Steam condensation by heat pipes

T Mallikharjuna Rao[1], S Srinivasa Rao[2]

[1]Central Power Research Institute, Bangalore, India

[2] National Institute of Technology, Warangal, India, sneni@nitw.ac.in

E-mail: tmrao@cpri.in

Abstract. The present paper describes the usage of heat pipes for phase transformation of steam that is steam condensation. The application of heat pipes were reviewed and it is found that heat pipes were never explored for steam condensation since its inception. Hence, a heat pipe had been designed for condensation purpose and the features of this designed heat pipe like, material of construction, length, and diameter were presented. The thermodynamic limits of the designed heat pipe were calculated theoretically. Practical results of experiments were also presented.

1. Introduction

March Perkins and his son Loftus Perkin introduced the heat transfer device called “Perkin Tube” was the initial model of heat pipe. Later in 1942, R.S. Gaugler [1] and in 1963 Geroge Grover [2] independently patented the heat transfer device and named as Heat Pipe.

The heat pipe is a sealed metal tube consisting of a condensable working fluid. If heat is added at one end of the pipe, the working fluid in the pipe absorbs the heat energy and get converted into vapour and travels to cooler end of the pipe. At this end the vapour releases heat energy to surrounding fluid around the pipe and will be condense back to the liquid state which will reach back to initial position. The cycle repeats till the higher heat energy available at one end and cooling liquid available at other end. The movement of condensable liquid will be through a wick, if pipe is horizontal or tilted position and through gravity if pipe is in vertical position. The portion of heat pipe, where heat will be absorbed is called evaporator section and the portion of heat pipe where heat will be released is called condenser section. The portion of pipe where no heat exchanges takes place is called adiabatic section.

2. Literature Review

After the work of Grover, the heat transfer community started usage of heat pipe in different applications. D.A. Reay and P.Dunn [3] described different application heat pipe in the areas of space craft, chemical reactors etc. The heat pipe based heat exchanger applications were discussed by Amir Faghri [4] in his book .The latest applications of heat pipes for heat exchangers and electronic industry was reviewed by Vasiliev L.L [5],[6]. F.Yang ,X.G.Yuan [7] explored usage of heat pipe heat exchangers for recovery of waste heat energy from automobiles. Hong Zhang, Jun Zhuang [8] reported the research & development and industrial applications of heat pipes in china. But however the usage of heat pipes for steam condensation is not explored.

3. Development of wickless heat pipe for steam condensation

As stated above, the heat transfer community have not explored possibility of steam condensation by the heat pipes, in spite of excellent heat transfer capabilities of heat pipes. The author of this paper made an attempt to design a wickless heat pipe and conducted experiments on the designed heat pipes to demonstrate the capability of heat pipes for steam condensation.

3.1 Concept of steam condensation using heat pipe

The pressure inside the heat pipe is fixed, such that, the working fluid inside the heat pipe absorbs the heat energy from steam incidents on evaporator section and get converted into the vapour. Then the vapour travels to condenser section of heat pipe and releases the absorbed heat energy to a cooling fluid present around the condenser section of heat pipe. The quantity of working fluid, pressure inside the heat pipe, diameter and length of heat pipe are dependent on steam and cooling fluid parameters.

In this paper , the heat pipe was designed to condense the steam at a temperature of 46˚C and cooling water at a temperature of 26 ˚ C. The steam parameters chosen were similar to turbine exhaust conditions of steam in a steam power plant. Now this designed heat pipe will be experimented for its capability for steam condensation. The heat pipe assumed to handle a thermal load of 30 kW.

4. Development of experimental set up for steam condensation.

To accomplish the objectives set forth in the previous paragraph, an experimental set-up was developed. The experimental facility was established in the Central Power Research Institute, India. The following sections presents the detailed description of the experimental setup used to prove the functionality of Heat pipes towards condensation.

4.1 Experimental Test Facility

The heat pipe has to condense the steam whose parameters will be similar to the inlet conditions of the steam power plant condenser that is, turbine exhaust of steam power plant. The working fluid of heat pipe, required to pick up the heat from steam of temperature 46 ° C. Based on these requirements, the dimensions of the heat pipe was designed. The details of designed heat pipe were presented in Table 1 and schematically depicted in Fig1.

