

Experiment – 12 Shell and Tube Heat Exchanger

Aim of this Experiment

The shell and tube exchanger is a simple model that demonstrates the basic principles of heat transfer consists of a number of tubes in parallel enclosed in a cylindrical shell. Heat is transferred between one fluid flowing through the tube bundle and the other fluid flowing through the cylindrical shell around the tubes.

Experimental Set – up

The shell and tube heat exchanger is an efficient design and finds application in food, chemical and refrigeration plant.

This type of heat exchanger consists of a number of tubes in parallel enclosed in a cylindrical shell. Heat is transferred between one fluid flowing through the tube bundle and the other fluid flowing through the cylindrical shell around the tubes. Baffles are often included inside the shell to increase the velocity and turbulence of the shell side fluid and thereby increasing the heat transfer.

In addition industrial applications often include end plate baffles so that the tube side fluid makes more than one pass through the tube bundle. This involves greater tube side pumping losses but results in an increase in the overall heat transfer coefficient. This can result in a smaller heat exchanger for the same capacity.

The H102C Shell and tube exchanger is a simple model that demonstrates the basic principles of heat transfer. The H102C is designed for use with the Heat Exchanger Service Unit H102.

The miniature heat exchanger is mounted on the H102 front panel that incorporates two mounting studs. These locate in the heat exchanger hanging bracket and two plastic thumbnuts retain the assembly.

The miniature heat exchanger supplied consists of a clear glass shell with end plates through which pass a bundle of seven equally spaced stainless steel tubes. 'O' ring seals in the end plates allow the stainless steel tubes to be removed for cleaning if necessary. Coupled to the end plates are end caps that allow hot water from the heater/circulator to pass through all seven tubes and then re-combine to return to the heater/circulator in a closed loop. Cold water from the mains supply passes through the clear glass outer shell and heat is transferred to this from the hot stream. Two baffles are located in the shell to promote turbulence and increase the cold fluid velocity.

In normal operation hot water from the heater/circulator passes into the end cap via a stainless steel braided hose and self-sealing coupling. Its temperature at entry to the heat exchanger is measured by a thermocouple sensor **T1** located on a copper tube at the '**HOT OUT**' connection. It then flows through the seven heat exchanger tubes to the opposite end cap and leaves via the braided hose connected to '**HOT RETURN**'. Its temperature on exit is measured by a similar thermocouple **T2**.

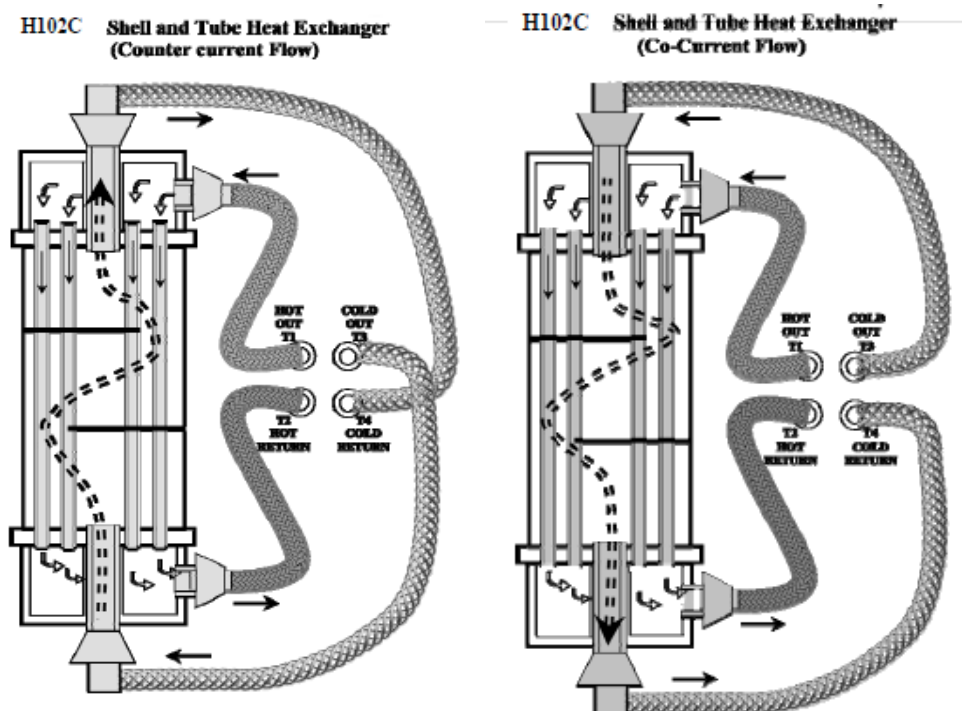
The cold water is fed into and out of the heat exchanger via plastic reinforced hoses with selfsealing couplings.

