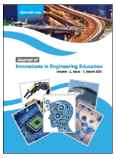

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Design modification of the existing cooling water system of Marsyangdi hydropower station using pipe flow modeling software

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Abstract

Marsyangdi Hydropower Station has adopted the Open Loop Cooling System (also called Once through Cooling System) in which the cooling water extracted from Penstock or the draft tube is circulated throughout the cooling system and discharged back to the draft tube. The water of the Marsyangdi River is muddy and sediment-rich in the rainy season, which causes the choking of tubes of the primary heat exchangers reducing the cooling efficiency and even leading to leakages in the tubes due to erosion. Cleaning and maintenance of the tubes are impossible without dismantling the primary heat exchangers from the Unit assembly. Hence, hours of machine shutdown are required to replace them with new or cleaned ones. A Close Loop Cooling System has been modeled in a Pipe Flow Modification Software, "AFT Fathom," to overcome the issue in the Existing Cooling System. The modified model was run to observe the performance of the modified system at different river water temperatures and increased heat duty in all the heat exchangers. Further, the System Curve was generated considering the effect of the increase in surface roughness of pipelines due to aging. The performance capacity of the modified system was justified considering the obtained results from the simulations. For the limit of the safe temperature of the Turbine guide bearing Oil Cooler, Upper guide bearing Oil Cooler, and Generator Air Cooler on the modified system, the corresponding river water temperature obtained was 27 °C, 28 °C, and 25 °C, which is beyond the available river temperature of 24 °C. Similarly, for the 10 % increment in heat load at all the heat exchangers, the reference temperatures were found to be well below the safe temperature. Further, the consideration of the effect of aging on the surface roughness revealed the requirement of the pumping head of additional 7 m. As the results of the simulation verify the capacity of the modified system to evacuate the required amount of heat, the modification in the existing system can be recommended.

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Abbreviations

NEA	Nepal Electricity Authority
MHPS	Marsyangdi Hydropower Station
HE	Heat Exchanger
INPS	Integrated Nepal Power System
TGB	Turbine Guide Bearing
LGB	Lower Guide Bearing
IEX	Indian Energy Exchange Limited
PHE	Plate Heat Exchanger
SHE	Secondary Heat Exchanger
CWS	Cooling Water System
UGB	Upper Guide Bearing
HE	Heat Exchanger

1. Introduction

Marsyangdi Hydropower Station (MHPS), commissioned in 1989 AD, is a peaking run-off-river type power station, located at Aaboo Khaireni, Tanahun in the Gandaki province with an installed capacity of 69 MW and an annual design generation of 462.5 GWh. The powerhouse consists of three identical vertically aligned generating units with a capacity of 23 MW each. All the units are equipped with Francis Turbine. The generated power is evacuated to INPS (Integrated Nepal Power System) via 132 kV transmission lines. Further, the power generated in this power station is exported to India via India Energy Exchange Limited (IEX). Hence, the continuous and reliable operation of this power station has become necessary.

The generating units use cooling water for the removal of heat generated mainly in bearings due to friction with the rotating shaft and the generator rotor-stator which is heated due to the flow of high current. MHPS has adopted the Open Loop Cooling System (also called Once through Cooling System) in which the cooling water tapped from the Penstock or the draft tube is circulated throughout the cooling system and discharged back to the draft tube. Marsyangdi River is one of the sediment-laden rivers in Nepal [1]. As the water becomes further muddy and sediment-rich in the rainy season, it causes the choking of tubes of the primary heat exchangers reducing the cooling efficiency and even leading to leakages in the tubes due to erosion. Cleaning and maintenance of the tubes are impossible without dismantling the primary heat exchangers from the Unit assembly. Hence, hours of machine shutdown is required to replace them with new or cleaned ones. A one-hour shutdown of a single Unit losses 23000 kW*1 hr=23000 kWh energy* Rs. 9.3= Rs. 2,13,900 of revenue, Rs.9.3 being the average per kWh energy selling price of NEA in the Fiscal Year 2021/22 [2]. Hence, the generation loss due to hours of the shutdown required to replace the heat exchangers as well as the purchasing costs of the new coolers is huge. Apart from these, the chance of damaging other electrical components due to leakage of water from the heat exchangers is always a high risk to the power station. This problem is possibly be overcome by introducing a closed-loop cooling water system in place of the currently working once-through cooling water system [3].

