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Design of Close Loop Cooling Water System for Khan Khwar Hydro Power Plant

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***Abstract*— Khan Khwar Hydropower Plant has an installed capacity of 72 MW. It started its commercial operation in November 2010, since then it has added 948.528 MWh of electricity to the national grid (as of 30th September 2017). This national asset is facing numerous unnecessary forced shutdowns due to its cooling water system. Currently installed cooling system is once through open loop cooling water system which pumps the water from tailrace, the water in the tailrace causes the problem of clogging due to sediments inside the cooling tubes responsible for the exchanging heat, it also damages pumps by choking them and may contaminate the lubricating oil because of the puncturing of the cooling coils in turn damaging the bearings. The clogs, sludge or fouling contains ion ferrite is believed to originates from the tailrace. This results in unforeseen plant shutdown. Due to above reasons plant management has given this case study for considering switching from once through open loop cooling water system to closed loop cooling water system. Closed loop cooling water system with tubular heat exchanger is considered. During the designing of the heat exchanger Log Mean Temperature Difference LMTD method is used. The scope of this paper is limited to the theories of thermodynamics.**

Key Words : Khan Khwar Hydro Power project (kkhpp) in Pakistan, Cooling Water system, LMTD (log mean temperature difference), Nusselt number (Nu), Prandtl number (Pr), Reynold number (Re)

I. INTRODUCTION

Khan Khwar Hydro Power Plant is in Besham, Shangla district of Pakistan with an installed capacity of 72MW. It has two main units each of them has an installed capacity of 34MW and one auxiliary unit of 4MW. It was constructed by WAPDA through Sino hydro Corporation and Dongfeng Electric Machinery Company Limited. KKHPP consists of RCC type of Dam structure from there a water tunnel is constructed along the right bank of Indus tributary. Water required for the power generation flows through that tunnel to the power house. Both main units generate power through Francis Turbine. The produced power is then transmitted to the National grid.

Fig. 1. KKHPP dam view from upstream

Khan Khwar Hydro power plant is facing severe clogging problems due to its open loop cooling water system. Cooling water is pumped from start of the tail race and discharged back to the end of the tail race after completion of cooling process. The cooling water system is required for the heat removal from bearing oil. The sediments problem not only causing frequent shutdowns but also damages various expensive components., it may also damage pumps by choking them and contaminate cooling oil upon the puncturing of the cooling coils in turn damaging the bearings. This problem is possible to be overcome by introducing a closed loop cooling water system in place of currently working once through cooling water system. This excessive silt problem is not only causing frequent unit breakdowns but also damaging various components associated with cooling water systems. Frequent replacements of these parts are not only expensive but time consuming.

The existing cooling water system pump water from draft tube and utilize for the cooling of different components and

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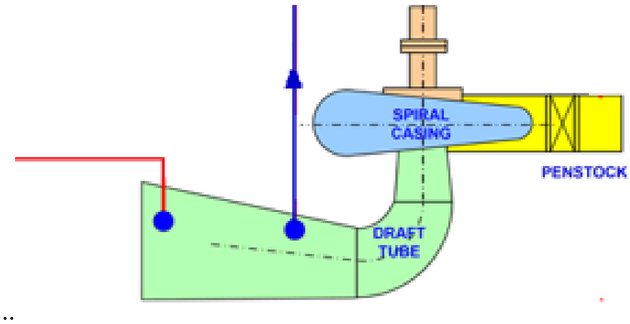

Fig. 2. Currently installed open loop cooling water system

afterwards it discharges that water again in the draft tube. Although this system is appropriate for these type of cooling purposes when there is small range of cooling load but considering the case of Khan Khwar hydro power plant where all the water in the rivers is coming directly from the mountainous region of Shangla district which contains excessive silt because of this open loop is not a good choice to fulfill the given requirement therefore it should be replaced with the system which is much more capable of removing heat effectively and that system is close loop cooling water system with sub merged heat exchanger. Hence the main purpose of this case study is to convert the open loop cooling water system to close loop system.

