Off-Design of a Steam Condenser in a Mathematical Model

MSK Chaitanya[1], K Srinivasarao[2], CH Pramod baba[3]

Mechanical Department, KL University, A.P, India

saikrishnachaitanyam@gmail.com
ksrao_me@klunivesity.in
pramodklc@gmail.com

Abstract: ***This project deals with the mathematical model of a steam condenser in changed conditions. In this paper we discuss about the list of parameters at which the water temperature from the steam condenser at the outlet depends was selected and by means of Buckinghamπ theorem a functional was obtained between two dimensionless quantities .The form of a function which is exact was determined from the characteristics of a steam condenser for a 200 MW power plant on the basis of data and the actual measurement data of a condenser which is different operating in a 200 MW power plant .So a linear relation is obtained between two dimensionless quantities .Then compare the calculated temperature from the proposed relation and the measured relation .After comparing the exactness and the correctness of the proposed relation is examined.***

Keywords: condenser, heat exchanger, off-design.

1. Introduction

The condensation of a steam occurs in a steam condenser which is a heat engine. From the turbine of the steam condenser, the wet steam (close to saturation) is directed. This wet steam flows through the outer side of the tubes and gives away the amount of heat i.e. condenses to the cooling water flowing inside the tubes. The water used as cooling water is usually from the natural water source like the seas, rivers etc. In a 200 MW power plant the location of the steam condenses with the accepted symbols of the heat transfer fluids as shown in figure 1.

The low source of heat which is a condenser plays a special role in a power plant, because the work parameters have a significant impact on the efficiency of installation. So, it is necessary to recognize the condenser operating parameters during the design and as well as the operation. Due to this purpose the mathematical models explaining the work of the condenser are created in the changed conditions.

The well-known mathematical model for a steam condenser is based on energy balance equation and Peclet's law {1,2} in changed conditions , which is completed with the overall heat transfer coefficient as constant or a function of the heat coefficients for both heat transfer fluids .

$$\dot{Q} = \dot{m}_h r = \dot{C}_c (T_{c2} - T_{c1}) \qquad (1)$$

$$\dot{Q} = kA \triangle T_{ln} \qquad (2)$$

The coefficients of heat transfer depend on dimensionless quantities such as the Prandtl number and the prandtl number. Approximate relations for heat transfer coefficients are used within relevant ranges of parameter changes {3} and are not always accurate {4}.

The equations 1 and 2 are rearranged and the work of the steam condenser can be described by using the heat transfer effectiveness {5 and 6} in changed conditions.

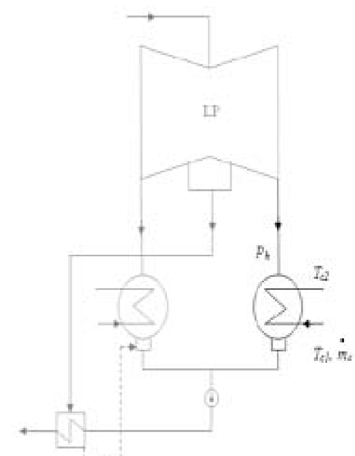

Figure 1: Location of a analyzed steam condenser in a 200MW power plant with accepted symbols.

$$\varepsilon = \frac{T_{c2} - T_{c1}}{T_{h1} - T_{c1}} = 1 - exp\left(-\frac{kA}{\dot{C}_c}\right) \qquad (3)$$

When analyzing the parameters on which the heat transfer coefficient depends in the relation 3 , Beckman proposed an approximate formula for the steam condenser for the heat transfer effectiveness with reference conditions in the following form {7 , 8}.

$$\frac{\varepsilon}{\varepsilon_o} = \left(\frac{T_{h1}}{T_{h1o}}\right)^{\alpha 1}\left(\frac{T_{c1}}{T_{c1o}}\right)^{\alpha 2}\left(\frac{\dot{m}_h}{\dot{m}_{ho}}\right)^{\alpha 3}\left(\frac{\dot{m}_c}{\dot{m}_{co}}\right)^{\alpha 4} \qquad (4)$$

The coefficients α_1, α_2, α_3, α_4 are calculated based on the measured data. When the parameters do not vary over a wide range the approximated relation proposed by Beckman works well for the steam condenser in the changed conditions. The aim of this paper is to create a simpler approximate relation, describing the work of the steam condenser in a changed conditions based on the measured parameters. For this purpose the Buckingham π theorem is used.

