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Comparative study of steam vs hot water as primary heat transfer medium for a laboratory scale two-tank heated system

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Abstract—**The need exists for a benchmark multi-domain practical system that could emulate typical process faults for the purposes of condition monitoring. A proposition was made to develop a heated two-tank system, due to its multi-domain nature i.e. thermal-fluid, mechanical, electrical as well as its non-linear nature. The paper presents an analysis of a helical coil heat exchanger. A comparison is made between steam and water as a heat transfer medium. The study is conducted to determine which medium will be the most feasible to implement in a laboratory scale two-tank heated system. The convection coefficients on the hot and cold side of the helical coil are calculated to determine the inlet and outlet temperatures of the system. The temperatures are compared at various mass flows.**

Keywords—Heat exchanger, Helical coil, Steam, Hot water

I. INTRODUCTION

The need exists for new technologies to be tested thoroughly before implementation to provide certainty that the product or model will operate as promised. Since testing a product in its intended application is hazardous it is necessary to test a product in an environment that replicates the environment it will be exposed to. Since experimenting with full-scale systems can be expensive and time consuming, the engineer seeking application opportunities is naturally led to consider the use of laboratory systems [1]. Liquid level control, heating of liquids and flow between tanks are problems commonly faced in process technologies. The need arises for a benchmark system for testing and evaluation of Fault Detection and Diagnosis algorithms (FDD) [1]. Existing benchmark systems include the Four-Tank system. The four-tank benchmark control problem presented by Johansson and Nunes, [2] is a novel multi-variable laboratory process that consists of four inter-connected water tanks. The quadruple tank process is ideal for illustrating various concepts in multi-variable control. The system consists of four interconnected water tanks and two pumps feeding the tanks. The four-tank system is an inter-connection of two, two-tank systems. The faculty of electronic engineering from the University of Niš proposed a three-tank system as a benchmark system for system modelling, identification, control, fault detection and diagnosis, as well as for fault-tolerant control. The system shows characteristics of a constrained hybrid system and serves as a test environment for algorithms on the subject of state estimation, parameter identification and control systems [3]. Quanser consulting's mission is to efficiently research, design, manufacture and deploy transformational labs for the global academic community. One of the systems that Quanser provides is the two-tank laboratory experimental system. The two-tank system consist of a pump with a water basin. The pump drives water from the water reservoir to the top tank. The two-tank system is configured such that the flow out of the first tank flows into the second tank. The water flowing out of the second tank flows into the reservoir. The outflow from the tanks are controlled by varying the orifice of each tank [4]. Previous literature on the design and experimentation of helical coil heat exchangers include: Experimental analysis of heat transfer enhancement in shell and helical tube heat exchangers by N. Jamshidi, M. Farhadi, D.D. Ganji and K. Sedighi [6]. The work attempts to enhance the heat transfer rate in shell and coiled tube heat exchangers. The design and thermal evaluation of shell and helical coil heat exchanger was presented by Amitkumar S. Puttewar and A.M. Andhare [7]. The work focuses on the design of a shell and helical coil heat exchanger and its thermal evaluation with a counter flow configuration. Thermal analysis of the heat exchanger considers various parameters such as flow rate, temperature effectiveness and heat transfer coefficient. T. J. Gaskill, presented a master's thesis on heat transfer of a multiple helical coil heat exchanger using a microencapsulated phase change material slurry [8]. The study focused on the use of coil heat exchangers with microencapsulated phase change material slurries to understand if coil heat exchangers can yield greater rate of heat transfer.

This paper presents the comparison of steam and hot water at atmospheric pressure. This is done to determine which medium will be the most feasible option to implement on an experimental two-tank system each containing a helical coil. The general belief is that steam will be the best choice of heating medium due to the latent heat associated with the change of phase from saturated gas to liquid. Steam and hot water are compared by conducting a thermal analysis considering various factors. The factors include the flow rate of the hot and cold side of the heat exchanger, temperature of the mediums the convection coefficients and the overall heat transfer coefficients. The capital and operating cost of steam generation is considerably higher than hot water.