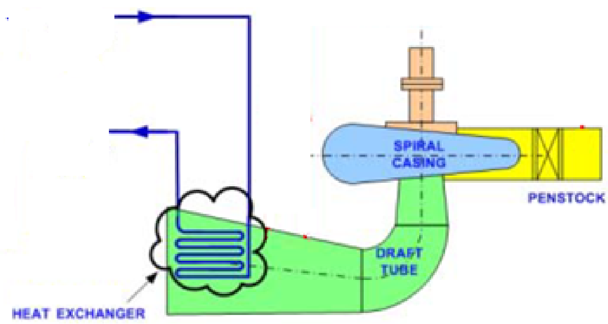

Fig. 3. Designed close loop cooling water system

II. Research Methodology

Review of the existing design was performed and all the necessary calculations regarding the feasibility and design parameters were carried out. In the close loop cooling system water flows in the following coolers to absorb energy with the given amount of flow rate

TABLE I
Cooling water rates in consumers

Thrust and Upper guide bearing	68 m^3/hr
Generator air coolers	165 m^3/hr
Lower guide bearing	17 m^3/hr
Turbine guide bearing	21.6 m^3/hr

Following parameters necessary for the designing of heat exchanger are taken from Khan Khwar Hydropower Plant drawing and operational manuals

- Quantity of water flowing inside the closed-circuit pipe; q_i = 265.6 m^3/h
- Flow velocity inside pipe; V_i=2 m/s
- Temperature of hot water coming out; T_o=33 °C
- Temperature of cold water entering in; T_i=31 °C
- Temperature of Draft Tube water; T_d=12 °C
- Flow velocity inside the tailrace; V_o=1.5 m/s
- Quantity of water flowing inside the tailrace; q_o=16.832 m^3/s

III. Design Calculations

The designing of heat exchanger is carried out step by step firstly the cooling load required is calculated and afterwards suitable material and nominal tube is selected according to the TEMA standards. This procedure is followed by calculating heat transfer coefficient of flow inside and outside of the tube. Next step is to calculate the overall heat transfer coefficient which results in the calculation of number of tubes. In heat exchanger designing selection of nominal tube diameter is carried out by trial method we go through the complete designing procedure with one fixed value of nominal diameter which ultimately effects number of tubes and surface area of heat exchanger and if it is not acceptable then we adopt some other value.

A. Cooling load calculation

Cooling requirement is the amount of heat that is required to be removed from our working/ primary flow or it is the amount of heat which should be removed from water flowing inside different components to ensure the continuous working of system. For flow inside the tube total energy lost by the fluid can be can be expressed in terms of bulk-temperature difference by following equation .

$$Q = m \cdot C_p \cdot \Delta T$$

B. Tube material selection

The material chosen for the designing of heat exchanger must be suitable for the type of physical construction, compatible with expected ranges of fluid temperature, and not corrosive when interacts fluid. Cost is also an important parameter in heat exchanger material selection. According to Tubular Exchanger Manufacturer Association, TEMA, standards tubular heat exchangers can be constructed from a large range of material. Favorite material for the construction of tubular heat exchangers is mild steel unless operating temperature is above 500°C or fluid is highly corrosive to material. [9] Due to above mentioned reason Mild Steel is selected as the material for tubular heat exchanger.

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C. Selection of Nominal tube diameter

Calculations were performed on different sizes, hence when the mild steel tube of 1.5in = 3.8 cm nominal diameter and 1.5m long was selected the required number of tubes were found to be 137. Increased number of tubes leads to the bulky heat exchanger. Since the objective is to design optimum size heat exchanger, 2in mild steel tube is considered. From Annexure A of Jack P. Holman. (2010). Heat Transfer (Tenth ed.). The McGraw-Hill Companies, Inc following values were obtained with respect to 2 in nominal diameter

- Nominal Diameter (D_n) = 2 in
- Outside Diameter (D_o) =2.374in =0.060325 m
- Inside Diameter (D_i) =2.067in = 0.052502 m
- Outer Radius (r_o) = 0.0301625 m
- Inner Radius (r_i) = 0.0262509 m

D. Calculation of heat transfer coefficients

To calculate heat transfer coefficient first Reynold number is calculated which leads to the calculation of Nusselt number and then finally by applying Nusselt number formula in terms of heat transfer coefficient we get the value of convective heat transfer coefficient (h). The above procedure is same for flow inside and outside of the tube

