FACULTY OF ENGINEERING

INGM 412

by:

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Exam Assignment

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Abstract

A heat exchanger to heat one fluid through heat transfer from another fluid is investigated in this assignment report. A model of the heat exchanger with parallel flow is made and simulated in EES to determine the heat transfer of the heat exchanger. The heat exchanger was then optimized until the hot and cold fluid outlet temperature is within 10% - 15% of each other. The heat exchanger is also simulated for cross flow in Part 2 of the assignment.

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Introduction

The purpose of the heat exchanger in this practical is to heat cold water through diversion of hot water in the system. The heat exchanger shown in Figure 1 below where the number of parallel sections 6. Fluid 2 flows through the outer channel of the heat exchanger and Fluid 1 flows though the inner channel. To minimize the energy losses to the environment the heat exchanger is well insulated on the outside [1].

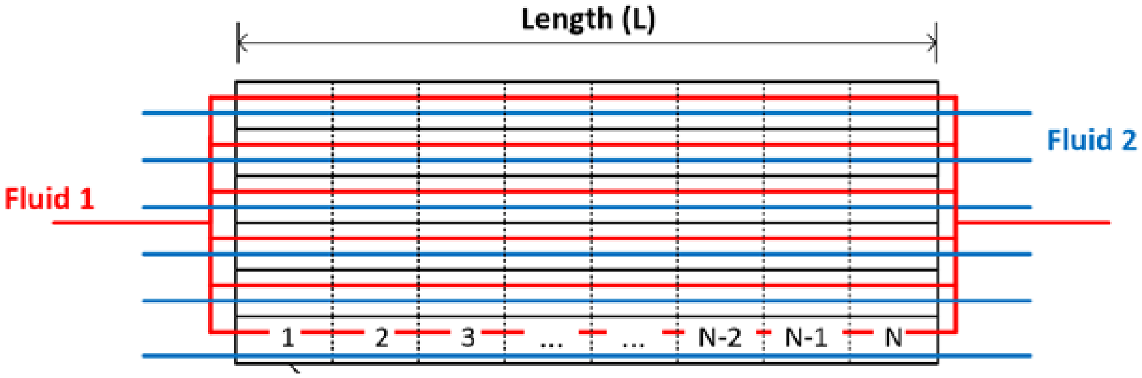

Figure 1: design of heat exchanger [1]

The Figure 2 below shows the tube form of the heat exchanger. Friction losses on the inside can be neglected [1].

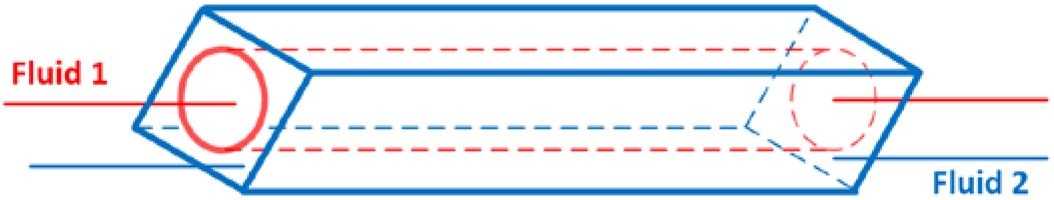

Figure 2: Tube used in heat exchanger [1]

The tube design can be seen in Figure 3 below. There is fouling inside the inner tube on the inside surface [1].

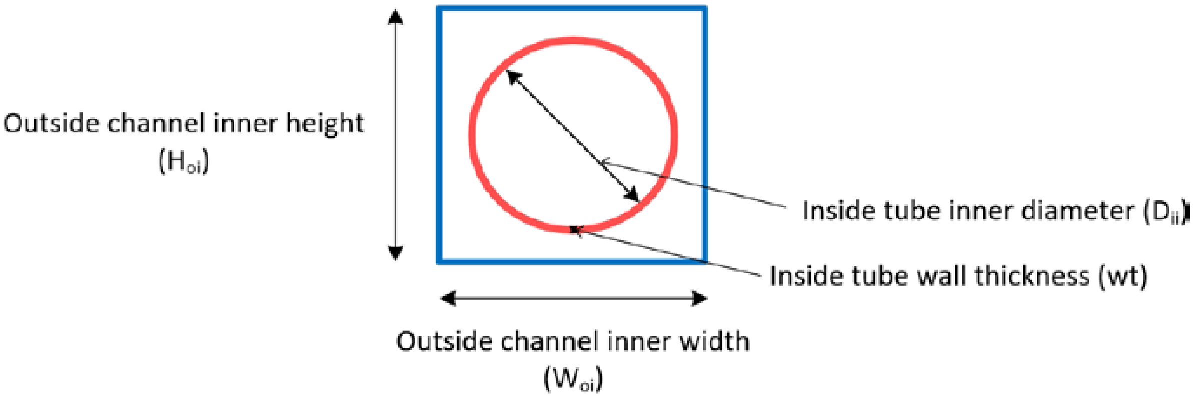

Figure 3: Tube design [1]

Background

Heat exchangers use heat transfer to cool or heat a fluid through flow configuration. The different types of flow configuration and heat exchanger types are discussed below.

Flow Configuration

The three main heat exchanger flow configuration types are [2] :

- Counter flow- the two fluids flow in opposite directions.
- Parallel flow- the fluids flow in the same direction
- Cross flow- the flow of the fluids are at right angles

Parallel and counterflow is the most common arrangement within heat exchangers [3]. Counter flow can be seen in Figure 4 below from [4]. Counterflow is considered the most effective method to get a change in temperature [2]. The counterflow advantages over the parallel flow is the thermal stresses in the heat exchanger is minimizes as the uniform temperature difference is minimized between the two fluids [3].

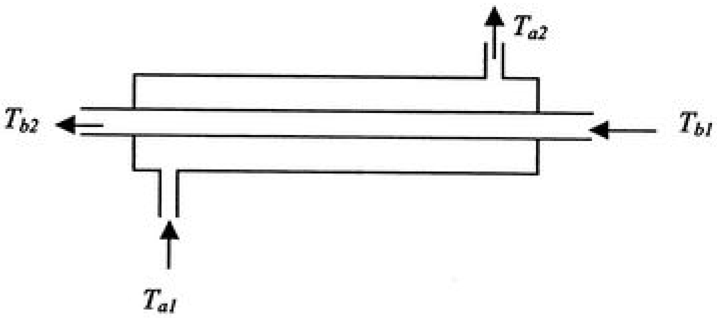

Figure 4: Counter flow [4]

Parallel flow in a heat exchanger can be seen in the Figure 5 below. For this assignment parallel flow and cross flow heat exchangers will be investigated. The cross flow through the heat exchanger can be seen in the Figure 7 below.

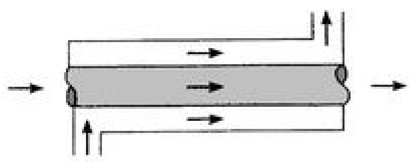

Figure 5: Parallel flow [4]

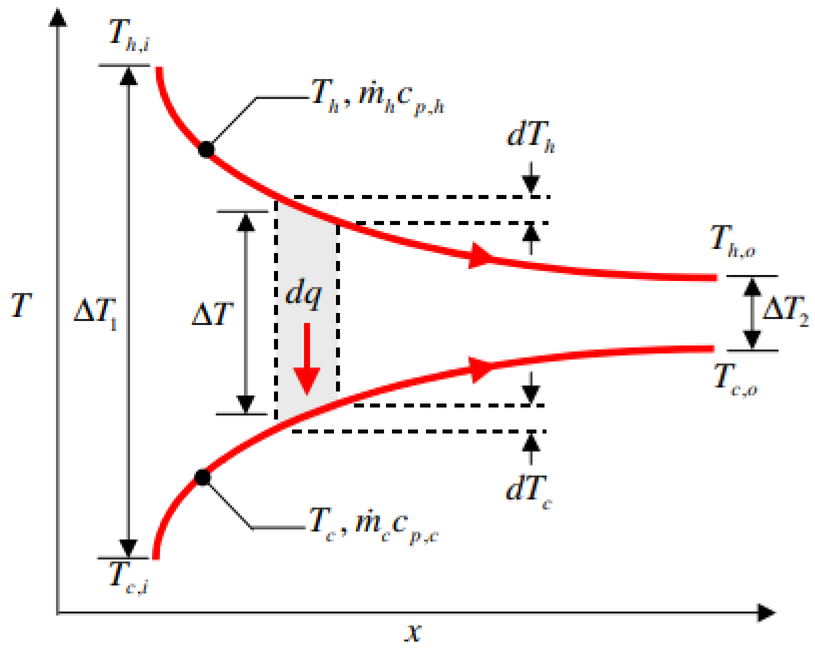

Figure 6: Parallel flow convergence [5]

From parallel flow convergence graph in Figure 6 the incremental heat transfer is determined from the heat transfer coefficient and the change in surface area. An example of cross flow heat exchanger is the radiator of a car. Cross flow heat exchanger is typically used for heat transfer between gas and liquid [6].

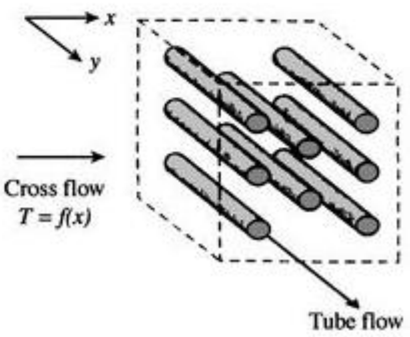

Figure 7: Cross flow [4]

It is clear from the cross-flow convergence diagram in Figure 8 below that counter flow is a more effective heat exchanger as the two curves are more parallel than the convergence of the parallel flow.

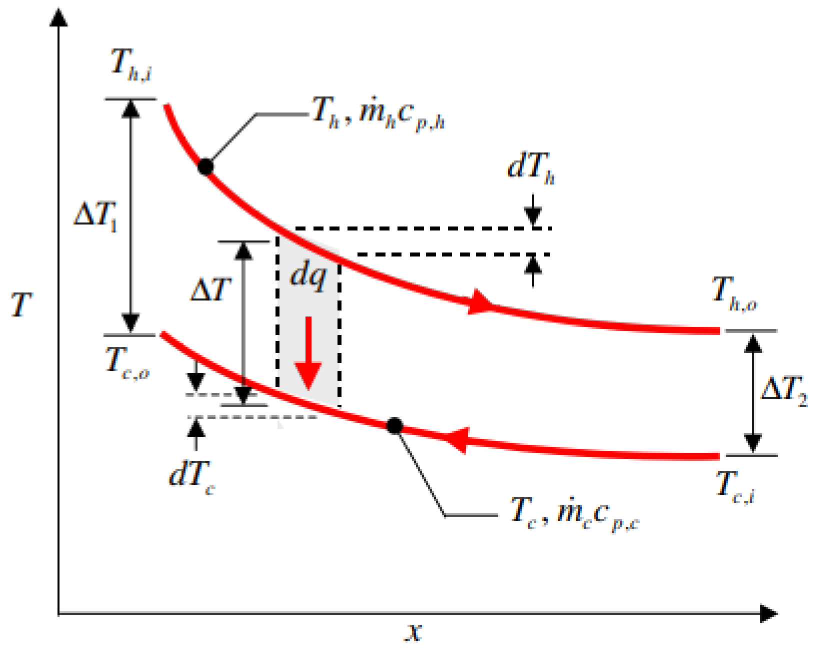

Figure 8: Counter flow convergence [5]

Heat Exchanger Types

The simplest type of heat exchanger is the concentric tube construction with counter or parallel tube arrangement [5]. An example of a concentric tube construction with parallel configuration can be seen in Figure 5 above. The shell and tube heat exchanger is another type of heat exchanger as shown in Figure 9 below. The shell and tube heat exchanger is only applicable for counter and parallel flow. To improve the convection coefficient of the shell fluid Baffles are installed to create turbulence and crossflow [5].

