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Comparison Between Heat Pipes Based Condenser and Conventional Condenser of Power Plant

Mallikharjuna Rao Tarla

Material Technology Division, Central Power Research Institute, Bangalore, India

Email address:
malliktarla@gmail.com

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Abstract: Condenser is a vital part in the steam circuit of power plant. But since inception there wre no modifications in the design of this vital component. The only variations are, the type of nonferrous tubes and tube matrix according load on the condenser. In this paper design modification of condenser suggested viz. type heat transfer utilized in the condenser. Two phase heat transfer suggested instead single heat phase heat transfer as in conventional condenser. This type of two phase heat transfer achieved by using heat pipes. The heat pipe designed for this special application of steam condensation. A laboratory model of condenser with 16 heat pipes fabricated and experiments were conducted on this heat pipe based condenser. The comparison of the performances of conventional condenser made of simple copper tubes and heat pipe based condenser were presented in this paper. Effectiveness calculations, heat transfer surface area comparison, comparison of exergy analysis for the both type of condenser presented in this paper. The comparative study reveals that the heat pipe based condenser had much improved performance parameters over the condenser made up with copper tubes.

Keywords: Wickless Heat Pipe, Thermosyphon, Steam Condenser, Exergy, Heat Transfer Coefficient

1. Introduction

At present increasing the energy efficiency and miniaturization are important challenges in all kinds of process industry, energy, oil, chemical, food and others industries. The heat exchangers and condenser are the key equipment for energy saving and reducing thermal pollution. Thermal pollution viz reduction in exergy loss can be reduced by using Heat Pipe Heat Exchangers (HPHEs). When properly designed, they may have reduced life cycle costs in comparison with conventional heat exchangers.

Heat pipe are well described in Ref [1]. These heat pipes are now widely used in the industries. Dunn and Reay [2] widely covered different applications of heat pipes. Amir Faghri [3] also reported in his text book wide applications of heat pipes.

In 1981, Littwin and McCurely [4] reported HPHE for steam generation or to preheat combustion air in fossil –fired power plants and in process furnaces. Vasiliev et al (1984) [5] described HPHE are used as waste heat recovery system where the scavenged heat is available for space heating. Then Commercial use of heat pipe heat exchangers also began slowly. They can be listed as below.

i. The heat pipe heat exchangers used as air preheaters for electric utility boilers,
ii. Processing industries.
iii. The standard and custom industrial air-to-air heat pipe heat exchangers for electronic cabinets used in clean rooms, transmitter and telecommunication stations, and computers.
iv. Heat pipes heat exchangers are typically charged with a refrigerant and used as in knurled-wall construction and also used for dehumidification and energy recovery.
v. Air-to-air heat pipe heat exchangers for building energy recovery also came into usage.

Hong Zhang, Jun Zhuang [6] in 2003 reported some typical cases of industrial applications. L. L Vasiliev in 2005 [7] described the application of Heat pipes in modern heat exchangers and indicated the use of heat pipes in thermal power plants and solar collectors.

But, the heat transfer community has not explored the condensation of steam using the heat pipe based condenser, in spite of excellent heat transfer capabilities of heat pipes.

The author of this paper made an attempt condensation by heat pipes [8] and also designed a condenser based on wickless heat pipe [9] and compare its performance with the existing conventional condenser. The comparison is made through a case study.

2. Case Study

A 210 MW thermal power plant and its existing condenser are considered**.** This plant operates with water as working fluid. The steam is generated from the feed-water in the coal fired boiler. This super-heated steam gets expanded in the turbine. The exhaust of the turbine will be dumped into condenser. Condenser converts this steam into water. This water again fed to the boiler as feed water. The cycle is depicted as below.

By examining above cycle, it can be easily concluded that condenser is also a vital component as boiler and turbine. In this condenser. In this condenser the heat transfers from the steam to cooling water takes place as apparent temperature rise in the cooling water, which indicates the heat transfer mechanism is by single phase only. Hence a large heat transfer area is required in the present condenser. The author proposes two phase heat transfer mechanism, using heat pipes in place of nonferrous tubes. The superiority of this concept is proven with help of case study of 210 MW thermal Power plant.

The details of Condenser chosen for this case study are presented in Table 1.