For flow inside tubes

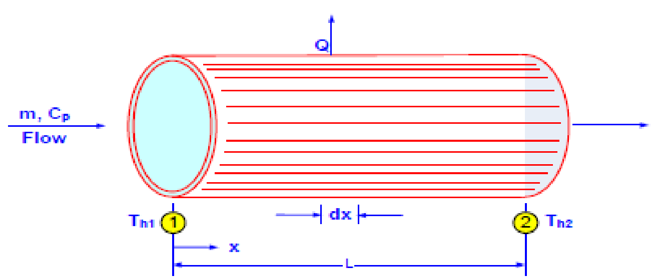

Fig. 4. Flow inside tubes

Reynold number is calculated as follows

$$R_e i = \frac{\rho \cdot V \cdot D_i}{\mu}$$

where, values of density and viscosity are taken at film temperature = 32°C

ρ= density = 996.6 kg/m^3

μ=viscosity = 9.2e-4 m^2/s

V= velocity of flow inside tube = 2 m/s

D_i = diameter = 0.052 m

Now after putting al the values,we get

R_e = 114134.78

values of and are taken at film temperature 32°C. Since $R_e > 4000$. Therefore it can concluded that the flow inside the tube is turbulent and fully developed. Nusselt number for turbulent and fully developed flow can be calculated by Dittus-Boelter equation given as,

$N_u = 0.023 \cdot R_e^{0.8} \cdot P_r^n$

where

R_e = Reynold number = 114134.78

P_r = Prandtl Number= $\frac{\mu \cdot C_p}{k}$ = 6.315

the value of n for cooling case is 3

After putting all the values in above equation Nusselt number calculated N_u = 444.4

Since Nusselt number is the ratio of convective heat transfer coefficient to conductive heat transfer ,

$N_u = \frac{h_i \cdot D_i}{k}$

where

h_i= heat transfer coefficient of fluid flowing inside the tubes

D_i = internal diameter of tubes = 0.052502m

k = conductive heat transfer coefficient = 0.606

h_i = 5154.84 W/ m^2°C

For flow outside the tubes

Now before calculating h_2 lets verify that whether the flow over the tubes is laminar or turbulent. For this calculating R_e number

$$R_e o = \frac{\rho \cdot V_o \cdot D_o}{\mu}$$

where,

V_o = velocity of water flowing in tail race = 1.5 m/s

D_o = outside diameter of tube = 0.060325m

while value of μ and ρ remains same

$R_e o$ = 98355.97

$R_e o > 4000$

Hence the flow over the tubes is turbulent. Now for turbulent and fully developed flow Nusselt number can be calculated from the Churchill and Bernstein equation, this equation is valid for the calculation of Nusselt number for the Reynold number ranging from 20,000 to 400,000 and Prandtl number greater than 0.2.

$$\mathrm{Nu}_d = 0.3 + \frac{0.62\,\mathrm{Re}_d^{1/2}\mathrm{Pr}^{1/3}}{[1+(0.4/\mathrm{Pr})^{2/3}]^{1/4}}\left[1+\left(\frac{\mathrm{Re}_d}{282{,}000}\right)\right]^{1/2}$$

After putting all the values in equation,

$N_u d$ = 550.987 i.e Nusselt number of flow over the tubes

Now by using Nusselt number formula in terms of heat transfer coefficients convective heat transfer of flow over the tubes is calculated (h_o)

$h_o = \frac{N_u d \cdot k}{D_o}$

h_o = 5562.37 W/ m^2°C

Over all heat transfer coefficient

Determining the overall heat transfer coefficient U value is central stage in any heat exchanger design problem. It is the combination of all the convective and conductive heat transfer coefficients. It may be calculated from following formula

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$$U_o = \frac{1}{\frac{r_o}{r_i}\frac{1}{h_i} + \frac{r_o \ln\frac{r_o}{r_i}}{k_{MS}} + \frac{1}{h_o} + f_r}$$

Value of $k_m s$ was found to be 54 W/m°C, similarly value of fr was found from TEMA standards as 0.00009

After putting all the values in the above formula , we get U_o = 2082.194 W/ m^2°C