2. A Mathematical Model

This paper analyzes the steam condenser for a 200 MW power plant. In the analyzed steam condenser the following parameters measured are;

Water temperature at the inlet – (T_{c1}) and the outlet temperature of steam condenser is - (T_{c2}) , the cooling water mass flow - $(\dot{m}_c)$
and vapor pressure - (p_h)

The paper attains to obtain the functional relation describing the work of steam condenser in changed conditions only using the measured parameters.

The analysis of the (1 , 2) relations show that the water temperature at the outlet of the steam condenser depends on the temperatures at the inlet of both the fluids , the heat capacity of the cooling water , the overall heat transfer coefficient (k) and the heat transfer surface area (A) .

$$T_{c2} = f\left(T_{h1},\, T_{c1},\, \dot{C}_c,\, k,\, A\right) \qquad (5)$$

The capacity of the cooling water equals to the product of the specific heat at constant pressure and the mass flow . Assuming that the physcial properties of the cooling water , in the analyzed range of parameters , are constant , the heat capacity is only a function of mass flow .

$$\dot{C}_c = c_{pc}\dot{m}_c = f\left(\dot{m}_c\right) \qquad (6)$$

We turn now to the parameters on which the overall heat transfer coefficient depends in our case . The overall heat transfer coefficint (k) is a function of heat transfer coefficients fo both fluids (α□ , α□) and wall thickness (δ) and wall thermal conductivity (λ) . In oder to simplify the analysis , the overall heat transfer coefficient for the flat wall was adopted {9} .

$$\frac{1}{k} = \frac{1}{\alpha_h} + \frac{\delta}{\lambda} + \frac{1}{\alpha_c} \qquad (7)$$

The heat transfer coefficient from the water side is a fuction of the cooling water mass flow and can be written as follows {3 , 10 , 11} .

$$\alpha_c = \frac{Nu_c\lambda_c}{d_i} = \frac{\lambda_c}{d_i}0.021Re_c^{0.8}Pr_c^{0.43} = C_c\dot{m}_c^{0.8} = f\left(\dot{m}_c\right) \qquad (8)$$

Where constant C_c is equal .

$$C_c = \frac{\lambda_c}{d_i}0.021\frac{d_i}{\eta_c}Pr^{0.43} \qquad (9)$$

The heat transfer coefficient from the steam side can be written as {6 , 11} .

$$\alpha_h = \left[\frac{\left(\rho_{con} - \rho_v\right) g\lambda_{con}^3 r}{n\nu_{con}\left(T_s - T_{wcon}\right) d_o}\right]^{\frac{1}{4}} \qquad (10)$$

The temperature of saturation (T_s) which is in the formula (10) is a function of measured steam pressure $T_s = f\left(p_h\right)$.

Likewise latent heat (r) is the steam pressure function $r = f\left(p_h\right)$. Assuming that the other physical parameters of the steam change over the small range , the heat transfer coefficient from the steam side can be written as

$$\alpha_h = f\left(p_h,\, g\right) \qquad (11)$$

Hence the overall heat transfer coefficient can be written as the function of the following parameters

$$k = f\left(\dot{m}_c,\, p_h,\, g\right) \qquad (12)$$

Finally the water temperature at the outlet of the steam condenser can be written as

$$T_{c2} - T_{c1} = f\left(T_{h1} - T_{c1},\, \dot{m}_c,\, p_h,\, A,\, g\right) \qquad (13)$$

A difference of temperatures was assumed , since if this is the case it is of importance in which units the temperature is expressed .

A dimensionless analysis may be used for the selected independent parameters . According to the dimensionl analysis it can be written as

$$T_{c2} - T_{c1} = C\left(T_{h1} - T_{c1}\right)^a \left(\dot{m}_c\right)^b p_h^c A^d g^e \qquad (14)$$

The relation (14) is true when the units on the left are equal to units in the right {10} .

$$K^1 = C{\cdot}K^a\left(kg\cdot s^{-1}\right)^b\left(kg\cdot s^{-2}\cdot m^{-1}\right)^c\left(m^2\right)^d\left(m\cdot s^{-2}\right)^e \qquad (15)$$

A comparision of the exponents at the appropriate units gives the following system of equations

[K] 1 = a
[kg] 0 = b+c
[s] 0 = - b - 2c - 2e
[m] 0 = - c + 2d + e

In the analyzed case we have six independent variables (n = 6) and four equations (r = 4) . According to Buckingham's π theorem , the number of dimensionless quantities is two (k = 2) .