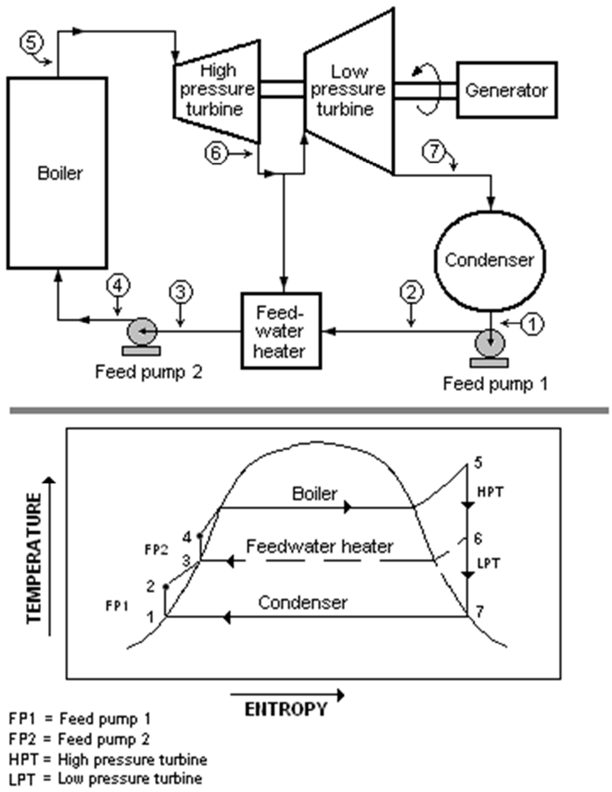

Figure 1. *Typical cycle for Thermal Power Plants.*

Table 1. *Plant Details.*

Sl.No	Parameter	Type/Numerical value
1	Plant	Coal based thermal power plant
1	Unit Load	210 MW (191 MW during the time of consideration)
2	Condenser type	Surface type, single pass
3	Steam inlet temperature	46 °C
4	Steam inlet pressure	0.09 bar
5	Inlet cooling water Temp	29.62 °C
6	Outlet cooling water Temp	39.65 °C
7	Total Condenser Tubes	19,208, Copper material
8	Copper Tube OD	25.4 mm
9	Copper Tube ID	24.0 mm
10	Copper Tube Length	11.28 m
11	Heat load	221171743.8 Kcal/hr, 260 MW
12	Water Flow	21033.95 t/hr, 5842.76 kg/s
13	Load on Each condenser tube and heat transfer rate per unit area	13.5 kW and 15 kW/m^2

3. Design of Heat Pipe for Condensation

Table 2. *Heat pipe design parameters.*

Sl.No	Parameter	Numerical value
1	Heat Pipe length	4.3 m
2	Heat Pipe material	Copper
3	Heat Pipe vacuum	0.07 bar
4	Fluid inside heat pipe	Distilled water
5	Saturation temperature of fluid	39.02 ° C
6	Wick material	Wickless heat pipe

A suitable heat pipe is designed to suit the requirement and its specifications are presented in Table 2. The design details are given in Ref [9] by same author. The thermodynamics details of the designed heat pipe are presented in the Table 4.

A condenser using the above designed heat pipe is proposed. The other details of the proposed condenser with heat pipes are presented in Table 3.

Table 3. *The details of heat pipe based condenser.*

Sl.No	Parameter	Value
1	Total heat pipes	9025
2	Arrangement of Heat pipes in HPHPE	Staggered, 95 x 95
3	Load on each Heat Pipe and heat transfer rate per unit area	28.8 kW ≈ 30 kW and 84.73 kW/m^2

Table 4. Thermodynamic details of Proposed heat pipe .

Sl. No	Parameters	Desired requirements of Heat Pipes in the proposed HPHE	Designed Heat pipes characteristics
1	Maximum heat transfer limit from the Boiling point of view	30 kW	71 kW *
2	Maximum heat transfer limit from the Flooding point of view	30 kW	59.3 kW *
3	Overall heat transfer coefficient under prevailing conditions		2447 *

(* The detailed calculations are in Ref 7 by same author)

4. Comparison of Conventional Condenser with HPHE Condenser

Performance of the two types of condensers are calculated and presented below.

4.1. Effectiveness Comparison

In let Steam Sat. Temp of 46°C

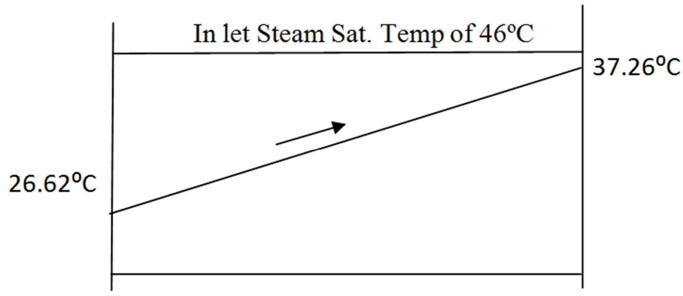

Figure 2. Temperatures in the Condenser.

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

Conventional Condenser

Actual Heat Transfer to the cooling water = m $c_p(t_{c,out} - t_{c,in})$ = 5843 x 4.178 x (37.26-26.62) = 259744.25 kW

Maximum possible heat transfer to the cooling water = 5843 x 4.178 x (46-26.62) = 473105.60 kW

Effectiveness of the Existing Condenser = Actual Heat Transfer/Max. Possible Heat Transfer = 259744.25/473105.60