The assessment of the operation of the CWS of Vidraru Hydro-Power Plant (HPP), a 220 MW underground HPP, on the Arges River in Romania using software, EPANET was done by [4]. The system behavior under critical operation conditions was studied. EPANET lacks physical components like heat exchangers. So, they were replaced artificially by throttle control valves set with equivalent loss coefficients In Fathom, there are inbuild heat exchangers that just need to be defined. [5] developed a complicated thermal-hydraulic model in AFT Fathom to perform the hydraulic analysis on International Thermonuclear Experimental Reactor (ITER) component cooling water system 2B. Via the analysis in the model, solutions were recommended to improve the insufficiency of fluid at some points by using the currently selected pump. [6] has studied the increase in the relative roughness of pipe with age and deducted an equation to anticipate the roughness of a pipe surface at different ages of the pipe. The absolute roughness of a 50-year-old pipe was found to increase by 160 times more than that of a new pipe. [7] studied for the Design Modification of the CWS of Middle Marsyangdi Hydropower Station in which a further modification on a Close Loop CWS was purposed to add a Shell & Tube HE along with existing PHE.

Hence, realizing the incapability of the existing cooling water system for the reliable operation of the Units, the study has been done to propose a Closed Loop Cooling Water System and design additional components required for the modified system. The modified design was modeled and analyzed in the software, "AFT Fathom." The performance of the modified system at variable river water temperature in the cooling system, the capability of increased heat generation in the bearings, and the effect of increment in the surface roughness of pipelines were studied to justify the performance of the modified system.

2. Analysis Methodology

The existing heat exchangers were reviewed for their physical dimensions and working conditions. The following heat exchangers were found to being used in the existing system:

1. Shell and Tube type HE: Turbine Guide Bearing (TGB) oil cooler
2. Shell and Tube type HE: Generator Combined Thrust and Upper Guide Bearing (UGB) Cooler
3. Finned tube water to air HE: Generator Air Cooler
4. Finned tube water to oil HE: Generator Lower Guide (LGB) oil cooler

The modeling parameters were calculated and extracted from documents/manuals along with measurements of the Heat Exchangers available at MHPS to use in the software.

2.1. Modeling in AFT Fathom

2.1.1. Performance Verification of the Existing Heat Exchangers

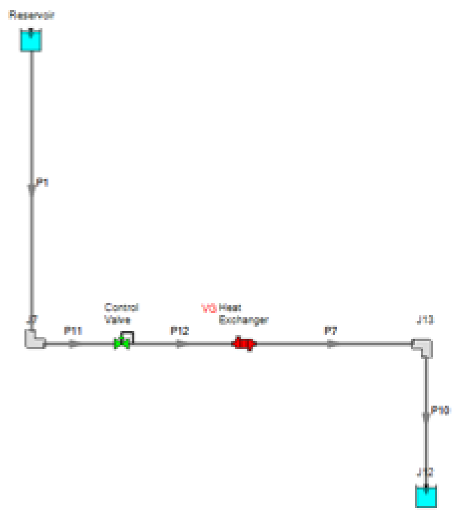

Figure 1: Model Layout for Performance Verification of Existing HE

First, the actual performance of each type of existing primary heat exchanger was verified with the result of the model in the software. For the verification, the model was constructed as in Figure 1, and the loss and thermal models were defined for the respective HEs.