The next section will describe the helical coil heat exchange system and the mathematical model used to determine the heat exchanger design. Following the design calculations is the mathematical model used to calculate heat transfer over the length of the coil. The outlet temperatures of the hot side and cold side are determined using the number of transfer units (NTU) or effectiveness method. The flow rate of the hot medium through the coil is varied. The results obtained from the mathematical models are discussed in the results and discussion section of the paper.

II. SYSTEM DESCRIPTION

Figure 1 represents a proposed benchmark system. The system differs from the existing systems in the sense that the water tanks are heated. Water flowing through the tanks will be heated by making use of a heat exchanger. More specifically a helical coil in each tank which will contain a heating medium. The addition of the heat exchanger to each tank will allow not only the control of the water level in each tank but also the temperature of the water in each tank.

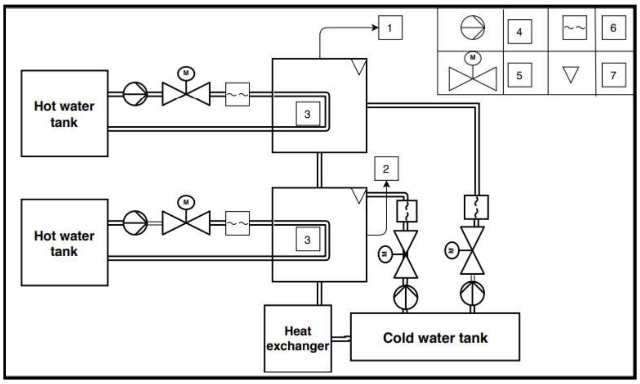

Figure 1: Proposed system

The system will be designed to emulate certain process faults commonly found in the industry. The destructive nature of a system defect and the long error latency makes it difficult to study the effect of defects on a system. It would be time consuming, expensive and difficult to recreate a failure condition on a large complex system. Therefore, experimental based approaches are used to study the effect of a defect on a small-scale experimental system. The information obtained from this study can later be implemented in larger complex systems [5]. Hardware-implemented fault emulation uses additional hardware to introduce faults into a system. Inducing faults into an operational system provides information about the failure process and test if the fault detection system is operating reliably. The design of the heat exchanger and the helical coil will depend on the type of heating medium used. This paper will focus on a comparative study of steam and hot water as primary heat transfer medium in a two-tank heated system. Due to the risk involved when working at high pressure, the system is designed to operate at atmospheric pressure. The helical coil increases the surface area available for heat exchange and influences the convection coefficients of the system. These factors impact how the system is modelled. The amount of steam that can be generated is limited by occupational health and safety regulations. In order to generate steam, it is necessary to buy a certified steam generator. The two-tank system will consist of two tanks connected in series. Two pumps will feed water from a tank containing water at room temperature to each of the tanks individually. The outlet of the first tank flows directly into the second tank. Each tank has a control valve and flow meter at the cold-water inlet to control the amount of water entering each tank. The tanks will each contain a heat exchanger, which will allow the water in each tank to be heated to a pre-set temperature. The heat transfer medium will be circulated through the heat exchanger allowing heat to be transferred to the water flowing through tank 1 and 2. The proposed heat exchange system will be indirect. The amount of energy transferred will be controlled by varying the flow rate of the medium flowing through the heat exchanger.

Table 1: Input variables

Input Variables			
Variable	**Value**	**Unit**	**Description**
T_{c_i}	25	[°C]	Cold water inlet temperature
T_{c_o}	40	[°C]	Cold water outlet temperature
$T_{h_{i_{steam}}}$	100	[°C]	Steam inlet temperature
$T_{h_{i_{water}}}$	80	[°C]	Hot water inlet temperature
T_{h_o}	(-)	[°C]	Hot side outlet temperature
D_c	0.5	[m]	Coil Diameter
L_{Wall}	0.00165	[m]	Wall thickness
P_{atm}	100	[kPa]	Atmospheric pressure
D_{i_o}	0.02165	[m]	Coil tube outer diameter
D_{i_i}	0.02	[m]	Coil tube inner diameter
D_o	0.6	[m]	Tank Diameter
h	0.8	[m]	Tank height
L	40	[m]	Total length of the coil when stretch out
P	0.025	[m]	Coil pitch
$\dot{m}_c$	0.5	$[kg/s]$	Mass flow through the shell
$\dot{m}_h$	0.5	$[kg/s]$	Mass flow through the coil
P_{atm}	100	[kPa]	Atmospheric pressure

Figure 2 shows the schematic of the helical coil and tank system. The steam or water will flow through the helical coil allowing heat transfer to water in the tank.