= 0.549 approximately 55 %

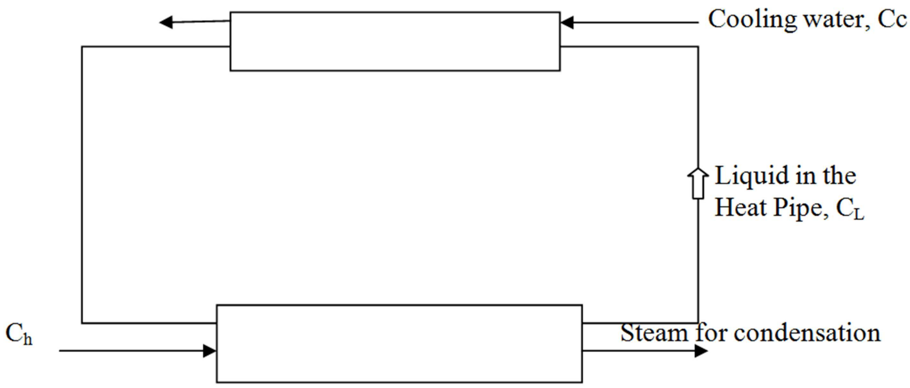

Figure 3. Equivalence between HP condenser and liquid coupled indirect Heat Exchanger.

HEAT PIPE BASED CONDENSER

As per Faghri [3], the heat pipe condenser can be considered as liquid-coupled, indirect-transfer-type exchanger system. The analysis procedure adopted from the [10] as liquid-coupled, indirect-transfer-type exchanger.

C = mass flow x specific heat =Flow Stream capacity, kcal/s.K, Subscripts L, c, h are coupling fluid, cold fluid, hot fluid respectively.

C_p is specific heat of the fluid in kcal/kg.K

$$C_c = \text{Mass of cooling water x } C_{p,c} = (5843/9025) \text{ x } 4.187 = 2.71 \text{ KJ/s.K}$$

(Assuming cooling water distributed equally to all heat pipes)

$$C_L = m_L \text{x } C_{p,L} = \text{mass of water used inside the heat pipe for the purpose} = 0.0125 \text{ x } 4.178 = 0.0522 \text{ KJ/s.K}$$

$$C_h = m_h \text{ x } C_{p,h} = \text{mass of steam condensed on each heat pipe x specific heat of steam} = 0.012 \text{ x } 1.895 = 0.023 \text{ KJ/s.K}$$

Now, Evaporator section of Heat pipe, $NTU_e = U_e\pi\ DL_eN / m_e.C_p$, Taken from E.Azd, F. Bahar et al, Design of Water –to – air Gravity assisted Heat Pipe Heat Exchanger, Peragon Press, 1985.

Now for evaporator section,

$$NTUe = \frac{UeAe}{mCp}$$

Where Ue = total thermal conductance of evaporator section (W/K).

Ae = outer area of evaporator section (m^2).

m = mass flow rate of steam (Kg/s).

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

$$Re = Ro,e + Rw,e + Ri,e$$

$$Ro,e = (1/h_1 \text{ x } Ao,e) = (1/31543 \text{ X } 0.34) = 9.32 \text{ x } 10^{-5} \text{ K/W}$$

$$Rw,e = \{\ln(do/di)/2\pi kL\} = \{\ln(0.04540/0.0497)/ 2\pi kL\} = 1.67 \text{ x } 10^{-5} \text{ K/W}$$

$$Ri,e = (1/h_2 \text{ x } Ai,e) = (1/16027 \text{ x } 0.312) = 1.99 \text{ x } 10^{-4} \text{ K/W}$$

$$Re = 9.32 \text{ x } 10^{-5} + 1.67 \text{ x } 10^{-5} + 1.99 \text{ x } 10^{-4} = 3.089 \text{ x } 10^{-4} \text{ K/W}$$

$$Ue = (1/Re) = 3237.3 \text{ W/K}$$

$$NTUe = (3237.3 \text{ x } 0.34/0.012 \text{ x } 1.895 \text{ x } 10^3) = 48.40$$

Effectiveness of evaporator section is $\varepsilon_e = 1- e^{-NTUe} = 1-e^{-48.40} = 1$

For condenser section

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

$$Rc = Ro,c + Rw,c + Ri,c$$

$$Ro,c = (1/h_4 \text{ x } Ao,c) = (1/19115 \text{ x } 0.34) = 1.54 \text{ x } 10^{-4} \text{ K/W}$$

$$Rw,c = \{\ln(do/di)/2\pi kL\} = 1.67 \text{ x } 10^{-5} \text{ K/W}$$

$$Ri,c = (1/h_3 \text{ x } Ai,c) = (1/14643 \text{ x } 0.312) = 2.19 \text{ x } 10^{-4} \text{ K/W}$$

$$Rc = 1.54 \text{ x } 10^{-4} + 1.67 \text{ x } 10^{-5} + 2.19 \text{ x } 10^{-4} = 3.89 \text{ x } 10^{-4} \text{ K/W}$$

Uc= total thermal conductance of condenser section (W/K)

$$Uc = (1/Rc) = 2570.7 \text{ (W/K)}$$

$$NTUc = (2570.7 \text{ x } 0.34 / 0.65 \text{ x } 4.187 \text{ x } 10^3) = 0.32$$

Effectiveness of condenser section is $\varepsilon_c = 1- e^{-NTUc} = 1-e^{-0.32} = 0.274$

For a heat pipe heat exchanger with n rows of heat pipes [11], For evaporator section,

$$\varepsilon_{en} = 1 - (1-\varepsilon_{e1})^n$$

For condenser section,

$$\varepsilon_{cn} = 1 - (1-\varepsilon_{c1})^n$$

The overall effectiveness of the heat exchanger ε_o is given by,

$$\varepsilon_o = \{ 1/\varepsilon_{en} + (C_h/C_c)/\varepsilon_{cn} \}^{-1}, \text{ since } C_c > C_h$$

Appling numerical, εo = 0.99
Hence it can be concluded that Heat pipe based condenser is more effective than conventional condenser.