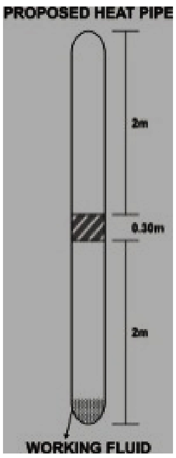

Figure 1. Proposed Heat Pipe

4.2. Thermodynamic Parameters of the Designed Heat Pipe

Distilled water chosen as working fluid and compatible material for this cooper.

Aspect Ratio (AR) = $L_e / d_i = 2/0.0497 = 40.24 \approx 40$ --- (1)

4.2.1 Calculation for the working Fluid inventory. It is decided to design the heat pipe such that, thermal Load on each heat pipe = 30 kW

According to ref [4] , the quantity of working fluid, V_t, was calculated as below.

$$V_t = [\ 0.8x(L_c + L_e) + L_a\ ]\ [\ 3Q_1\mu_l (\pi\ d_i)^2 / \rho_l^2 g h_{fg}\ ]^{1/3} = 1.4x\ 10^{-4}\ m^3$$

The safety factor proposed was 7.865 . accordingly the working fluid will be,

$$= 1.4x\ 10^{-4}\ x\ 7.865 = 1.1011\ x\ 10^{-3}\ m^3$$

The Filling Ratio (FR) = Volume of the Working Fluid / Volume of the Evaporator section

$$= 4\ x\ 1.1011\ x\ 10^{-3} / \pi\ (0.0497)^2\ x\ 2 = 0.28 \text{ or } 28\ \% \quad \text{--- (2)}$$

4.2.2 BOILING LIMIT. The highest heat transfer quantity, Q_2, from boiling point of view, will be {According to Gorbis, Z. R & Savchenkov , G.A (1976)}

$$Q_2 = Ku\ \{ h_{fg}\ \rho_v^{0.5}[\sigma\ g\ (\rho_l - \rho_v)]^{0.25}\}$$

Where , $Ku = 0.0093\ (AR)^{-1.1}[d_i/L_e]^{-0.88}\ (FR)^{-0.74}(1 + 0.03\ Bo)^2$

Bo = Bond Number,

$= 0.0497\ \{9.81 \times (992- 0.05)/69.6 \times 10^{-3}\}^{1/2}$

$= 18.6$

Hence, $Q2 = Ku\ \{ h_{fg}\ \rho_v^{0.5}[\sigma\ g\ (\rho_l - \rho_v)]^{0.25}\}$

$= 0.026\{2408 \times 10^3 \times 0.05^{0.5}[69.6 \times 10^{-3} \times 9.81\ (992- 0.05)]^{0.25}\}$

$= 71417.86\ W \approx 71\ kW$ --- (3)

4.2.3 Flooding limit.

According to ref [4], the highest transfer Quantity, from the flooding point of view, Q_3 will be given as,

$$Q_3 = K\ h_{fg}A_{cross}[g\sigma(\rho_l - \rho_v)]^{0.25} \times [\ \rho_v^{-1/4} + \ \rho_l^{-1/4}]^{-1/2}$$

Now $K = [\rho_l / \rho_v]^{0.14}\tanh^2 (Bo)^{1/4}$

$K = 4 \times 0.942 = 3.77$

And $Q_3 = 3.77 \times 2408000 \times 1.94 \times 10^{-3} \times 5.10 \times 0.66 = 59.3$ kW --- (4)

Summarizing the above results in a Table 2.

Table 1. Experimental setup specifications

Sl. No	Components	Specifications
1	Heat Pipe	Material is Copper L = 4.3 m d_o = 0.0540 m d_i = 0.0497 m Tube is 'K' type Nominal Standard Size t = 2.1082 x 10-3 m Vacuum inside heat pipe = 0.07 bar
2	Steam and Cooling Jacket	1. For the experiments with hot water, the evaporator and condenser portions were covered by 100 mm PVC pipes which will act like jackets. 2. For the experiments with the steam, evaporator and condenser portions were covered by GI pipe of 100 m OD which will act like jackets.
3	Boiler for Steam Supply	The boiler for the experiments was fabricated by M/s. Joyes Engineering with multiple heaters of 40 kW capacity with standard accessories. The system is also fitted with super heater capacity and throttling device.
4	Temperature indicator	Digital type thermometer used in the experiment. The temperature indicators are of range from 0- 300 Deg. C. These thermometers were well calibrated.
5	Flow Meter	Flow meters are used for the experiments. But however the condensate quantity measured using standard laboratory measuring flasks.
6	Measuring Beaker	1000 ml beaker used.
7	Clamp tester	Standard clamp tester (200 Amp and 440 V) was used to measure current and voltage input to the boiler.

