detailed calculations are in Ref 7 by same author *)
6.0 Comparison between conventional condenser and HPHE condenser.
Performance of the two types of condensers are calculated and presented below.

6.a Effectiveness Comparison

Inlet Steam Sat. Temp of 46 °C

| Temperature | C | 26.62 °C |
|-------------|---|----------|
| 37.26 °C    |   |          |

Total Steam Load on the condenser = Q = 260,000 kW
Cooling Water Quantity = 5843 Kg/s

**Conventional Condenser**
Total Steam Load on the condenser = Q = 260,000 kW
Cooling Water Quantity = 5843 Kg/s

Actual Heat Transfer to the cooling water = \( m \cdot c_p \cdot (T_{cl,\text{out}} - T_{cl,\text{in}}) \)
\[
= 5843 \times 4.178 \times (37.26 - 26.62) = 259744.25 \text{ kW}
\]

Maximum possible heat transfer to the cooling water = \( 5843 \times 4.178 \times (46 - 26.62) = 473105.60 \text{ kW} \)

Effectiveness of the Existing Condenser = \( \frac{\text{Actual Heat Transfer}}{\text{Max. Possible Heat Transfer}} \)
\[
= \frac{259744.25}{473105.60} = 0.549 \approx 55 \%
\]

**PROPOSED HEAT PIPE BASED CONDENSER**

As per Faghri (Ref 2), the heat pipe condenser can be considered as liquid-coupled, indirect-transfer-type exchanger system. The analysis procedure adopted from the [9] as **liquid-coupled, indirect-transfer-type exchanger**.

\[
C_{cl} = \text{Mass of cooling water} \times c_{p,c} = (5843/9025) \times 4.187 = 2.71 \text{ kJ/s.K}
\]
(Assuming cooling water distributed equally to all heat pipes)

\[
C_{cl} = m_{hl} \times c_{p,hl} = \text{mass of water used inside the heat pipe for the purpose}
\]
\[
= 0.0125 \times 4.178 = 0.0522 \text{ kJ/s.K}
\]

\[
C_{hl} = m_{hl} \times c_{p,hl} = \text{mass of steam condensed on each heat pipe x specific heat of steam}
\]
\[
= 0.012 \times 1.895 = 0.023 \text{ kJ/s.K}
\]

\[
NOW, \text{ Evaporator section of Heat pipe, } NTU_e = \frac{U_e \pi}{A_e} \frac{D_L}{m_e \cdot c_p}, \text{ \{Adapted from E.Azd, F. Bahar et al., Design of Water –to –air Gravity assisted Heat Pipe Heat Exchanger, Peragon Press, 1985.\}}
\]

\[
\text{Now for evaporator section, } NTU_e = \frac{U_e A_e}{m_e c_p}
\]

Where \( h_e = \text{total thermal conductance of evaporator section (W/K)} \)

\[
A_e = \text{outer area of evaporator section (m²)}
\]

\[
m = \text{mass flow rate of steam (Kg/s)}
\]

\[
\text{Thermal resistance of evaporator section} = \text{resistance due to steam entering} + \text{resistance due to wall} + \text{resistance inside heat pipe}
\]

\[
Re = R_{o,e} + R_{w,e} + R_{i,e}
\]

\[
h_1 = \text{heat transfer coefficient at outside of evaporator section of heat pipe}
\]

\[
h_2 = \text{heat transfer coefficient at inside side of evaporator section of heat pipe}
\]

\[
h_3 = \text{heat transfer coefficient at inside of condenser section of heat pipe}
\]

\[
h_4 = \text{heat transfer coefficient at outside of condenser section of heat pipe}
\]

\[
R_{o,e} = \frac{1}{h_1 \times A_o,e} = (1/31543 \times 0.34) = 9.32 \times 10^{-5} \text{ K/W}
\]

\[
R_{w,e} = \frac{\ln(d_o/d_i) \times 2\pi kL}{\ln(0.0454/0.0497) \times 2\pi kL} = 1.67 \times 10^{-5} \text{ K/W}
\]

\[
R_{i,e} = \frac{1}{h_2 \times A_i,e} = (1/15521 \times 0.312) = 2.0 \times 10^{-5} \text{ K/W}
\]

\[
Re = 9.32 \times 10^{-5} + 1.67 \times 10^{-5} + 2.0 \times 10^{-5} = 1.3 \times 10^{-4} \text{ K/W}
\]

\[
h_e = \frac{1}{Re} = 7698.2 \text{ W/K}
\]

\[
NTU_e = (7698.2 \times 0.34/0.012 \times 1.895 \times 10^3) = 115.10
\]
Effectiveness of evaporator section is \( \varepsilon_e = 1 - e^{-\frac{1}{NTU_e}} = 1 - e^{-115.10} = 1 \)