E. Calculation of Number of tubes

Now to calculate the number of tubes first surface area of heat exchanger is calculated and then by applying area formula number of tubes are calculated. To calculate the area we have two methods LMTD or NTU. Both of these methods are valid but since inlet and outlet temperatures of the fluid flowing through tubes is available and the inlet temperature of the fluid flowing over the tubes also, so LMTD method is used Log mean temperature difference can be calculated by following formula

$$\text{LMTD} = \Delta T_m = \frac{\Delta T_1 - \Delta T_2}{\ln\frac{\Delta T_1}{\Delta T_2}}$$

where, $\Delta T_1 = T_h i - T_c o$
$\Delta T_2 = T_h o - T_c i$
Now to find the value of $T_c o$ using the following formulas

$$T_{Co} = \frac{Q}{\rho\, q_o C_p} + T_{Ci}$$

$$T_{Co} = \frac{625}{996.6 \times 16.832 \times 4.179} + 12$$

$$T_{Co} = 12.009\ ^\circ\text{C}$$

So,

$$\text{LMTD} = \Delta T_m = \frac{(T_{Hi} - T_{Co}) - (T_{Ho} - T_{Ci})}{\ln\frac{T_{Hi} - T_{Co}}{T_{Ho} - T_{Ci}}}$$

$$\text{LMTD} = \Delta T_m = \frac{(33 - 12.009) - (31 - 12)}{\ln\frac{33 - 12.009}{31 - 12}}$$

$$\text{LMTD} = \Delta T_m = 19.978\ ^\circ\text{C}$$

Heat transfer can be calculated as follows
$A_s = \frac{Q}{U \cdot \delta T_m}$
where A_s = surface area
Q = cooling load i.e amount of heat required to be removed from working fluid
U = over all heat transfer coefficient
δT_m = LMTD

By putting all the values we get,
A_s = 15.024 m^2
Now number of tubes can be obtain by simple applying surface area formula
$A_s = \pi \cdot D_o \cdot L \cdot n$
D_o = outer diameter of the tube
L= length of tube which is taken as 1.5 m
where n= no of tubes
$\Rightarrow n = 54$

F. Tube bundle diameter

The diameter of tube bundle for submerged tubular heat exchanger can be calculated from following formula.

$$D_b = D_o \left[\frac{N}{K}\right]^{\frac{1}{n}}$$

where, D_b = tube bundle diameter
while value of n and K can be obtained from TEMA standards with respect to tube arrangement and number of passes. By putting all the values $\Rightarrow = D_b = 0.662m$

G. Tube arrangement

30° Triangular tube arrangement is recommended for the designing of tubular heat exchanger due to its high heat transfer rate. They have high tube density for a given number of tubes thus consume relatively small area. The center to center distance of each tube in triangular tube arrangement is 1.25 time the outer diameter of the tube.
$s = 1.25 \cdot D_o\ s = 7.54cm$

Design Summary

Complete design summery obtained from above calculations is listed below.
Tube material = Mild steel
Tube nominal diameter= 2 in
Tube schedule number = 40
Number of tubes = 54
Length of each tube = 1.5m
Tube pitch = 0.754
Tube arrangement = 30° Triangular
Tube bundle diameter = 0.6m
Inlet and outlet pipe material is Mild steel

IV. Revenue Benefit

The extra revenue which will be generated after the installation of sub-merged heat exchanger is calculated as follows

- The price of one unit sold to the relevant authority is Rs 10
- The total number of shutdowns that the management is facing is approx 5/month.
- The total generation is 68000 KWh

Now if we simply calculate the extra revenue it turns out be
Rs = 5 x 12 x 68000 x 10
$\Rightarrow = Rs = 40,800,000$
or , apprx 0.4mUSD per year

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V. Conclusion

The above calculations show that by installing heat exchanger in the draft tube WAPDA can generate an additional revenue of 0.4m USD also it results in less shutdown and reduces maintenance cost. The above study can be further utilized for the other 74 planned hydro projects in the same region. The scope of this study is not limited to be utilized locally but can also be used in any part of the world to overcome that same problem

APPENDIX

- Table A-11: Jack P. Holman. (2010). Heat Transfer (Tenth ed.). The McGraw-Hill Companies, Inc.
- Table A-9: Jack P. Holman. (2010). Heat Transfer (Tenth ed.). The McGraw-Hill Companies, Inc.
- Table A-2: Jack P. Holman. (2010). Heat Transfer (Tenth ed.). The McGraw-Hill Companies, Inc.

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