Journal of Physics: Conference Series **1473** (2020) 012028 doi:10.1088/1742-6596/1473/1/012028

Table 2. Comparison of thermodynamic parameters

Sl. No.	Parameters	Assumed Heat Pipe capacity	Designed Heat pipes characteristics as per different calculations
A	Highest heat transfer from the view of Boiling .	30 kW	71 kW from (3)
B	Highest heat transfer limit from the view of Flooding	30kW	59.3 kW from (4)

The Heat pipe with above design details were fabricated by M/s. THERMOSYS HEAT PIPE MANUFACTURERS, Vadodara, Gujarat – 390 010, India. The photograph of the fabricated heat pipe was shown in Fig .2

Fig 2 Fabricated heat pipes

4.3 Designing and fabricating the steam generator required for the experiments

The steam generator required for the experiment was designed as below. The line diagram of steam generator and actual photograph is shown in Fig 3.3. The boiler is fitted with 4 x 3 kW heaters and also 3 x 9 kW heaters so that energy input can be varied according to requirement. All the heaters are electrically controlled. The boiler also fitted with a fine mesh screen so that the liquid droplet will be screened down. The Fitting of heaters into the condenser also shown in Figure 3.

Figure 3. Line diagram of steam generator and different stages of fabrication

5. Experiments and Discussion of Results

5.1Experimental set up for Experiments with hot water

The line diagram and actual photograph of the experimental set up is presented in Figure 4. The evaporator was enclosed with a jacket (made of PVC pipe) which acts like hot water jacket. This jacket is provided with two openings, one for hot water inlet and other for hot water outlet. The temperatures of hot water at inlet and outlet were measured at these points with the help of digital thermometers. The condenser portion of the heat pipe was enclosed with another jacket which acts like a cooling water jacket. This jacket was also having two openings, one for cooling water inlet and other for cooling water outlet. The inlet and outlet temperatures were measured with digital thermometers at these openings. The middle portion of the heat pipe was insulated.

The portion of heat pipe enclosed with hot water jacket acts as evaporator and the portion which is enclosed by cold water jacket as condenser of the heat pipe. The middle portion of the pipe is insulated and it acts like adiabatic section.

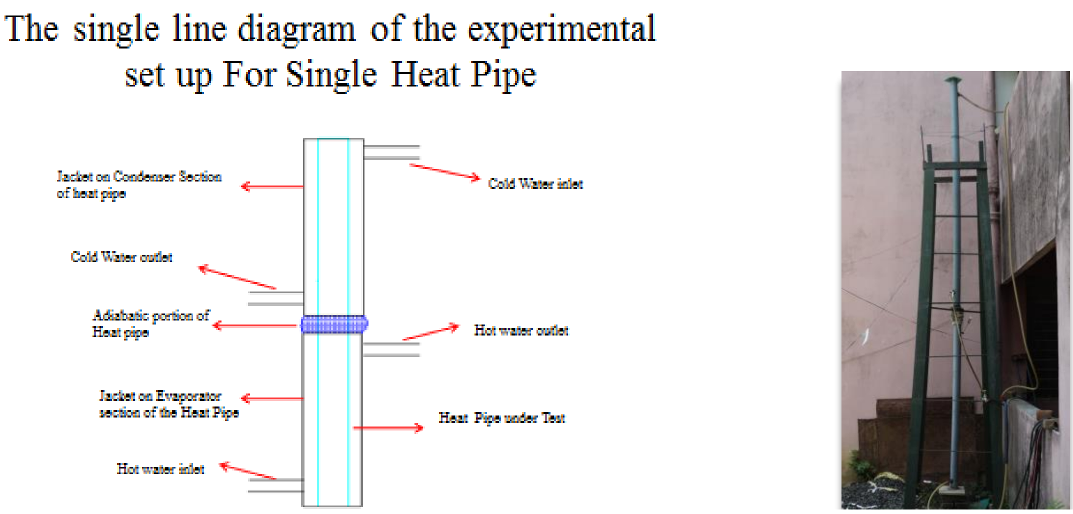

Figure 4. Line diagram and experimental set up for experiments with hot water

5.1.1 Hot Water Experiments with single heat pipe. Water heated to different temperatures is allowed to enter hot water jacket from bottom opening and this water exited from top opening of the hot water jacket. Cold water is allowed to enter the cold water jacket bottom opening and allowed to exit from the top opening. The inlet and out let temperatures are measured with the digital thermometers implanted at the inlet and outlet openings. Flow meters were fixed in the hot and cold water line to measure the quantity of hot and cold water supplied to the heat pipe. The readings were noted after steady state established. Number of trial were conducted on this experimental set up using hot water at different temperatures and energy transported by the heat pipe was determined and presented in Table 3. The performance of the heat pipe with hot water experiments was presented in the Figure 5.