The solution of the equation gives

$$a = 1,\; c = -b,\; d = -\frac{3}{4}b,\; e = \frac{b}{2}$$

The solution (14) takes the following form

$$T_{c2} - T_{c1} = C\left(T_{h1} - T_{c1}\right)^1\left(\dot{m}_c\right)^b\left(p_h\right)^{-b}A^{-\frac{3}{4}b}g^{\frac{b}{2}} \quad (16)$$

Arrangement of the expressions with the same exponents gives

$$\frac{T_{c2} - T_{c1}}{T_{h1} - T_{c1}} = C\left(\frac{\dot{m}_c}{p_h}\frac{\sqrt{g}}{A^{\frac{3}{4}}}\right)^b \qquad (17)$$

After the introduction of the two dimensionless quantities we get -

$$\Pi_1 = \frac{T_{c2} - T_{c1}}{T_{h1} - T_{c1}} \quad (18)$$

$$\Pi_2 = \frac{\dot{m}_c}{p_h} \frac{\sqrt{g}}{A^{\frac{3}{4}}} \quad (19)$$

The (14) relation may be eventually written as follows

$$\Pi_1 = f(\Pi_2) \quad (20)$$

On the basis of the conducted analysis a relation was obtained between the two dimensionless quantities in which there are the following measured parameters :

Water temperature at the inlet to the steam condenser (T_{c1}),

cooling water mass flow $(\dot{m}_c)$

and steam pressure (p_h).

The exact form of the function is determined on the basis of the characteristics and measured data for the steam condenser .

3. Results

At first , the relation (20) between two dimensionless quantities was checked using data obtained from the characteristics of the steam condenser for a 200 MW power plant . Table 1 sets out the values ofparameters obtained from characteristics of the steam condenser.

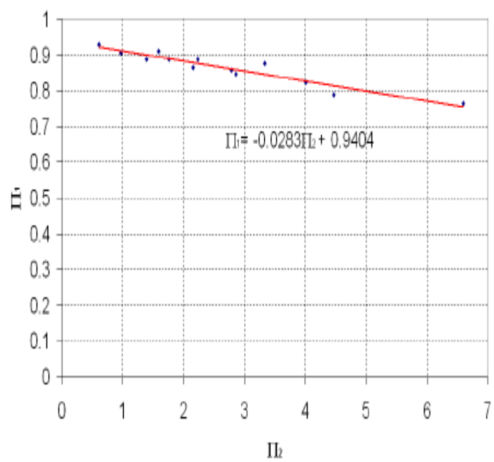

Figure 2: A comparison between two dimensionless quantities.

Two dimensionless quantities were determined based on the data in table 1 and their values are presented in fig.2. On the basics of the data obtained, a linear relation between the dimensionless quantities can be assumed with a good approximation.

With the help of least square method the coefficients in the straight line were determined and the following values were obtained: for the directional coefficient a= -0.0283 and for the intercept coefficient b=0.9404.

The relation between the dimensional quantities can be written as

$$\Pi_1 = -0.0283 \cdot \Pi_2 + 0.9404 \quad (21)$$

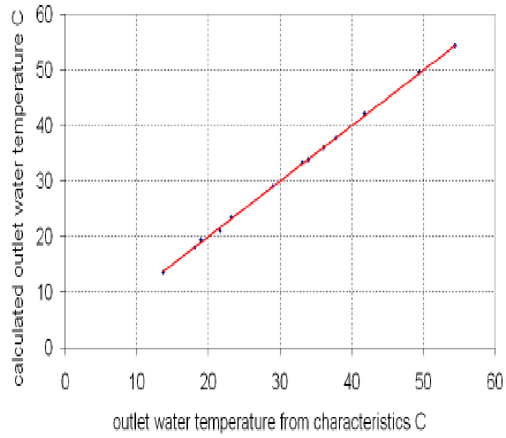

Figure 3: A comparison between water temperature at the outlet of the steam condenser, from the characteristics and calculated (21).

A comparison between the water temperatures at the outlet of the steam condenser obtained from the characteristics and calculated from (21) for 14 values is presented in fig3.

The very good correlation between these two temperatures can be observed.