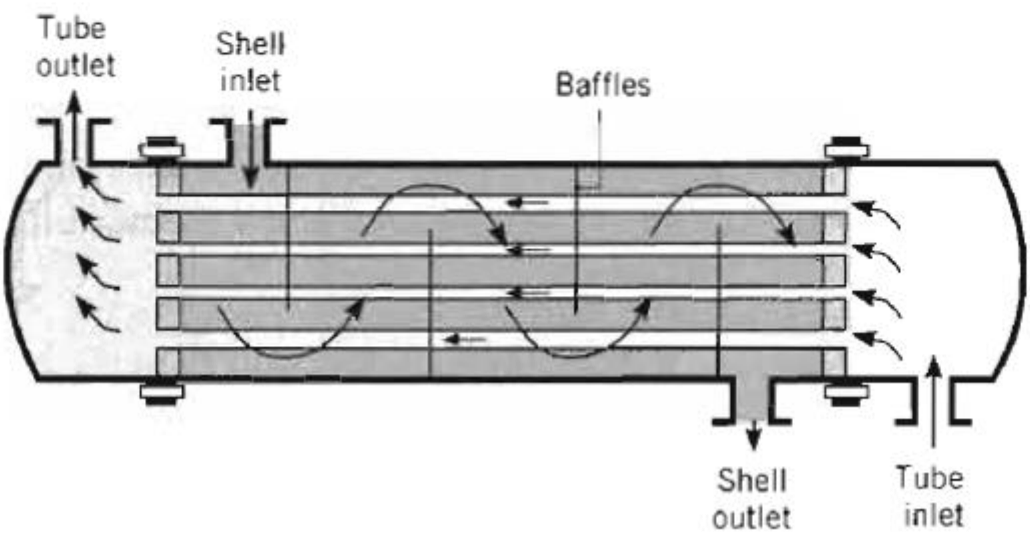

Figure 9: Shell and tube heat exchanger [5]

In finned heat exchangers the fluid moves in cross flow as can be seen in Figure 10 below. The fins prevent the fluid from mixing therefore both fluids remain unmixed [5].

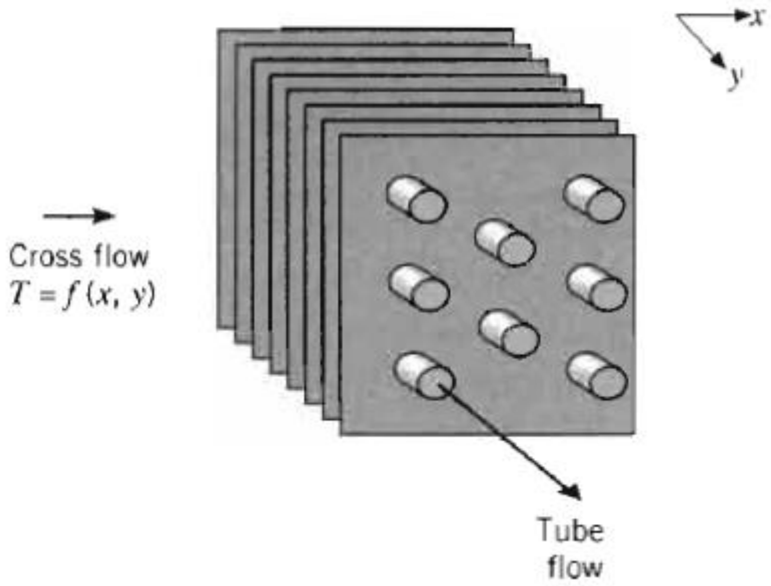

Figure 10: Finned with both fluids unmixed [5]

In the plate fin heat exchanger such as shown below in Figure 11 the flat plates are separated by corrugated metal fins [2]. The fins act as both a structural joint and heat transfer [2].

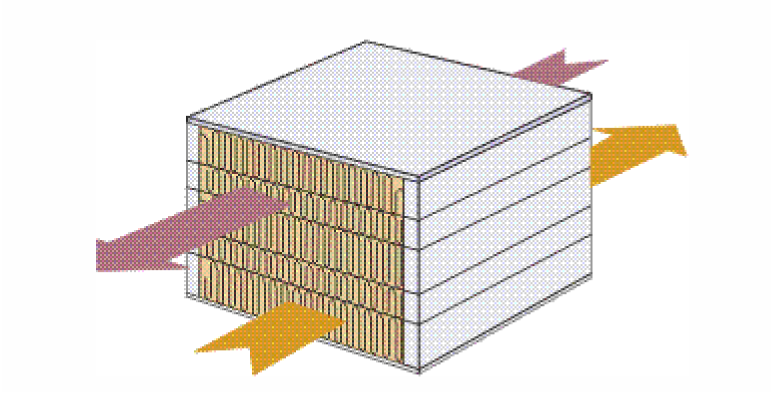

Figure 11: Fin plate heat exchanger [2]

It is clear from Figure 1 that the heat exchanger construction used in this practical will be a tube in a tube or a concentric construction.

Methodology

The heat exchange heat transfer is determined using the effectiveness number of transient unit method (ε-NTU). Accurate results may be achieved using the ε-NTU method to solve the heat exchanger output. The ε-NTU may also be used to solve problems with little information. Using the ε-NTU the output parameters are calculated using EES where the heat exchanger is simulated for parallel and then cross flow. EES is utilized to calculated the parameters as it is an accurate and powerful informational technology tool to solve engineering problems. The parallel flow parameters are calculated by hand to check the results obtained in EES. The calculations are done by hand not only to check that no errors were made during the coding in EES but also to apply mathematical and engineering knowledge to solve the problem. The heat transfer equation is given by [5],

$$q = C_{min}(T_{hi} - T_{ci})\varepsilon \tag{1}$$

Where C_{min} is the heat capacity of the fluid. The effectiveness ε that changes with the flow. The inlet hot and cold temperatures are T_{hi}, T_{ci} respectively. The parallel flow effectiveness is calculated with [5],

$$\varepsilon = \left(\frac{1 - e^{-NTU(1+C_r)}}{1 + C_r}\right) \tag{2}$$

Where C_r is the ratio of the maximum to minimum capacity.

Problem Statement

A manufacturing company is looking for a second-hand heat exchanger that operates with two fluids. The heat exchanger must heat a fluid with another fluid from another source in the facilities. The existing heat exchanger must be simulated and a performance report produced for the manufacturing company to review.

1 Part 1

The general specifications if the heat exchanger can be seen in Table 1 below.

Table 1: general specifications for heat exchanger

Parameter	Inner tube	Annulus	SI Unit
Fluid pressure	150	150	kPa
Wall thickness	0.7	-	mm

1.1 Heat exchanger calculations Parallel flow

The Table 2 below shows the heat exchanger configuration. It is assumed that each tube is identical.

Table 2: Parameters of heat exchanger configuration

Parameter	**Value**	**Unit**
Fluid 1	Engine oil unused	-
Fluid 2	Water	-

Flow direction	Parallel	-
Increments (N)	5	-
Length	18	m
Diameter (Dii)	14	mm
Height (Hoi)	20	mm
Width (Woi)	18	mm
Inner tube pipe material	Copper	-
Fouling on inside surface of inner tube R_f"	0.001	m^2K/W
T in Fluid1	67	°C
T in Fluid2	14	°C
Inlet velocity per HX section Fluid 1	1.0	m/s
Inlet velocity per HX section Fluid 2	0.7	m/s

The length if the heat exchanger is divided into 6 increments. Calculations code done in EES can be seen in Appendix A. The heat exchanger is simulated in EES using the ε-NTU method. The results of the calculations done in EES can be seen in Table 3 below.

Table 3: EES code results parallel flow heat exchanger

Parameter	**Value**	**SI Unit**
Fluid 2 outlet temperature	62.5	°C
Fluid 1 outlet temperature	16.42	°C
Heat exchanger total heat transfer	1232	kW

The inlet velocity was given and therefore the mass flow rate can be calculated with equation (3) below,

$$\dot{m} = \rho V A \tag{3}$$

Where, $\dot{m}$ is the mass flow rate, ρ is the fluid density, A the area and v the velocity of the fluid. The mass flow through the tubes remain constant die to the low of conservation of mass. It is assumed that it is steady state flow. In the Figure 12 below the converging of the outlet temperatures of the fluids can be seen as a function of the pipe sections of the heat exchanger.

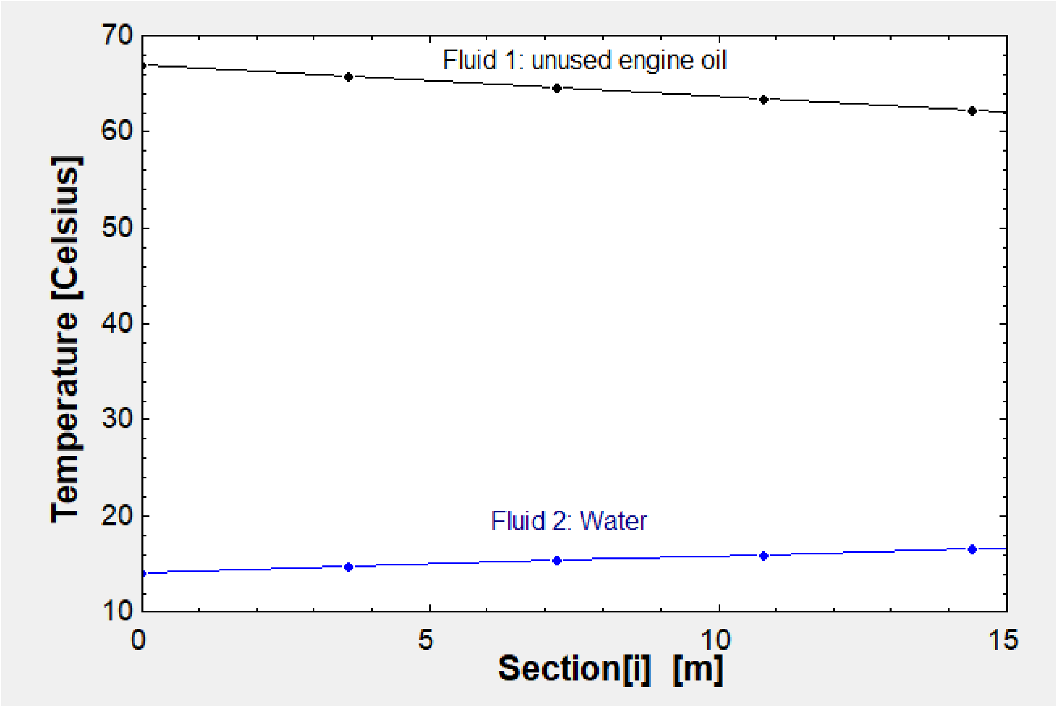

Figure 12: Converging of the fluid outlet temperatures for parallel flow of given values for HX

From the graph we can see that the unused engine oil cools down quicker than the water heats up. The heat exchanger therefore loses a lot of heat from the inlet to the outlet. At present the water outlet temperature is 75.49% from the Unused engine oil input temperature. As the purpose of the heat exchanger is to heat up the water, improvements should be made to the heat exchanger in order to heat the water more effectively.