Heat Balance, considering a typical reading,

Hot fluid quantity = 6.19 lit/min = 0.103 kg /sec ,
T_1 = Hot fluid inlet temperature = 53.26 ^{0} C
T_2 = Hot fluid outlet temperature = 42.49 ^{0} C ,

Heat energy supplied to the heat pipe = 0.103 x 4.180 x (10.77) = 4.64 kJ/sec

This is amount of energy transported by heat pipe to the cold fluid.

Cold fluid quantity = 6.56 lit/min = 0.109 kg/sec,
T_3 = Cooling water inlet temperature = 25.79 ^{0} C
T_4 = Cooling water outlet temperature = 35.55 ^{0} C
Heat energy gained by cooling water = Heat energy supplied by the heat pipe
= 0.109 x 4.180 x (9.76) = 4.45 kJ/sec

The above experiment informs the heat energy supplied to heat pipe being transported to the cold fluid with an efficiency of 96 %.

Hence it can be concluded the designed heat pipe is working satisfactorily.

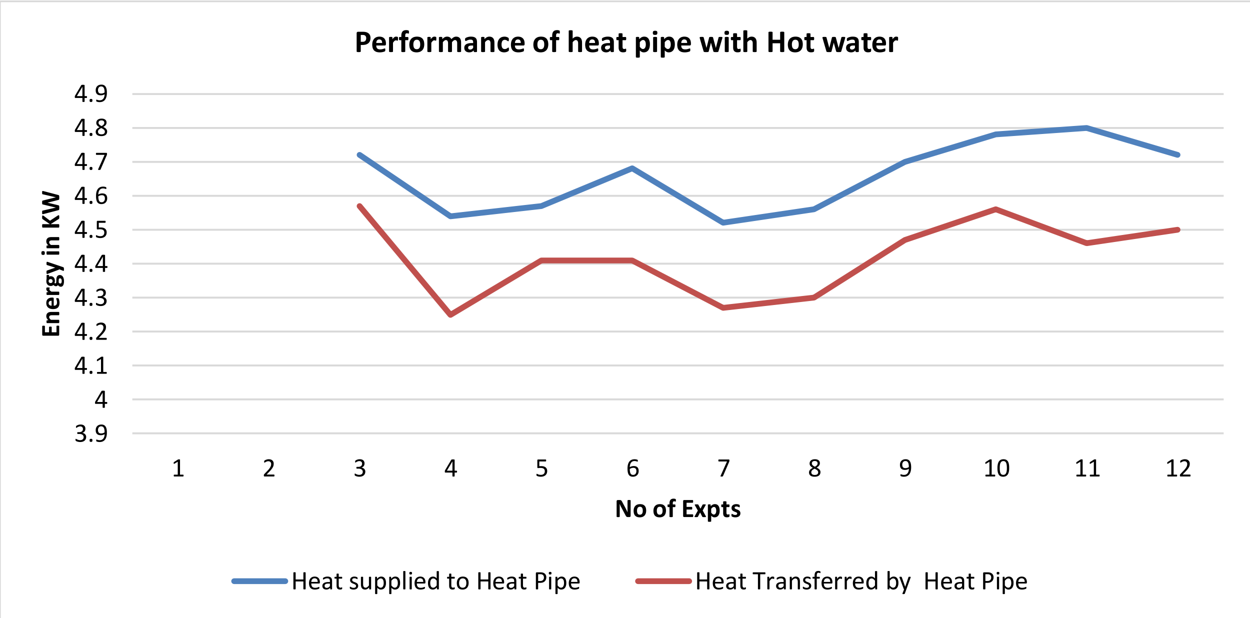

Figure 5. Graph showing the performance of heat pipe with hot water

5.1.2 Discussion of Results. The above experiments and calculations proves that the designed heat pipe can transport the energy successfully. The performance is consistent over the entire range of experimental values. Hence it is decided to two conduct two phase experiments on this heat pipe to test the capability of heat pipe for steam condensation.

