APPENDIX C

EXPERIMENTAL

OPERATING

AND

MAINTENANCE PROCEDURES

OPTIONAL SHELL AND TUBE HEAT EXCHANGER

H100C

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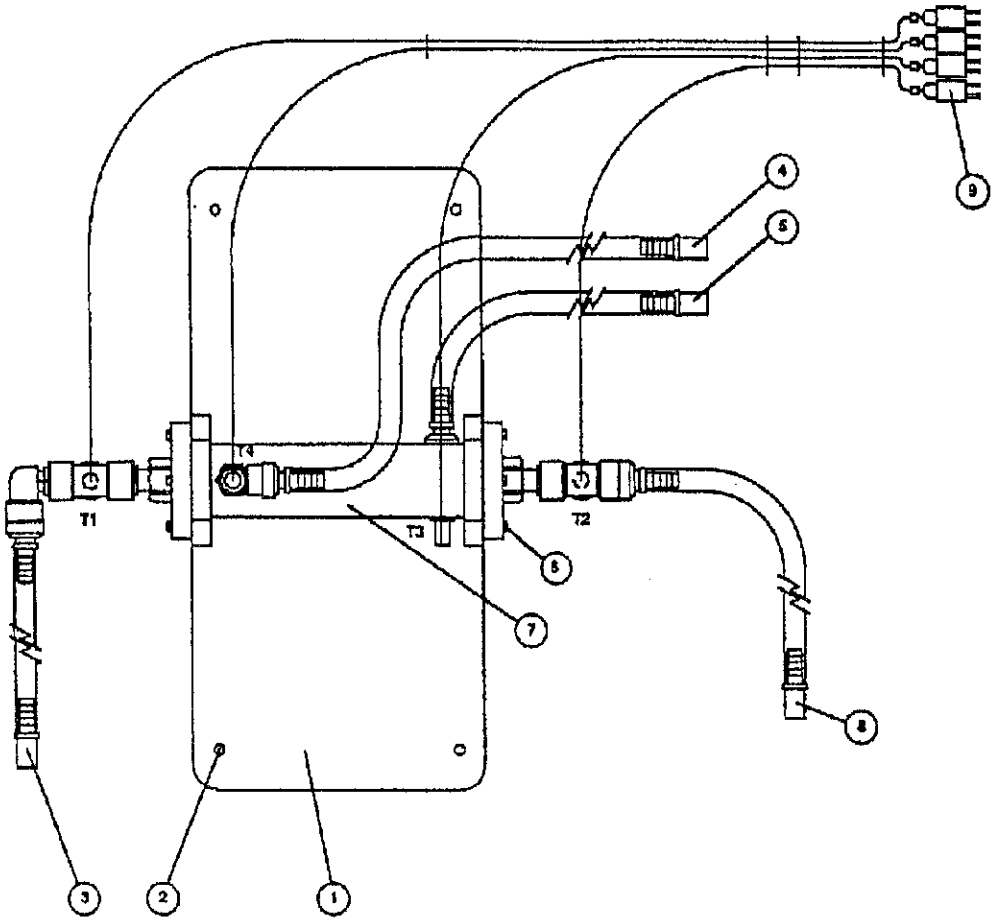
INDEX

SYMBOLS AND UNITS

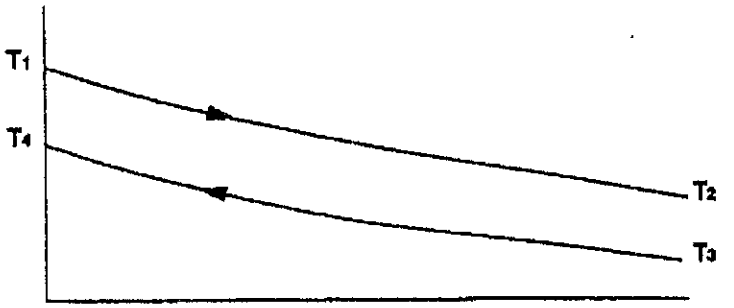
Symbol		Units
V_{cold}	Cold stream flow rate	litre s^{-1}
V_{hot}	Hot stream flow rate	litre s^{-1}
T1	Hot fluid inlet temperature	°C
T2	Hot fluid outlet temperature	°C
T3	Cold fluid inlet temperature	°C
T4	Cold fluid outlet temperature	°C
Δt_{hot}	Decrease in hot fluid temperature	K
Δt_{Cold}	Increase 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