In Figure 13 the EES calculations for the parallel flow heat exchanger with the values provided in the assignment, Heat transfer of the fluids over the length of the heat exchanger can be seen. From the heat transfer over the length of the heat exchanger displayed it is clear that the heat transfer of the fluid decreases with each subsequent section.

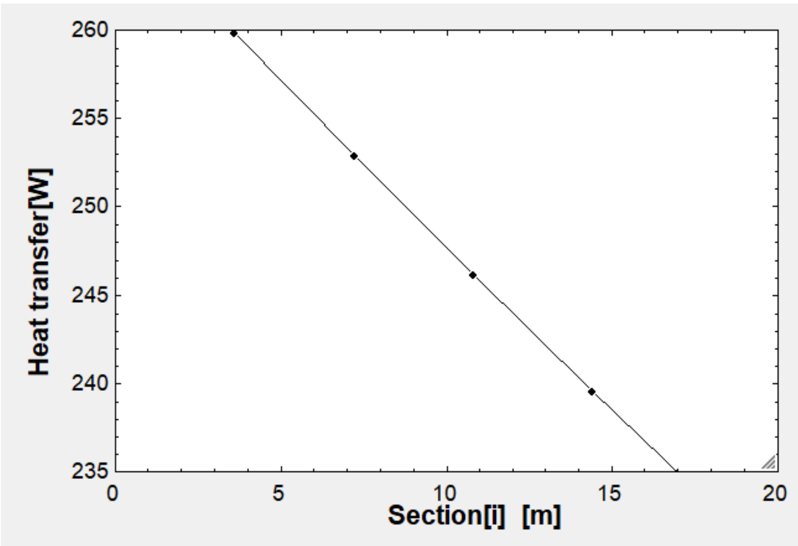

Figure 13: Parallel flow heat transfer for HX values

1.2 Heat exchanger improvement

Improvements are made to obtain a could fluid outlet temperature of 10 to 15 % of the hot fluid inlet temperature for the fixed inlet temperatures. The mass flow, tube length, number of tubes, diameter, height, width, material and flow configuration may be changed to improve the heat exchanges [1].

1.2.1 Effect of flow configuration

From theory it is assumed that counter flow is more effective than parallel flow configuration. From the simulation in Figure 14 of the model for counter flow configuration the effect is negligible at the given parameters. The counter flow configuration will be revisited once a more favourable temperature gradient is found.

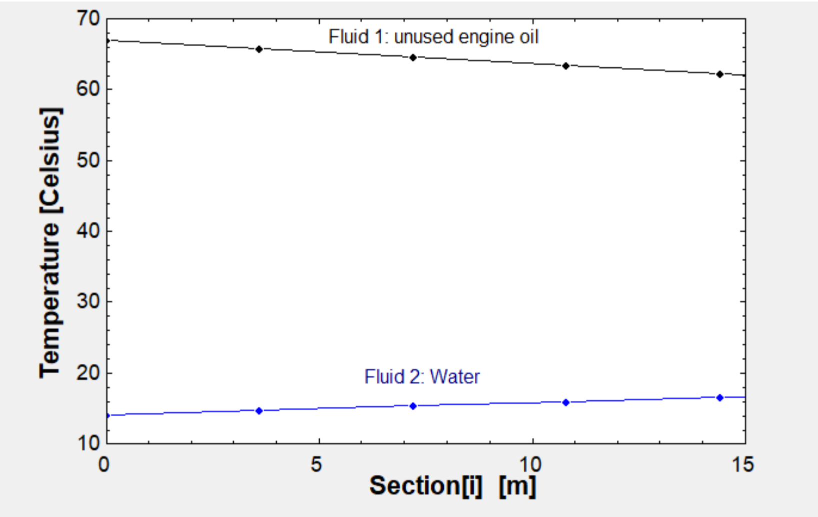

Figure 14: Output temperature for fluid 1 and 2 when flow configuration is changed

In the Figure 15 below the heat transfer for the heat exchanger with a counter flow configuration can be seen as a function of the position in the tube, where the tube length is 18m.

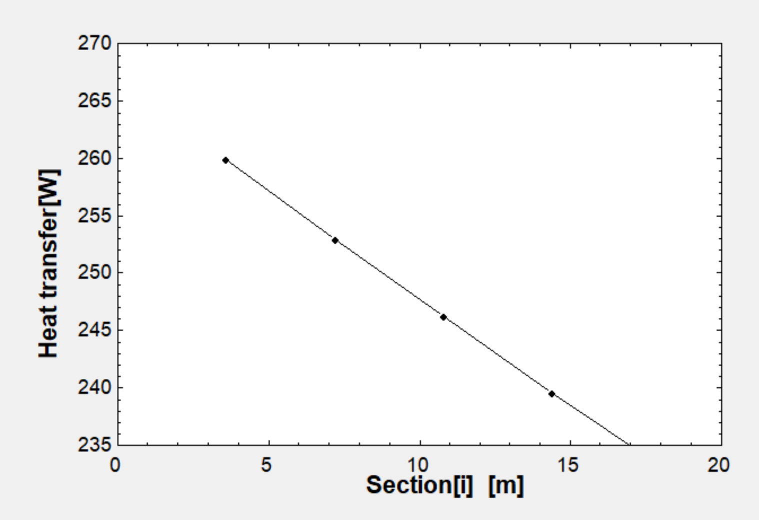

Figure 15: Heat transfer for flow configuration change

1.2.2 Effect of mass flow

The effect of mass flow in the out put temperatures of the two fluids is arguably the greatest. From the Figure 16 below it is clear that the mass flow rate improves the temperature change drastically. In order to change the mass flow rate, the input speed for the two fluids must be changed. From the Table 4 below it is clear that the increase in fluid 1's input velocity results in the increase in output temperature of fluid 2. However to successfully change the output temperatures to required temperature the velocity of fluid 2 must also be altered. The increase in fluid 2's input velocity results in a decrease in the output temperature. Therefore it is reasonable to conclude that the input velocity of fluid 1 must be large and the input velocity of fluid 2 must be small.

Table 4: mass flow rate effect on output temperatures

Input [m/s]	Temperature	Value	SI Unit
V_hx_1=10	Fluid 1 outlet temperature	48.13	°C
	Fluid 2 outlet temperature	24.05	°C
25	Fluid 1 outlet temperature	60.91	°C
	Fluid 2 outlet temperature	17.28	°C

In the Figure 16 below the output voltage of the two fluids are plotted over the length of the heat exchanger. In the figure the blue line represents fluid 2 and the black line represents fluid 1. The figure is plotted for fluid 1 with an input velocity of 10 meter per second and fluid 2 with an input velocity of 0.01 meter per second.

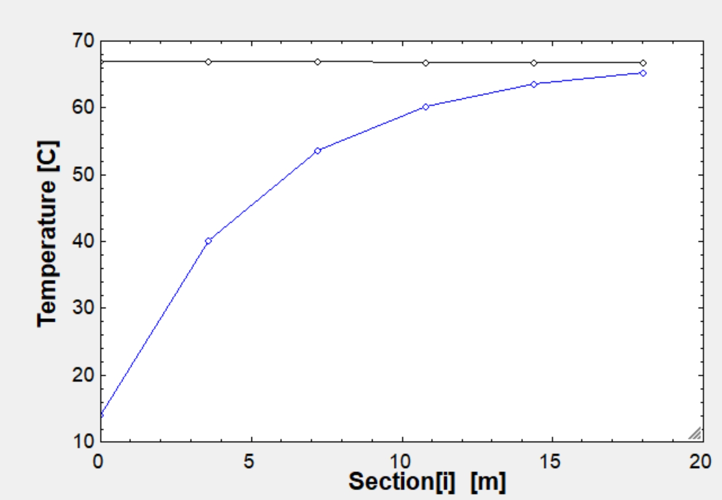

Figure 16: mass flow rate effect on output temperatures

From the results of Figure 16 the output temperature of fluid 2 is 2.593% from the input temperate of fluid 1. In Figure 17 below the effect of mass flow rate on heat transfer [W] as a function of the length of the heat exchanger can be seen.

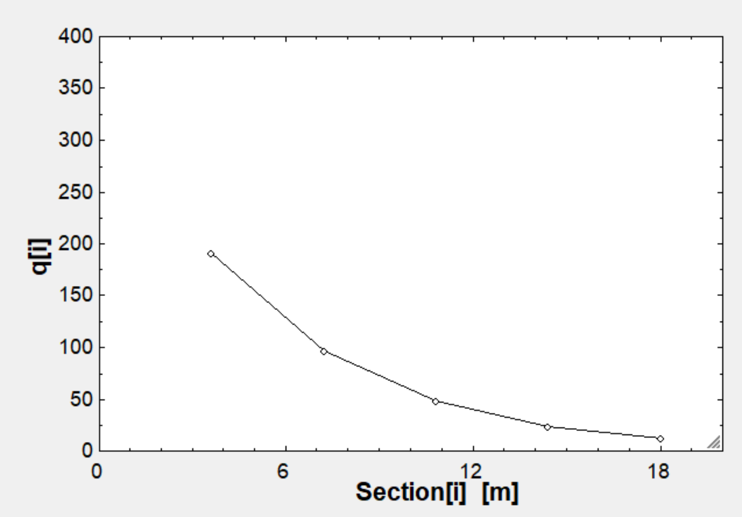

Figure 17: effect of mass flow rate on heat transfer

1.2.3 Effect of tube length

In the Figure 18 below the effect of increasing the length of the heat exchanger from 18 m to 100 m can be seen. It is clear from the graph that though the temperature of fluid 2 increases as desired, the temperature of fluid 1 decreases dramatically and it would be impossible to have a fluid 2 output temperature of 15% from the input temperature of fluid 1.