4.2. Heat Transfer Per Unit Area

The Table 5 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

Table 5. *Design Comparison of two types condensers.*

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 m^2	3062.1 m^2
Heat Transfer Rate	15 kW/m^2	85 kW/m^2

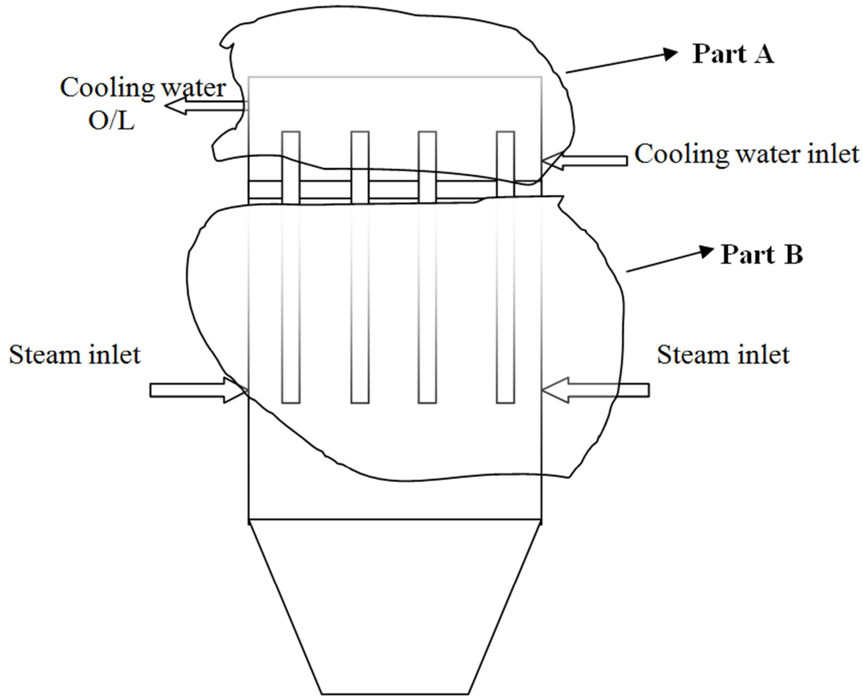

Figure 4. *Exergy Analysis.*

4.3. Exergy Analysis

For Conventional Condenser

$$\sigma = \text{Quantity of Exergy} = T_{env} [Cc \ln(T_1^{''}/T_1^{'}) + C_c (T_1^{'} - T_1^{''})/T_2^{'}] \text{ (Equation of 5 Of Reference 14)}$$

Now, C_1 = Cooling water quantity = 5843 kg/s.
T_{env} = Temp. Of the Environment = 28°C = 301 K.
$T_1^{''}$ = Cooling water out let Temp = 37.62°C = 310.62 K.
$T_1^{'}$ = Cooling water inlet Temp = 26.62°C = 299.62 K.

T_2' = Steam inlet temperature = 46°C =319 K.
Applying numerical,

$$\text{Hence, } \sigma = 301 \text{ x } 5843 \text{ x}4.18 \text{ x}[\ln(310.62/299.62 + (299.62\text{-}310.62/319)]$$

$$= 303 \text{ x } 5843 \text{ x } 4.18 \text{ x } (0.0361\text{-}0.0345) = 11{,}761 \text{ kW}$$

For HPHE Condenser
For Part B
Where steam condenses into water and fluid inside the heat pipe evaporates.

$$\sigma = U_o A_o [(\pi_T -1)^2 / \pi_T] \text{ (source: [12])}$$

U_o = Overall heat transfer coefficient = 2406 W/m^2.K.
A_o = Overall heat transfer area = 1.3 m^2.
π_T = the ratio of input thermodynamic temperature of the streams = 46/39.02 = 1.179.
Applying numerical,

$$\text{Hence, } \Delta E_{ex} = 2406 \text{ x } 1.3\text{x } (1.179\text{-}1)^2 / 1.179 = 85 \text{ W}$$

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

$$\sigma = T_{env} [C_1 \ln (T_1'' / T_1') + C_1 (T_1' - T_1'')/T_2']$$

C_c = Heat capacity of water stream, W/k.
T_1' = temperature in K of cooling water at inlet = 299.62.
T_1'' = temperature in K of cooling water at outlet = 310.26.
T_2' = temperature in K of vapor inside heat pipe before condensation. = 312.02.

$$\text{Hence, } \Delta E_{ex} = 301 \text{ x } 5843 \text{ x } 4.178 \text{ x } [\ln(310.26/299.62) + (299.62\text{-}310.26)/312.02]$$

$$= 7348028.3 \text{ x } (0.0349\text{-}0.0341) = 5878.4 \text{ kW}$$

Total Exergy in Part A and Part B = 5878kW+ 85 kW = 5963.4 ≈ 5963 kW.