a. Model of the TGB Oil Cooler and UGB Oil Cooler

The TGB and UGB oil coolers are of Shell and Tube type, which consists of multiple tubes inside a shell. Hence, for the loss model, details of tubes including tube material, size, inner diameter, tube length, no. of tubes, no. of passes, and surface roughness were necessary. Similarly, for the thermal model, the "Shell & tube, 1 shell pass, multiple of 2 tube passes," option was selected. For this purpose, the thermal data required were; Heat Transfer Area, Overall Heat Transfer Coefficient and Secondary fluid data such as; Flow rate, Inlet temperature and Specific heat. The heat transfer area was calculated from the physical data as given in the Loss model. The overall heat transfer coefficient was calculated using Equation 1.

$$U = \frac{1}{\frac{1}{h_{hot}} + \frac{t_p}{k_p} + \frac{1}{h_{cold}}} \quad (1)$$

For the tube side fluid, Equation 2, 3 and 4 were solved. The basic theories and equations for heat transfer were referred to from [8].

$$\text{Nusselt No. } N_u = \; hD_e/k \quad (2)$$

$$\text{Prandtl No.} = \frac{c_p \mu}{k} \quad (3)$$

The calculation of heat transfer in fully developed turbulent flow in smooth tubes for heating of the fluid as recommended in [9] is

$$N_u = \; 0.023 \; R_e^{0.8} \; P_r^{0.4} \quad (4)$$

Where,

h_{hot}	=	convective heat transfer coefficient of the hot fluid
h_{cold}	=	convective heat transfer coefficient of the hot fluid
t_p	=	plate thickness
k_p	=	plate thermal conductivity
D_e	=	characteristic length
C_p	=	specific heat capacity of fluid
k	=	thermal conductivity of fluid

For the shell side, the overall heat transfer coefficient was calculated using Bell-Delaware method [10].

b. Model of the Generator Air Cooler

The generator air cooler is the Finned Tube type of heat exchanger, consisting of multiple tubes connected with frames from both ends and multiple fins in between them. The tubes are arranged in two passes. Water flow is maintained through the tubes and air is forced to flow in a cross-flow direction to the tubes. Hence, the loss model is defined using the tube configuration option which includes tube material, size, inner diameter, tube length, no. of tubes, no. of passes and surface roughness. The water flows through the tubes and air, guided by fins, and flows perpendicularly with the water flow direction. Hence, cross flow, both fluid unmixed model is selected. In this model also, the thermal data required were; Heat Transfer Area, Overall Heat Transfer Coefficient and secondary fluid data such as; Flow rate, Inlet temperature and Specific heat. For the tube side, the heat transfer coefficient was calculated using Equation 1, 2, 3 and 4 as earlier.

c. Model of the Generator Lower Guide Bearing (LGB) Oil Cooler

The LGB Oil Cooler is a finned tube of heat exchanger. The cooler is immersed in an oil pan around a rotating hydro turbine shaft. Hence, the Loss model was defined using the tube configuration option. The cooling water flows inside tubes that are immersed in the oil pan. The oil flow inside the cooler can't be controlled and oil inlet temperature can't be measured. Hence, the cooler was modeled to dissipate a constant amount of heat from the bearing pan. The constant amount of heat rejected by the LGB Oil Cooler is obtained from the commissioning report of MHPS.

3. Simulation Analysis

3.1. Performance Verification of Heat Exchangers

All the models were run individually and the outputs were compared with the heat exchangers' performance recorded on the Commissioning Reports of Units at MHPS. The comparison is summarized in Table 1.

Table 1: Performance Verification of Heat Exchangers

Heat Exchangers	Values	Heat rejection (kW)	Water Outlet T °C	Oil outlet T °C
TGB Oil Cooler	Report Value	4.18	26	32
	Simulated Value	4.40	26.11	31.74
	Difference	-0.22	-0.11	0.26
UGB Oil Cooler	Report Value	62.20	23.58	40
	Simulated Value	59.79	23.52	40.45
	Difference	2.41	0.06	-0.45
LGB Oil Cooler	Report Value	8.2	16.24	-
	Simulated Value	8.2	16.1	-
	Difference	-	0.14	-
Generator Air Cooler	Report Value	116.83	-	-
	Simulated Value	119.90	-	-
	Difference	-3.08	-	-

For the TGB and UGB Oil Coolers, heat rejection, water outlet temperature, and oil outlet temperatures of the reported value and simulated value were compared. For the LGB Oil Cooler, only cold water outlet temperature was compared taking the heat rejection value as input because the other data couldn't be measured as the LGB Oil Cooler is immersed in the oil pan. Similarly, for the Generator Air Cooler, only the heat rejection value was compared.