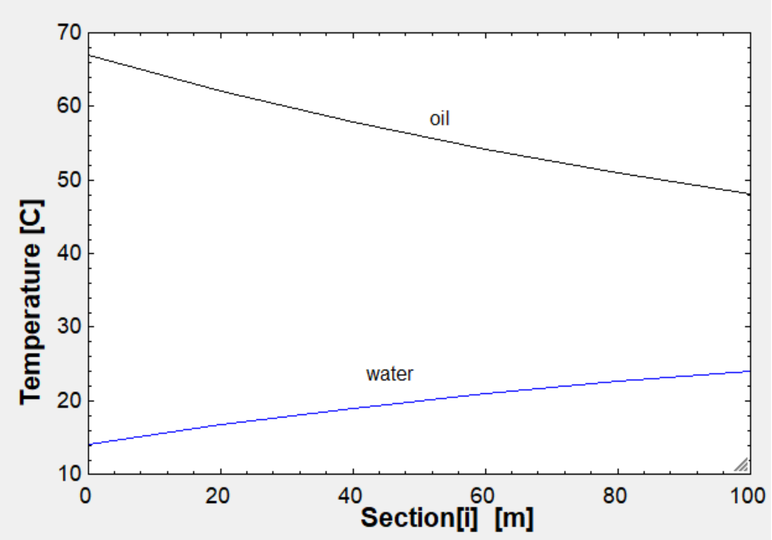

Figure 18: Effect of 100m length heat exchanger on the output temperatures

In the Figure 19 below the effect of the change in the heat exchanger pipe length can be seen on the heat transfer.

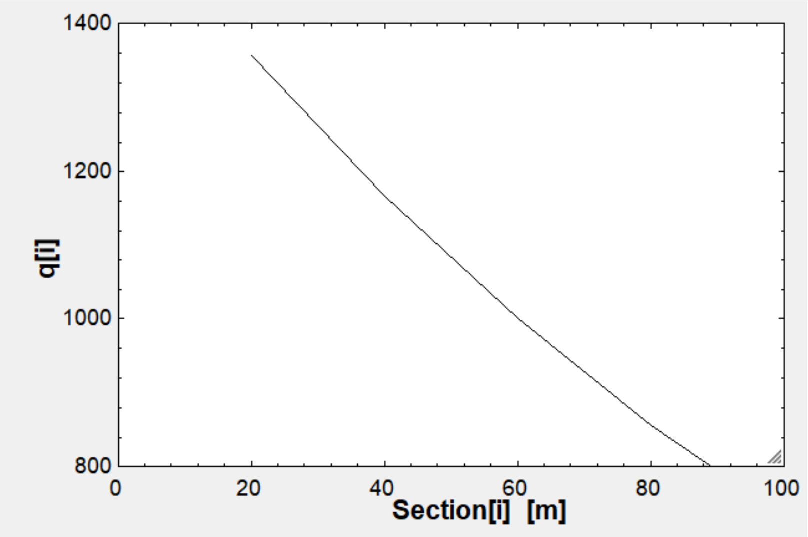

Figure 19: Effect of heat exchanger length on the heat transfer [W]

From the Table 5 the effect of different lengths of the heat exchanger pipe can be seen. It is clear that the increase in fluid 2's temperature comes at the cost of decreasing the temperature of fluid 1 dramatically.

Table 5: Effect of heat exchanger pipe length on output temperature

Length [m]	Temperature	Value	SI Unit
100	Fluid 1 outlet temperature	48.13	°C
	Fluid 2 outlet temperature	24.05	°C
25	Fluid 1 outlet temperature	60.91	°C

	Fluid 2 outlet temperature	17.28	°C

1.2.4 Effect of diameter

The effect of changing the inner diameter of the pipe through which fluid 1 flows can be seen below. In the Figure 20 below the effect of changing the diameter to 1 mm is shown it clear that the output temperature of fluid 1 drops while the output temperature of fluid 2 barely rises.

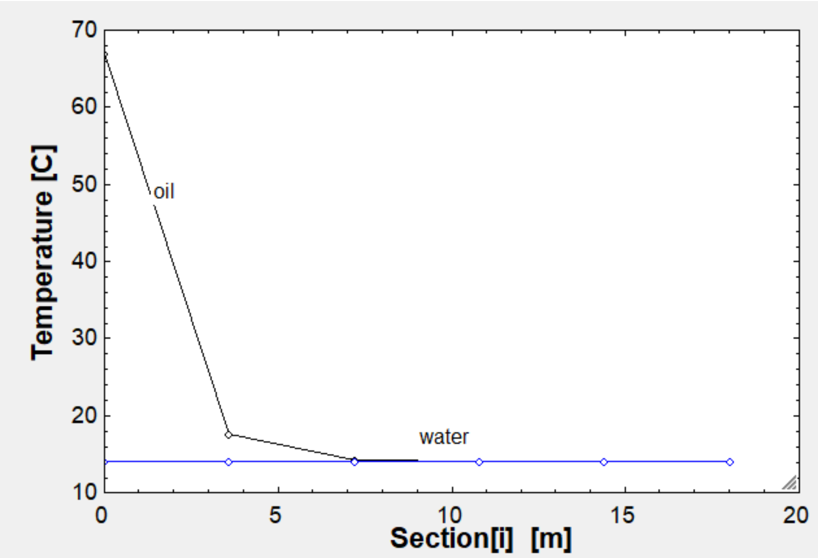

Figure 20: Effect of diameter on output temperatures

In Figure 21 below the effect of changing the diameter to 1mm can be seen. It is clear that the heat transfer was significantly lowered.

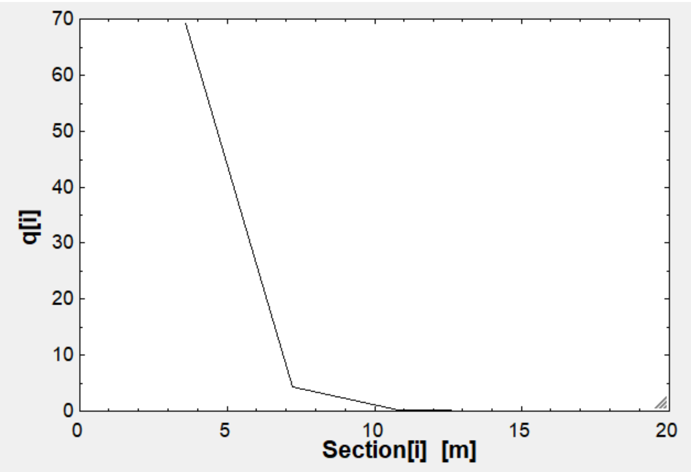

Figure 21: Effect of diameter on heat transfer [W]

In the Table 6 below the effect of increasing the diameter to 16 mm can also be seen. Increasing the diameter to 16 mm increased the output temperature of fluid 1, however the output temperature of fluid 1 decreased.

Table 6: Effect of diameter on output temperatures

Diameter [mm]	temperature	Value	SI Unit
1	Fluid 1 outlet temperature	14.07	°C
	Fluid 2 outlet temperature	14.07	°C
16	Fluid 1 outlet temperature	63.59	°C
	Fluid 2 outlet temperature	17.41	°C

1.2.5 Effect of height

The effect of the height Hoi as shown in Figure 3 on the output temperatures of the two fluids can be seen in Figure 22 below. In the Figure 22 the effect of increasing the diameter to 15,8mm is depicted. The output temperature of fluid 1 is higher than the original 20 mm's output temperature. Though the output temperature of fluid 2 is increased it is not sufficient for the requirements of the assignment.

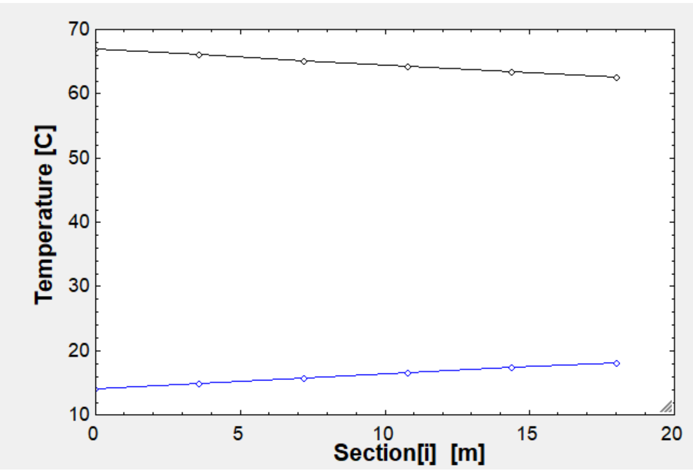

Figure 22: effect of height on outlet temperature

From the heat transfer in Figure 23 below it is clear that the heat transfer is less than the original height.

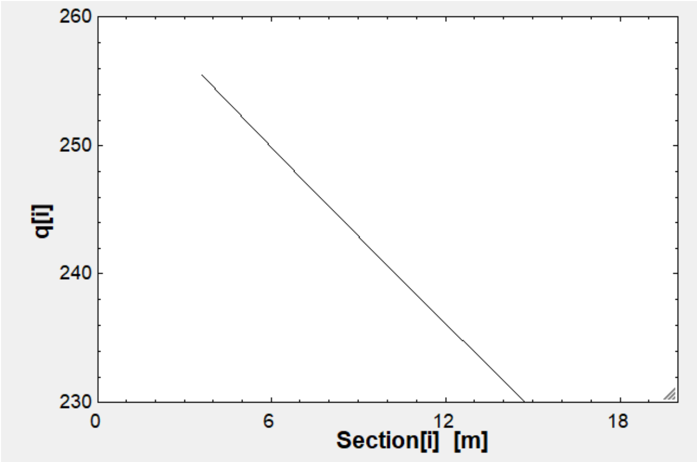

Figure 23: effect of height on heat transfer

It is clear from Table 7 that the height must be decreased in order to increase the outlet temperature of fluid 2.

Table 7: Effect of height on the outlet temperatures

height [mm]	temperature	Value	SI Unit
100	Fluid 1 outlet temperature	61.69	°C
	Fluid 2 outlet temperature	14.31	°C
15.8	Fluid 1 outlet temperature	62.64	°C
	Fluid 2 outlet temperature	18.16	°C

1.2.6 Effect of width

The effect of the width on the output temperature of fluid 1 and 2 can be seen in Figure 24 below. It is unclear what the difference in width makes in comparison to the difference in height from the graph therefore the outlet temperature are shown in Table 8 below.

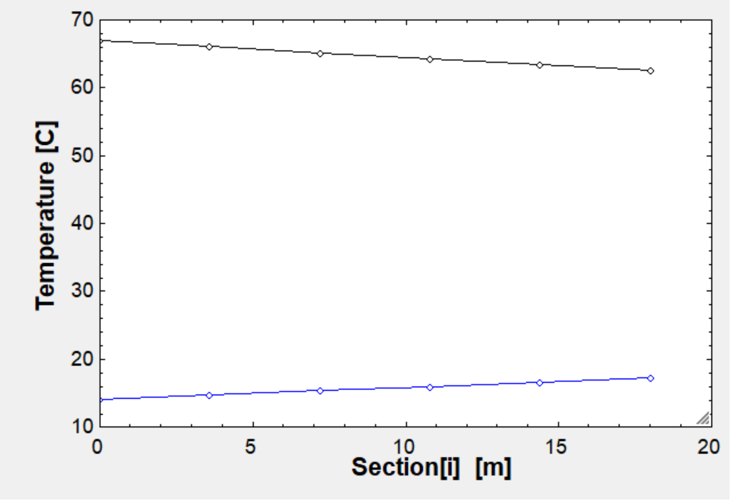

Figure 24: Effect of width on outlet temperatures

The heat transfer distribution in Figure 25: effect of width on heat transfer. From the graph it is clear that the heat transfer distribution is similar to the base value width heat transfer distribution.