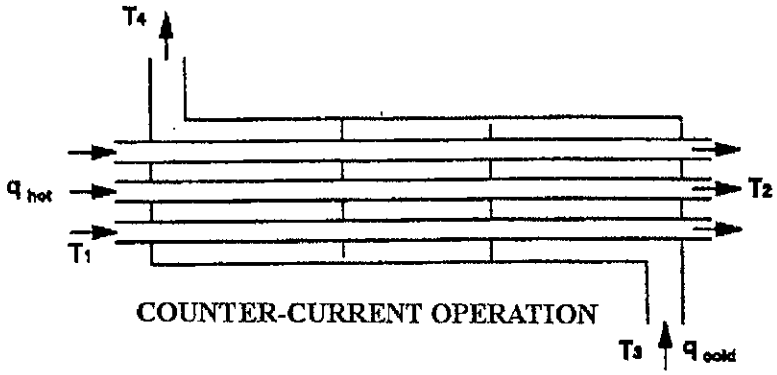
FIGURE C1



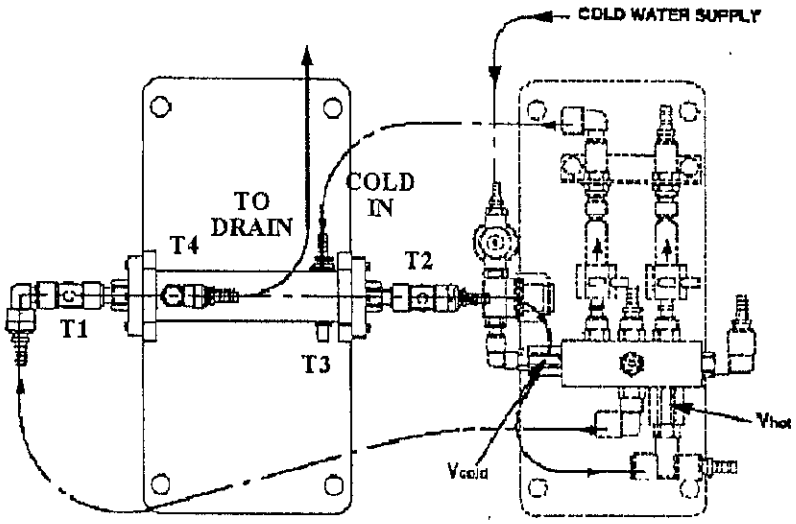
SHELL AND TUBE HEAT EXCHANGER H100C

Figure C2



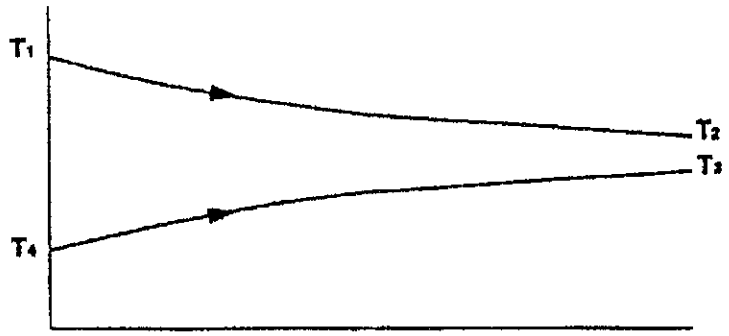


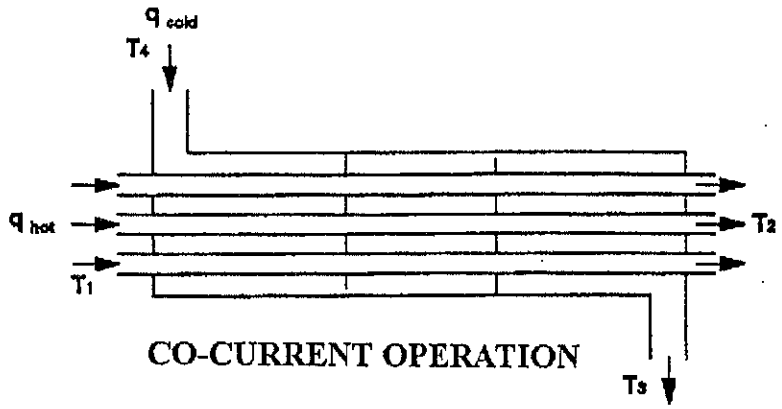
COUNTER-CURRENT OPERATION



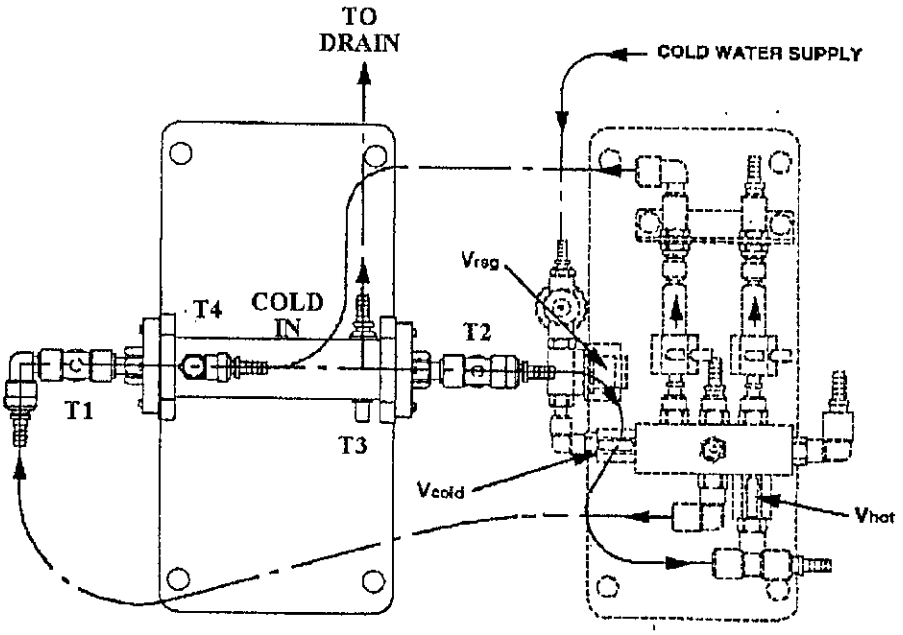
COUNTER-CURRENT PIPE ARRANGEMENT

Figure C3





CO-CURRENT OPERATION



CO-CURRENT PIPE ARRANGEMENT

DESCRIPTION
SHELL AND TUBE HEAT EXCHANGER H100C
(Figure Notation)

In this section of the manual figures are referenced with **"C"** prefix to identify them as relating to the H100**"C"** unit. For example Figure **C1** on page C1. Numbered items on the figures are referenced as follows **C1(2)** , this refers to Item **2** (The mounting holes) on the base board of Figure **C1** on page **C1**. This follows the similar procedure used in the main manual.

Please refer to figure C1 on page C1.
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.

For more detailed examination of multi-pass shell and tube heat exchangers **the Hilton Steam to Water Heat Exchanger H930** is recommended. This allows one two and four pass operation to be investigates and the increased pumping losses to be demonstrated. Details are available from P.A.Hilton Ltd or their local agent on request.

The H100C Shell and tube exchanger is a simple model that demonstrates the basic principles of heat transfer. The H100C is designed to be used with the Heat Exchanger Service Module H100.

The miniature The heat exchanger is mounted on a white PVC base plate **C1(1)** which incorporates four mounting holes **C1(2)**. These locate on studs on the base unit and are secured with knurled nuts.

The miniature heat exchanger supplied consists of a clear plastic shell **C1(7)** 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 headers **C1(6)** which 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 plastic 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 left hand header from the flexible coupling **C1(3)**. Its temperature at entry to the heat exchanger is measured by a thermocouple sensor **T1** located in a T fitting as shown in the diagram. It then flows through the heat exchanger and leaves via flexible hose **C1(8)**. Its temperature on exit is measured by a similar thermocouple **T2**.

The cold water is fed into and out of the heat exchanger by flexible couplings **C1(4)** ad **C1(5)**.
Identical T fittings to those on the hot stream contain thermocouples T3 and T4 that measure the cold water inlet and exit temperatures.

The four thermocouple sensor points are labelled T1 to T4 on Figure C1 and each lead is terminated with a miniature thermocouple plug **B(9)** designed to be plugged into the first four numbered sockets on the base unit H100.

Flexible tubing attached to each fluid inlet/outlet is terminated in a male spigot that is designed to push into the quick release sockets on the Heat Exchanger Service unit H100. 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.

The sockets on the Heat Exchanger Service Unit H100 are colour coded **RED for Hot Water** and **BLUE for Cold Water**.

INSTALLATION

Heat Exchanger Installation H100C

Refer to Figure C1 on page C1, Figure C2 on page C2, Figure C3 on page C3.

It is assumed that the basic **INSTALLATION AND COMMISSIONING** procedures for the Heat Exchanger Service unit H100 have been completed as detailed in the main manual on pages 5 to 6. Locate the base **C1(1)** of the heat exchanger onto the studs on the base unit in the orientation shown in Figure C2 or C3 relative to the valve plate. Secure the base plate with the knurled nuts provided.

Temperature Sensors

Each of the four temperature sensors is terminated with a miniature plug and has an identification number. Connect the numbered plugs to the numbered sockets on the control console **2(8)**. Figure 2 page C2.

Note that the plugs have pins of different widths to ensure correct orientation.

Hot Water Circuit

Refer to Figure C1 on page C1.
This is **always** connected in the following manner.
Connect the flexible tube **C1(3)** from the left hand end of the heat exchanger (adjacent to sensor T1) to the hot water outlet socket shown in Figure C2 and fitted with a red collar.

Connect the flexible tube **C1(8)** from the right hand end of the heat exchanger to the hot water return socket shown in Figure C2 and fitted with a red collar.

The connection of the hot water circuit is common for all experiments and all configurations. However the cold water circuit may be configured in one of two directions according to the directions in the experimental procedure.

Cold Water Circuit Counter-current Flow

Refer to Figure C1 on page C1 and C2 on page C2.

In **counter-current flow** the hot and cold water streams flow in opposing directions through the heat exchanger.

The cold water circuit is connected for **counter current** flow as shown in Figure C2 on page C2.

Connect the flexible tube **C1(5)** from the bottom right hand side of the shell assembly (adjacent to sensor T3) to the cold water outlet socket shown in figure C2 and coloured blue.

Connect the flexible tube **C1(4)** from the top left hand side of the shell assembly (adjacent to sensor T4) to the drain hose provided using the adapter provided. The drain hose is reinforced nylon with a brass stub pipe at on end. This fits into the adapter provided and the adapter couples to the overflow flexible pipe. **The drain hose should be arranged so that it travels in a continuously downward direction to the drain.**

Once the connections have been made the hot water circuit must be re-filled and the system started according to the **OPERATING PROCEDURE** in the main manual on pages 16 to 19.

Cold Water Circuit Co-current Flow

Refer to Figure C1 on page C1 and C3 on page C3.

In **co-current** flow the hot and cold water streams flow in the same directions through the heat exchanger.

The cold water circuit is connected for **co-current** flow as shown in Figure C3 on page C3.

Connect the flexible tube **C1(5)** from the bottom right hand side of the shell assembly (adjacent to sensor T3) to the drain hose provided using the adapter provided. The drain hose is reinforced nylon with a brass stub pipe at on end. This fits into the adapter provided and the adapter couples to the overflow flexible pipe. **The drain hose should be arranged so that it travels in a continuously downward direction to the drain.**

Connect the flexible tube **C1(4)** from the top left hand side of the shell assembly (adjacent to sensor T4) to the cold water outlet socket shown in figure C2 and coloured blue.

Once the connections have been made the hot water circuit must be re-filled and the system started according to the **OPERATING PROCEDURE** in the main manual on pages 16 to 19.

USEFUL DATA
SHELL AND TUBE EXCHANGER H100C

Tube Material	Stainless steel
Tube Outside Diameter	0.00635m
Tube Wall Thickness	0.0006m
Number of tubes in bundle	7
Effective length of tube bundle	0.144m
Effective heat transfer area	$0.02m^2$
Shell Material	Clear Acrylic
Shell Inside Diameter	0.039m
Shell Wall Thickness	0.003m
Number of baffles	2

Cold fluid passes over and under two transverse baffles inside the shell before leaving.
The effective heat transfer area of the shell and tube heat exchanger H100C is the same as that of the concentric tube heat exchanger H100A 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 $C\rho = 6x10^{-9}\, t^4 - 1.0x10^{-6}\, t^3 + 7.0487x10^{-5}\, t^2 - 2.4403x10^{-3}\, t + 4.2113$
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 $\rho = -4.582\text{x}10^{-6}\, t^2 - 4.0007\text{x}10^{-5}\, t + 1.004$
may be used if the data is to be calculated using a spreadsheet.