Analog flow meters and thermometers are used to measure the flow rate and temperatures of fluids, respectively. Hence, the main cause for this deviation can be attributed to the data reading precision considered during the commissioning time. Also, the overall heat transfer coefficients that are used in the models were calculated using the available literature and empirical equations. This has also contributed to the deviations from the reported value. However, the differences obtained in the compared values were found well within the acceptable limit. Hence, the heat exchangers were accepted as valid models.

3.1.1. Performance Verification of the Overall Existing CWS

After the performance verification of the existing individual HEs, an overall equivalent system was modeled in the software. The size and length of pipelines and elevation of heat exchangers were defined as per the site condition.

The total heat rejection by the model was obtained as;

Table 2: Performance Verification of Overall Existing System

	Total Water Vol. Flow (m3/hr)	Heat rejection (kW)
Actual Site Value	181.98	1634.1
Simulated Value	181.1	1619
Difference		-15.1
Difference %		-0.9%

The output obtained is in close agreement with the actual site data. The reasons for minor deviation have been mentioned earlier in 3.1.

3.2. Design Modification in the Existing System

The existing Open Loop CWS has been modified to a Close Loop CWS as shown in the Figure 3.

In the modified CWS, two separate circuits of cooling water are arranged which are described below as an Open loop circuit and a Close loop circuit.

Open Loop Circuit
The open loop circuit starts with a tapping point of cooling water at the penstock pipe. The penstock water gets collected at the Gravity water tank on the ground at elevation level 271.25 masl. after undergoing screening and filtration processes via the existing system.

In the present system, the water hence collected is distributed to all three units from a common pipe at the drainage gallery at elevation level 236 masl. But, here, it has been modified to pass through three Secondary Heat Exchangers(SHE) connected in parallel. The SHEs have been designed so that only two SHEs operating at a time can perform the cooling operation of all three units. Hence, one SHE is kept on standby for operation in case of maintenance of other SHEs. The cooling water is then directed to the draft tube via existing pipelines.