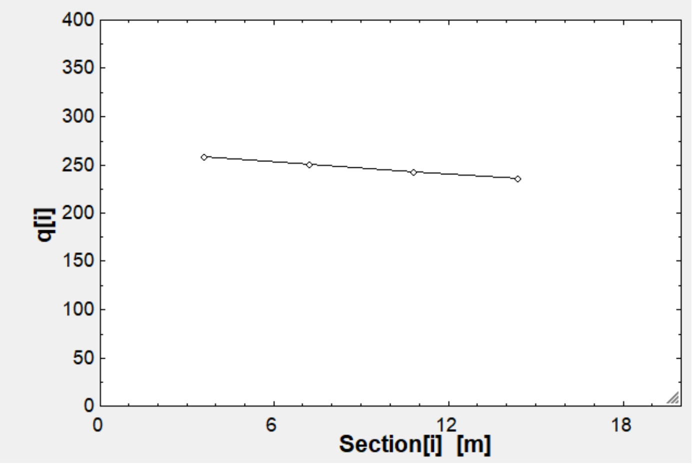

Figure 25: effect of width on heat transfer

Comparing Table 7 and Table 8 we can see that changing the height has a greater effect on the outlet temperature than changing the width. This however is simply due to the starting value of the height being larger than the starting value of the width. In order to have as high an outlet temperature for fluid 2 as possible the height and width should be kept as small as possible therefore in this case, they should be equal so that a square can be made around the inner tube instead of a rectangle. Ideally however two concentric cylinders would produce more effective results in heating the fluid 2.

Table 8: Effect of width on outlet temperatures

width [mm]	temperature	Value	SI Unit
100	Fluid 1 outlet temperature	61.09	°C

	Fluid 2 outlet temperature	14.3	°C
15.8	Fluid 1 outlet temperature	62.56	°C
	Fluid 2 outlet temperature	17.2	°C

1.2.7 Effect of material

The material used in the heat exchanger is Copper which is a very conductive material. However, a more conductive material is silver and a less conductive material is stainless AISI106 which is investigated below. In the Figure 26 the effect on the outlet temperature for fluid 1 and 2 is shown when the material is changed to silver.

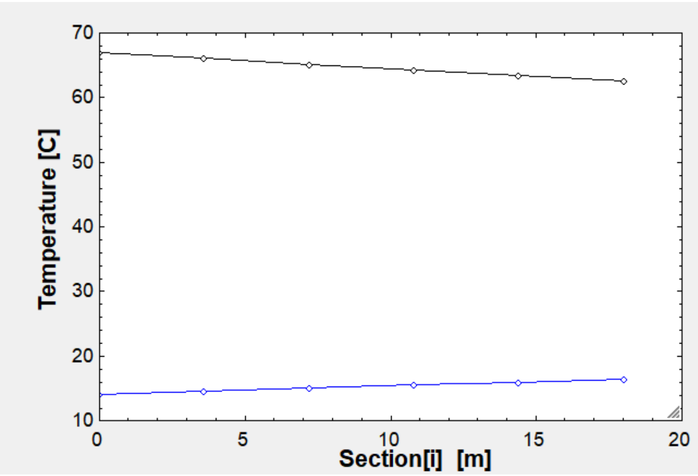

Figure 26: Effect of material on outlet temperatures

In the Figure 27 below the heat transfer distribution of silver can be seen, it is similar to the heat transfer distribution of copper.

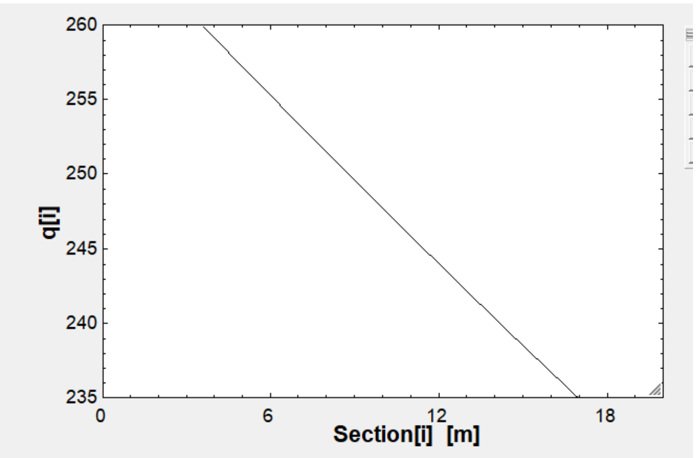

Figure 27: Effect of material on heat transfer

In the Table 9 the effect of silver and Stainless steel is compared. From the comparison it is clear that the two materials produce negligible amount of difference in the outlet temperature.

Therefore, changing the material of the heat exchanger is not advised as an improvement to the design.

Table 9: Effect of material on outlet temperature

Material	temperature	Value	SI Unit
silver	Fluid 1 outlet temperature	62.5	°C
	Fluid 2 outlet temperature	16.42	°C
Stainless AISI316	Fluid 1 outlet temperature	62.51	°C
	Fluid 2 outlet temperature	16.42	°C

1.2.8 Improvement advised

When taking into account the physical aspects of improving the heat exchanger to operate with an output temperature for fluid 2 of 10 to 15% of the input temperature of fluid 1. I would advise that the mass flow rates' be improved in order to achieve the desired output temperatures. The mass flow rates should be changed by altering the input velocities of the unused engine oil and the water. These velocities may be changed as follow. The input velocity of fluid 1 should be increased to 10m/s and the input velocity of fluid 2 should be decreased to 0,015m/s. When these values are applied to the parameters the output temperature of fluid 2 is 7.981% from the input temperature of fluid 1. As can be seen in Figure 28 where the output temperature of fluid 1 is 66.81 degrees Celsius and the output temperate of fluid 2 is 61.65 degrees Celsius. The percentage error is well within the provided boundaries.

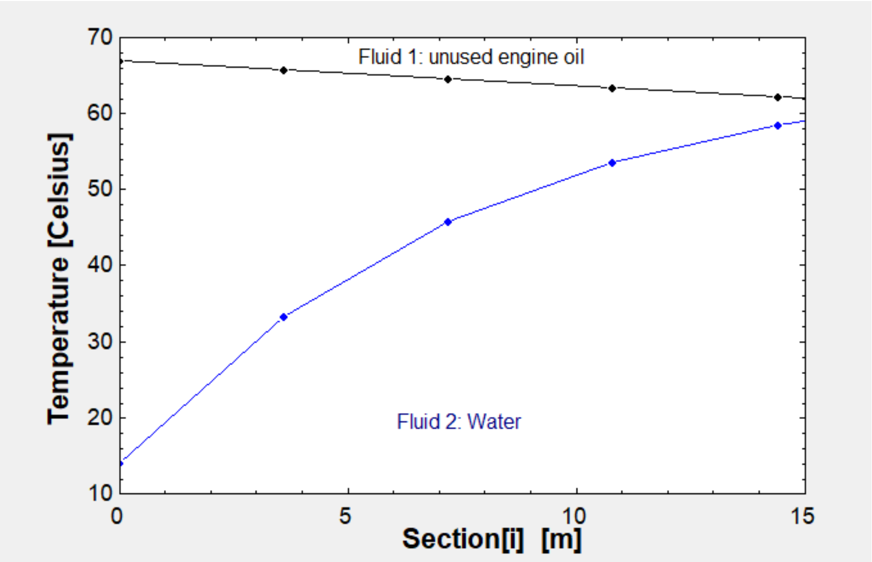

Figure 28: advised heat exchanger parameters temperature outputs

I would advise against changing the other parameters as the effect is minimal on the output temperature as can be seen in the sections above. And the impact of the cost of construction changes on the heat exchanger will outweigh any of the minimal impact the other parameters have on the output temperature.

1.3 Verification of heat exchanger calculations

The ε-NTU method is used to do hand calculations for one of the six parallel sections of the heat exchanger. The inlet and outlet of the complete section calculations results is compared to the final results of the EES calculations. The hand calculations can be seen below. To calculate the parameters the EES properties of the two fluids are used as follow.

Table 10: EES properties of parameters in HX used for hand calculations

Parameter	Fluid 1: Engine oil unused	Fluid 2: Water	Copper	Unit
c_p	2077	4184	-	kJ/kg.K
k	0.1401	0.5751	395.4	W/m.K
ρ	859.8	999.3	-	kg/m³
μ	0.05284	0.001169	-	N.s/m

From the Table 10 the hand calculations are made and documented below. Results of the hand calculations are shown in Table 11 below. The hand calculations were done using the following mathematics.

Table 11: Hand calculations results

Parameter	Value	Unit
Fluid 1 (HOT)	Engine oil unused	-
Fluid 2 (COLD)	Water	-
A_1	0.0001539	m^2
A_2	0.0001737	m^2
$\dot{m}_1$	0.1324	Kg/s
$\dot{m}_2$	0.1215	Kg/s
C_1	274.9948	J/s K
C_2	508.356	J/s K
C_r	0.540949256	-

UA	24.85729745	W/K
Re_1	227.8805501	-
Re_2	158.1330532	-
h_1	43.63114286	W/m^2 K
h_2	72.99668122	W/m^2 K

The mass flow rate for the unused engine oil and water was calculated using equation (3). The areas for the two fluids are calculated as follow,

$$A_{1-cross\ section} = \frac{\pi {D_{ii}}^2}{4} \tag{4}$$

$$\frac{\pi 0.014^2}{4} = 0.0001539\ m^2$$

And,

$$A_{2-cross\ section} = H_{oi}W_{oi} - \frac{\pi {D_{io}}^2}{4} \tag{5}$$

Where the D_{io} is calculated with,

$$D_{io} = 2t + D_{ii} \tag{6}$$

$$D_{io} = 2(0.0007) + 0.014 = 0.0154\ m$$

Therefore, area for fluid 2 is calculated as,

$$A_{2-cross\ section} = (0.02)(0.018) - \frac{\pi 0.0154^2}{4} = 0.0001737 m^2$$

The mass flow rate for the two fluids are therefore calculated as follow. The mass flow rate for fluid one is calculated as.

$$\dot{m}_1 = \rho_1 v_1 A_1 = (859.8)(1)(0.0154) = 0.1324\ kg/s$$

And mass flow rate of fluid 2 is calculated as.

$$\dot{m}_2 = \rho_2 v_2 A_2 = (999.3)(0.7)(0.0001737) = 0.1215\ kg/s$$

Next the fluid heat capacity rate for the hot and cold fluid is calculated respectively C_1 and C_2 [5]. The fluid heat capacity rate is equal to the product of the fluid specific heat pressure constant and the mass flow rate of the fluid as shown in equation (7) below.