CAPABILITIES OF THE SHELL AND TUBE HEAT EXCHANGER H100C WITH THE HEAT EXCHANGER SERVICE UNIT H100

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.

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).

The following procedure demonstrates heat transfer from one fluid stream to another when separated by a solid wall.

NOTE that the observations from experiment No 2 may be used for the calculations in this procedure in order to save experimental time.

It is assumed that the basic INSTALLATION AND COMMISSIONING procedures for the Heat Exchanger Service Unit H100 have been completed as detailed in the main manual on pages 5 to 7.

Procedure

Install the Shell and Tube Exchanger H100C as detailed in **INSTALLATION / Heat Exchanger Installation H100C** on page C5 and connect the cold water circuit to give Counter-Current flow as detailed in the same section.

Follow the **OPERATING PROCEDURE** detailed in the main manual on page 16 onwards in order to establish the following operating conditions.

Fill the hot water circuit, set the cold water pressure regulator, and turn on the power to the unit. Then set the hot water temperature controller to 60°C and turn on the circulating pump.

Set the cold water flow rate V_{cold} to 1 litre min^{-1} and the hot water flow rate V_{hot} to between 2.5 and 3.0 litre min^{-1}.

If the optional Computer Interface HC100 and software is being used:

It is assumed that the Installation and commissioning of both the hardware and software has been carried out according to the procedures on page 5 of the main manual. Ensure that the power lead to the Hilton data logger is connected, that the serial lead from the computer to the data logger is connected and that the ribbon cable from the interface to the base unit is also connected.

It is assumed that the computer is already running in Windows™ mode. Click on the H100 icon to start the software.

Language Screen:

The first screen will show the language section. If this option has been purchased then the preferred language may be selected.

H100 Main Menu:

The next screen is the main menu for the H100 series of optional units. Select ***the H100C Shell and Tube Heat Exchanger*** *(Note that only one option can be selected and that if the wrong unit is selected the procedure may be repeated).*

It is assumed that the data is to be captured on disc and therefore this option should be selected in the lower box. When all selections have been made click OK.

Communications Test:

As the user has selected to collect data the next screen carries out a communications test with the H100 base unit. Select the serial port of the computer that the unit is connected to and then click the Go button with the mouse pointer.

Assuming communications is confirmed the next screen will show the H100C Shell and Tube Heat Exchanger Main Menu.

If communications fails for any reason check the parameters indicated on the screen and repeat the test. If communications cannot be established for any reason the Cancel button may be used and the cause investigated.

H100C Shell and Tube Heat Exchanger Main Menu.

*This lists the optional experiments that may be carried out with the H100CShell and Tube Heat Exchanger. To continue with the above experiment select 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)*** *and then click OK.*

H100C Experiment Number 1:

Assuming that the above procedure is being followed select the Counter-Current flow option and check the Instructions on the screen have been observed. If data is to be recorded to disc then select the Store data on disc for later review option. Then click OK.

If the user DOES select to record data to disc then a file name will be requested. Note that a partially fixed file name is used together with a fixed file suffix. This enables the software to recognise data during the review option that is compatible with the review mode selected. The user is required to enter the remaining digits that will be of relevance to them in the future. Once a valid file name is entered the Recording data screen is displayed.

Recording data:

The next screen shows three tabs Flow, Temperature and Data Point. The Flow and Temperature graphs may be used to set the hot and cold stream flow rates to the desired values and the temperature graph used to determine when the unit has reached a stable condition.

Once stable conditions have been established the Data point tab may be clicked and the Record button clicked to record and display a captured data point. Note that data may be sent to a printer (If a printer is connected) if required The option of Raw (end results not calculated) or Calculated data may be selected for the printing option.

The results shown in the table are updated each time the record button is clicked. NOTE that if no changes are made to the H100C settings of flow rate and hot stream temperature the captured results will all be similar.

The software should be utilised to automate the data recording procedures detailed as follows in the manual procedure.

To return to the H100C Shell and Tube Heat Exchanger Main Menu click the End button on the Data capture screen.

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 set the flow indicator to F_{cold} and adjust the cold water flow valve so that V_{cold} is approximately 2 litre min^{-1}. Maintain the Hot water flow rate at approximately 2.5 to 3.0 litre min^{-1} (the original setting). *If the optional Computer Interface HC100 and software is being used then the Flow screen and Temperature screen may again be used to adjust the hot and cold flow rates and to monitor the system for stability.*

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.

OBSERVATIONS

Flow Direction: Counter-Current

Sample No.	T1	T2	T3	T4	V_{hot}	V_{cold}
----	°C	°C	°C	°C	L min^{-1}	L min^{-1}
1	58.5	53.9	15.4	26.9	2.89	1.00
2						
3						
4						
5						

Calculated Data

Sample No.	Δt_{hot}	Δt_{cold}
---	K	K
1	4.6	11.5

If the optional Computer Interface HC100 and software is being used then it will be seen that the tabular displays are similar to those used on screen.

CALCULATIONS

For the example result the calculations are as follows.

Reduction in Hot fluid temperature Δt hot = T1 - T2
= 58.9 - 53.9
= 4.6 K

Increase in Cold fluid temperature Δt cold = T4 – T3
=26.9 - 15.4
= 11.5 K

Note that if the system is set up for **Co-Current flow** the hot stream temperature difference will remain the same but the cold stream temperature difference will become:

Δt cold = T3 – T4

The test results show the effect upon the temperature differences when the flow rates through a simple heat exchanger are varied.

The results from this experiment may also be used in experiment **No 2 To perform an energy balance across a shell and tube heat exchanger and calculate the overall efficiency at different fluid flow rates.**

If the optional Computer Interface HC100 and software is being used then the user can return to the H100C Shell and Tube Heat Exchanger Main Menu by clicking the End and Back keys.

Once back at the main menu the user can opt to record more data in another experiment on the same heat exchanger or review the data recorded during the preceding experiment. Alternatively the user can return to the H100 Main Menu by continuing to click the Back key and the select to use another optional heat exchanger if available.

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

The following procedure demonstrates heat transfer from one fluid stream to another when separated by a solid wall and shows that the heat release rate of the hot stream should equal the heat absorption rate of the cold stream.

NOTE that the observations from experiment No 1 may be used for the calculations in this procedure in order to save experimental time.

I It is assumed that the basic **INSTALLATION AND COMMISSIONING** procedures for the Heat Exchanger Service Unit H100 have been completed as detailed in the main manual on pages 5 to 7.

Procedure

Install the Shell and Tube Heat Exchanger H100C as detailed in **INSTALLATION / Heat Exchanger Installation H100C** on page C5 and connect the cold water circuit to give Counter-Current flow as detailed in the same section.

Follow the **OPERATING PROCEDURE** detailed in the main manual on page 16 onwards in order to establish the following operating conditions.

Fill the hot water circuit, set the cold water pressure regulator, and turn on the power to the unit. Then set the hot water temperature controller to 60°C and turn on the circulating pump.

Set the cold water flow rate V_{cold} to 1 litre/ minute and the hot water flow rate V_{hot} to between 2. 5 and 3.0 litre/minute.

If the optional Computer Interface HC100 and software is being used:

It is assumed that the Installation and commissioning of both the hardware and software has been carried out according to the procedures on page 5 of the main manual. Ensure that the power lead to the Hilton data logger is connected, that the serial lead from the computer to the data logger is connected and that the ribbon cable from the interface to the base unit is also connected.

It is assumed that the computer is already running in Windows™ mode. Click on the H100 icon to start the software.

Language Screen:

The first screen will show the language section. If this option has been purchased then the preferred language may be selected.

H100 Main Menu:

The next screen is the main menu for the H100 series of optional units. Select ***the H100C Shell and Tube heat exchanger*** *(Note that only one option can be selected and that if the wrong unit is selected the procedure may be repeated.)*

It is assumed that the data is to be captured on disc and therefore this option should be selected in the lower box. When all selections have been made click OK.

Communications Test:

As the user has selected to collect data the next screen carries out a communications test with the H100 base unit. Select the serial port of the computer that the unit is connected to and then click the Go button with the mouse pointer.

Assuming communications is confirmed the next screen will show the H100C Shell and Tube Heat Exchanger Main Menu.

If communications fails for any reason check the parameters indicated on the screen and repeat the test. If communications cannot be established for any reason the Cancel button may be used and the cause investigated.

H100C Shell and Tube Heat Exchanger Main Menu.