Thermocouples **T3** ('COLD OUT') and **T4** ('COLD RETURN') measure the cold water inlet and exit temperatures.

Hot braided hoses terminate with a socket and Cold hoses with a plug to prevent cross-connection of the hot and cold streams. The flow direction of the cold stream relative to the hot stream can be reversed by changing the location of the inlet and exit tubes.



Schematic Representation of Linear Conduction Experiment Unit



Capabilities Of The Shell and Tube Heat Exchanger Unit

1. To demonstrate indirect heating or cooling by transfer of heat from one fluid stream to another when separated by a solid wall (fluid to fluid heat transfer).
2. To perform an energy balance across a shell and tube exchanger and calculate the overall efficiency at different fluid flow rates
3. To demonstrate the differences between counter-current flow (flows in opposing directions) and co-current flows (flows in the same direction) and the effect on heat transferred, temperature efficiencies and temperature profiles through a shell and tube heat exchanger.
4. To determine the overall heat transfer coefficient for a shell and tube heat exchanger using the logarithmic mean temperature difference to perform the calculations (for counter-current and co-current flows).
5. To investigate the effect of changes in hot fluid and cold fluid flow rate on the temperature efficiencies and overall heat transfer coefficient.
6. To investigate the effect of driving force (difference between hot stream and cold stream temperature) with counter-current and co-current flow.

Operating Procedure Of Shell and Tube Heat Exchanger Unit

Starting

Fit the chosen heat exchanger and connect the Hot/Cold hoses to suit co-current or counter current flow.

Turn on the cooling water supply and open the cooling water flow control valve on the cooling water flowmeter(7) . Ensure that cooling water flows freely through the flowmeter and heat exchanger to the drain. Set the cooling water flow to a low value (10-25g/s depending upon water inlet temperature).

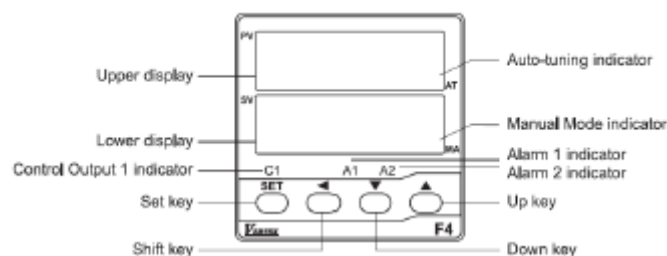
Supply power to the unit and turn on the main switch. The hot water flowmeter(8) should indicate a circulating flow.

Both the digital temperature indicator(6) and the digital water temperature control(5) will illuminate and carry out a self-test before displaying numeric values.

Setting the hot water temperature

The water temperature controller is a digital PID (Proportional Integral Derivative) controller that operates an internal solid state relay which in turn controls power to the 3.0kW water heater. The measured value (Upper display) is sensed at a point close to T1 (Hot Water to Heat Exchanger).

The water temperature controller has the following components.



- PV (Upper display) : Display the process Value, parameter index code or error code
- SV (Lower display) : Display the set point value or the set value of parameter
- C1 : Control output 1 indicator
- A1 : Alarm 1 indicator
- A2 : Alarm 2 indicator
- AT : Auto-tuning indicator (The right-most decimal point of upper display)
- MA : Manual mode indicator (The right-most decimal point of lower display)

The Lower Display (shown in the diagram above) shows the SV set point value (the hot water temperature required).

The Upper Display (also shown above) shows Process Value PV (or the ACTUAL temperature of the hot water at the controller sensor). Note that there may be a difference between T1 (Hot Out) temperature and the temperature at the controller sensor. This is normal.

Note that the user has access to the SET, Shift, Up and Down keys. These have different uses.

Setting a New Temperature

To set a new hot water temperature press the Shift key. This will, cause one digit in the Lower display to highlight. The highlighted digit can be changed by using the up and down keys:-

Up Key to increase or Down key to decrease.

This procedure can be repeated for all of the digits in the display by pressing the Shift key repeatedly.