For condenser section

Thermal resistance of condenser section = resistance due to steam entering +
Resistance due to wall + resistance inside heat pipe

\[ R_c = R_{o,c} + R_{w,c} + R_{i,c} \]

\[ R_{o,c} = \frac{1}{h_4 \times A_o,c} = \frac{(1/21405 \times 0.34)}{1.59 \times 10^{-5}} \text{ K/W} \]

\[ R_{w,c} = \frac{1}{\ln(d_o/d_i) / 2\pi k L} = 1.67 \times 10^{-5} \text{ K/W} \]

\[ R_{i,c} = \frac{1}{h_3 \times A_i,c} = \frac{1/14065 \times 0.312}{2.21 \times 10^{-5}} \text{ K/W} \]

\[ R_c = 1.59 \times 10^{-5} + 1.67 \times 10^{-5} + 2.21 \times 10^{-5} = 5.47 \times 10^{-5} \text{ K/W} \]

The heat transfer coefficients \( h_1 \) to \( h_4 \) are calculated as per the procedure adopted in Ref [7] published by same author

\[ h_c = \text{total thermal conductance of condenser section (W/K)} \]

\[ h_c = \frac{1}{R_c} = 18,281.5 \text{ (W/K)} \]

\[ NTU_c = (2570.7 \times 0.34 / 0.65 \times 4.187 \times 10^3) = 2.3 \]

Effectiveness of condenser section is \( \varepsilon_c = 1 - e^{-\frac{1}{NTU_c}} = 1 - e^{-2.3} = 0.89 \)

For a heat pipe heat exchanger with \( n \) rows of heat pipes (Ref 8),

For evaporator section, with \( n \) number of rows of heat pipes,

The net effectiveness, \( \sum \varepsilon_e = 1 - (1 - \varepsilon_e)^n \)

For condenser section, with \( n \) number of rows of heat pipes,

The net effectiveness, \( \sum \varepsilon_c = 1 - (1 - \varepsilon_c)^n \)

The overall effectiveness of the heat exchanger \( \varepsilon_o \) is given by, Ref[9]

\[ \varepsilon_o = \{ \frac{1}{\sum \varepsilon_e} + \frac{(C_{dl}/C_{cl}) \times (1/\sum \varepsilon_c - 1)}{C_{cl} > C_X > C_{nl}} \}^{1} \]

Applying numerical, \( \varepsilon_o = 0.99 \)

**Hence it can be concluded that Heat pipe based condenser is more effective than conventional condenser.**

**6.b Heat Transfer per unit area**

The Table 6 clearly brings out the comparison of heat transfer area of the conventional and heat pipe based condenser.

Heat transfer Load on the condenser = 260 MW

| Parameter                          | Conventional Condenser | Heat Pipe Based Condenser |
|------------------------------------|------------------------|---------------------------|
| Number of Tubes                    | 19208                  | 9025 Heat pipes           |
| Diameter of tubes                  | 0.0254 m               | 0.0540 m                  |
| Length of tubes exposed for steam condensation | 11.28 m | 2 m                      |
| Total Heat Transfer area (Length x Perimeter x Number of Tubes) | 17289.2 m² | 3062.1 m² |
| Heat Transfer Rate                 | 15 kW/m²               | 85 kW/m²                  |

**6. c. EXERGY ANALYSIS**

For Conventional Condenser

\[ \Xi = \text{Destruction in Exergy} = T_{env} \left[ \frac{C_{W} \ln \left( T_{cl, out} / T_{cl, in} \right) + C_{W} \left( T_{cl, in} - T_{cl, out} / T_{s, in} \right)}{T_{s, in}} \right] \]

Now, \( C_W = \text{Cooling water quantity} = 5843 \text{ kg/s} \)

\[ T_{env} = \text{Temp. Of the Environment} = 28 \text{ °C} = 301 \text{ K} \]

\[ T_{cl, out} = \text{Cooling water out Temp} = 37.62 \text{ °C} = 310.62 \text{ K} \]

\[ T_{cl, in} = \text{Cooling water inlet Temp} = 26.62 \text{ °C} = 299.62 \text{ K} \]

\[ T_{s, in} = \text{Steam inlet temperature} = 46 \text{ °C} = 319 \text{ K} \]

Applying numerical,

\[ \Xi = 301 \times 5843 \times 4.18 \times \ln \left( 310.62/299.62 + (299.62-310.62/319) \right) \]

\[ = 301 \times 5843 \times 4.18 \times \ln \left( 310.62/299.62 + (299.62-310.62/319) \right) \]

5
For HPHE Condenser

\[
0.0361-0.0345 = 0.0361 - 0.0345 = 0.0016
\]

\[
= 303 \times 5843 \times 4.18 \times 0.0016
\]

\[
= 11,761 \text{ kW}
\]

For Part B

Where steam condenses into water and fluid inside the heat pipe evaporates.