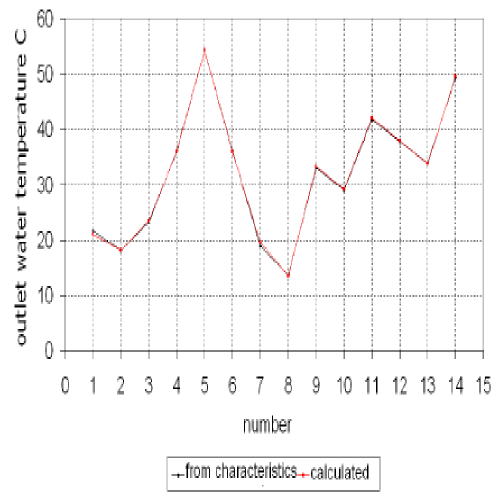

Figure 4: Change in water temperature at the outlet of the steam condenser from the characteristics and calculated.

Fig4 sets out the change in water temperature at the outlet of the steam condenser from the characteristics calculated 14 values. Between these two temperatures in fig4 a very good correspondence may be observed.

After determining the coefficients in (21) relation, the correctness of this formula was checked for the next 11 different values. In table 2 the next 11 parameters from the characteristics of the steam condenser are presented.

The change in water temperature at the outlet of the steam condenser, from characteristics and calculated for the next 11 values, is presented in fig5. The correlation between these two temperatures is very good.

The correctness of 20 relations was checked on the basis of measured data for the steam condenser working in different 200MW power plants. The following measurements of parameters within the steam condenser were made, steam pressure and total mass of the cooling water flowing through the two parts of the steam condenser.

The mass of cooling water flowing through one part of the steam condenser was obtained by dividing the total mass flow of cooling water by two. And the data in the control system were recorded every hour during the operation of the power plant (average value per hour). Two dimensionless quantities based on 100 values at the beginning of the year were calculated.

The comparison between these two dimensionless quantities is present in fig 6. On the basis of the data obtained a linear relation between these two dimensionless quantities can be assumed with a good approximation.

The coefficients in the straight line were determined by the least squares method for 100 measured values were obtained: for the directional coefficient a = - 0.0314 and for intercept coefficient b = 0.7643

The relation between the dimensionless quantities can be written as

$$\Pi_1 = -0.0314 \cdot \Pi_2 + 0.7643 \qquad (22)$$

Table 1: Values of the parameters from the characteristics of the steam condenser

Number	$\dot{m}_h$, kg/s	p_k, kPa	T_{c1}, °C	$T_s(p_k) - T_{c2}$, °C	$\dot{m}_c$, kg/s
1	60	3	4	2.5	3200
2	80	2.5	4	3	3200
3	110	3.5	4	3.5	3200
4	60	6.3	26	1	3200
5	120	16.4	35	1.5	3200
6	60	6.3	26	1	3200
7	110	2.8	4	4	4000
8	70	1.9	4	3	4000
9	120	9	17	2.5	4000
10	90	7.1	17	2	4000
11	120	9	26	2	4000
12	90	7.1	26	1.5	4000
13	60	5.6	26	1	4000
14	110	12.9	35	1.5	4000

Table 2: Values of the parameters from the characteristics of the steam condenser

Number	$\dot{m}_h$, kg/s	p_k, kPa	T_{c1}, °C	$T_s(p_k) - T_{c2}$, °C	$\dot{m}_c$, kg/s
15	110	4.75	17	2.5	4800
16	70	9	35	1	4800
17	80	1.7	4	4	6400
18	40	1.15	4	2	6400
19	120	4.3	17	3	6400
20	100	3.8	17	2.5	6400
21	60	2.95	17	1.5	6400
22	130	7.05	26	2.5	6400
23	80	6.6	26	1.5	6400
24	60	6	30	1	6400
25	130	11	35	2	6400

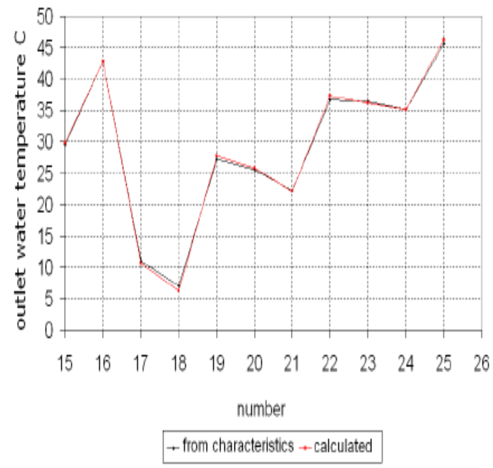

Figure 5: Change in water temperature at the outlet of the steam condenser, from characteristics and calculated for the next 11values

A comparison between the water temperature at the outlet of the steam condenser, measured and calculated from (22), is present in Fig .7.

