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.

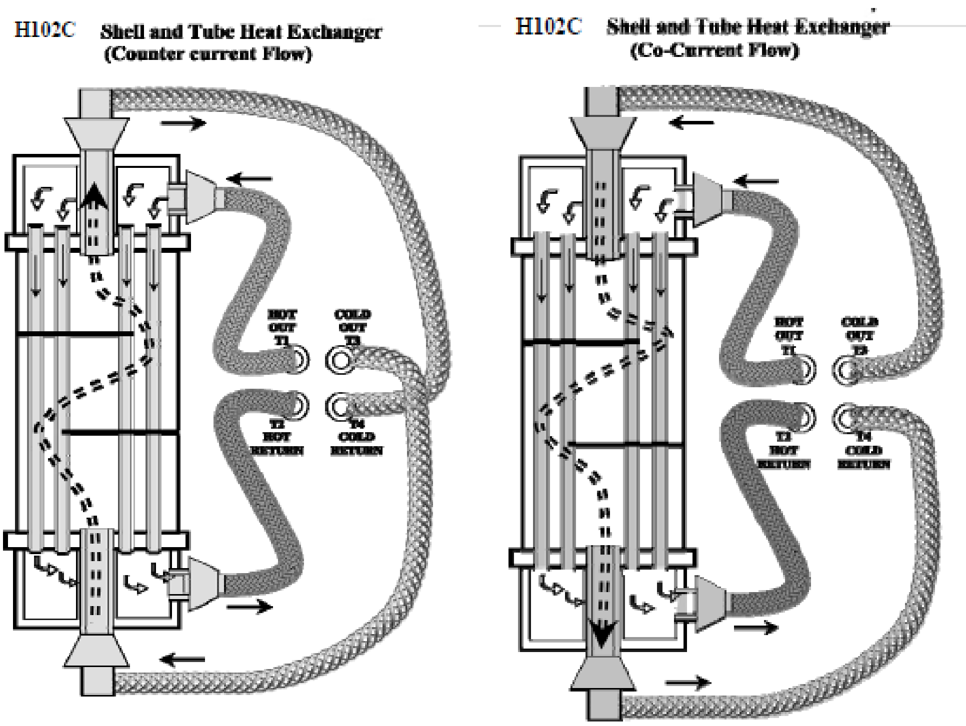
In normal operation hot water from the heater/circulator passes into the end cap via a stainless steel braided hose and self-sealing coupling**.** Its temperature at entry to the heat exchanger is measured by a thermocouple sensor **T1** located on a copper tube at the **'HOT OUT'** connection. It then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

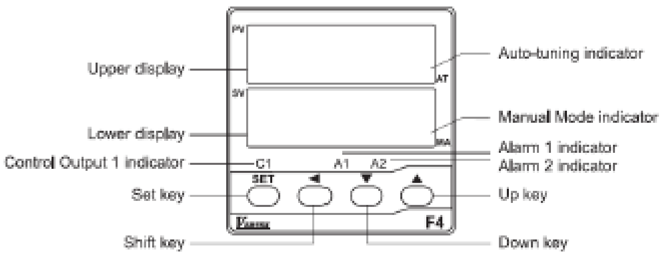


Figure 3. Front panel description

- 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 100ºC and the maximum normal operating value is 70ºC and is limited by the safety cut out at 80ºC.

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

Display	Description	Range
PVoF	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)
oUtL	Control output percentage	0.0~100.0%
rUn	Control mode	oFF : Off on : On At1 : AT1 At2 : AT2 mAn : 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 form one fluid stream to another one when fluids seperated 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 Vcold 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, Vhot and Vcold

Then adjust the cold-water flow valve so that Vcold 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 Vcold 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, Vhot and Vcold

Then adjust the cold-water flow valve so that Vcold 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 Vcold 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, Vhot and Vcold