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

5. Experimental Set up and Fabricating the Heat Pipe Condenser

A heat pipes based condenser with the above designed heat pipes is fabricated with 16 numbers heat pipes in the laboratory. The sketch of the experimental set up shown in Figure 5.

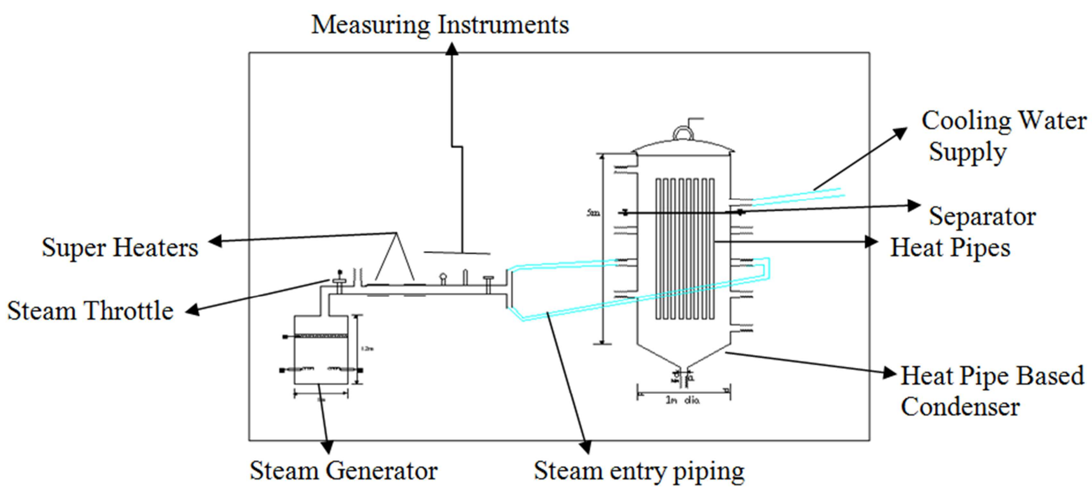

***Figure 5.** Line Diagram of Experimental Set up.*

The heat pipe condenser required for the experiment was designed as below. The line diagram of steam condenser and actual photograph is shown in Figures 5-7.