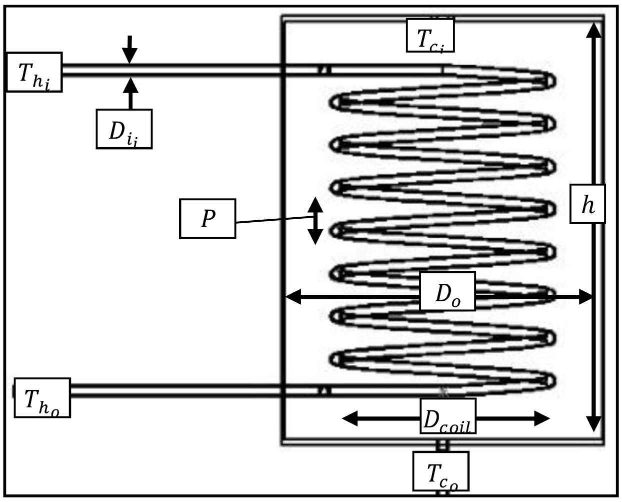

Figure 2: Helical coil and tank side view

III. ANALYTICAL MODEL

In order to determine which heat exchange medium will be used in the heat exchanger, the system needs to be modelled and assessed. This will be done by evaluating the requirement, efficiency, cost and practicality of the heat transfer medium. The two heat transfer mediums are compared to determine if steam offers a clear advantage in temperature increase in the system when compared to water. The cost associated with steam generation is higher than hot water generation. If steam does not offer distinct advantages to the system, it would be more feasible to use water as a heat transfer medium. The mathematical model used in the design of the heat exchanger makes use of the log mean temperature difference method (LMTD). The length of the helical coil (L) must be determined to produce a certain cold side outlet temperature.

A. Heat exchanger design with water as primary heat exchange medium

The heat transfer from the hot water flowing through the helical coil to the cold water flowing through the tank can be calculated using equation (1). The mass flow ($\dot{m}_c$), specific heat (c_{p_c}) and temperature difference is used :

$$q = \dot{m}_c \times c_{p_c} \times \left(T_{c_o} - T_{c_i}\right) \quad (1)$$

From this it is possible to determine the hot side outlet temperature using equation (2):

$$q = \dot{m}_h \times c_{p_h} \times \left(T_{h_i} - T_{h_o}\right) \quad (2)$$

The convection coefficient is needed to determine the overall heat transfer coefficient. The convection coefficients are determined by the Reynolds (Re_D) and Nusselt (Nu_D) number for the hot side (subscript h indicating hot) and the cold side (subscript c indicating cold):

$$Re_{D_h} = \frac{4 \times \dot{m}_h}{\pi \times D_{coil} \times \mu_h} \quad (3)$$

The Dittus-Boeler correlation was used in equation (4) to determine the Nusselt number for flow inside the coil [9]:

$$Nu_{D_h} = 0.023 \times Re_{D_h}^{0.8} \times \Pr_h^{0.3} \quad (4)$$

$$h_i = \frac{Nu_{D_h} \times k_h}{D_{coil}} \quad (5)$$

$$Re_{D_c} = \frac{4 \times \dot{m}_c}{\pi \times (D_H) \times \mu_c} \quad (6)$$

The Nusselt number on the outside of the coil was calculated based on methodology of previous works [10] [11].

$$Nu_{D_c} = 0.6 \times Re_{D_c}^{0.5} \times \Pr_c^{0.31} \quad (7)$$

.