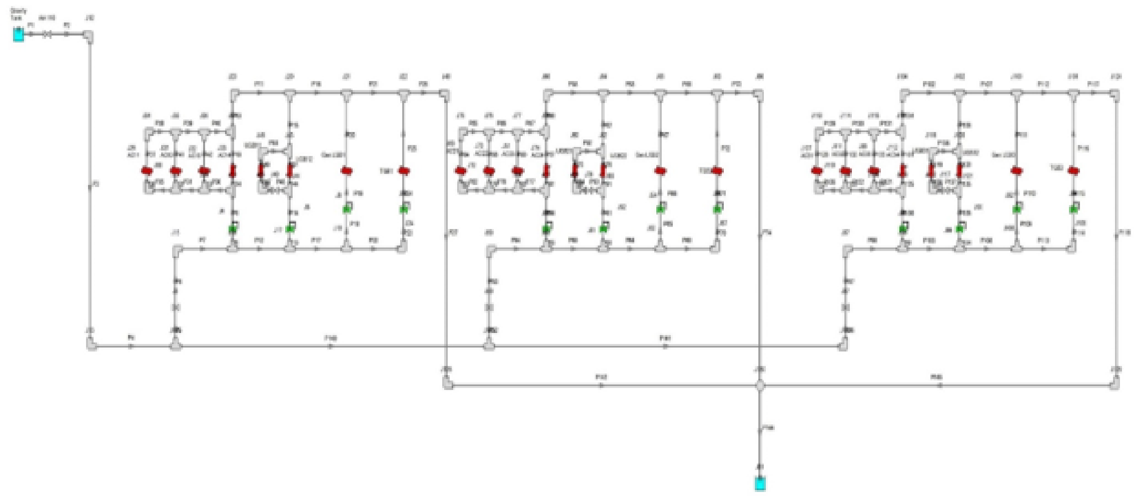

Figure 2: Model of the Existing CWS

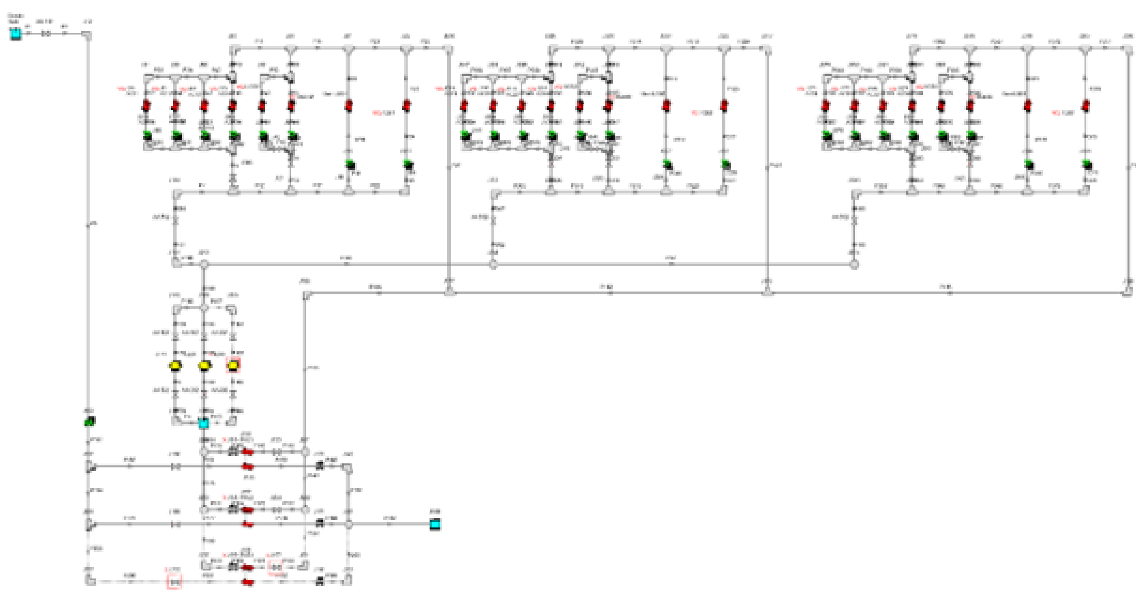

Figure 3: Layout of the Modified CWS

Hence, the major modification here is the addition of three SHEs and pipelines which bypass the existing supply line to units as shown in Figure 3.

In the pipeline to SHEs, a flow regulating valve has been proposed to control the flow rate of water. The valves are arranged to allow the selection of any SHEs for operation as per requirement and check valves are fitted on the downstream side of each SHE to prevent the backflow of water to the non-operating or the standby valve.

Closed Loop

For the Close loop circuit, the existing pipelines for unit distribution remain unchanged. The closed-loop starts with a balancing tank at which returning pipeline from all units ends up. The capacity of the tank is 1.5 m^3. The outlet of the tank is connected to three Secondary

Table 3: Specifications of Designed Plate Heat Exchanger

Parameters	**Symbol**	**Value**	**Unit**
Plate width	W_p	0.60	m
Plate length	L_p	1.30	m
Plate area enlargement factor (1.15 to1.25)	φ	1.20	m^2
Plate effective heat transfer area	A_p	0.94	m^2
No. of plates	N_p	200.00	
Plate thickness	t_p	0.0005	m
Diameter of port	D_p	0.30	m
Compressed plate pack length		0.600	m
Plate thermal conductivity	k_p	16.30	W/mK
Channel average thickness	b	0.00250	m
Plate pitch	p	0.00300	m

Heat Exchangers which in turn connect with three water pumps in parallel. The operational methodology of the pumps is such that only two operate at any time, the remaining one being on standby. The pumps circulate water to existing distributing pipelines at the drainage gallery. Here, the modification is the blockage of existing pipelines that carry water to draft tubes and the addition of water circulating pumps, Secondary Heat Exchangers, and a balancing tank including pipelines in place of that.