The good correlation between the calculated and measured temperature can be observed. The change in water temperature at the outlet of the steam condenser, measured and calculated for 100 values at the beginning of the year, is presented in fig.8.

After determining the coefficients in relation (22) measured and calculated temperature at the outlet of the steam condenser for the next 100 values were compared (Fig.9).

The change in water temperature at the outlet of the steam condenser, measured and calculated for 100 values in the middle of the year, is presented in Fig 10.

The change in water at the outlet of the steam condenser, measured and calculated for 100 values at the end of the year, is presented in Fig 11.

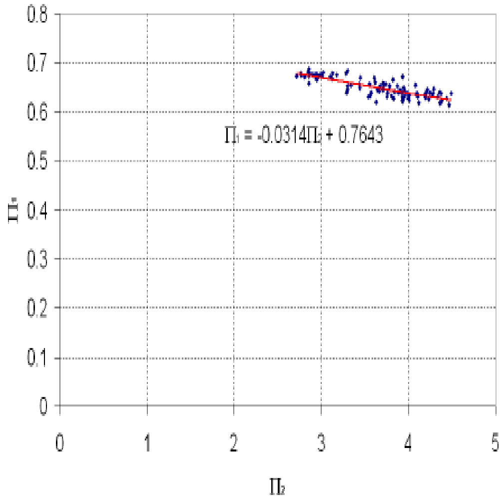

Figure 6: A comparison between two dimensionless quantities (measured data)

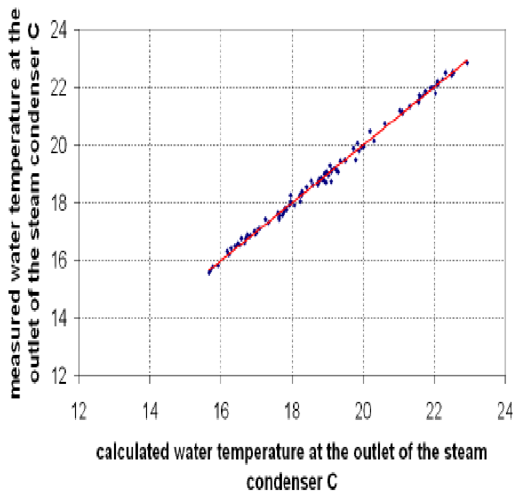

Figure 7: A comparison between water temperatures at the outlet of the steam condenser measured and calculated.

Based on the performed analysis, it appears that the proposed linear relation for the steam condenser in changed conditions is correct. Introducing the concept of heat transfer effectiveness and knowing the constant value of the condenser heat transfer surface and gravity acceleration, the relation which describes the work of the steam condenser in changed conditions can be written as a linear function with two constants.

$$\varepsilon = \frac{T_{c2} - T_{c1}}{T_{h1} - T_{c1}} = D \cdot \frac{\dot{m}_c}{p_h} + E \qquad (23)$$

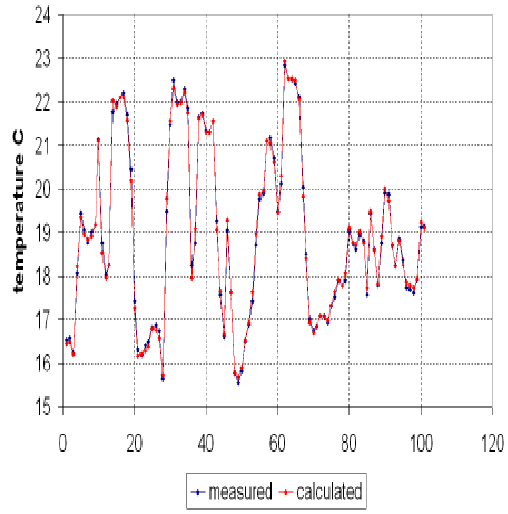

Figure 8: Change in water temperature at the outlet of the steam condenser, measured and calculated for the 100 values at the beginning of the year.