$$h_o = \frac{Nu_{D_c} \times k_c}{D_H} \quad (8)$$

The overall heat transfer coefficient (U) is determined using equation (9):

$$U = \left(\frac{1}{h_i} + \frac{1}{h_o}\right)^{-1} \quad (9)$$

The log mean temperature difference can be determined using equation (10):

$$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\mathbf{ln}\left(\frac{\Delta T_1}{\Delta T_2}\right)} \quad (10)$$

$$\Delta T_1 = T_{h_i} - T_{c_i}$$

$$\Delta T_2 = T_{h_o} - T_{c_o}$$

With all the variables calculated except length (L) of the helical coil. The required length of the coil to produce the cold side outlet temperature can be determined:

$$q = U \times A \times \Delta T_{lm} \quad (11)$$

$$A = \pi \times D_{coil} \times L \quad (12)$$

B. Heat exchanger design with steam as primary heat exchange medium

The same process used to determine the length of the helical coil for water was used to determine the length of the coil for steam. A small adjustment was made to calculate the amount of heat transfer from the hot side to the cold side, enthalpy difference was used opposed to temperature difference. Equation (2) was adapted due to the condensation of steam in the coil.

$$q = \dot{m}_h \times \left(h_{h_i} - h_{h_o}\right) \quad (13)$$

C. Heat exchange model using water as primary heat transfer medium

In order to design or to predict the performance of a heat exchanger, it is essential to relate the total heat transfer rate to quantities such as the inlet and outlet fluid temperatures, the overall heat transfer coefficient, and the total surface area for heat transfer. The heat exchange model for hot water and steam was calculated using the Number of transfer units (NTU) method, this method is also known as the effectiveness method. The NTU method was used since the log mean temperature difference (LMTD) method requires a cumbersome iterative procedure when only the inlet temperature of the system is known. Before the NTU method can be used to determine the hot and cold side outlet temperatures the convection coefficients of the system must be determined [9]. The Reynolds number is calculated to determine if flow through and over the helical coil is laminar or turbulent. Equation (14) and (15)

$$Re_{D_h} = \frac{4 \times \dot{m}_h}{\pi \times D_i \times \mu_h} \quad (14)$$

$$Re_{D_c} = \frac{4 \times \dot{m}_c}{\pi \times (D_H) \times \mu_c} \quad (15)$$

The Reynolds number will be used to determine the Nusselt number for each of the components:

$$Nu_{D_h} = 0.023 \times Re_{D_h}^{0.8} \times \Pr_h^{0.3} \quad (16)$$

$$Nu_{D_c} = 0.6 \times Re_{D_c}^{0.5} \times \Pr_c^{0.31} \quad (17)$$

The convection coefficients can now be calculated:

$$h_i = \frac{Nu_{D_h} \times k_h}{D_i} \quad (18)$$

$$h_o = \frac{Nu_{D_c} \times k_c}{D_H} \quad (19)$$

The overall convection coefficient:

$$U = \left(\frac{1}{h_i} + \frac{1}{h_o}\right)^{-1} \quad (20)$$

The effectiveness of the heat exchanger must be calculated, this is done by calculating the maximum theoretical heat transfer.

$$q_{\max} = C_{\min} \times \left(T_{h_i} - T_{c_i}\right) \quad (21)$$

The specific heat capacity of the hot medium and the cold medium as determined:

$$C_c = c_{p_c} \times \dot{m}_c \quad (22)$$

$$C_h = c_{p_h} \times \dot{m}_h \quad (23)$$

From equations (22) and (23) the maximum and minimum heat capacity is calculated and used in equation (21) to determine the maximum possible heat transfer for the system. Calculate C_r which is the ratio of C_{min} and C_{max}:

$$\mathrm{C_r} = \left(\frac{\mathrm{C_{min}}}{\mathrm{C_{max}}}\right) \quad (24)$$

The NTU is calculated by equation (25):

$$NTU = U \times \frac{A_s}{C_{min}} \quad (25)$$

The effectivity (ϵ) of the system can be calculated using equation (26) for a parallel flow configuration:

$$\epsilon = \frac{1 - \exp\left(-NTU \times (1 + C_r)\right)}{(1 + C_r)} \quad (26)$$