3.2.1. Design of Secondary Heat Exchanger

For the secondary heat exchanger, the three types of heat exchangers; Air to Water cooled heat exchanger, Shell & Tube heat exchanger, and Plate heat exchanger were compared and the most suitable heat exchanger was selected. For the comparison, five criteria; compactness, cost per area, maintenance ease, fouling risk, and leakage risk were considered. Keeping in mind, the availability of limited space in MHPS and the Fouling risk due to the presence of raw river water, the heat exchanger having higher compactness and lower fouling risk was preferred. With reference to the star rating table given in [11] from 0 to 5, the Plate Heat Exchanger (PHE) was found to be the most suitable as the Secondary Heat Exchanger and hence, so was selected.

With reference to [12], the PHE was designed with the following specifications as mentioned in Table 3.

4. Results and Discussion

The modified model was run to observe the performance of the modified system at different river water temperatures and increased heat generation in all the heat exchangers. Further, the effect of an increase in surface roughness of pipelines due to aging on the selection of circulating pumps was studied.

i. Effect of the River water temperature

According to the recorded data, the minimum temperature of river water ranges from 12 °C during the winter season to 24 °C in the summer. So, it becomes necessary to test whether the cooling capacity of the modified system is enough to evacuate the generated heat. The river water temperature was varied from 10 °C to 30 °C and the corresponding change in the oil inlet temperature in TGB and UGB oil cooler was observed. Similarly, the air outlet temperature was observed in the generator air cooler. The observed temperature was compared with the corresponding alarming temperature and the safe temperature. For the generator air cooler, safe temperature was set as the maximum observed value, 32 °C, as per the site record. For the TGB and UGB oil cooler, the oil inlet temperature was not found recorded. Hence, safe temperature was set at a value 5% below the alarm temperature.

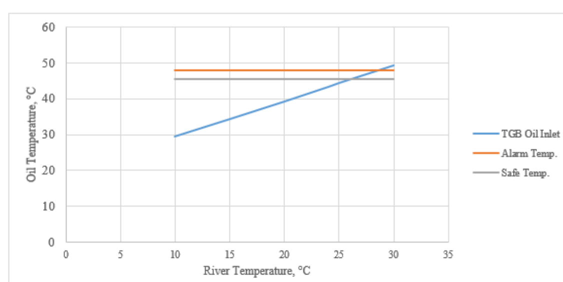

Figure 4: Effect of River Temperature on TGB Oil Cooler

In the case of TGB Oil Cooler, the Alarm and the Safe oil inlet temperature are 48 °C and 46 °C respectively. In Figure 4, it can be observed that the TGB Oil Inlet Temperature reached the Safe Temperature when the River Temperature was 27 °C, which is beyond the maximum available river temperature.

The Alarm and the Safe oil inlet temperatures for UGB Oil Cooler are 55 °C and 52.25 °C respectively. As

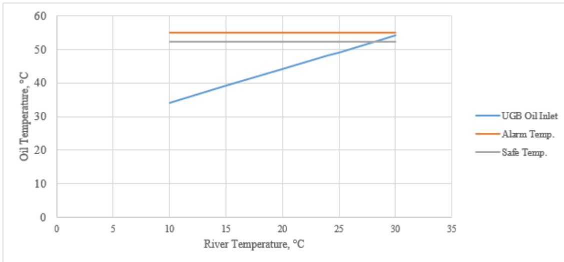

Figure 5: Effect of River Temperature on UGB Oil Cooler

in Figure 5, the UGB oil inlet temperature reached the safe temperature limit when the river temperature was around 28 °C.