This lists the optional experiments that may be carried out with the H100C Shell and Tube Heat Exchanger. To continue with the above experiment select 2 ***To perform an energy balance across a shell and tube heat exchanger and calculate the overall efficiency at different fluid flow rates****, and then click OK.*

H100C Experiment Number 2:

Assuming that the above procedure is being followed select the Counter-Current flow option and check the Instructions on the screen have been observed. If data is to be recorded to disc then select the Store data on disc for later review option. Then click OK.

If the user DOES select to record data to disc then a file name will be requested. Note that a partially fixed file name is used together with a fixed file suffix. This enables the software to recognise data during the review option that is compatible with the review mode selected. The user is required to enter the remaining digits that will be of relevance to them in the future. Once a valid file name is entered the Recording data screen is displayed.

Recording data:

The next screen shows three tabs Flow, Temperature and Data Point. The Flow and Temperature graphs may be used to set the hot and cold stream flow rates to the desired values and the temperature graph used to determine when the unit has reached a stable condition.

Once stable conditions have been established the Data point tab may be clicked and the Record button clicked to record and display a captured data point. Note that data may be sent to a printer (If a printer is connected) if required The option of Raw (end results not calculated) or Calculated data may be selected for the printing option.

The results shown in the table are updated each time the record button is clicked. NOTE that if no changes are made to the H100C settings of flow rate and hot stream temperature the captured results will all be similar.

The software should be utilised to automate the data recording procedures detailed as follows in the manual procedure.

To return to the H100C Shell and Tube Heat Exchanger Main Menu click the End button on the Data capture screen.

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 set the flow indicator to F_{cold} and adjust the cold water flow valve so that V_{cold} is approximately 2 litres/minute. Maintain the Hot water flow rate at approximately 2.5 to 3.0 litres/minute (the original flow rate)

If the optional Computer Interface HC100 and software is being used then the Flow screen and Temperature screen may again be used to adjust the hot and cold flow rates and to monitor the system for stability.

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.

OBSERVATIONS

Flow Direction: Counter-Current

Sample No.	T1	T2	T3	T4	V_{hot}	V_{cold}
----	°C	°C	°C	°C	L min^{-1}	L min^{-1}
1	58.5	53.9	15.4	26.9	2.89	1.00
2						
3						
4						
5						

Calculated Data

Sample No.	Δt_{hot}	Δt_{cold}	$\dot{Q}e$	$\dot{Q}a$	$\eta_{Thermal}$
---	K	K	W	W	%
1	4.6	11.5	913	800	87.6

If the optional Computer Interface HC100 and software is being used then it will be seen that the tabular displays are similar to those used on screen.

CALCULATIONS

For the example the calculations are as follows.

It is necessary to convert the volume flow rates to mass flow rates using the conversion factors in table 1 and 2 on page C7. The water density ρ (kg litre^{-1}) and specific heat capacity Cp (kJ kg^{-1} K^{-1}) is dependant upon the temperature and the mean fluid temperature

$$T_{mean} = \frac{T_{inlet} + T_{outlet}}{2}$$

is used to calculate the relevant temperature.

For the Hot stream:

T_{mean} = (58.5+53.9) / 2 = 56.2 °C

From table 1 and 2 at T_{mean} = 56.2 °C ρ_{hot} = 0.9852 kg litre^{-1}, Cp = 4.182 kJ kg^{-1} k^{-1}

Hence the power emitted from the hot stream $\dot{Q}e$

$$Q_e = V_{hot}\ \dot{Q}e = \frac{V_{hot}}{60}\ \rho_{hot}\ Cp_{Hot}\,(T1 - T2) \times 1000 \quad \text{Watts}$$

$$= \frac{2.89}{60} \times 0.9852 \times 4.182 \times (58.5 - 53.9) \times 1000$$

$$= 913 \text{ Watts}$$

For the cold stream:

T_{mean} = (26.9 + 15.4) / 2 = 21.2 °C

From table 1 and 2 at T_{mean} = 21.2 °C ρ_{hot} = 0.998kg litre^{-1}, Cp = 4.181 kJ kg^{-1} k^{-1}

The power absorbed by the cold stream $\dot{Q}a$

$$\dot{Q}a = \frac{V_{cold}}{60}\ \rho_{cold}\ Cp_{cold}\,(T4 - T3) \times 1000 \quad \text{Watts}$$

$$= \frac{1.0}{60} \times 0.998 \times 4.181 \times (26.9 - 15.4) \times 1000$$

$$= 800 \text{Watts}$$

The overall thermal efficiency

$$\eta_{\text{Thermal}} = \frac{\dot{Q}a}{\dot{Q}e} \times 100(\%)$$

Hence

$$\eta_{\text{Thermal}} = \frac{800}{913} \times 100(\%)$$
$$= 87.6\%$$

Note that as the shell is not insulated in order to allow student examination of the components heat will be lost or gained depending upon the ambient temperature. In extreme cases this can result in an *apparent* thermal efficiency greater than 100%.

If the optional Computer Interface HC100 and software is being used then the user can return to the H100C Shell and Tube Heat Exchanger Main Menu by clicking the End and Back keys.
Once back at the main menu the user can opt to record more data in another experiment on the same heat exchanger or review the data recorded during the preceding experiment. Alternatively the user can return to the H100 Main Menu by continuing to click the Back key and the select to use another optional heat exchanger if available.

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

The following procedure demonstrates the effect of changing the direction of fluid flow on the heat transfer and temperature distribution in a shell and tube heat exchanger.

NOTE that the observations from experiment No 4 may be used for the calculations in this procedure in order to save experimental time.

It is assumed that the basic INSTALLATION AND COMMISSIONING procedures for the Heat Exchanger Service Unit H100 have been completed as detailed in the main manual on pages 5 to 7.

Procedure

Install the Shell and tube Heat Exchanger H100C as detailed in **INSTALLATION / Heat Exchanger Installation H100C** on page C5 and connect the cold water circuit to give **Counter-Current** flow as detailed in the same section.

Follow the **OPERATING PROCEDURE** detailed in the main manual on page 16 onwards in order to establish the following operating conditions.

Fill the hot water circuit, set the cold water pressure regulator, and turn on the power to the unit. Then set the hot water temperature controller to 60°C and turn on the circulating pump.

Set the cold water flow rate V_{cold} to 1 litre min^{-1} and the hot water flow rate V_{hot} to 2 litre min^{-1}.

If the optional Computer Interface HC100 and software is being used:

It is assumed that the Installation and commissioning of both the hardware and software has been carried out according to the procedures on page 5 of the main manual. Ensure that the power lead to the Hilton data logger is connected, that the serial lead from the computer to the data logger is connected and that the ribbon cable from the interface to the base unit is also connected.

It is assumed that the computer is already running in Windows™ mode.. Click on the H100 icon to start the software.

Language Screen:

The first screen will show the language section. If this option has been purchased then the preferred language may be selected.

H100 Main Menu:

The next screen is the main menu for the H100 series of optional units. Select ***the H100C Shell and Tube heat exchanger*** *(Note that only one option can be selected and that if the wrong unit is selected the procedure may be repeated).*

It is assumed that the data is to be captured on disc and therefore this option should be selected in the lower box. When all selections have been made click OK.

Communications Test:

As the user has selected to collect data the next screen carries out a communications test with the H100 base unit. Select the serial port of the computer that the unit is connected to and then click the Go button with the mouse pointer.

Assuming communications is confirmed the next screen will show the H100C Shell and Tube Heat Exchanger Main Menu.

If communications fails for any reason check the parameters indicated on the screen and repeat the test. If communications cannot be established for any reason the Cancel button may be used and the cause investigated.

H100C Shell and Tube Heat Exchanger Main Menu:

*This lists the optional experiments that may be carried out with the H100C Shell and Tube Heat Exchanger. To continue with the above experiment select **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** and then click OK.*

H100C Experiment Number 3:

*Assuming that the above procedure is being followed select the **Counter-Current** flow option initially and check the Instructions on the screen have been observed. If data is to be recorded to disc then select the Store data on disc for later review option. Then click OK.*

If the user DOES select to record data to disc then a file name will be requested. Note that a partially fixed file name is used together with a fixed file suffix. This enables the software to recognise data during the review option that is compatible with the review mode selected. The user is required to enter the remaining digits that will be of relevance to them in the future. Once a valid file name is entered the Recording data screen is displayed.

Recording data:

The next screen shows four tabs Flow, Temperature, Data Point and Temp. distribution. The Flow and Temperature graphs may be used to set the hot and cold stream flow rates to the desired values and the temperature graph used to determine when the unit has reached a stable condition.

Once stable conditions have been established the Data point tab may be clicked and the Record button clicked to record and display a captured data point. Note that data may be sent to a printer (If a printer is connected) if required. The option of Raw (end results not calculated) or Calculated data may be selected for the printing option.