5.2 Experimental Set up for Experiments with steam

The line diagram and actual photograph of the experimental set up is presented in Figure 6.The heat pipe lower portion was enclosed with a jacket of GI pipe in which steam was injected for condensation purposes. Top portion was 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 was enclosed by cold water jacket as condenser of the heat pipe. The inlet and out let temperatures were measured with the digital thermometers implanted at the inlet and outlet openings.

Steam with different temperatures was allowed to enter steam jacket from opening and allowed for condensation. The condensate will be exited from provided tap. Cold water allowed to enter the cold water jacket bottom opening and allowed to exit from the top opening. The inlet and out let temperatures were measured with the digital thermometers implanted at the inlet and outlet openings. The boiler operated with 39 kW heaters. After reaching the steady state conditions, the readings were noted.

Figure 6. The line diagram and actual photograph of the experimental set up

5.2.1 Steam experiments with the single heat pipe. Steam with different temperatures is allowed to enter steam jacket from opening and this steam is condensed and condensate is collected from tap provided. Cold water allowed to enter the cold water jacket bottom opening and allowed to exit from the top opening. The inlet and out let temperatures are measured with the digital thermometers implanted at the inlet and outlet openings.

The boiler is operated with 39 kW heaters. After reaching the steady state conditions, the readings were taken and presented in Table. The flow of Condensate is shown in Figure7. Number of trial were conducted on this experimental set up using steam at different temperatures and energy transported by the heat pipe was determined and presented in Table 4. The performance of the heat pipe with hot water experiments was presented in the Fig 8.

Figure 7. The flow of condensate as a result of steam condensation

Heat Balance, considering a typical reading,

Steam inlet temperature = 105 ^{0}C ,
Steam inlet pressure = 1.2 bar
Collected condensate temperature = 104 ^{0}C ,
Heat energy supplied to the heat pipe = 29.3 kW
This energy being transported by heat pipe to the cooling water.
Cooling water quantity = 35 lit/min = 0.583 kg/sec
Cooling water inlet temperature = 22.5 0 C , Cooling water outlet temperature = 32.1 ^{0}C
Heat energy transported by the heat pipe to the cooling water = 23.41 kW
Heat Energy carried out by condensate = 5.7 kW
Unaccounted heat energy loss or heat energy lost to surrounding = 0.19 kW

The performance of the heat pipe with steam can be represented in the Figure 8.

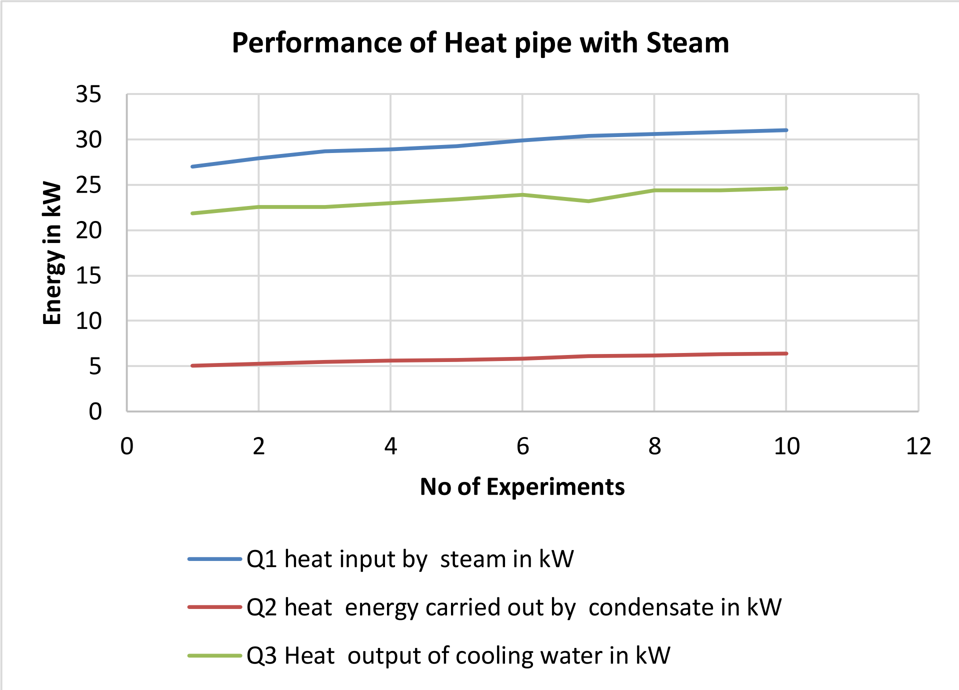

Figure 8. Graph showing the performance of heat pipe with steam

5.3 Results and Discussion

The typical calculations and Figure 8 proves that heat pipe can condense the steam successfully. The performance is consistent over the entire range of experimental values.