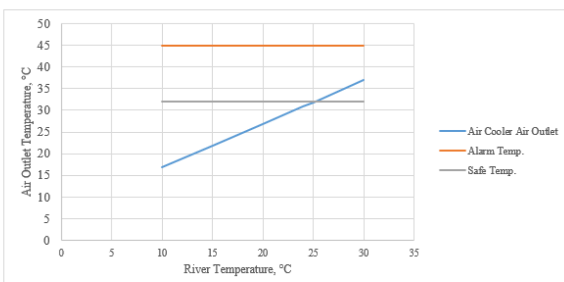

Figure 6: Effect of River Temperature on Generator Air Cooler

In Figure 6, the air outlet temperature reached the safe temperature when the river temperature was 25 °C. Observing the above plots, for all the Heat Exchangers, the operational temperature range was found below the safe temperature and hence, the alarm limit. Hence, the capacity of the modified system was justified at the working range of river water temperature.

ii. Increment in Heat generation by 10%

The amount of heat generation may not be the same every time. That may increase during the partial load operation of Units, the increased vibration of Units due to mechanical or electrical imbalance, etc. Hence, assuming the maximum increment in heat generation in all the HEs as 10%, the resulting temperatures were compared with the safe temperatures.

As in Figure 7, the TGB oil inlet, air coolers air outlet and UGB oil inlet temperatures were obtained as 45.57 °C, 31.53 °C and 50.58 °C respectively. The reference temperatures were found to be within the safe temperature limits. Hence, it was inferred that the modified system can evacuate the heat generation increased by 10%.

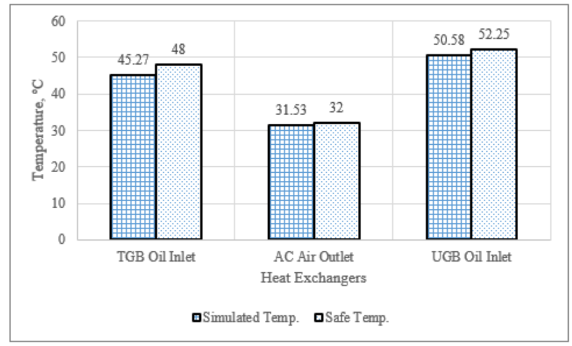

Figure 7: Performance of System During Increased Heat Load Condition

iii. Effect of the surface roughness on the selection of the Pump

The roughness of a pipe increases with time. The increment in surface roughness of the pipe results in the increment in the frictional loss in the flow which determines the selection of pump capacity. MHPS is currently running in the third decade of its continuous operation. Hence, the effect of the surface roughness was considered. The surface roughness values after multiple years of operation calculated for steel pipe carrying raw water according to [6] is

Table 4: Change in Surface Roughness of Pipe with Time

Time (Years)	Absolute Surface Roughness (cm)
10	0.03
20	0.13
30	0.29
40	0.51
50	0.80

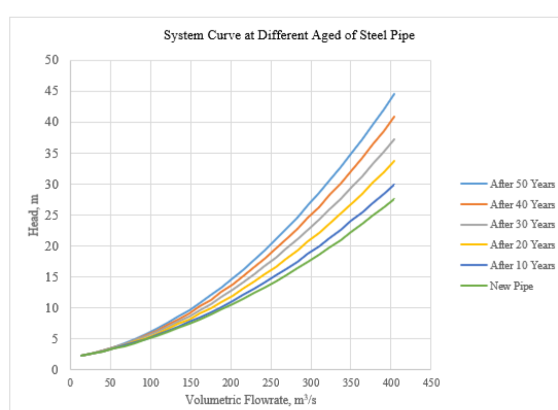

Figure 8: System Curve of Aged Pipe

The system curve of the modified system was obtained as in Figure 8 . The rated discharge for operating all three Units at 10% increased heat generation was obtained as 285 m^3/s. From the plot, after 50 years the head loss in the system at that discharge was found to be 24.6 m. Hence, suggests the breakeven power rating of each pump is 13.64 kW, at a rated discharge of 142.5 m^3/s and head 24.6 m.