$$C_i = c_{pi}\dot{m}_i \tag{7}$$

Where i=1,2 for the hot and cold fluid respectively. Therefore fluid 1 is calculated as,

$$C_1 = c_{p1}\dot{m}_1 = (2077)0.1324 = 274.9948\ \frac{J}{s}K$$

And Fluid 2 is,

$$C_2 = c_{p2}\dot{m}_2 = (4184)0.1215\ = 508.356\ \frac{J}{s}K$$

From this we can see that,

$$C_{min} = C_1$$

And,

$$C_{max} = C_2$$

Next the ratio C_r is calculated by from the minimum value over the maximum value of the fluid heat capacity rate, therefore,

$$C_r = \frac{C_{min}}{C_{max}} = \frac{274.9948}{508.356} = 0.540949256 \tag{8}$$

The flow region of the fluid is determined from the fluids Reynolds number (Re) calculated with equation (9) [5].

$$Re_1 = \frac{4\dot{m}_1}{\pi\mu D_{ii}} = \frac{4(0.1324)}{\pi(0.05284)(0.014)} = 227.8805501 < 2300 \tag{9}$$

Where D_{ii} is the inner diameter of the fluid 1. Where tit is laminar flow when R_e<2300, turbulent flow when 2300<R_e<4000 and turbulent flow at R_e>4000 [7].Therefore fluid 1 flows laminar and therefore the Nusselt number is,

$$Nu_1 = 4.36$$

For fluid 2 the Reynolds number is calculated with,

$$Re_2 = \frac{\dot{m}_2 D_{h2}}{\left(H_{oi}W_{oi} + \frac{\pi D_{io}}{4}\right)\mu} \tag{10}$$

$$Re_2 = \frac{0.1215(0.01895)}{\left((0.02)(0.018) + \frac{\pi(0.0154)}{4}\right)0.001169} = 158.1330532 < 2300$$

Therefore, the flow is also laminar flow and therefore,

$$Nu_2 = 4.36$$

For turbulent flow the Nusselt number is calculated with:

$$Nu_T = 0.023Re^{4/5}Pr^{0.4} \tag{11}$$

The laminar flow Nusselt number is calculated with,

$$Nu_L = 0.667Re^{0.4}Pr^{1/3} \tag{12}$$

To calculate one tube's overall heat transfer coefficient (UA) the following formula is used in equation (8) [5] the overall thermal resistance,

$$\frac{1}{UA} = \frac{1}{h_i \pi D_{ii} L \eta_o} + \frac{R"_f}{\pi D_{ii} L \eta_o} + \frac{\ln\left(\frac{D_{io}}{D_{ii}}\right)}{2\pi k_{copper} L} + \frac{1}{h_2\left((2W_{oi} + 2H_{oi})\right)L} \tag{13}$$

Where η_o is equal to 1 and h for fluid 1 is calculated with [5],

$$h_1 = \frac{Nuk}{D_{ii}} = \frac{(4.36)(0.1401)}{0.014} = 43.63114286 \text{ W/m}^2 K \tag{14}$$

And enthalpy h for fluid 2 is calculated with the following equation,

$$h_2 = \frac{Nuk}{D_{h2} + D_{io}} = \frac{(4.36\,)(0.5751)}{0.01895 + 0.0154} = \;72.99668122 \text{ W/m}^2 K \tag{15}$$

Where the hydraulic diameters for the outer rectangular pipe is calculated as follow,

$$D_{h2} = \frac{2H_{oi}W_{oi}}{H_{oi} + W_{oi}} = \frac{2(0.02)(0.018)}{0.02 + 0.018} = 0.01894736842\, m \tag{16}$$

Therefore, the heat transfer coefficient is calculated as follow for the full length,

$$\frac{1}{UA} = \frac{1}{43.63114286\pi(0.014)(18)(1)} + \frac{0.001}{\pi(0.014)(18)(1)} + \frac{\ln\left(\frac{0.0154}{0.014}\right)}{2\pi(395.4)(18)} + \frac{1}{(72.99668122)\left(18(2(0.018) + 2(0.02)\right)}$$

$$UA = 24.85729745\, W/K$$

To determine the heat transfer q the number of transfer unit must first be calculated.

$$NTU = \frac{UA}{C_{min}} = \frac{24.85729745}{274.9948} = 0.09039188177 \tag{17}$$

From which the heat transfer is calculated with,

$$q = C_{min}(T_{1i} - T_{2i})\left(\frac{1 - e^{-NTU(1+C_r)}}{1 + C_r}\right) \tag{18}$$

$$q = 274.9948(67 - 14)\left(\frac{1 - e^{-0.09039188177(1+0.540949256)}}{1 + 0.540949256}\right)$$

$$q = 1229.800078\, W$$

The output temperatures are then calculated as follow for i=1,2

$$T_{i\,out} = T_{i\,in} + \frac{q}{C_i} \tag{19}$$

Therefore, the fluid 1 output temperature is calculated as follow,

$$T_{1\,out} = T_{1\,in} + \frac{q}{C_1} = 67 - \frac{1229.800078}{274.9948} = 62.5791515\ ℃$$

And fluid 2 output temperature is calculated as follow,

$$T_{2\,out} = T_{2\,in} + \frac{q}{C_2} = 14 + \frac{1229.800078}{508.356} = \ 16.41917097\ ℃$$

The result of the hand calculations for one of the intervals compared to the EES calculations can be seen in Table 12 below.

Table 12: EES calculation results vs hand calculations results

Parameter	EES Calculations	Hand Calculations	Unit
Fluid 1 Outlet Temperature	62.5	62.5791515	°C
Fluid 2 Fluid Outlet Temperature	16.42	16.41917097	°C
Heat Exchanger Total Heat Transfer	1232	1229.00078	kW

From Table 12 it can be seen that the values for the hand ad EES calculations are very similar. There are however some discrepancies. This is due to the N increments into which the EES model was divided while only one increment was looked at in the hand calculations. Rounding done in the hand calculations also play a part in the accuracy of the hand calculations output. The manner in which the EES calculations were conducted make the EES calculation results more accurate than the hand calculations.

2 Part 2

For part 2 of the assignment the configuration is changed to crossflow as can be seen in the Figure 29 below. Fluid 2 passes through the top and bottom of the channel opening. Fluid 1 is mixed and fluid 2 is unmixed because if separation plates.

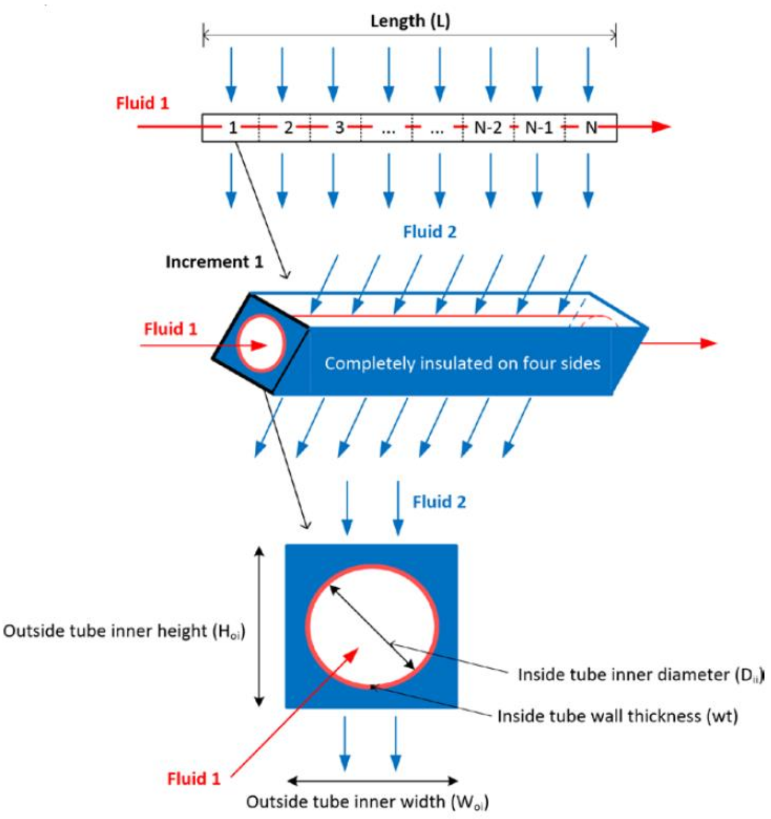

Figure 29: Part 2 cross flow

For the cross flow the following condition apply [5]:

For C_{max} mixed fluid and C_{min} unmixed fluid,

$$X = 1 - \frac{1}{e^{NTU}} \tag{20}$$

And,

$$\varepsilon = \frac{1}{C_r}\left(1 - \frac{1}{e^{C_r X}}\right) \tag{21}$$

With NTU,

$$NTU = -\ln\left(1 + \frac{1}{C_r}\ln(1 - \varepsilon C_r)\right) \tag{22}$$

For C_{min} mixed fluid and C_{max} unmixed fluid,

$$Y = 1 - \frac{1}{e^{C_r NTU}} \tag{23}$$

And,

$$\varepsilon = 1 - \frac{1}{e^{\frac{Y}{C_r}}} \tag{24}$$

With NTU,

$$NTU = -\frac{1}{C_r}\ln(C_r\ln(1-\varepsilon)+1) \tag{25}$$

2.1 2.1 Cross flow heat exchanger results

The following parameters where calculated with EES, the code is attached in appendix A at the end of the report.

Table 13: Cross flow heat exchanger parameters

Parameter	Value	SI Unit
Hot fluid outlet temperature	63.05	°C
Cold Fluid temperature	16.13	°C
Heat exchanger total heat transfer	1083	kW

The temperature distribution for fluid 1 and fluid 2 through the heat exchanger can be seen in the Figure 30 below. It is clear that the heat distribution is similar to the heat distribution of the parallel flow.

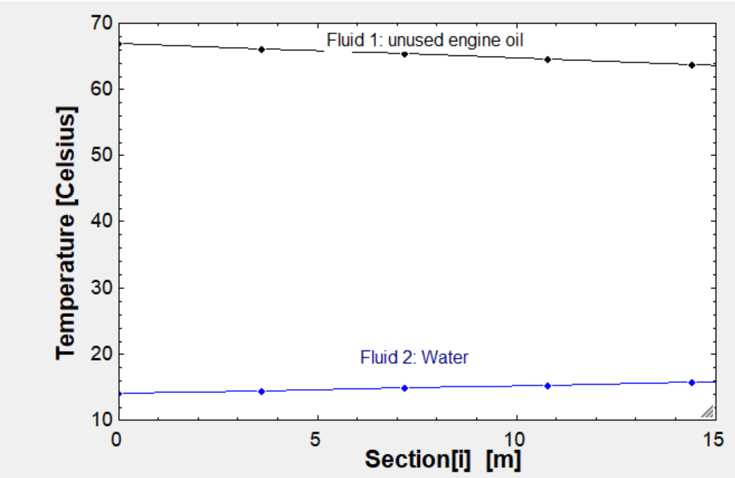

Figure 30: Cross flow outlet temperature

The heat transfer distribution of the heat exchanger can be seen in the Figure 31 below. From the heat transfer distribution it is clear that the heat transfer distribution of the cross flow configuration is much higher than the heat distribution of the parallel flow distribution.