\[
\mathcal{E} = h_{ov} A_{ov} (\pi_T - 1)^2 / \pi_T \quad [10]
\]

\[h_{ov} = \text{Overall heat transfer coefficient} = 2406 \text{ W/m}^2\text{K}\]

\[A_v = \text{Overall heat transfer area} = 1.3 \text{ m}^2\]

\[\pi_T = \text{the ratio of input thermodynamic temperature of the streams} = 46/39.02 = 1.179\]

Applying numerical,

Hence, \[\mathcal{E} = 2406 \times 1.3 \times (1.179-1)^2 \div 1.179 = 85 \text{ W}\]

For Part A

Where cooling water gets heated and vapor inside heat pipe condenses into liquid.

\[
\mathcal{E} = T_{env} \left[ C_1 \ln \left( T_{cl, out}/T_{cl, in} \right) + C_1 \left( T_{cl, in} - T_{cl, out} \right) \right] / T_2
\]

\[C_c = \text{Heat capacity of water stream, W/k}\]

\[T_{cl, in} = \text{temperature in K of cooling water at inlet} = 299.62\]

\[T_{cl, out} = \text{temperature in K of cooling water at outlet} = 310.26\]

\[T_2 = \text{temperature in K of vapor inside heat pipe before condensation} = 312.02\]

Hence, \[\mathcal{E} = 301 \times 5843 \times 4.178 \times [ \ln (310.26/299.62) + (299.62-310.26)/312.02 ] = 7348028.3 \times (0.0349-0.0341) = 5878.4 \text{ kW}\]

Total Exergy destruction in Part A and Part B = 5878kW + 85 kW = 5963.4 \approx 5963 \text{ kW}\]

Hence it can be concluded that Heat pipe based condenser is more suitable than conventional condenser from the point of view of Exergy.

7.0 EXPERIMENTAL SET UP AND FABRICATION PROCESS

The heat pipe lower portion is enclosed with a jacket in which steam is injected for condensation purposes. Top portion is enclosed with another jacket which acts like a cooling water jacket. The portion of heat pipe enclosed for steam condensation acts as evaporator of the heat pipe and the portion which is enclosed by cold water jacket as condenser of the heat pipe. The inlet and outlet temperatures are measured with the digital thermometers implanted at the inlet and outlet openings. Steam with different temperatures is allowed to enter steam jacket from opening and this steam is condensed and condensate is exited from tap provided. Cold water allowed to enter the cold water jacket bottom opening and allowed to exit from the top opening.

Experiments were carried out on single heat pipe as shown in Fig 8.0

Fig 8.0 Experimental set up with single Heat pipe

The inlet and outlet temperatures are measured with the digital thermometers at the inlet and outlet openings. The boiler is operated with 33 kW heaters. After reaching the steady state conditions, the readings were taken and the performance of heat pipe shown in the Fig 9
After successful experiments with single heat pipe, the steam condensation with heat pipe based condenser was tried.

Heat pipes based condenser with the above designed heat pipes is fabricated with 16 numbers of heat pipes in the laboratory. The sketch of the experimental setup shown in Fig 10.

The heat pipe condenser used for the experiments and experimental set up is shown in Fig 6.3

It is hereby concluded that the heat pipe based condenser is capable of converting the steam into condensate. The outflow of condensate from the tank clearly indicates that the heat pipes are converting the steam continuously. Hence it can concluded that the heat pipes placed inside the condenser are capable of converting steam into the water.

**Performance of Heat Pipe based Condenser**

After reaching the steady state conditions, the readings were taken and presented in Table. The performance of the heat pipe based condenser experiments can be represented in the following graph.
8.0 The comparison between conventional and heat pipe based condenser is tabulated and presented in the Table 7.

| S. No | Parameters           | Conventional Condenser | Heat pipe based condenser |
|-------|----------------------|-------------------------|---------------------------|
| 1     | Effectiveness        | 55 %                    | 0.99 %                    |
| 2     | Heat transfer rate   | 15 kW/m²                | 85 kW/m²                  |
| 3     | $\Delta E_{ex}$ = Quantity of Exergy | 11,761 kW | 5963 kW |

9.0 CONCLUSIONS

Heat pipes can be used for steam condensation purpose and may be replaced with the conventional nonferrous tubes used in the conventional condenser. Use of the heat pipes in place of conventional condenser increase the effectiveness of condenser as well as reduces the size of condenser and also exergy destruction can be reduced.

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NOMENCLATURE

**English**

A cross sectional area, m²
C Heat Capacity
C Specific heat
d diameter, m
g gravitational acceleration, m.s⁻²
H height, m
n total number of tubes
L length, m
m mass flow rate, kg/s
P atm atmosphere pressure, N. m⁻²
P sys system pressure, N. m⁻²
Q Steam Load
r radius, m
S Specific heat
h Heat transfer coefficient
t thickness in m
T Temperature
CW Cooling water quantity
R Thermal Resistance

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