The hot medium outlet temperature can be calculated using equation (27):

$$\epsilon = \frac{T_{h_i} - T_{h_o}}{T_{h_i} - T_{c_i}} \quad (27)$$

The equations used to calculate the heat transfer rate from the hot side to the cold side can be used to calculate the tank outlet temperature:

$$q = C_h \times \left(T_{h_i} - T_{h_o}\right) \quad (28)$$

$$q = C_c \times \left(T_{c_o} - T_{c_i}\right) \quad (29)$$

D. Heat exchange model using steam as primary heat exchange medium

The Reynolds numbers, Nusselt numbers, convection coefficients and maximum heat transfer is calculated by using the same procedure and equations as with water. During the condensation of steam, it can be assumed that the surface temperature of the coil stays at a constant temperature. $C_h > C_c$ and $C_h \rightarrow \infty$. Thus:

$$C_r = 0 \quad (30)$$

The NTU can be calculated with the same equation used in the previous model:

$$NTU = U \times \frac{A_s}{C_{min}} \quad (31)$$

Since $C_r = 0$ the effectiveness equation reduces to:

$$\epsilon = 1 - \boldsymbol{exp}(-NTU) \quad (32)$$

During the condensation of steam, the temperature of the steam does not change between the inlet and outlet of the helical coil. The temperature difference between the coil inlet and outlet was used to determine the amount of heat transfer in the hot water model. Since there is no temperature difference between the inlet and outlet of the coil when steam is used. The heat transfer must be determined from the system effectivity. The effectivity is determined using equation (33):

$$\epsilon = \frac{q}{q_{max}} \quad (33)$$

With the effectivity of the system known, the amount of heat transfer can be calculated using equation (34):

$$q = C_c \times \left(T_{c_o} - T_{c_i}\right) \quad (34)$$

From equation (34) the cold-water outlet temperature can be determined.

IV. Results and Discccusion

The results obtained from the LMTD method determining the length of the coil, showed that the required cold side outlet temperature is obtained at 40 [m]. The heat exchange was evaluated over a coil length of 50 [m]. This is done due to size restrictions limiting the coil height to 0.8 [m].

A. Heat exchange at various mass flows.

1) Hot water as primary heat transfer medium

The heat exchange over the length of the helical coil is evaluated at various mass flows. The outlet temperature at each mass flow is shown in Table 2:

Table 2: Temperature change at varying mass flow

Mass flow [kg/s]	Length [m]	Temperature [°C]
0.1	40	33.38
0.2	40	37.29
0.3	40	39.34
0.4	40	40.59
0.5	40	41.44

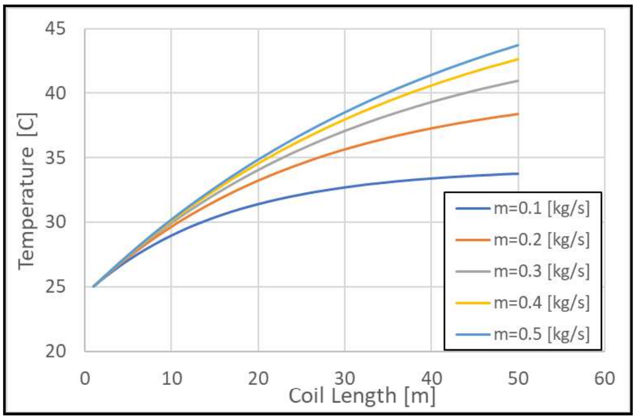

Figure 3: Temperature increase using hot water

Evaluating the graph in Figure 3, the outlet temperature of the cold side increases as the mass flow through the coil increases. The trend of the curves suggests that the difference in temperature rise, decreases with each mass flow increment.

2) Steam as primary heat transfer medium

Table 3 shows the heat exchange at various mass flows used to evaluate steam as primary heat transfer medium. By comparing the cold side outlet temperatures obtained using steam as the heat transfer medium a considerably higher temperature can be obtained.