Note that the maximum value that can be set on the H102 unit is 100°C and the maximum normal operating value is 70°C and is limited by the safety cut out at 80°C.

The SET key gives the user access to the following options.

Display	Description	Range
P_{OFF}	Process value offset correction	-1000~1000 ($dP = 0000$) -100.0~100.0 ($dP = 0000$) -10.00~10.00 ($dP = 0000$) -1.000~1.000 ($dP = 0000$)
αUEL	Control output percentage	0.0~100.0%
rUn	Control mode	αFF : Off αn : On $RL1$: AT1 $RL2$: AT2 $\bar{n}Rn$: Man

IMPORTANT NOTE that if rUn (the control mode) shows anything OTHER than on, then the PID controller is NOT necessarily controlling the heater.

Under normal running conditions when the set value SV (Lower display) is above the measured value MV the controller will indicate a heating demand by illuminating (or flashing) the white C1 LED Control Output 1 Indicator . When the set value is below the measured value the green C1 LED will be extinguished.

When the heater switch(3) is OFF even if the controller is indicating a heating demand the heater will be off.

Turn on the heater supply switch and if the temperature controller is demanding heat the Red 'HEAT INPUT' neon adjacent to the controller will illuminate or flash.

(Note:- A certain amount of air will come out of solution as the water is heated, but this will be automatically vented).

If this is the first time that the unit has been operated then it may need to run for approximately 15 minutes in order to ensure that the majority of dissolved air is released from the hot water circuit.

Note that there will be a slight difference between T1 and the value indicated on the water temperature controller due to sensor location.

Once the system is stable readings may be taken as required.

Shutting Down

1. Turn off the heater switch.
2. Turn the cooling water flow to a high value, and fully open the hot water flow control valves.
3. When the system has cooled to about 40°C, turn off the mains switch and isolate the unit from the mains.
4. Turn off the cold water supply.

Experiment -12.1

Demonstration of indirect heating or cooling by transfer of heat from one fluid stream to another when separated by a solid wall (fluid to fluid heat transfer).

Aim of This Experiment

This experiment aimed to observe effect of heat transfer from one fluid stream to another one when fluids separated by a solid wall.

Procedure

Install the Shell and Tube Exchanger H102C as detailed before and connect the cold water circuit to give Counter-Current flow as detailed.

Follow the **OPERATING PROCEDURE** in order to establish the following operating conditions.

Turn on the 'MAIN SWITCH' and 'HEATER SWITCH'

Set the hot water temperature controller to 60°C.

Set the cold water flow rate V_{cold} to 15g/sec

Set the hot water flow rate V_{hot} to 50g/sec.

The procedure may be repeated with different hot and cold flow rates and different hot water inlet temperature if required.

Monitor the stream temperatures and the hot and cold flow rates to ensure these too remain close to the original setting. Then record the following: T1, T2, T3, T4, V_{hot} and V_{cold}

Then adjust the cold-water flow valve so that V_{cold} is approximately 35g/sec. Maintain the Hot water flow rate at approximately 50g/sec (the original setting).

Allow the conditions to stabilise and repeat the above observations.

The procedure may be repeated with different hot and cold flow rates and different hot water inlet temperature if required.

Sample Test Results

Sample No.	T1	T2	T3	T4	V_{hot}	V_{cold}
---	°C	°C	°C	°C	G/sec	G/sec
1	58.5	53.9	15.4	26.9	48	16
2						
3						
4						
5						

Experiment -12.2

To perform an energy balance across a Shell and Tube heat exchanger and calculate the efficiency at different fluid flow rates

Aim of This Experiment

This experiment aimed to calculate overall heat transfer efficiency in shell and tube heat exchanger at different fluid flow rates.

Procedure

Install the Shell and Tube Exchanger H102C as detailed before and connect the cold water circuit to give Counter-Current flow as detailed.

Follow the **OPERATING PROCEDURE** in order to establish the following operating conditions.

Turn on the 'MAIN SWITCH' and 'HEATER SWITCH'

Set the hot water temperature controller to 60°C.

Set the cold water flow rate V_{cold} to 15g/sec

Set the hot water flow rate V_{hot} to 50g/sec.

The procedure may be repeated with different hot and cold flow rates and different hot water inlet temperature if required.