5. Conclusion

Both the existing and modified CWS was modeled in AFT Fathom. At first, the model of the Existing system was run which yielded the deviation of the simulation result from the reported value in the heat rejection by 5.2% in TGB Oil cooler, 0.2% in UGB Oil cooler, 2.6% in Generator Air Cooler. The performance verification of the overall existing layout yielded a total heat rejection of 1619 kW which is 0.9% below than that of existing system in the reported value. Referring to these data, it is inferred that the model verifies with the actual cooling system of MHPS.

For the safe temperature limit of the Turbine guide bearing Oil Cooler (48 °C), Upper guide bearing Oil Cooler (52.25 °C), and Generator Air Cooler (32 °C) on the modified system, the corresponding river water temperature obtained was 27 °C, 28 °C, and 25 °C, which is beyond the available river temperature of 24 °C. Hence, the capacity of the modified system was found enough to operate within the available minimum, 12 °C, and maximum, 24 °C, temperature range of river water. Similarly, for the 10% increment in heat load at all the heat exchangers, the reference temperatures for Turbine guide bearing Oil Cooler, Upper guide bearing Oil Cooler, and Generator Air Cooler were found to be 45.27 °C, 31.53 °C, and 50.58 °C respectively, which are well within the safe temperature limit. Hence, the modified system was found capable of evacuating heat generation increased by 10%. Further, The System Curve was generated considering the effect of the increase in surface roughness of pipelines due to aging up to 50 years for the selection of circulating pump. The curve revealed the requirement of the pumping head by additional 7 m. The breakeven power rating of each pump was found to be 13.64 kW, at a rated discharge of 142.5 m3/s and a head 24.6 m.

As the results of the simulation verify the capacity of the modified system to evacuate the required amount of heat, the modification in the existing system can be recommended.

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References

[1] Kumar S, Varshney B. Estimation of silt erosion in hydro turbine[J]. Int. J. Eng, 2015, 4.

[2] NEA. A year in review 2021/2022[M]. NEA, 2022.

[3] Ahmed S F, Hafeez H, Jamal B, et al. Design of close loop cooling water system for khan khwar hydro power plant[J]. Lect. Notes Eng, 2018, 2238: 697-701.

[4] Maria D, Ioan C, Gabriela R, et al. Assessing the operation of the cooling water system of a hydro- power plant using epanet[J/OL]. Energy Procedia, 2017, 112: 51-57. DOI: 10.1016/j.egypro.2017.03.1058.

[5] Zhang W, Guo B, Zheng J, et al. Hydraulic analysis on iter component cooling water system 2b[J/OL]. Fusion Eng, 2017, 121: 204-210. DOI: 10.1016/j.fusengdes.2017.06.038.

[6] Abdelmonem Y, Ead S A, Shabayek S A. Effect of time on pipe roughness[J/OL]. 2020. www.hydrotechnics.ca/hydro2005/.

[7] Shah S K, Shrestha R. Design modification of cooling water system for hydropower plants [a case study of middle marsyangdi hydropower plantin nepal][J]. 2015, 15(6).

[8] Holman J P. Heat transfer, thent edition (mcgraw-hill series in mechanical engineering).[M/OL]. McGraw Hill Higher Education, 2010. www.mhhe.com.

[9] Dittus F, Boelter L. Dittus+boelter_1930.pdf[J]. 1930, 2(3): 443-461.

[10] Serth R, Lestina T. [M]. Process Heat Transfer, 2007.

[11] Larowski A. Systematic procedure for selection of heat exchangers[J]. 1983, 1982.

[12] Kazi S N. Heat transfer studies and applications[M]. 2015.