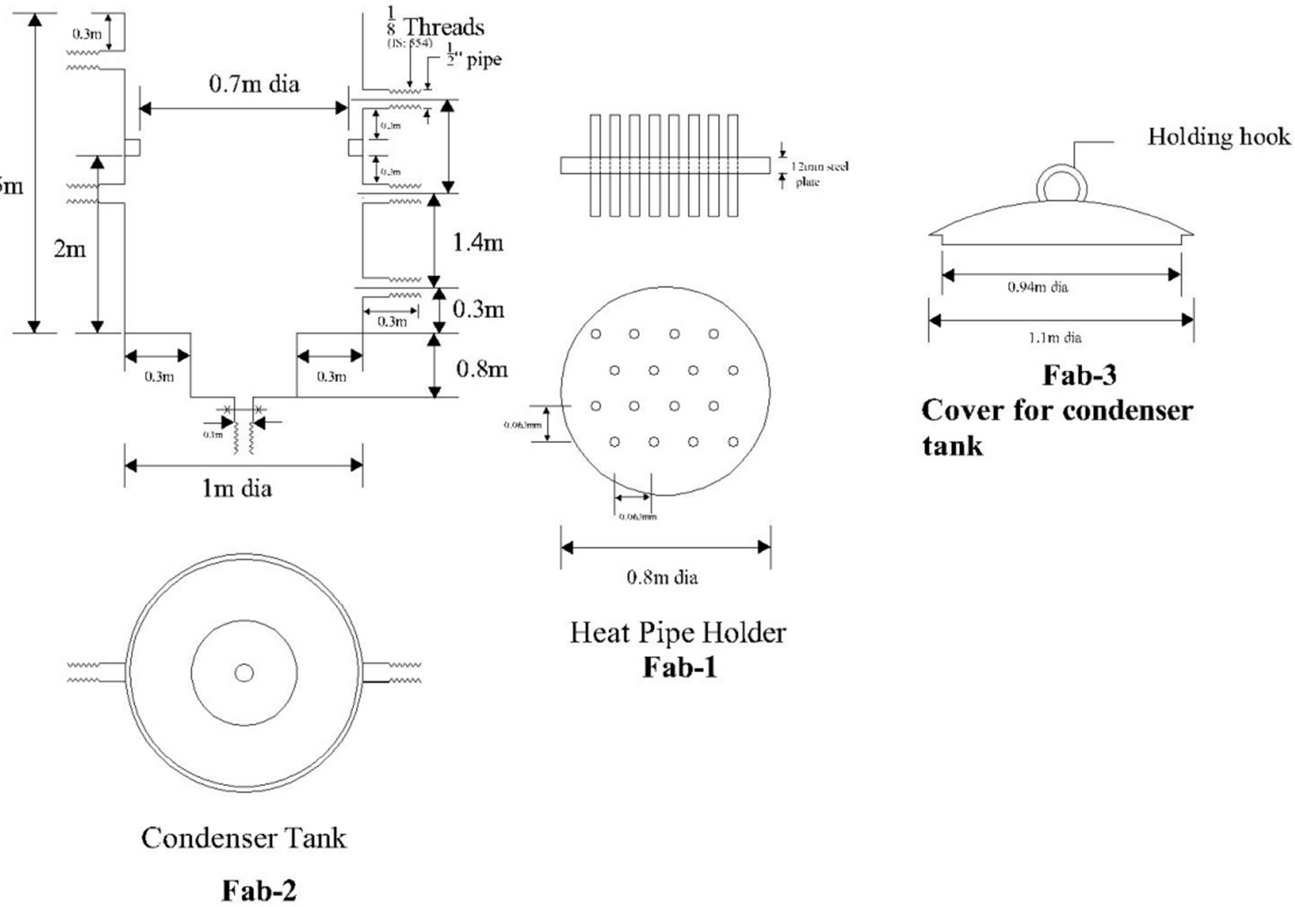

Figure 6. *Line Diagram of HPHE condenser.*

Figure 7. *Fabrication of Heat Pipe Heat Exchanger.*

Instruments Used during Experiment: Flow Meters, Digital temperature indicators, compound pressure gauge, vacuum pump. Bucket and beaker (to measure the quantity of cooling water) Power Analysers to measure the power input to boiler heaters.

No of heat pipes used are 16. A miniature steam generator whose heating capacity will be 33 kW made use to supply the steam. A superheating system is arranged to superheat the generated steam. Then the superheated steam and throttled and fed into the heat pipe condenser. The temperature and pressure of the steam measured before throttle valve. The line diagram and experimental set up actual photo are shown in Figure 8 and Figure 9.