6. Conclusions

The heat pipes can used for steam condensation purpose. The concept was proved with help of a heat pipe which was designed and fabricated in the laboratory for the purposed of steam condensation. The experiments carried over the heat pipe also proves that the efficiency of heat energy transportation was reasonably high.

Acknowledgments

The authors would like to thank M/s. Central Power Research Institute for sponsoring the experimental expenditure and also according permission to publish this paper.

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Nomenclature

English

A	cross sectional area, m^2
C	Heat Capacity
d	diameter, m
g	gravitational acceleration, $m.s^{-2}$
H	height, m
h	enthalpy
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
T	Temperature
t	thickness
U	Heat transfer coefficient
V	volume

Greek symbols

μ	dynamic viscosity, N,s. m-2
ρ	density, kg.m-3
σ	surface tension of liquid, N.m-1
ε	Effectiveness
α	Destruction in Exergy

Subscripts

g	gas phase
l	liquid phase
TP	two-phase
p	constant pressure
L	coupling liquid
o	outside
i	inside
t	total
c	condenser
e	evaporator
a	adiabatic

Table 3.

Exp. No.	**Hot Fluid temp in °C**				**Cold Fluid temp in °C**				**kW**		
	T_1	T_2	ΔT_H	Quantity in lit /min	T_3	T_4	ΔT_C	Quantity in lit/min	**Energy supplied to Heat Pipe**	**Energy Transferred by Heat Pipe**	**Difference or Un accountable energy loss**
1	66.4	56.0	10.4	6.5	26.8	36.9	10.1	6.5	4.72	4.57	0.15
2	57.4	47.4	10.0	6.5	26.8	35.5	8.7	7.0	4.54	4.25	0.29
3	56.8	45.5	11.3	5.8	22.3	32.5	10.2	6.2	4.57	4.41	0.16
4	56.5	45.5	11.0	6.1	22.4	32.5	10.1	6.5	4.68	4.41	0.27
5	56.3	45.5	10.8	6.0	22.3	32.5	10.2	6.0	4.52	4.27	0.25
6	54.9	44.0	10.9	6.0	26.5	37.0	10.5	6.1	4.56	4.30	0.26
7	49.8	39.1	10.7	6.3	22.8	32.5	9.7	6.6	4.70	4.47	0.23
8	49.4	38.0	11.4	6.0	22.8	32.0	9.2	7.1	4.78	4.56	0.22
9	43.0	31.9	11.1	6.2	22.6	32.0	9.4	6.8	4.8	4.46	0.34
10	42.1	32.0	10.1	6.5	22.6	32.1	9.5	6.8	4.72	4.50	0.22

Table 4.

Sl. No	$\dot{M}_{condensate}$ Lit/min	T_1 of Condensate in ^oC	T_2 of steam inlet in ^oC	P of steam inlet in bar	$\dot{m}$ of cooling water in lit/min	T_3 of inlet cooling water ^oC	T_4 of outlet cooling water ^oC	Q_1 heat input of condensate in kW	Q_2 heat energy carried out by condensate in kW	Q_3 Heat output of cooling water in kW	Difference of heat input and output in kW $(Q_1-\{Q_2+Q_3\})$
1	0.760	42.5	44	0.09	33	22.5	32.0	29.659	2.32	21.84	5.50
2	0.762	43.0	44	0.09	33	22.5	32.3	29.810	2.34	22.53	4.94
3	0.769	43.5	44	0.09	33	22.5	32.3	30.096	2.36	22.53	5.21
4	0.775	43.8	44	0.09	33	22.5	33.0	30.360	2.37	24.14	3.85
5	0.782	45.3	46	0.10	35	22.5	32.8	30.734	2.50	25.11	3.13
6	0.789	47.5	48	0.11	35	22.5	33.0	31.020	2.64	25.60	2.78
7	0.792	49.4	50	0.12	35	21.0	31.5	31.306	2.76	25.60	2.95
8	0.794	51.6	52	0.13	35	21.0	32.0	31.592	2.87	26.82	1.90
9	0.796	52.6	53	0.14	35	21.0	31.5	31.700	2.92	25.60	3.18
10	0.800	52.8	53	0.14	35	21.0	32.0	31.850	2.93	26.82	2.10