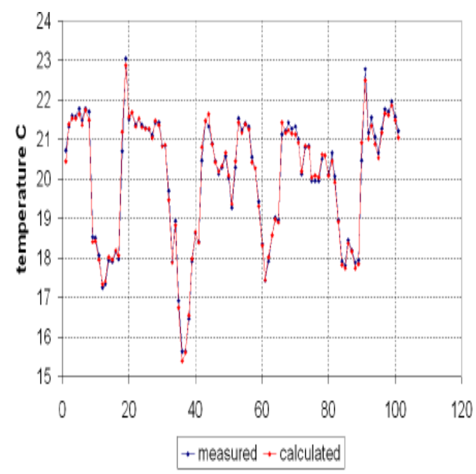

Figure 9: Change in water temperature at the outlet of the steam condenser, measured and calculated for the next 100 values.

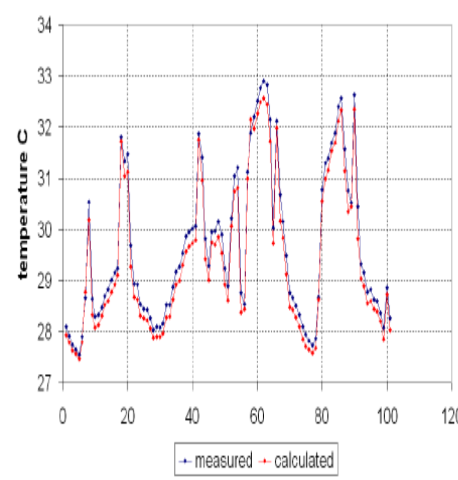

Figure 10: change in water temperature at the outlet of the steam condenser, measured and calculated for 100 values in the middle of the year.

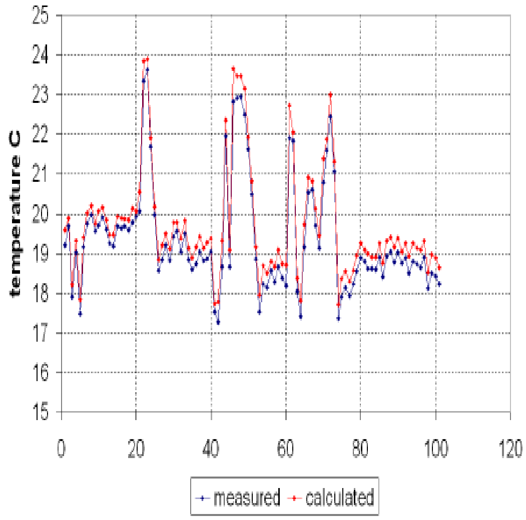

Figure 11: Change in water temperature at the outlet of the steam condenser, measured and calculated for 100 values at the end of the year.

4. Conclusion

This article presents the steam condensers mathematical model in changed conditions. By means of Bucking π theorem a list of independent parameters was selected and two dimensionless quantities were obtained based on the data from the characteristics as well as the actual measurement data for a steam condenser in a 200MW power plant, a linear relation between two dimensionless quantities was obtained. A simple linear relation was obtained which allows one to determine the work of the steam condenser in changed conditions, basic parameters must be known and two coefficients in the linear relation must be determined.

A comparison between measured and calculated water temperature from the proposed linear relation at the outlet of the steam condenser was performed. A very good correspondence was obtained between these two temperatures for both the characteristics of the steam condenser as well as for measured data.

The observed differences between the measured and calculated water temperature at the outlet of the steam condenser from the proposed relation may result from deterioration in working conditions of the steam condenser. Data from the characteristics and actual measurement data are for two different condensers working in different 200MW power plants.

References

[1] Refrigeration and air conditioning by Kurmi.
[2] A. I. Elfeituri, The influence of heat transfer conditions in feed water heaters on the energy losses and the economic effects of a steam power station, Ph.D. thesis, Warsaw University of Technology (1996).
[3] Refrigeration and air conditioning – C.P. Arora
[4] Modern Refrigeration and air conditioning –Andrew D.Althouse
[5] Heat transfer book by R.K.Rajput
[6] Engineering heat transfer –Rathore ,R.Kapuno
[7] Fundamentals of heat and mass transfer [haredcore] Theodore L. Bergman
[8] Introduction to Fluid Mechanics by G.K.Batchelor. Fluid Mechanics by Dr.R.K.Bansal.
[9] Fluid Mechanics by Dr.R.K.Bansal.
[10] A.Grzebielec, A.Rusowicz, Thermal resistance of steam condensation in horizontal tube bundles