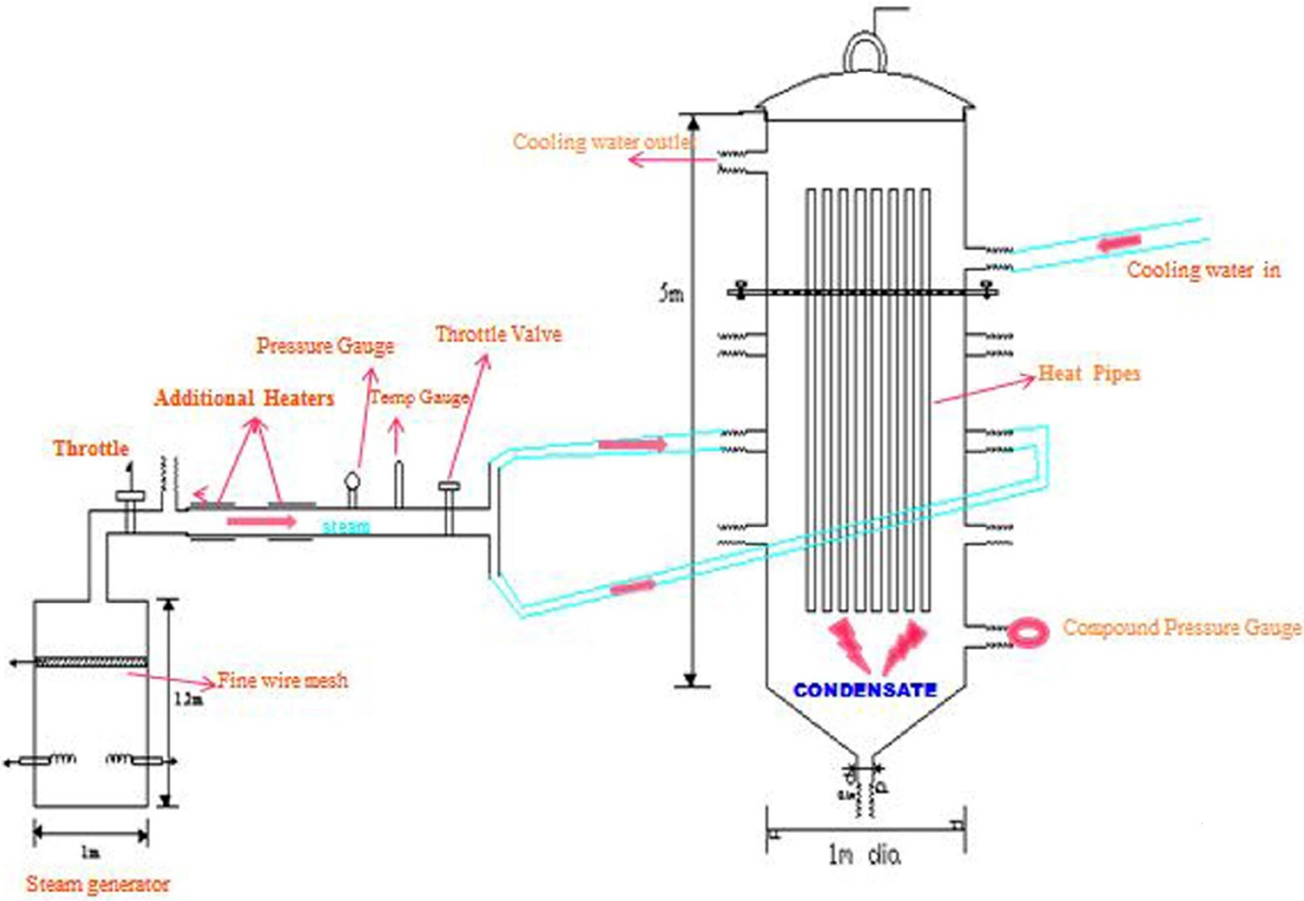

Figure 8. *Scheme of Experimental Setup.*

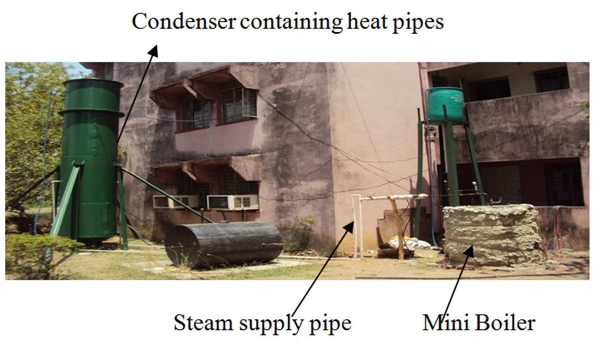

Figure 9. *Photograph of Experiment.*

6. Discussion of Experiments

6.1. Experimental Results

The output of mini boiler is super-heated and fed into the condenser built by heat pipes.

This condenser with the help of heat pipes converts the steam into condensate as shown in Figure 10.

This is to informs that the heat pipe based condenser can 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 and as result the outlet water flow as shown in Figure 7. Hence it is thermodynamically proven that the heat pipes placed inside the condenser are capable of converting steam into the water.

Figure 10. *Flow of Condensate.*

6.2. Analysis of Experiments

As indicated in the diagram stem admission into the condenser is from both sides and exit of steam is from lower portion. No of heat pipes used are 16. A miniature steam generator whose heating capacity will be 33 kW made use to supply the steam. A superheating system is arranged to superheat the generated steam. Then the superheated steam and throttled and fed into the heat pipe condenser. The temperature and pressure of the steam measured before throttle valve. The actual photo experimental set up is given above. 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 in Figure 11.