Monitor the stream temperatures and the hot and cold flow rates to ensure these too remain close to the original setting. Then record the following: T1, T2, T3, T4, V_{hot} and V_{cold}

Then adjust the cold-water flow valve so that V_{cold} is approximately 35g/sec. Maintain the Hot water flow rate at approximately 50g/sec (the original setting).

Allow the conditions to stabilise and repeat the above observations.

The procedure may be repeated with different hot and cold flow rates and different hot water inlet temperature if required.

Sample Test Results

Sample No.	T1	T2	T3	T4	V_{hot}	V_{cold}
----	°C	°C	°C	°C	G/sec	G/sec
1	58.5	53.9	15.4	26.9	48	16.6
2						
3						
4						
5						

Experiment -12.3

To demonstrate the differences between counter-current flow (flows in opposing directions) and co-current flows (flows in the same direction) and the effect on heat transferred, temperature efficiencies and temperature profiles through a shell and tube heat exchanger

Aim of This Experiment

This experiment aimed to demonstrate differences between counter current and co-current flows through a shell and tube heat exchanger

Procedure

Install the Shell and Tube Exchanger H102C as detailed before and connect the cold water circuit to give Counter-Current flow as detailed.

Follow the **OPERATING PROCEDURE** in order to establish the following operating conditions.

Turn on the 'MAIN SWITCH' and 'HEATER SWITCH'

Set the hot water temperature controller to 60°C.

Set the cold water flow rate V_{cold} to 15g/sec

Set the hot water flow rate V_{hot} to 35g/sec.

The procedure may be repeated with different hot and cold flow rates and different hot water inlet temperature if required.

Monitor the stream temperatures and the hot and cold flow rates to ensure these too remain close to the original setting. Then record the following: T1, T2, T3, T4, V_{hot} and V_{cold}

This completes the basic Counter-Current flow experiment observations.

Next connect the cold water circuit to give **Co-Current flow** as detailed before. Note that there is no need to disconnect the hot water circuit or to turn off the hot water pump during this operation.

Monitor the stream temperatures and the hot and cold flow rates to ensure these remain close to the original setting. Then record the following: T1, T2, T3, T4, V_{hot} and V_{cold}

This completes the basic Co-Current flow experiment observations

Sample Test Results

Sample No.	T1	T2	T3	T4	V_{hot}	V_{cold}
----	°C	°C	°C	°C	G/sec	G/sec
1	58.9	53.1	15.5	26.2	35	16.3
2						
3						
4						
5						

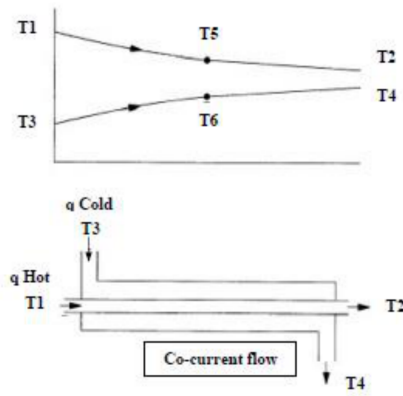
Theory of Experiments

1. Temperature measuring stations

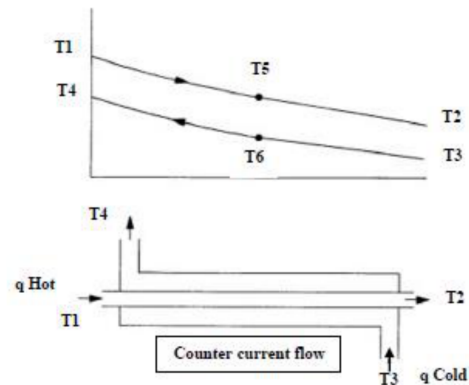
Thermocouples sense the stream temperatures at four fixed stations on the service unit panel:

Station	Panel socket	Stream	Position
T_1	HOT OUT	Hot water	INLET to the heat exchanger
T_2	HOT RETURN	Hot water	RETURN from the heat exchanger
T_3	COLD OUT	Cold water	INLET to the heat exchanger
T_4	COLD RETURN	Cold water	RETURN from the heat exchanger

The stations are on the panel sockets, not on the heat exchanger itself. Changing from co-current to counter-current flow is done by swapping the cold hoses between the two cold ports of the exchanger; T_3 therefore always measures the cold inlet and T_4 the cold outlet, whichever arrangement is used. What changes is *which end of the exchanger* the cold inlet is at, and hence how the four temperatures pair up at the two ends (see Section 4).