Table 3: Temperature change at varying mass flow

Mass flow [kg/s]	Length [m]	Temperature [°C]
0.1	40	46.52
0.2	40	49.11
0.3	40	50.22
0.4	40	50.86
0.5	40	51.27

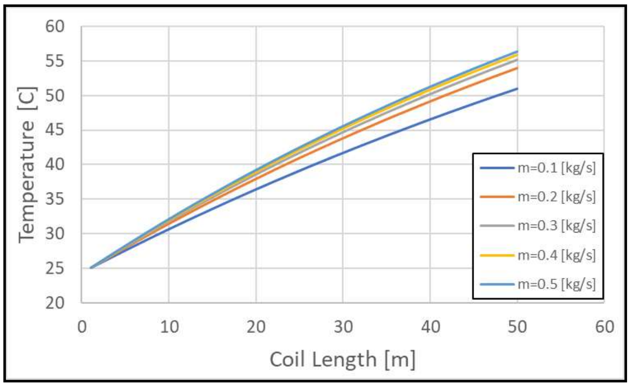

Figure 4: Temperature increase using steam

Although steam delivers higher cold side outlet temperatures when the same mass flow as water is used, this is not a realistic comparison. The maximum amount of steam that can be generated is 0.004 [kg/s]. Table 4 shows the achievable cold side outlet temperature at 0.004 [kg/s].

Table 4: Temperature at 0.004 [kg/s] mass flow

Mass flow [kg/s]	Length [m]	Temperature [°C]
0.004	40	29.74

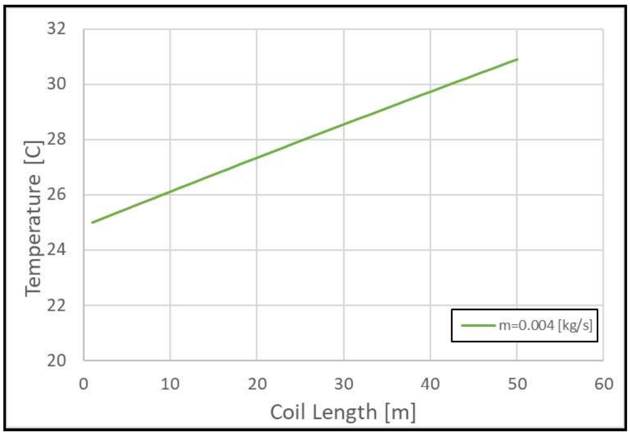

Figure 5: Temperature increase using steam at $\dot{m}_h = 0.004$ [kg/s]

B. Hot and cold side temperature change over the length of the coil

1) Hot water as primary heat transfer medium

The graph in Figure 6 shows the change in temperature of the hot and the cold water over the length of the coil. The temperatures at each length was determined at mass flow $\dot{m}_h = 0.5$ [kg/s]. The temperature obtained at a coil length of 40 [m] is 41.4 [°C].

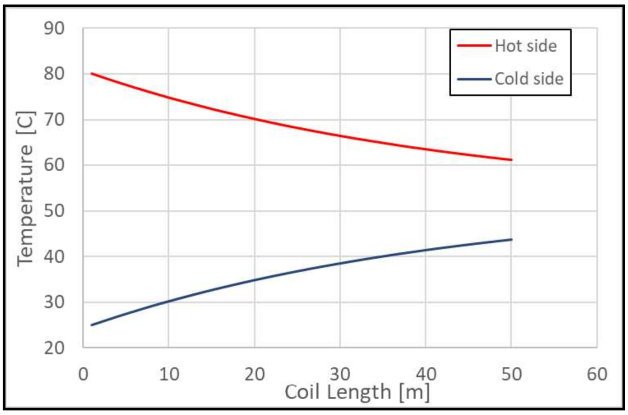

Figure 6: Difference in hot and cold side temperature over the length of the coil at $\dot{m}_h = 0.5$ [kg/s]

2) Steam as primary heat transfer medium

The steam flowing in the helical coil and condensing, causes a constant wall temperature. This is shown in Figure 7 by the red horizontal line representing the wall temperature of the helical coil. The achievable temperature using steam with a mass flow of $\dot{m}_h = 0.004$ [kg/s] is 29.7 [°C].