The results shown in the table are updated each time the record button is clicked. NOTE that if no changes are made to the H100C settings of flow rate and hot stream temperature the captured results will all be similar.

If the Temp Distribution tab is clicked then a simple line diagram graph will be displayed showing the temperature distribution of the last sample.

The software should be utilised to automate the data recording procedures detailed as follows in the manual procedure.

To return to the H100C Shell and Tube Heat Exchanger Main Menu click the End button on the Data capture screen.

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 in the **INSTALLATION / Heat Exchanger Installation H100C** on page C5. Note that there is no need to disconnect the hot water circuit or to turn off the hot water pump during this operation.

Set the flow indicator to Fcold and adjust the cold water flow valve so that V_{cold} is approximately 1 litre min^{-1}. Select Fhot and adjust the hot water flow rate V_{hot} to approximately 2 litre min^{-1}. Set the hot water temperature to 60 °C if this has been adjusted.

*If the optional Computer Interface HC100 and software is being used then from the H100C Shell and Tube Heat Exchanger Main Menu select **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** and then click OK.*

H100A Experiment Number 3:

*Assuming that the above procedure is being followed select the **Co-Current** flow option initially and check the Instructions on the screen have been observed. If data is to be recorded to disc then select the Store data on disc for later review option. Then click OK.*

If the user DOES select to record data to disc then a file name will be requested. Note that a partially fixed file name is used together with a fixed file suffix. This enables the software to recognise data during the review option that is compatible with the review mode selected. The user is required to enter the remaining digits that will be of relevance to them in the future. Once a valid file name is entered the Recording data screen is displayed. The data display and capture procedure is the same as above in the Counter-current flow procedure.

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

OBSERVATIONS

Flow Direction: Counter-Current

Sample No.	T1	T2	T3	T4	V_{hot}	V_{cold}
----	°C	°C	°C	°C	L min^{-1}	L min^{-1}
1	58.9	53.1	15.5	26.2	2.1	0.98
2						
3						
4						
5						

Calculated Data

Sample No.	Δt_{hot}	Δt_{cold}	$\dot{Q}e$	$\dot{Q}a$	$\eta_{Thermal}$	η_{Cold}	η_{Hot}	η_{Mean}
---	K	K	W	W	%	%	%	%
1	5.8	10.7	837	729	87.1	24.6	13.3	18.9
2								
3								
4								
5								

If the optional Computer Interface HC100 and software is being used then it will be seen that the tabular displays are similar to those used on screen.

Flow Direction : Co-Current

Sample No.	T1	T2	T3	T4	V_{hot}	V_{cold}
----	°C	°C	°C	°C	L min^{-1}	L min^{-1}
1	59.2	52.8	21.7	14.2	1.95	1.18
2						
3						
4						
5						

Calculated Data

Sample No.	Δt_{hot}	Δt_{cold}	$\dot{Q}e$	$\dot{Q}a$	$\eta_{Thermal}$	η_{Cold}	η_{Hot}	η_{Mean}
---	K	K	W	W	%	%	%	%
1	6.4	7.5	857	616	71.8	20.0	17.1	18.5
2								
3								
4								
5								

If the optional Computer Interface HC100 and software is being used then it will be seen that the tabular displays are similar to those used on screen.

CALCULATIONS

For the examples the calculations are as follows.

Counter-Current Flow

It is necessary to convert the volume flow rates to mass flow rates using the conversion factors in table 1 and 2 on page C7. The water density ρ (kg litre^{-1}) and specific heat capacity Cp (kJ kg^{-1} K^{-1}) is dependant upon the temperature and the mean fluid temperature Tmean

$$T_{mean} = \frac{T_{inlet} + T_{outlet}}{2}$$

is used to calculate the relevant temperature.

For the Hot Stream:

T_{mean} = (58.9 + 53.1) / 2 = 56.0 °C

From table 1 and 2 at T_{mean} = 56.0 °C ρ_{hot} = 0.985kg litre^{-1}
Cp = 4.182kJ kg^{-1} k^{-1}

Hence the power emitted from the hot stream $\dot{Q}$ e

$$\dot{Q}e = \frac{V_{hot}}{60}\ \rho_{hot}\ Cp_{Hot}\,(T1 - T2) \times 1000 \quad \text{Watts}$$

$$= \frac{2.1}{60} \times 0.9852 \times 4.180 \times (58.9 - 53.1) \times 1000$$

$$= 837 \ \text{Watts}$$

For the Cold stream:

T_{mean} = (26.2 + 15.5) / 2 = 20.9 °C

From table 1 and 2 at T_{mean} = 20.9 °C ρ_{hot} = 0.998 kg litre^{-1}
Cp = 4.181 kJ kg^{-1} k^{-1}

Hence the power absorbed by the cold stream $\dot{Q}$ a

$$\dot{Q}a = \frac{V_{cold}}{60}\ \rho_{cold}\ Cp_{Cold}\,(T4 - T3)\ 1000 \quad \text{Watts}$$

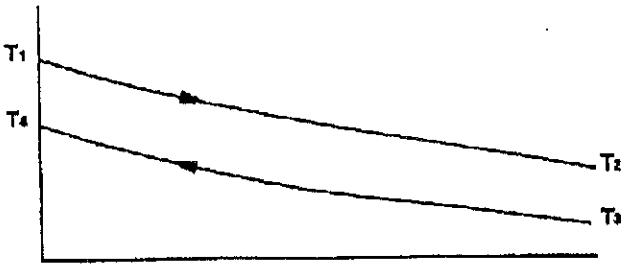
$$= \frac{0.98}{60} \times 0.998 \times 4.181 \times (26.2 - 15.5) \times 1000$$

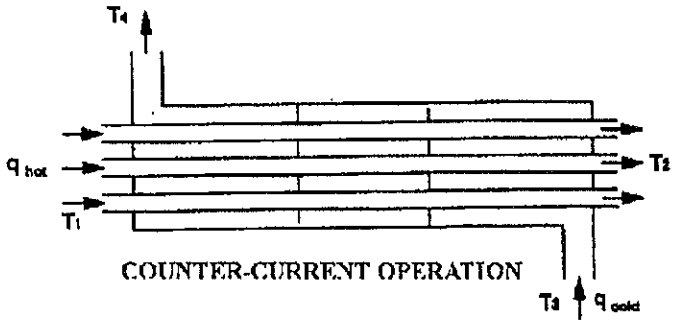
$$= 729 \ \text{Watts}$$

Reduction in Hot fluid temperature Δt hot = T1 - T2
= 58.9 - 53.1
= 5.8 K

Increase in Cold fluid temperature Δt cold = T4 - T3
= 26.2 - 15.5
= 10.7 K

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

$$\eta_{Hot} = \frac{T1 - T2}{T1 - T3} \times 100\%$$
$$= \frac{58.9 - 53.1}{58.9 - 15.5} \times 100\%$$
$$= 13.3\%$$

The temperature efficiency of the cold stream from the above diagram

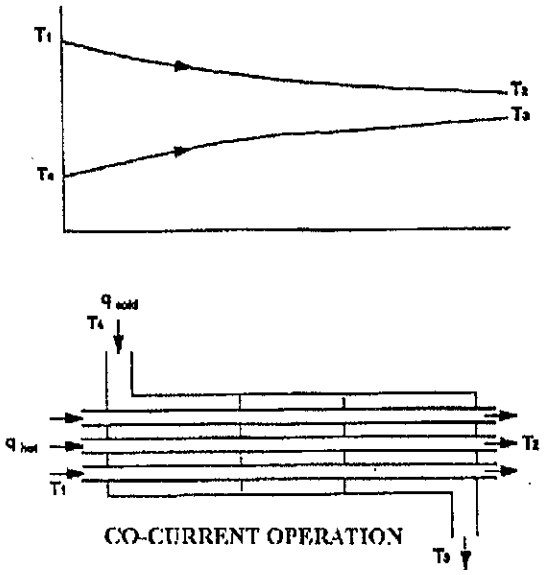
$$\eta_{Cold} = \frac{T4 - T3}{T1 - T3} \times 100\%$$
$$= \frac{26.2 - 15.5}{58.9 - 15.5} \times 100\%$$
$$= 24.6\%$$

The mean temperature efficiency

$$\eta_{Mean} = \frac{\eta_{Hot} + \eta_{Cold}}{2}$$
$$= \frac{13.3 + 24.6}{2}$$
$$= 18.9\%$$

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 $\dot{Q}e$

$$\dot{Q}e = \frac{V_{hot}}{60}\ \rho_{hot}\ Cp_{Hot}\,(T1 - T2) \times 1000 \quad \text{Watts}$$

The power absorbed by the cold stream $\dot{Q}a$

$$\dot{Q}a = \frac{V_{cold}}{60}\ \rho_{cold}\ Cp_{Cold}\,(T3 - T4) \times 1000 \quad \text{Watts}$$

Reduction in Hot fluid temperature $\Delta t\ hot = T1 - T2\ K$

Increase in Cold fluid temperature $\Delta t\ cold = T3 - T4\ K$

The temperature efficiency of the hot stream from the above diagram

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

The temperature efficiency of the cold stream from the above diagram

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

The mean temperature efficiency

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

The tabulated and calculated results show the differences between Counter-Current flow and Co-Current flow and the effect upon temperature efficiency and Δt for the hot and cold stream.