Co-current flow



Counter-current flow

(The mid-position stations T_5 and T_6 shown in the sketches exist only on the concentric tube exchanger H102A and are not used here.)

2. Heat transfer rates

The flow rates V_{hot} and V_{cold} are read from the flowmeters in g/s, i.e. they are already mass flow rates:

$$\dot{m} = \frac{V}{1000} \text{ kg/s}$$

The heat emitted by the hot stream and the heat absorbed by the cold stream are

$$\dot{Q}_e = \dot{m}_{hot} c_{p,hot} (T_1 - T_2) \quad [\text{W}]$$

$$\dot{Q}_a = \dot{m}_{cold} c_{p,cold} (T_4 - T_3) \quad [\text{W}]$$

with c_p in J/kg K, evaluated at the mean temperature of each stream, $(T_1 + T_2)/2$ and $(T_3 + T_4)/2$, from Table 1 of Appendix II. The difference is the heat lost to (or gained from) the surroundings:

$$\dot{Q}_f = \dot{Q}_e - \dot{Q}_a$$

In a well insulated exchanger $\dot{Q}_a$ is slightly smaller than $\dot{Q}_e$; the ratio $\dot{Q}_a/\dot{Q}_e$ (the thermal efficiency, $\eta_{thermal}$) is a useful check on the measurements. Note that the density ρ in Appendix II is only needed if the flow is expressed as a volume flow (litre/s); it is not used when the flowmeter reading is in g/s.

3. Temperature efficiencies

The temperature change in each stream is compared with the maximum temperature difference between the two streams, $(T_1 - T_3)$, which could only be reached in a perfect exchanger of infinite size with no external losses:

$$\eta_{hot} = \frac{T_1 - T_2}{T_1 - T_3} \times 100\% \quad \eta_{cold} = \frac{T_4 - T_3}{T_1 - T_3} \times 100\% \quad \eta_{mean} = \frac{\eta_{hot} + \eta_{cold}}{2}$$

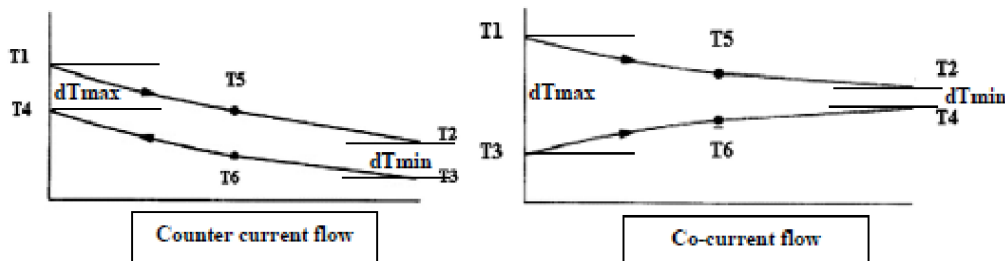
These definitions are the same for co-current and counter-current flow.

4. Logarithmic mean temperature difference

The temperature difference between the hot and cold fluids varies along the length of the exchanger, so a suitable mean value is required for heat transfer calculations. The logarithmic mean temperature difference (LMTD) is defined from the temperature differences at the two ends of the exchanger:

$$LMTD = \frac{\Delta T_{max} - \Delta T_{min}}{\ln\left(\frac{\Delta T_{max}}{\Delta T_{min}}\right)}$$

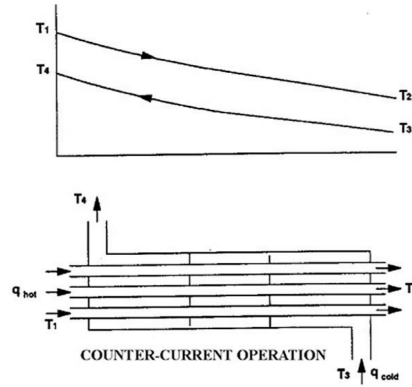
Its derivation may be found in most heat transfer textbooks. Because the four thermocouples are fixed on the panel (Section 1), the two end differences are formed from different pairs of temperatures in the two flow arrangements.