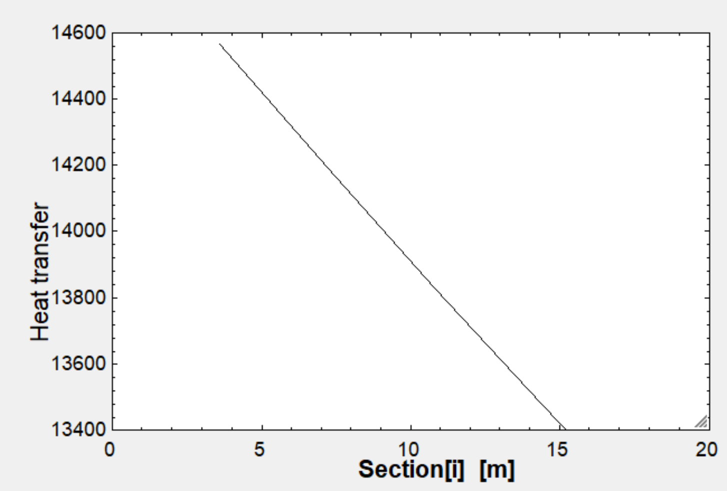

Figure 31: Cross flow Heat transfer

From the results obtained of the cross flow, the outlet temperature of fluid 1 and 2 are very similar. However, the parallel flow had a larger outlet temperature for fluid 2 than the cross flow. Therefore, the parallel is preferable as the important factor is to increase the outlet temperature of fluid. Thither more, calculating the parallel flow for concentric tube construction is simpler and therefore, less liable to human error leading to error in the calculation.

3 Part 3

3.1 ECSA exit level outcome 2

ELO 2 focuses on complex engineering problem solving through the application of knowledge of mathematics, natural sciences, engineering fundamentals and engineering speciality [1]. This is characterized by the following points:

- A systematic, theory-based understanding of natural science applicable to the discipline [1] . Proof of adherence to this in the exam assignment can be seen in:
    - In order to solve the heat exchanger problem, the fundamental laws of engineering and science must be understood and applied. As these laws dictate how the heart exchanger will act and therefore dictate how the problem should be treated in order to come to a logical conclusion.
- Application of mathematics, numerical analysis, statistics and formal aspects of computer and information science to support the analysis and modelling applied to the discipline [1]. Proof of adherence to this in the exam assignment can be seen in:
    - Computer and information science were used in order to create a mathematical model of the heat exchanger. The program used to model the heat exchanger was EES. This allowed the simple analysis of the heat exchanger output temperatures and heat

transfer when different parameters where selected and changed in order to improve the heat exchanger design to operate more efficiently.

- A systematic, theory-based formulation of engineering fundamentals must be displayed [1]. Proof of adherence to this in the exam assignment can be seen in:
    - In order to create the model in EES the theory behind heat exchangers were studied extensively. From the theory a formulation of the theory-based knowledge can be seen in the EES program as the theory was required to program the simulation. Systematic theory-based formulation of the engineering fundamentals of heat exchangers is displayed in the verification of results section of the report. Where the formulas used for the calculations as well as the reasoning behind the formulas is displayed to solve the problem with the ε-NTU method.
- Engineering specialist knowledge that provides theoretical frameworks and bodies of knowledge for the accepted practice areas in the engineering discipline; much is at the forefront of the discipline [1]. Proof of adherence to this in the exam assignment can be seen in:
    - This is shown through the design and improvement of the heat exchanger through modelling of the heat exchanger for different scenarios and formulating a improvement to satisfy the client's needs.

4 Conclusion

A manufacturing company desires to know the operation of a second hand heat exchanger. The manufacturing facility requires the outlet temperature of the cold fluid to be within 10 % to 15% of the inlet temperature of the hot fluid. Therefore, it was determined how to modify the heat exchanger in order to produce an outlet temperature within 10-15% of the inlet temperature of the hot fluid. The ε-NTU method was used to calculate the required output parameters for the heat exchanger. From the simulation in EES of the existing heat exchanger provided parameter the output temperature for the Engine_Oil_Unused is 62.5 C and the output temperature for the water is 16.42 C while the power output is1232 W.

In order to improve the heat exchanger, the mass flow rate was altered. To alter the mass flow rate the input velocities of the two fluids were changed. As the purpose of the heat exchanger is for fluid 1 to heat fluid 2, the input velocity of fluid 1 was increased and the input velocity of fluid 2 was decreased. Simply by altering these two mass flow rates the outlet temperature of fluid 1 was changed to 66.81 degrees Celsius and the outlet of fluid 2 equal to 61.65 degrees Celsius. Therefore, the outlet temperature of fluid 2 is equal to 7.981% of the inlet of fluid 1.

5 References

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6 Appendix A: EES Code

6.1 Parallel flow code

```
Function Nu_1(Re_1;Pr_1)

"determine the Nusselt number of Unused Oil"
if(Re_1>2300) Then

"Laminar If Re<2300, else Turbulent"
Nu_1=0,023*Re_1^0,8*Pr_1^0,4

"Nusselt number for turbulent flow"
Else
Nu_1=4,36

"Nusselt number for laminar flow"
Endif
End

Function Nu_2(Re_2;Pr_2)

"nusselt number"
if(Re_2>2300) Then

"Laminar If Re<2300, else Turbulent"
Nu_2=0,023*Re_2^0,8*Pr_2^0,4

"Nusselt number for turbulent flow"
Else
Nu_2=4,36

"Nusselt number equation for laminar flow"
Endif
End

{CF Greyling 25924974 1.1. Heat transfer for parallel flow}
"Parameters for heat exchanger"
{Fluid 1: Engine oil unused
Fluid 2: Water
Pipe: Copper
Flow direction : parallel }
N=5[-]
L=18[m]
Dii=14/1000[m]
Hoi=0,02[m]
Woi=0,018[m]
Rf=0,001[K.m^2/W]
T_1[0]=67[C]

"Fluid 1 inlet temperature HOT Fluid"
T_2[0]=14[C]

"Fluid 2 inlet temperature COLD Fluid"
v_hx_1=1[m/s]

"Inlet velocity per HX section Fluid 1"
v_hx_2=0,7[m/s]

"Inlet velocity per HX section Fluid 2"
P_i=150[kPa]
t=0,0007[m]

"Wall thickness"
Dio=2*t+Dii
n_0=1[-]
Dh_1=Dii
Dh_2=(2*Hoi*Woi)/(Hoi+Woi)
A_1=Dii^2*pi/4
A_2=(Hoi*Woi)-(Dio^2*pi/4)
Section[0]=0[m]


{Density}
```

```
rho_1[0]=density(Engine_Oil_Unused;T=T_1[0]) {kg/m^3}
rho_2[0]=density(Water; T=T_2[0];P=P_i) {kg/m^3}

{Mass flow rate}
m_dot_1[0] = rho_1[0] * v_hx_1 * (pi/4) * (Dii)^2 {kg/s}
m_dot_2[0] = rho_2[0] * v_hx_2 * A_2 {kg/s}

{increments}
Duplicate i=1;N

T_1i[i]=T_1[i-1] {C}

T_2i[i]=T_2[i-1] {C}

"Fluid 1 parameters: Engine oil unused"
mu_1[i]=viscosity(Engine_Oil_Unused; T=T_1i[i]) {kg/m.s}
c_p_1[i]=1000*cp(Engine_Oil_Unused; T=T_1i[i]) {J/kg.K}
k_1[i]=conductivity(Engine_Oil_Unused; T=T_1i[i]) {W/m.K}

"Fluid 2 parameters: Water"
mu_2[i]=viscosity(Water; T=T_2i[i];P=P_i) {kg/m.s}
c_p_2[i]=1000*cp(Water; T=T_2i[i];P=P_i) {J/kg.K}
k_2[i]=conductivity(Water; T=T_2i[i];P=P_i) {W/m.K}

"Copper pipe"
T_avg[i]=(T_1i[i]+T_2i[i])/2 {C}
k_copper[i]=conductivity(Copper; T=T_avg[i]) {W/m.K}

{Reynold and Pressure}

Re_1[i]=(4*m_dot_1[0])/(pi*(Dii)*mu_1[i]) {-}
Pr_1[i]=(c_p_1[i]*mu_1[i])/k_1[i] {-}
Re_2[i]=(m_dot_2[0]*Dh_2)/((Hoi*Woi+(pi*Dio/4))*mu_2[i]) {-}
Pr_2[i]=(c_p_2[i]*mu_2[i])/k_2[i] {-}

C_1[i]= m_dot_1[0]*c_p_1[i] {kg/s(J/kg.K)}
C_2[i]= m_dot_2[0]*c_p_2[i] {kg/s(J/kg.K)}
C_max[i]=max(C_1[i];C_2[i]){ kg/s(J/kg.K)}
C_min[i]=min(C_1[i];C_2[i])  {kg/s(J/kg.K)}
C_r[i]=C_min[i]/C_max[i] {-}

Nusselt_1[i]=Nu_1(Re_1[i];Pr_1[i]) {-}
Nusselt_2[i]=Nu_2(Re_2[i];Pr_2[i]) {-}

h_1[i]=(k_1[i]/Dii)*Nusselt_1[i] {W/m^2.K}
h_2[i]=(k_2[i]/(Dh_2+Dio))*Nusselt_2[i] {W/m^2.K}
x1[i]=1/(h_1[i]*pi*Dii*(L/N)*n_0)

UA[i]= 1/(x1[i]+Rf/(pi*Dii*(L/N)*n_0)+ ln(Dio/Dii)/(2*pi*(L/N)*k_copper[i]) + 1/(h_2[i]*((2*Woi+2*Hoi)*(L/N)))) {W/K}
NTU[i]=UA[i]/C_min[i] {-}

epsilon[i]=(1-exp(-NTU[i]*(1+C_r[i])))/(1+C_r[i]) {-}

"episilon"
q_max[i]= C_min[i]*(T_1i[i]-T_2i[i]) {W}

q[i]=epsilon[i]*q_max[i] {W}

T_1[i]=T_1i[i]-q[i]/C_1[i] {C}
T_2[i]=T_2i[i]+q[i]/C_2[i] {C}

Section[i]=i*L/N {m}

End
UA_total=(sum(UA[i];i=1;5))

T_1=T_1[5] {C}
T_2=T_2[5] {C}

q_total=(sum(q[i];i=1;5)) {W}
q_total_6Pipes=6*q_total

{6 pipes in parallel}

Percentage_change=(1-(T_2[5]/T_1[0]))*100 {%}

{$ST$ON}
```