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).

The following procedure demonstrates the effect of changing the direction of fluid flow on the overall heat transfer coefficient. The Logarithmic mean temperature difference is used to calculate the overall heat transfer coefficient.

NOTE that the observations from experiment No 3 may be used for the calculations in this procedure in order to save experimental time.

I It is assumed that the basic INSTALLATION AND COMMISSIONING procedures for the Heat Exchanger Service Unit H100 have been completed as detailed in the main manual on pages 5 to 7.

Procedure

Install the Shell and Tube Heat Exchanger H100c as detailed in **INSTALLATION / Heat Exchanger Installation H100C** on page C5 and connect the cold water circuit to give **Counter-Current** flow as detailed in the same section.

Follow the **OPERATING PROCEDURE** detailed in the main manual on page 16 onwards in order to establish the following operating conditions.

Fill the hot water circuit, set the cold water pressure regulator, and turn on the power to the unit. Then set the hot water temperature controller to 60°C and turn on the circulating pump.

Set the cold water flow rate V_{cold} to 1 litre min^{-1} and the hot water flow rate V_{hot} to 2 litre min^{-1}.

If the optional Computer Interface HC100 and software is being used:

It is assumed that the Installation and commissioning of both the hardware and software has been carried out according to the procedures on page 5 of the main manual. Ensure that the power lead to the Hilton data logger is connected, that the serial lead from the computer to the data logger is connected and that the ribbon cable from the interface to the base unit is also connected.

It is assumed that the computer is already running in Windows™ mode. Click on the H100 icon to start the software.

Language Screen:

The first screen will show the language section. If this option has been purchased then the preferred language may be selected.

H100 Main Menu:

The next screen is the main menu for the H100 series of optional units. Select ***the H100C Shell and Tube heat exchanger*** *(Note that only one option can be selected and that if the wrong unit is selected the procedure may be repeated.)*

It is assumed that the data is to be captured on disc and therefore this option should be selected in the lower box. When all selections have been made click OK.

Communications Test:

As the user has selected to collect data the next screen carries out a communications test with the H100 base unit. Select the serial port of the computer that the unit is connected to and then click the Go button with the mouse pointer.

Assuming communications is confirmed the next screen will show the H100C Shell and Tube Heat Exchanger Main Menu.

If communications fails for any reason check the parameters indicated on the screen and repeat the test. If communications cannot be established for any reason the Cancel button may be used and the cause investigated.

H100C Shell and Tube Heat Exchanger Main Menu.

This lists the optional experiments that may be carried out with the H100 Shell and Tube Heat Exchanger. To continue with the above experiment select 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),*** *and then click OK.*

H100A Experiment Number 4:

Assuming that the above procedure is being followed select the ***Counter-Current*** *flow option initially and check the Instructions on the screen have been observed. If data is to be recorded to disc then select the Store data on disc for later review option. Then click OK.*

If the user DOES select to record data to disc then a file name will be requested. Note that a partially fixed file name is used together with a fixed file suffix. This enables the software to recognise data during the review option that is compatible with the review mode selected. The user is required to enter the remaining digits that will be of relevance to them in the future. Once a valid file name is entered the Recording data screen is displayed.

Recording data:

The next screen shows four tabs Flow, Temperature and Data Point. The Flow and Temperature graphs may be used to set the hot and cold stream flow rates to the desired values and the temperature graph used to determine when the unit has reached a stable condition.

Once stable conditions have been established the Data point tab may be clicked and the Record button clicked to record and display a captured data point. Note that data may be sent to a printer (If a printer is connected) if required The option of Raw (end results not calculated) or Calculated data may be selected for the printing option.

The results shown in the table are updated each time the record button is clicked. NOTE that if no changes are made to the H100C settings of flow rate and hot stream temperature the captured results will all be similar.

The software should be utilised to automate the data recording procedures detailed as follows in the manual procedure.

To return to the H100C Shell and Tube Heat Exchanger Main Menu click the End button on the Data capture screen.

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 in the **INSTALLATION / Heat Exchanger Installation H100C** on page C5. Note that there is no need to disconnect the hot water circuit or to turn off the hot water pump during this operation.

Set the flow indicator to F_{cold} and adjust the cold water flow valve so that V_{cold} is approximately 1 litre min^{-1}. Select F_{hot} and adjust the hot water flow rate to approximately 2 litre min^{-1}. Set the hot water temperature to 60 °C if this has been adjusted.

If the optional Computer Interface HC100 and software is being used then from the H100C Shell and Tube Heat Exchanger Main Menu select 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)*** *and then click OK.*

H100C Experiment Number 4:

*Assuming that the above procedure is being followed select the **Co-Current** flow option initially and check the Instructions on the screen have been observed. If data is to be recorded to disc then select the Store data on disc for later review option. Then click OK.*
If the user DOES select to record data to disc then a file name will be requested. Note that a partially fixed file name is used together with a fixed file suffix. This enables the software to recognise data during the review option that is compatible with the review mode selected. The user is required to enter the remaining digits that will be of relevance to them in the future. Once a valid file name is entered the Recording data screen is displayed. The data display and capture procedure is the same as above in the Counter-current flow procedure.

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.

OBSERVATIONS
Flow Direction: Counter-Current

Sample No.	T1	T2	T3	T4	V_{hot}	V_{cold}
----	°C	°C	°C	°C	L min^{-1}	L min^{-1}
1	58.9	53.1	15.5	26.2	2.1	0.98
2						
3						
4						
5						

Calculated Data

Sample No.	Δt_{hot}	Δt_{cold}	$\dot{Q}e$	$\dot{Q}a$	$\eta_{Thermal}$	η_{Cold}	η_{Hot}	η_{Mean}
---	K	K	W	W	%	%	%	%
1	5.8	10.7	837	729	87.1	24.6	13.3	18.9
2								
3								
4								
5								

Sample No.	LMTD	U
---	K	W m^{2}K^{-1}
1	35.09	1310.6
2		
3		
4		
5		

If the optional Computer Interface HC100 and software is being used then it will be seen that the tabular displays are similar to those used on screen.

Flow Direction: Co-Current

Sample No.	T1	T2	T3	T4	V_{hot}	V_{cold}
----	°C	°C	°C	°C	L min^{-1}	L min^{-1}
1	59.2	52.8	21.7	14.2	1.95	1.18
2						
3						
4						
5						

Calculated Data

Sample No.	Δt_{hot}	Δt_{cold}	$\dot{Q}e$	$\dot{Q}a$	$\eta_{Thermal}$	η_{Cold}	η_{Hot}	η_{Meanl}
---	K	K	W	W	%	%	%	%
1	6.4	7.5	857	616	71.8	20.0	17.1	18.5
2								
3								
4								
5								

Sample No.	LMTD	U
---	K	W m^2K^{-1}
1	37.6	1252.3
2		
3		
4		
5		

If the optional Computer Interface HC100 and software is being used then it will be seen that the tabular displays are similar to those used on screen.

CALCULATIONS

For the examples the calculations are as follows.