4.1 Counter-current flow

The hot inlet and the cold outlet are at the same end of the exchanger, the hot outlet and the cold inlet at the other end:

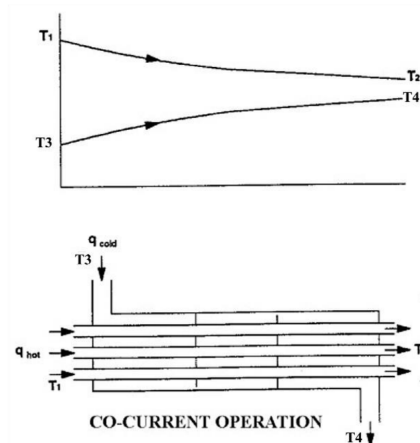
$$LMTD_{counter} = \frac{(T_1 - T_4) - (T_2 - T_3)}{\ln\left(\frac{T_1 - T_4}{T_2 - T_3}\right)}$$



4.2 Co-current flow

Both inlets are at one end and both outlets at the other:

$$\text{LMTD}_{co} = \frac{(T_1 - T_3) - (T_2 - T_4)}{\ln\left(\frac{T_1 - T_3}{T_2 - T_4}\right)}$$



5. Overall heat transfer coefficient

$$U = \frac{\dot{Q}_e}{A \cdot \text{LMTD}} \quad [\text{W/m}^2 \text{ K}]$$

where A is the heat transfer area of the exchanger (m^2), $\dot{Q}_e$ the heat emitted by the hot stream (W) and LMTD the value from Section 4 for the flow arrangement used (K).

For the shell and tube exchanger H102C the area is the outside-to-inside mean surface of all n tubes in the bundle:

$$d_m = \frac{d_o + d_i}{2}, \quad A = n \pi d_m L$$

where d_o and d_i are the outside and inside diameters of a tube, L the effective tube length and n the number of tubes. With the data of Appendix II ($d_o = 0.00476$ m, wall thickness 0.0006 m, so $d_i = 0.00356$ m and $d_m = 0.00416$ m; $L = 0.205$ m; $n = 7$):

$$A = 7 \times \pi \times 0.00416 \times 0.205 = 0.0187 \text{ m}^2$$

which is the value quoted in Appendix II. (Omitting n gives an area seven times too small and hence a U value seven times too large.)

To visualise the effect of the driving temperature difference, U may be plotted against LMTD, and the temperature efficiencies against the hot and cold flow rates.

6. Summary of formulae

Quantity	Formula
Mass flow rate	$\dot{m} = V/1000 \text{ kg/s}$ (V in g/s)
Heat emitted by hot stream	$\dot{Q}_e = \dot{m}_{hot} c_{p,hot} (T_1 - T_2)$
Heat absorbed by cold stream	$\dot{Q}_a = \dot{m}_{cold} c_{p,cold} (T_4 - T_3)$
Heat loss	$\dot{Q}_f = \dot{Q}_e - \dot{Q}_a$
Hot stream temperature efficiency	$\eta_{hot} = (T_1 - T_2)/(T_1 - T_3) \times 100\%$
Cold stream temperature efficiency	$\eta_{cold} = (T_4 - T_3)/(T_1 - T_3) \times 100\%$
Mean temperature efficiency	$\eta_{mean} = (\eta_{hot} + \eta_{cold})/2$
LMTD, counter-current	$[(T_1 - T_4) - (T_2 - T_3)] / \ln[(T_1 - T_4)/(T_2 - T_3)]$
LMTD, co-current	$[(T_1 - T_3) - (T_2 - T_4)] / \ln[(T_1 - T_3)/(T_2 - T_4)]$
Overall heat transfer coefficient	$U = \dot{Q}_e / (A \cdot \text{LMTD})$
Heat transfer area	$A = n \pi d_m L = 0.0187 \text{ m}^2$ (Appendix II)