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, Vhot and Vcold

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

Co-current and Counter current flow

Thermocouples sense the stream temperatures at the four fixed stations: -

T1 – Hot Water INLET to Heat Exchanger

T2 – Hot Water RETURN from Heat Exchanger

T3 – Cooling Water INLET to Heat Exchanger

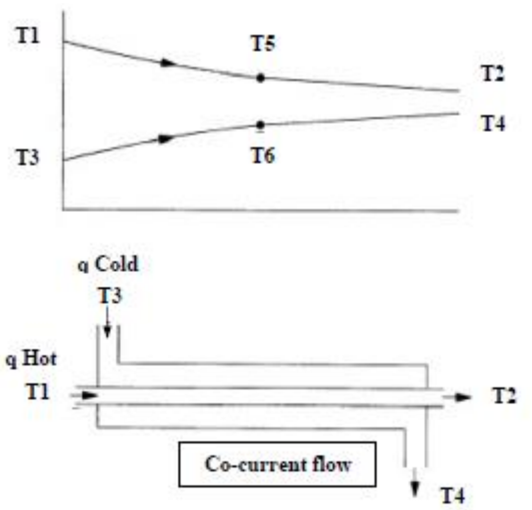
T4 – Cooling Water RETURN from Heat Exchanger

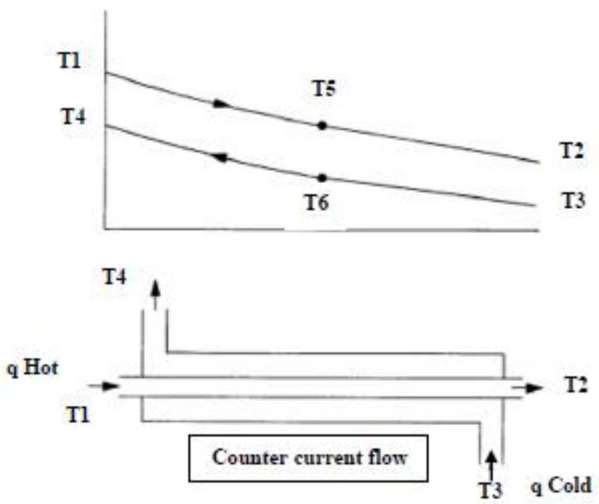
In addition, two plug-in stations: -

T5 – Hot Mid-position (for Concentric Tube)

T6 – Cold Mid-position (for Concentric Tube)

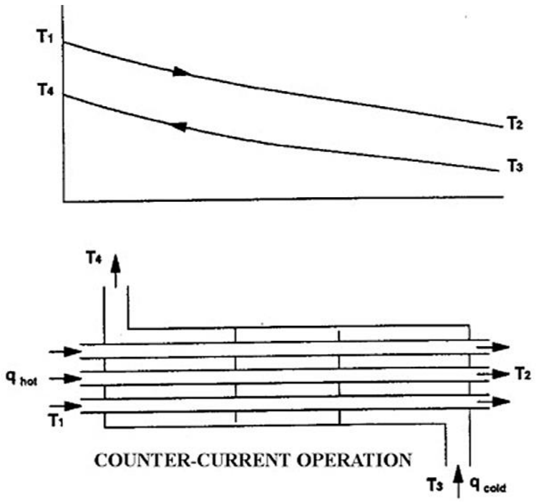
All thermocouples are duplex sensors, the spare sensor is utilised when HC102A Data Acquisition upgrade is fitted.





A useful measure of the heat exchanger performance is the temperature efficiency.

The temperature change in each stream (hot and cold) is compared with the maximum temperature difference between the two streams. This could only occur in a perfect heat exchanger of infinite size with no external losses or gains.



The temperature efficiency of the hot stream from the above diagram

$$\eta_{Hot} = \frac{T1\text{-}T2}{T1\text{-}T3} \times 100\%$$

The temperature efficiency of the cold stream from the above diagram

$$\eta_{Cold} = \frac{T4\text{-}T3}{T1\text{-}T3} \times 100\%$$

The temperature efficiency of the hot stream from the above diagram

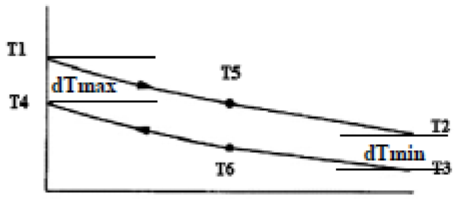
$$\eta_{Hot} = \frac{T1 - T3}{T1 - T4} \times 100\%$$

The mean temperature efficiency

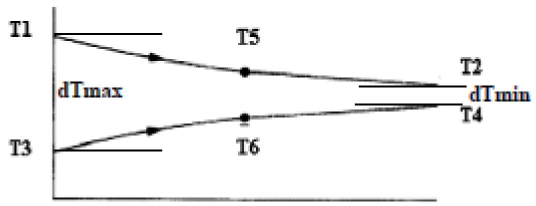
$$\eta_{Mean} = \frac{\eta_{Hot} + \eta_{Cold}}{2}$$

As the temperature difference between the hot and cold fluids vary along the length of the heat exchanger, it is necessary to derive a suitable mean temperature difference that may be used in heat transfer calculations. These calculations are not only of relevance in experimental procedures but also of more importance in the design of heat exchangers to perform a particular duty.