Counter-Current Flow

It is necessary to convert the volume flow rates to mass flow rates using the conversion factors in table 1 and 2 on page C7. The water density ρ (kg litre^{-1}) and specific heat capacity Cp (kJ kg^{-1} K^{-1}) is dependant upon the temperature and the mean fluid temperature Tmean

$$T_{mean} = \frac{T_{inlet} + T_{outlet}}{2}$$

is used to calculate the relevant temperature

For the Hot stream: T_{mean} = (58.9 + 53.1) / 2 = 56.0 °C

From table 1 and 2 at T_{mean} = 56.0 °C ρ_{hot} = 0.985kg litre^{-1}

Cp = 4.182kJ kg^{-1} k^{-1}

Hence the power emitted from the hot stream $\dot{Q}e$

$$\dot{Q}e = \frac{V_{hot}}{60}\,\rho_{hot}\,Cp_{Hot}\,(T1 - T2) \times 1000 \quad \text{Watts}$$

$$= \frac{2.1}{60} \times 0.9852 \times 4.180 \times (58.9 - 53.1) \times 1000$$

$$= 837 \ \text{Watts}$$

For the Cold stream:
$T_{mean} = (26.2 + 15.5) / 2 = 20.9$ °C

From table 1 and 2 at $T_{mean} = 20.9$ °C $\quad \rho_{hot} = 0.998$ kg litre^{-1}
$\quad Cp = 4.181$ kJ kg^{-1} k^{-1}

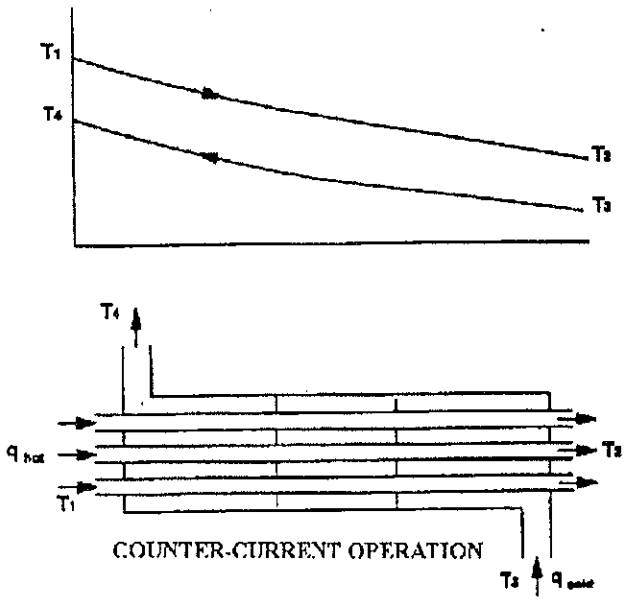
Hence the power absorbed by the cold stream $\dot{Q}$ a

$$\dot{Q}a = \frac{V_{cold}}{60} \rho_{cold} \, Cp_{Cold} (T4 - T3) \; 1000 \quad \text{Watts}$$
$$= \frac{0.98}{60} \times 0.998 \times 4.181 \times (26.2 - 15.5) \times 1000$$
$$= 729 \quad \text{Watts}$$

Reduction in Hot fluid temperature $\quad \Delta t$ hot $= T1 - T2$
$= 58.9 - 53.1$
$= 5.8$ K

Increase in Cold fluid temperature $\quad \Delta t$ cold $= T4 - T3$
$= 26.2 - 15.5$
$= 10.7$ K

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

$$\eta_{Hot} = \frac{T1 - T2}{T1 - T3} \times 100\%$$
$$= \frac{58.9 - 53.1}{58.9 - 15.5} \times 100\%$$
$$= 13.3\%$$

The temperature efficiency of the cold stream from the above diagram

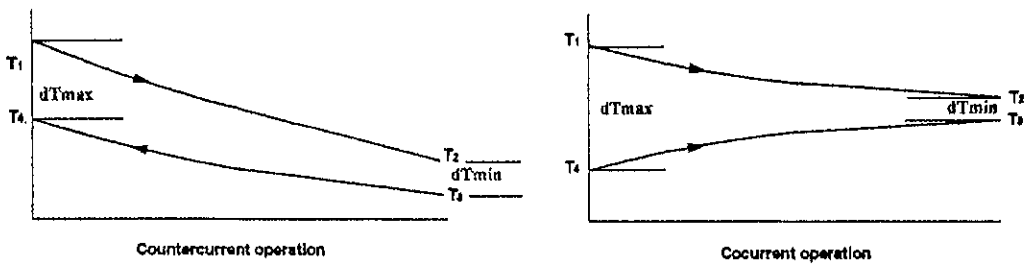
$$\eta_{Cold} = \frac{T4 - T3}{T1 - T4} \times 100\%$$
$$= \frac{26.2 - 15.5}{58.9 - 15.5} \times 100\%$$
$$= 24.6\%$$

The mean temperature efficiency

$$\eta_{Mean} = \frac{\eta_{Hot} + \eta_{Cold}}{2}$$
$$= \frac{13.3 + 24.6}{2}$$
$$= 18.9\%$$

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 text books.



The LMTD is defined as

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

Hence from the above diagrams of temperature distribution

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

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.

Hence for the Counter-current example

$$\text{LMTD} = \frac{(58.9-26.2)-(53.1-15.5)}{\ln\left(\frac{(58.9-26.2)}{(53.1-15.5)}\right)}$$

$$= \frac{-4.9}{\ln(0.8696)}$$

$$= \frac{-4.9}{-0.1396}$$

$$= 35.09\,\text{K}$$

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

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

Where

A	Heat transfer area of heat exchanger (m^2)
$\dot{Q}$ 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

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

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)
n	Number of heat transfer tubes (Non dimensional)

Hence for the heat exchanger from the **USEFUL DATA** section on page C7.

$$d_m = \frac{(0.00635)+(0.00635-(2\times 0.0006))}{2}$$

$$= \frac{0.00635+0.00515}{2}$$

$$= 0.00575\,\text{m}$$

$$A = \pi \times 0.00575 \times 0.144 \times 7$$

$$= 0.0182\,\text{m}^2$$

Hence for the test conditions the overall heat transfer coefficient:-

$$U = \frac{\dot{Q}_e}{A \times LMTD}$$
$$= \frac{837}{0.0182 \times 35.09}$$
$$= 1310.6\ Wm^{-2}K^{-1}$$

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 $\dot{Q}e$

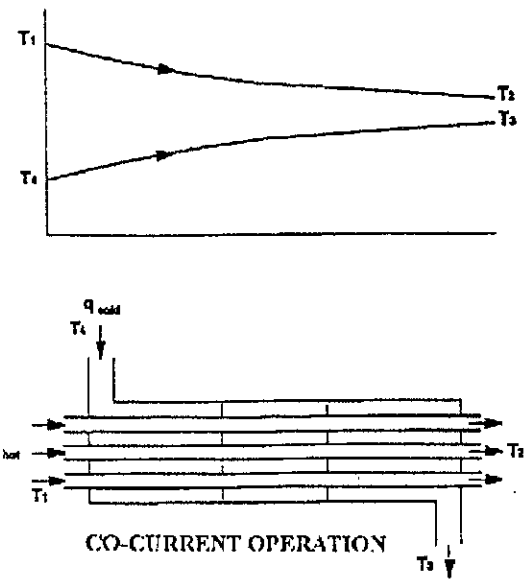
$$\dot{Q}e = \frac{V_{hot}}{60}\ \rho_{hot}\ Cp_{Hot}\,(T1 - T2) \times 1000 \quad \text{Watts}$$

The power absorbed by the cold stream $\dot{Q}a$

$$\dot{Q}a = \frac{V_{cold}}{60}\ \rho_{cold}\ Cp_{Cold}\,(T3 - T4)\ 1000 \quad \text{Watts}$$

Reduction in Hot fluid temperature $\Delta t\ hot = T1 - T2\ K$

Increase in Cold fluid temperature $\Delta t\ cold = T3 - T4\ K$



The temperature efficiency of the hot stream from the above diagram

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

The temperature efficiency of the cold stream from the above diagram

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

The mean temperature efficiency

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

The logarithmic mean temperature difference LMTD

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

The Overall heat transfer coefficient U

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

The tabulated and calculated results show the differences between Counter-Current flow and Co-Current flow and the effect upon temperature efficiency, Δt, and the overall heat transfer coefficient.

If the optional Computer Interface HC100 and software is being used then the user can return to the H100C Shell and Tube Heat Exchanger Main Menu by clicking the End and Back keys.
Once back at the main menu the user can opt to record more data in another experiment on the same heat exchanger or review the data recorded during the preceding experiment. Alternatively the user can return to the H100 Main Menu by continuing to click the Back key and the select to use another optional heat exchanger if available.

5. To investigate the effect of changes in hot fluid and cold fluid flow rate on the temperature efficiencies and overall heat transfer coefficient.

The following procedure demonstrates the effect of changing the flow rate of both the hot and cold streams on the overall heat transfer coefficient. The Logarithmic mean temperature difference is used to calculate the overall heat transfer coefficient.

I It is assumed that the basic INSTALLATION AND COMMISSIONING procedures for the Heat Exchanger Service Unit H100 have been completed as detailed in the main manual on pages 5 to 7.

Procedure

Install the Shell and Tube Heat Exchanger H100C as detailed in **INSTALLATION / Heat Exchanger Installation H100C** on page C5 and connect the cold water circuit to give **Counter-Current** flow as detailed in the same section.

Follow the **OPERATING PROCEDURE** detailed in the main manual on page 16 onwards in order to establish the following operating conditions.