6.2 Counter flow code

```
Function Nu_1(Re_1;Pr_1)

"determine the Nusselt number of Unused Oil"
if(Re_1>2300) Then

"Laminar If Re<2300, else Turbulent"
Nu_1=0,023*Re_1^0,8*Pr_1^0,4

"Nusselt number for turbulent flow"
Else
Nu_1=4,36

"Nusselt number for laminar flow"
Endif
End

Function Nu_2(Re_2;Pr_2)

"nusselt number"
if(Re_2>2300) Then

"Laminar If Re<2300, else Turbulent"
Nu_2=0,023*Re_2^0,8*Pr_2^0,4

"Nusselt number for turbulent flow"
Else
Nu_2=4,36

"Nusselt number equation for laminar flow"
Endif
End

Function epsi_1(C_r;NTU) " {epsilon if statement}"

if(C_r<1) Then

epsi_1=(1-exp(-NTU*(1-C_r)))/(1-C_r*exp(-NTU*(1-C_r)))

Else
epsi_1=NTU/(1+NTU)
Endif
End

{CF Greyling 25924974 1.1. Heat transfer for counter}
"Parameters for heat exchanger"
{Fluid 1: Engine oil unused
Fluid 2: Water
Pipe: Copper
Flow direction : parallel }
N=5[-]
L=18[m]
Dii=14/1000[m]
Hoi=0,02[m]
Woi=0,018[m]
Rf=0,001[K.m^2/W]
T_1[0]=67[C]

"Fluid 1 inlet temperature HOT Fluid"
T_2[0]=14[C]

"Fluid 2 inlet temperature COLD Fluid"
v_hx_1=1[m/s]

"Inlet velocity per HX section Fluid 1"
v_hx_2=0,7[m/s]

"Inlet velocity per HX section Fluid 2"
P_i=150[kPa]
t=0,0007[m]

"Wall thickness"
Dio=2*t+Dii
n_0=1[-]
Dh_1=Dii
Dh_2=(2*Hoi*Woi)/(Hoi+Woi)
```

```
A_1=Dii^2*pi/4
A_2=(Hoi*Woi)-(Dio^2*pi/4)
Section[0]=0[m]



{Density}
rho_1[0]=density(Engine_Oil_Unused;T=T_1[0]) {kg/m^3}
rho_2[0]=density(Water; T=T_2[0];P=P_i) {kg/m^3}

{Mass flow rate}
m_dot_1[0] = rho_1[0] * v_hx_1 * (pi/4) * (Dii)^2 {kg/s}
m_dot_2[0] = rho_2[0] * v_hx_2 * A_2 {kg/s}

{increments}
Duplicate i=1;N

T_1i[i]=T_1[i-1] {C}

T_2i[i]=T_2[i-1] {C}

"Fluid 1 parameters: Engine oil unused"
mu_1[i]=viscosity(Engine_Oil_Unused; T=T_1i[i]) {kg/m.s}
c_p_1[i]=1000*cp(Engine_Oil_Unused; T=T_1i[i]) {J/kg.K}
k_1[i]=conductivity(Engine_Oil_Unused; T=T_1i[i]) {W/m.K}

"Fluid 2 parameters: Water"
mu_2[i]=viscosity(Water; T=T_2i[i];P=P_i) {kg/m.s}
c_p_2[i]=1000*cp(Water; T=T_2i[i];P=P_i) {J/kg.K}
k_2[i]=conductivity(Water; T=T_2i[i];P=P_i) {W/m.K}

"Copper pipe"
T_avg[i]=(T_1i[i]+T_2i[i])/2 {C}
k_copper[i]=conductivity(Copper; T=T_avg[i]) {W/m.K}

{Reynold and Pressure}

Re_1[i]=(4*m_dot_1[0])/(pi*(Dii)*mu_1[i]) {-}
Pr_1[i]=(c_p_1[i]*mu_1[i])/k_1[i] {-}
Re_2[i]=(m_dot_2[0]*Dh_2)/((Hoi*Woi+(pi*Dio/4))*mu_2[i]) {-}
Pr_2[i]=(c_p_2[i]*mu_2[i])/k_2[i] {-}

C_1[i]= m_dot_1[0]*c_p_1[i] {kg/s(J/kg.K)}
C_2[i]= m_dot_2[0]*c_p_2[i] {kg/s(J/kg.K)}
C_max[i]=max(C_1[i];C_2[i]){ kg/s(J/kg.K)}
C_min[i]=min(C_1[i];C_2[i])  {kg/s(J/kg.K)}
C_r[i]=C_min[i]/C_max[i] {-}

Nusselt_1[i]=Nu_1(Re_1[i];Pr_1[i]) {-}
Nusselt_2[i]=Nu_2(Re_2[i];Pr_2[i]) {-}

h_1[i]=(k_1[i]/Dii)*Nusselt_1[i] {W/m^2.K}
h_2[i]=(k_2[i]/(Dh_2+Dio))*Nusselt_2[i] {W/m^2.K}
x1[i]=1/(h_1[i]*pi*Dii*(L/N)*n_0)

UA[i]= 1/(x1[i]+Rf/(pi*Dii*(L/N)*n_0)+ ln(Dio/Dii)/(2*pi*(L/N)*k_copper[i]) + 1/(h_2[i]*((2*Woi+2*Hoi)*(L/N)))) {W/K}
NTU[i]=UA[i]/C_min[i] {-}


epsilon[i]=epsi_1(C_r[i];NTU[i]){-}

"episilon"
q_max[i]= C_min[i]*(T_1i[i]-T_2i[i]) {W}

q[i]=epsilon[i]*q_max[i] {W}

T_1[i]=T_1i[i]-q[i]/C_1[i] {C}
T_2[i]=T_2i[i]+q[i]/C_2[i] {C}

Section[i]=i*L/N {m}

End
UA_total=(sum(UA[i];i=1;5))

T_1=T_1[5] {C}
T_2=T_2[5] {C}
```

q_total=(sum(q[i];i=1;5)) {W}
q_total_6Pipes=6*q_total

{6 pipes in parallel}

Percentage_change=(1-(T_2[5]/T_1[0]))*100 {%}

6.3 Cross flow code

Hoi=0,02[m]
Woi=0,018[m]
Rf=0,001[K.m^2/W]
T_1[0]=67[C]

"Fluid 1 inlet temperature HOT Fluid"
T_2[0]=14[C]

"Fluid 2 inlet temperature COLD Fluid"
v_hx_1=1[m/s]

"Inlet velocity per HX section Fluid 1"
v_hx_2=0,7[m/s]

"Inlet velocity per HX section Fluid 2"
P_i=150[kPa]
t=0,0007[m]

"Wall thickness"
Dio=2*t+Dii
n_0=1[-]
Dh_1=Dii
Dh_2=(2*(L/N)*Woi)/((L/N)+Woi)
A_1=Dii^2*pi/4
A_2=(Hoi*Woi)-(Dio^2*pi/4)
Section[0]=0[m]
Hi=Hoi

{Density}
rho_1[0]=density(Engine_Oil_Unused;T=T_1[0]) {kg/m^3}
rho_2[0]=density(Water; T=T_2[0];P=P_i) {kg/m^3}

{Mass flow rate}
m_dot_1[0] = rho_1[0] * v_hx_1 * (pi/4) * (Dii)^2 {kg/s}
m_dot_2[0] = rho_2[0] * v_hx_2 * A_2 {kg/s}

{increments}
Duplicate i=1;N

T_1i[i]=T_1[i-1] {C}

T_2i[i]=T_2[i-1] {C}

"Fluid 1 parameters: Engine oil unused"
mu_1[i]=viscosity(Engine_Oil_Unused; T=T_1i[i]) {kg/m.s}
c_p_1[i]=1000*cp(Engine_Oil_Unused; T=T_1i[i]) {J/kg.K}
k_1[i]=conductivity(Engine_Oil_Unused; T=T_1i[i]) {W/m.K}

"Fluid 2 parameters: Water"
mu_2[i]=viscosity(Water; T=T_2i[i];P=P_i) {kg/m.s}
c_p_2[i]=1000*cp(Water; T=T_2i[i];P=P_i) {J/kg.K}
k_2[i]=conductivity(Water; T=T_2i[i];P=P_i) {W/m.K}

"Copper pipe"
T_avg[i]=(T_1i[i]+T_2i[i])/2 {C}
k_copper[i]=conductivity(Copper; T=T_avg[i]) {W/m.K}

{Reynold and Pressure}

Re_1[i]=(4*m_dot_1[0])/(pi*(Dii)*mu_1[i]) {-}
Pr_1[i]=(c_p_1[i]*mu_1[i])/k_1[i] {-}
Re_2[i]=(m_dot_2[0]*Dh_2)/((Hoi*Woi+(pi*Dio/4))*mu_2[i]) {-}
Pr_2[i]=(c_p_2[i]*mu_2[i])/k_2[i] {-}

C_1[i]= m_dot_1[0]*c_p_1[i] {kg/s(J/kg.K)}
C_2[i]= m_dot_2[0]*c_p_2[i] {kg/s(J/kg.K)}
C_max[i]=max(C_1[i];C_2[i]){ kg/s(J/kg.K)}

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C_min[i]=min(C_1[i];C_2[i])  {kg/s(J/kg.K)}
C_r[i]=C_min[i]/C_max[i] {-}

Nusselt_1[i]=Nu_1(Re_1[i];Pr_1[i]) {-}
Nusselt_2[i]=Nu_2(Re_2[i];Pr_2[i]) {-}

h_1[i]=(k_1[i]/Dii)*Nusselt_1[i] {W/m^2.K}
h_2[i]=(k_2[i]/(Dh_2+Dio))*Nusselt_2[i] {W/m^2.K}
x1[i]=1/(h_1[i]*pi*Dii*(L/N)*n_0)


UA[i]= 1/(x1[i]+Rf/(pi*Dii*(Hi)*n_0)+ ln(Dio/Dii)/(2*pi*(Hi)*k_copper[i]) + 1/(h_2[i]*(2*Woi+2*L/N*(Hi)))) {W/K}

NTU[i]=UA[i]/C_min[i] {-}

Y[i]=1-1/(exp(NTU[i]*C_r[i]))
{X[i]=1-1/exp(NTU[i])}
{epsilon[i]=1/C_r[i]*(1-1/exp(C_r[i]*X[i]))}

epsilon[i]=1-1/(exp(Y[i]/C_r[i])){-}

"episilon"
{epsilon[i]=(1-exp(-NTU[i]*(1+C_r[i])))/(1+C_r[i]) {-}

"episilon"}
q_max[i]= C_min[i]*(T_1i[i]-T_2i[i]) {W}

q[i]=epsilon[i]*q_max[i]*6 {W}

T_1[i]=T_1i[i]-q[i]/C_1[i] {C}
T_2[i]=T_2i[i]+q[i]/C_2[i] {C}

Section[i]=i*L/N {m}


End
UA_total=(sum(UA[i];i=1;5))

T_1=T_1[5] {C}
T_2=T_2[5] {C}

q_total=(sum(q[i];i=1;5)) {W}
q_total_6Pipes=6*q_total

{6 pipes in parallel}
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