The derivation and application of the Logarithmic Mean Temperature Difference (LMTD) may be found in most thermodynamics and heat transfer textbooks.



Counter current flow



Co-current flow

The LMTD is defined as

$$LMTD = \frac{dTmax - dTmin}{\ln\left(\frac{dTmax}{dTmin}\right)}$$

Hence from the above diagrams of temperature distribution for Counter current flow

$$LMTD = \frac{(T1\text{-}T4) - (T2 - T3)}{\ln\left(\frac{(T1\text{-}T4)}{(T2 - T3)}\right)}$$

Note that as the temperature measurement points are not fixed on the heat exchanger the LMTD is not the same formula for both Counter-current flow and Co-current flow.

In order to calculate the overall heat transfer coefficient the following parameters must be used with consistent units:

$$U = \frac{\dot{Q}_e}{A \times LMTD}$$

Where

A	Heat transfer area of heat exchanger (m2)
$\dot{Q}$ e	Heat emitted from hot stream (Watts)
LMTD	Logarithmic mean temperature difference (K)

The heat transfer area may be calculated from: -

$$d_m = \frac{d_o + d_i}{2}$$

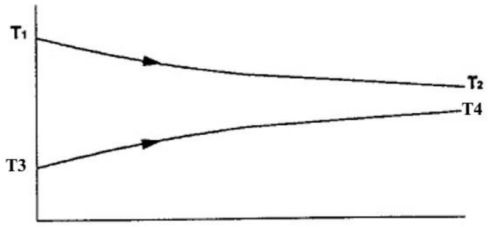
And

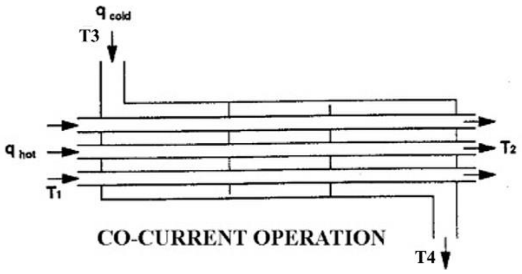
$$A = \pi\, d_m\, L$$

Where

do	Heat transfer tube outside diameter (m)
di	Heat transfer tube inside diameter (m)
dm	Heat transfer tube mean diameter (m)
L	Heat transfer tube effective length (m)

The temperature change in each stream (hot and cold) is compared with the maximum temperature difference between the two streams. This could only occur in a perfect heat exchanger of infinite size with no external losses or gains.





CO-CURRENT OPERATION

The temperature efficiency of the hot stream from the above diagram

$$\eta_{Hot} = \frac{T1\text{-}T2}{T1\text{-}T3} \times 100\%$$

The temperature efficiency of the cold stream from the above diagram

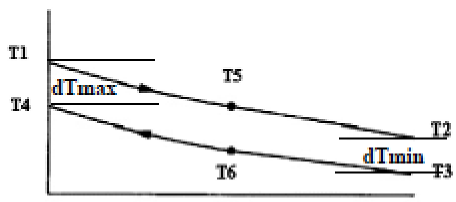
$$\eta_{Cold} = \frac{T4\text{-}T3}{T1\text{-}T3} \times 100\%$$

The mean temperature efficiency

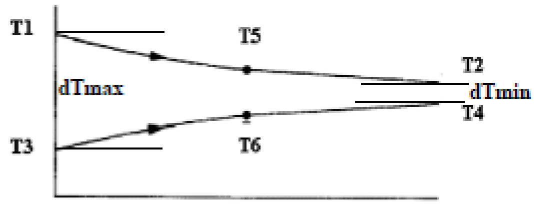
$$\eta_{Mean} = \frac{\eta_{Hot} + \eta_{Cold}}{2}$$

As the temperature difference between the hot and cold fluids vary along the length of the heat exchanger it is necessary to derive a suitable mean temperature difference that may be used in heat transfer calculations. These calculations are not only of relevance in experimental procedures but also more importantly to be used in the design of heat exchangers to perform a particular duty.