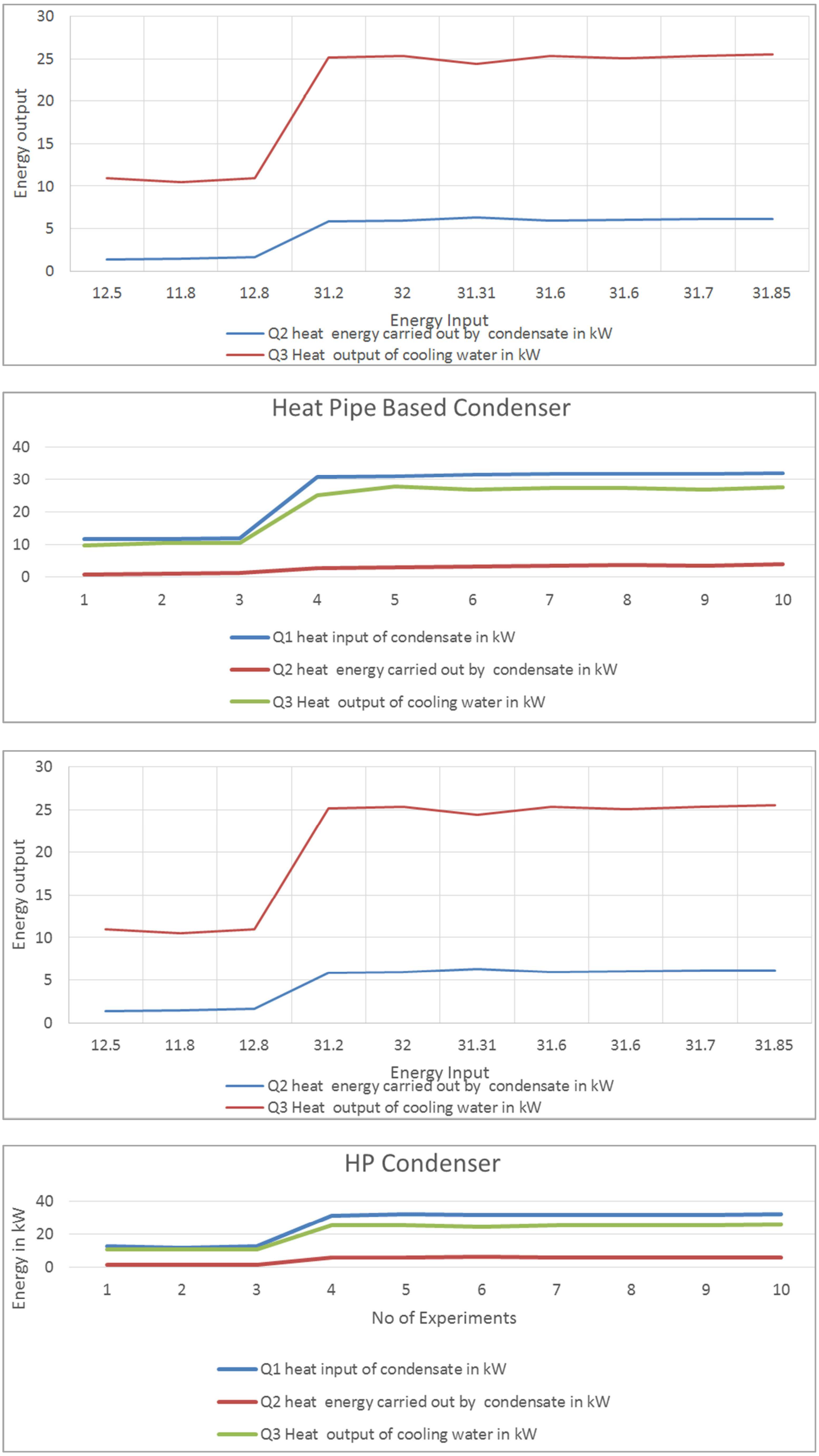

Figure 11. *Performance of Heat Pipe Based Condenser.*

7. Comparison of Two Types of Condensers

The parameters of condenser like effectiveness, heat transfer rate etc are calculated for the both conventional and het pipe based condenser and presented in Table 6. The comparison brings out the advantages of heat pipe based condenser over conventional condenser. More over heat pipe based condenser occupies less space than conventional condenser and also maintenance of 9025 tube bundle is much easier than the maintenance of 19,200 tubes. Hence there will be a lot of saving in maintenance cost. Also the exergy destruction in the heat pipes based condenser is far less than conventional condenser that implies that heat pipe based condenser is more environment friendly device.

Table 6. *Performance Comparison of two types condensers.*

Sl.No	Parameters	Conventional Condenser	Heat pipe based condenser
1	Effectiveness	55 %	0.99 %
2	Heat transfer rate	15 kW/m^2	85 kW/m^2
3	ΔE_{ex} = Quantity of Exergy	11,761 kW	5963 kW
4	Operating and Maintenance	19,200 tubes are to be handled	9025 tubes are to handled

8. Conclusions

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

Nomenclature

English	
A	cross sectional area, m^2
C	Heat Capacity
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},
Psys	system pressure, N. m^{-2}
Q	Steam Load
r	radius, m
S	Specific heat
U	Heat transfer coefficient
Greek symbols	
μ	dynamic viscosity, N,s. m^{-2}
ρ	density, kg.m^{-3}
σ	surface tension of liquid, N.m-1
ε	Effectiveness
σ	Destruction in Exergy
Subscripts	
g	gas phase
l	liquid phase
TP	two-phase
p	constant pressure
L	coupling liquid
o	overall

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References

[1] S. Seshan and D. Vijayalakshmi," Heat Pipes- concepts, Materials, and Applications" Energy MANAGEMENT, Vol 26, 1986.

[2] Heat Pipes, Second Edition, P. Dunn and D. A. Reay, Pergamon Press.

[3] Amir Faghri "Heat Pipe Science and Technology" Taylor and Francis, Washngton Dc, USA, 1995.

[4] Heat Pipe Waste Heat Recovery by D. A. Littwin, J. M. C. Curley Journal of Heat Recovery System, Elseveir Vol 1, Issue 4, 1981, Page: 339-348.

[5] Vasiliev L. L., Grakovich P., Khrustalev D. K., Kiselev V. G., Matveev Yu. (1984) Heat pipes and heat pipe exchangers for heat recovery systems, *Journal of Heat Recovery Systems*, Vol. 4, Iss. 4, pp. 227-233.

[6] Hong Z, Jun Zhuang: Research, Development and Industrial Application of Heat Pipe Technology in China, Applied Thermal Engineering, 2003, 23, 9, 1067-1083.

[7] L Vasiliev, Review "Heat Pipes in modern Heat Exchangers, Applied Thermal Engineering 25 (2005) 1-19.

[8] Steam condensation by Heat Pipes, Journal of Physics, conference series, 1473 (2020) 012028 doi. 10.1088/1742-6596/1473/1/012028.

[9] T. Mallikharjuna Rao and S. S. Rao: Retrofitting of power plant condensers with heat pipe heat exchanger: A case STUDY by *VIII Minsk International Seminar "Heat Pipes, Heat Pumps, Refrigerators, Power Sources", Minsk, Belarus, September 12–15, 2011.*

[10] Compact Heat Exchangers by Kays and London, Mc Graw Hill Book Company.

[11] Azad, E, “A design procedure for gravity assisted heat pipe heat exchanger, Journal of heat recovery system, 1984.

[12] Antun Galovic, Marija Zivic and Mato Kokanovic: Analysis of Exergy Destruction of an Evaporator or/and a Condenser Published in Strojarstvo 51 (1) 73-78 2000, ISSN 056201887.