Appendix – I Symbolas and Units

Symbols and units

<u>Symbol</u>		<u>Units</u>
V_{cold}	Cold stream flow rate	gram s ⁻¹
V_{hot}	Hot stream flow rate	gram s ⁻¹
T1	Hot fluid inlet temperature	°C
T2	Hot fluid outlet temperature	°C
T3	Cold fluid inlet temperature	°C
T4	Cold fluid outlet temperature	°C
Δt_{hot}	Decrease in hot fluid temperature	K
Δt_{Cold}	Increase in cold fluid temperature	K
dT hot	Decrease in hot fluid temperature	K
dT cold	Increase in cold fluid temperature	K
di	Inside diameter of hot tube	m
do	Outside diameter of hot tube	m
dmean	Mean diameter	m
n	Number of hot tubes	-
L	Effective length of hot tube	m
T_{mean}	Mean temperature	°C
ρ	Density of stream fluid	kg litre
Cp	Specific Heat of stream fluid	kJkg ⁻¹ K ⁻¹
$\dot{Q}_e$	Heat flow rate from hot stream	Watts
$\dot{Q}_a$	Heat flow rate to cold stream	Watts
$\dot{Q}_f$	Heat loss to surroundings	Watts
LMTD	Logarithmic mean temperature difference	K
A	Heat transfer surface area	m ²
U	Overall heat transfer coefficient	Wm ⁻² K ⁻¹
$\eta_{Thermal}$	Thermal efficiency	%
η_{hot}	Temperature efficiency hot stream	%
η_{cold}	Temperature efficiency cold stream	%
η_{mean}	Mean temperature efficiency	%
L	Hot tube effective length	m
dTmax	Maximum temperature difference across heat exchanger	K
dTmin	Minimum temperature difference across heat exchanger	K

Appendix – II Some Useful Data

Shell and Tube Exchanger H102C

Tube Material	Stainless steel
Tube Outside Diameter	0.00476m
Tube Wall Thickness	0.0006m
Number of tubes in bundle	7
Effective length of tube bundle	0.205m
Effective heat transfer area	0.0187m ²
Shell Material	Clear Borosilicate (Pyrex type glass)
Shell Inside Diameter	0.075m
Shell Wall Thickness	0.01m
Number of baffles	2

Cold fluid is deflected by two transverse baffles inside the shell before leaving.

The effective heat transfer area of the Shell and Tube heat exchanger H102C is close to that of the Concentric Tube heat exchanger H102A and Plate heat exchanger H102B, for direct comparison of performance.

Table 1 Specific Heat capacity Cp of Water in kJ kg⁻¹

°C	0	1	2	3	4	5	6	7	8	9
0	4.1274	4.2138	4.2104	4.2074	4.2054	4.2019	4.1996	4.1974	4.1954	4.1936
10	4.1919	4.1904	4.189	4.1877	4.1866	4.1855	4.1864	4.1837	4.1829	4.1822
20	4.1816	4.181	4.1805	4.1801	4.1797	4.1793	4.1790	4.1787	4.1785	4.1783
30	4.1782	4.1781	4.1780	4.1780	4.1779	4.1779	4.1780	4.1780	4.1781	4.1782
40	4.1783	4.1784	4.1786	4.1788	4.1789	4.1792	4.1794	4.1796	4.1799	4.180
50	4.1804	4.1807	4.1811	4.1814	4.1817	4.1821	4.1825	4.1829	4.1833	4.1837
60	4.1841	4.1846	4.1850	4.1855	4.1860	4.1865	4.1871	4.1876	4.1882	4.1887
70	4.1893	4.1899	4.1905	4.1912	4.1918	4.1925	4.1932	4.1939	4.1964	4.1954

To use the table the vertical columns denote whole degrees and the Horizontal rows denote tens of degrees. For example the bold value 4.1792 kJ kg⁻¹ is at 40 + 5 = 45 °C.

Alternatively the equation $C_p = 6 \times 10^{-6} t^4 - 1.0 \times 10^{-6} t^3 + 7.0487 \times 10^{-6} t^2 - 2.4403 \times 10^{-3} t + 4.2113$ may be used if the data is to be calculated using a spreadsheet.

Table 2 Density of Water in kg Litre⁻¹

°C	0	2	4	6	8
0	0.9998	0.9999	0.9999	0.9999	0.9999
10	0.9997	0.9995	0.9992	0.9989	0.9986
20	0.9982	0.9978	0.9973	0.9968	0.9962
30	0.9957	0.9950	0.9944	0.9937	0.9930
40	0.9922	0.9914	0.9906	0.9898	0.9889
50	0.9880	0.9871	0.9862	0.9852	0.9842
60	0.9832	0.9822	0.9811	0.9800	0.9789
70	0.9778	0.9766	0.9754	0.9742	0.9730

To use the table the vertical columns denote degrees and the Horizontal rows denote tens of degrees. For example the bold value 0.9906 kg is at 40 + 4 = 44 °C.

Alternatively the equation $\rho = -4.582 \times 10^{-6} t^3 - 4.0007 \times 10^{-5} t + 1.004$ may be used if the data is to be calculated using a spreadsheet.