The derivation and application of the Logarithmic Mean temperature Difference (LMTD) may be found in most thermodynamics and heat transfer textbooks



Counter current flow



Co-current flow

The LMTD is defined as

$$LMTD = \frac{dTmax - dTmin}{\ln\left(\frac{dTmax}{dTmin}\right)}$$

Hence from the above diagrams of temperature distribution

$$LMTD = \frac{(T1\text{-}T4) - (T2 - T3)}{\ln\left(\frac{(T1\text{-}T4)}{(T2 - T3)}\right)}$$

Note that as the temperature measurement points are fixed on the heat exchanger the LMTD is the same formula for both Counter-current flow and Co-current flow.

In order to calculate the overall heat transfer coefficient the following parameters must be used with consistent units:-

$$U = \frac{\dot{Q}_e}{A \times LMTD}$$

Where

A Heat transfer area of heat exchanger (m^2)
Q e Heat emitted from hot stream (Watts)
LMTD Logarithmic mean temperature difference (K)

The heat transfer area may be calculated from:-

$$d_m = \frac{d_o + d_i}{2}$$

And

$$A = \pi\, d_m\, L$$

Where

do Heat transfer tube outside diameter (m)
di Heat transfer tube inside diameter (m)
dm Heat transfer tube mean diameter (m)
L Heat transfer tube effective length (m)

Co-Current Flow

For the co-current flow system the calculation procedure is similar but the formulae are as follows

The power emitted from the hot stream Qe

$$\dot{Q}e = V_{hot}\, \rho_{hot}\ Cp_{Hot}\ (T1 - T2)\ \text{Watts}$$

The temperature efficiency of the hot stream from the above diagram

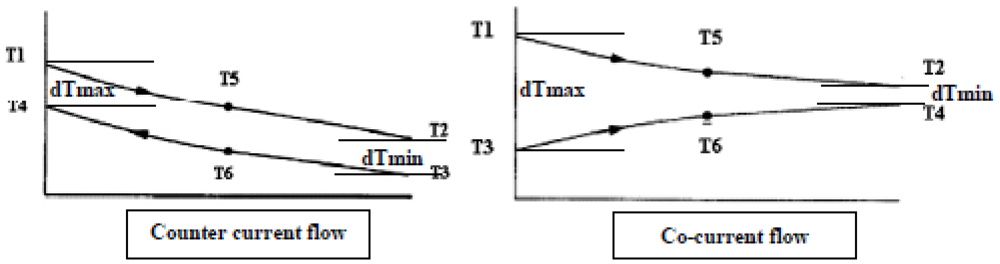
$$\eta_{Hot} = \frac{T1\text{-}T2}{T1\text{-}T4} \times 100\%$$

The temperature efficiency of the cold stream from the above diagram

$$\eta_{Cold} = \frac{T4\text{-}T3}{T1\text{-}T3} \times 100\%$$

The mean temperature efficiency

$$\eta_{Mean} = \frac{\eta_{Hot} + \eta_{Cold}}{2}$$



The logarithmic mean temperature difference LMTD (Co-current flow)

$$LMTD = \frac{(T1\text{-}T3) - (T2 - T4)}{\ln\left(\frac{(T1\text{-}T3)}{(T2 - T4)}\right)}$$

The Overall heat transfer coefficient U

$$U = \frac{\dot{Q}_e}{A \times LMTD}$$

In order to visualise the effect of temperature difference on the overall heat transfer coefficient the calculated data may be plotted against logarithmic mean temperature difference.

For the Hot stream:

$$\dot{Q}e = V_{hot}\,\rho_{hot}\;Cp_{Hot}\;(T1\text{-}\,T3)\;\;\text{Watts}$$

For the Cold stream:

$$\dot{Q}a = V_{cold}\,\rho_{cold}\;Cp_{Cold}\;(T4\text{-}\,T3)\;\;\text{Watts}$$

Appendix – I Symbolas and Units

Symbols and units

Symbol		Units
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	$0.0187 m^2$
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 $\mathbf{Cp = 6x10^{-9}\ t^4 - 1.0x10^{-6}\ t^3 + 7.0487x10^{-5}\ t^2 - 2.4403x10^{-3}\ t + 4.2113}$
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 $\mathbf{\rho = -4.582x10^{-6}\ t^2 - 4.0007x10^{-5}\ t + 1.004}$
may be used if the data is to be calculated using a spreadsheet.