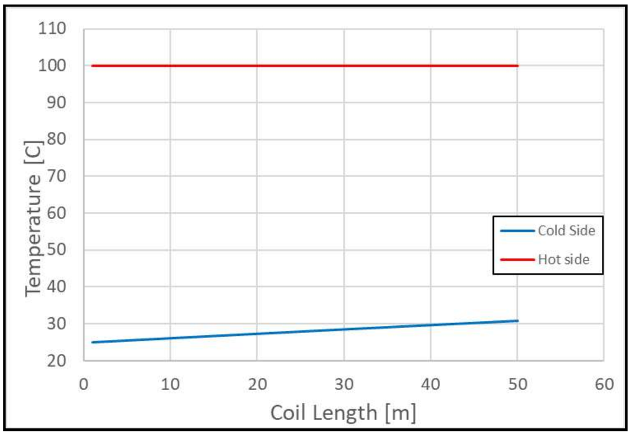

Figure 7: Difference in hot and cold side temperature over the length of the coil at $\dot{m}_h = 0.004$ [kg/s]

C. *Comparison between steam and hot water as primary heat transfer medium*

The heat exchange characteristics of steam and hot water will be considered. This is done to determine the most feasible option in the application of a two-tank heated laboratory scale system emulating typical fault conditions. Evaluating the graphs in Figure 3 and Figure 4 steam constantly delivers higher cold side temperatures when compared at the same mass flows as water. Due to financial and practicality limitations the maximum mass flow that can be achieved in a laboratory scale system is 0.004 [kg/s]. Comparing the graphs in Figure 6 and Figure 7 hot water delivers higher cold side outlet temperatures than that of steam. The graph in Figure 8 shows the temperature change of the water over the length of the coil, flowing through the shell side of the helical coil in tank system. The outlet temperatures were calculated using steam as heat exchange medium, at the maximum possible mass flow rate for this system. This produced considerably lower outlet temperatures.

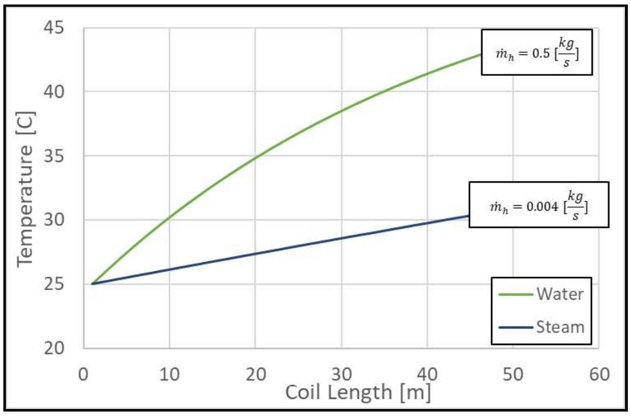

Figure 8: Steam and hot water comparison

V. SUMMARY AND CONCLUSION

The study was conducted to compare steam and hot water to determine which will be used as the heat transfer medium in a two-tank heated laboratory scale system. The system consists of two tanks coupled in series where water flows directly from the first tank in to the second and then into a reservoir. The tanks each contain a helical coil containing a hot medium used to heat the water flowing through the tanks. This system is used as a benchmark control problem used for fault emulation. The heat exchange in the system was modeled using the NTU method to determine the temperature change of the hot and cold fluid over the length of the helical coil. The mass flow of the hot fluid flowing through the helical coil was varied and then compared.

The results indicated that steam delivers higher outlet temperatures than that of hot water when compared at the same mass flows. Due to limitations regarding the amount of steam that can be generated when working with a laboratory scale system. The mass flow rate of the steam used in the calculations and final comparison had to be lowered to 0.004 [kg/s].

Future work will include simulation of various fouling factors and leaks in the system. Detailed heat transfer and flow simulations of the entire two-tank heated laboratory scale system will be developed. The simulations will be verified by constructing and testing the system.

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