Fill the hot water circuit, set the cold water pressure regulator, and turn on the power to the unit. Then set the hot water temperature controller to 60°C and turn on the circulating pump.

Set the cold water flow rate V_{cold} to 1 litre min^{-1} and the hot water flow rate V_{hot} to 1.0 litre min^{-1}.

If the optional Computer Interface HC100 and software is being used:

It is assumed that the Installation and commissioning of both the hardware and software has been carried out according to the procedures on page 5 of the main manual. Ensure that the power lead to the Hilton data logger is connected, that the serial lead from the computer to the data logger is connected and that the ribbon cable from the interface to the base unit is also connected.

It is assumed that the computer is already running in Windows™ mode. Click on the H100 icon to start the software.

Language Screen:

The first screen will show the language section. If this option has been purchased then the preferred language may be selected.

H100 Main Menu:

The next screen is the main menu for the H100 series of optional units. Select ***the H100C Shell and Tube heat exchanger*** *(Note that only one option can be selected and that if the wrong unit is selected the procedure may be repeated).*

It is assumed that the data is to be captured on disc and therefore this option should be selected in the lower box. When all selections have been made click OK.

Communications Test:

As the user has selected to collect data the next screen carries out a communications test with the H100 base unit. Select the serial port of the computer that the unit is connected to and then click the Go button with the mouse pointer.

Assuming communications is confirmed the next screen will show the H100C Shell and Tube Heat Exchanger Main Menu.

If communications fails for any reason check the parameters indicated on the screen and repeat the test. If communications cannot be established for any reason the Cancel button may be used and the cause investigated.

H100C Shell and Tube Heat Exchanger Main Menu:

This lists the optional experiments that may be carried out with the H100C Shell and Tube Heat Exchanger. To continue with the above experiment select 5 ***To investigate the effect of changes in hot fluid and cold fluid flow rate on the temperature efficiencies and overall heat transfer coefficient,*** *and then click OK.*

H100C Experiment Number 5:

Assuming that the above procedure is being followed select the ***Counter-Current*** *flow option initially and check the Instructions on the screen have been observed. If data is to be recorded to disc then select the Store data on disc for later review option. Then click OK.*

If the user DOES select to record data to disc then a file name will be requested. Note that a partially fixed file name is used together with a fixed file suffix. This enables the software to recognise data during the review option that is compatible with the review mode selected. The user is required to enter the remaining digits that will be of relevance to them in the future. Once a valid file name is entered the Recording data screen is displayed.

Recording data:

The next screen shows four tabs Flow, Temperature and Data Point. The Flow and Temperature graphs may be used to set the hot and cold stream flow rates to the desired values and the temperature graph used to determine when the unit has reached a stable condition.

Once stable conditions have been established the Data point tab may be clicked and the Record button clicked to record and display a captured data point.

A dialogue box will be displayed where the user must enter the nominal hot stream flow rate to the nearest 0.5 litre min^{-1}. This is then used to group data points even though the ACTUAL hot stream flow recorded may deviate slightly from the original set value.

Note that data may be sent to a printer (If a printer is connected) if required. The option of Raw (end results not calculated) or Calculated data may be selected for the printing option. The results shown in the table are updated each time the record button is clicked. NOTE that if no changes are made to the H100A settings of flow rate and hot stream temperature the captured results will all be similar.

The software should be utilised to automate the data recording procedures detailed as follows in the manual procedure.

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}

The hot and cold flows should then be adjusted according to the following suggested values and the procedure repeated.

V_{hot} (Litre min^{-1})	V_{cold} (Litre min^{-1})
1.0	1.0
1.0	2.0
1.0	3.0
1.0	1.0
2.0	2.0
2.0	3.0
Max	1.0
Max	2.0
Max	3.0

If time permits the increments between the hot and cold stream flow rates may be made smaller to 0.5 litre min^{-1} if required.

If the optional Computer Interface HC100 and software is being used:

All of the observations may be carried out without leaving the experiment 5 Recording data screens. The water flow rate tab and temperature tabs should be used to check the required flow rates and temperature stability and the Recording data procedures used to collect each data point. Note that for each reading a Nominal hot flow will be required and the user must select the nearest nominal hot flow value.

This completes the basic Counter-Current flow experiment observations.

If the optional Computer Interface HC100 and software is being used then the user can return to the H100C Shell and Tube Heat Exchanger Main Menu by clicking the End and Back keys.

Next connect the cold water circuit to give **Co-Current flow** as detailed in the **INSTALLATION / Heat Exchanger Installation H100C** on page C5. Note that there is no need to disconnect the hot water circuit or to turn off the hot water pump during this operation.

If the optional Computer Interface HC100 and software is being used:

Select H100C Experiment Number 5:

Assuming that the above procedure is being followed select the ***Co-Current*** *flow option and check the Instructions on the screen have been observed. If data is to be recorded to disc then select the Store data on disc for later review option. Then click OK.*

If the user DOES select to record data to disc then a file name will be requested. Note that a partially fixed file name is used together with a fixed file suffix. This enables the software to recognise data during the review option that is compatible with the review mode selected. The user is required to enter the remaining digits that will be of relevance to them in the future. Once a valid file name is entered the Recording data screen is displayed.

Recording data:

The next screen shows four tabs Flow, Temperature and Data Point. The Flow and Temperature graphs may be used to set the hot and cold stream flow rates to the desired values and the temperature graph used to determine when the unit has reached a stable condition.

Once stable conditions have been established the Data point tab may be clicked and the Record button clicked to record and display a captured data point.

A dialogue box will be displayed where the user must enter the nominal hot stream flow rate to the nearest 0.5 litre min^{-1}. This is then used to group data points even though the ACTUAL hot stream flow recorded may deviate slightly from the original set value.

Note that data may be sent to a printer (If a printer is connected) if required. The option of Raw (end results not calculated) or Calculated data may be selected for the printing option. The results shown in the table are updated each time the record button is clicked. NOTE that if no changes are made to the H100C settings of flow rate and hot stream temperature the captured results will all be similar.

The software should be utilised to automate the data recording procedures detailed as follows in the manual procedure.

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}

The hot and cold flows should then be adjusted according to the following suggested values and the procedure repeated.

V_{hot} (Litre min^{-1})	V_{cold} (Litre min^{-1})
1.0	1.0
1.0	2.0
1.0	3.0
2.0	1.0
2.0	2.0
2.0	3.0
Max	1.0
Max	2.0
Max	3.0

This completes the basic Co-Current flow experiment observations

OBSERVATIONS

Flow Direction: Counter-Current

Sample No.	T1	T2	T3	T4	V_{hot}	V_{cold}
----	°C	°C	°C	°C	L min^{-1}	L min^{-1}
1	60.5	48.7	14.7	23.1	0.98	0.95
2						
3						
4						
5						

Calculated Data

Sample No.	Δt_{hot}	Δt_{cold}	$\dot{Q}e$	$\dot{Q}a$	η_{Cold}	η_{Hot}	η_{Mean}
---	K	K	W	W	%	%	%
1	11.8	8.4	795	555	18.3	25.8	22.1
2							
3							
4							
5							

Sample No.	LMTD	U	Nominal Hot Flow
---	K	W m^2K^{-1}	litre min^{-1}
1	35.67	1224.6	1.0
2			
3			
4			
5			

If the optional Computer Interface HC100 and software is being used then it will be seen that the tabular displays are similar to those used on screen.

Flow Direction: Co-Current

Sample No.	T1	T2	T3	T4	V_{hot}	V_{cold}
----	°C	°C	°C	°C	L min^{-1}	L min^{-1}
1	60.8	49.5	22.8	14.4	0.99	1.06
2						
3						
4						
5						

Calculated Data

Sample No.	Δt_{hot}	Δt_{cold}	$\dot{Q}e$	$\dot{Q}a$	η_{Cold}	η_{Hot}	η_{Meanl}
---	K	K	W	W	%	%	%
1	11.3	8.4	769	620	22.1	29.7	25.9
2							
3							
4							
5							

Sample No.	LMTD	U
—	K	$W\ m^{-2}K^{-1}$
1	35.64	1153.2
2		
3		
4		
5		

CALCULATIONS

For the examples the calculations are as follows.

Counter-Current Flow

It is necessary to convert the volume flow rates to mass flow rates using the conversion factors in table 1 and 2 on page C7. The water density ρ (kg $litre^{-1}$) and specific heat capacity Cp (kJ kg^{-1} K^{-1}) is dependant upon the temperature and the mean fluid temperature Tmean

$$T_{mean} = \frac{T_{inlet} + T_{outlet}}{2}$$

is used to calculate the relevant temperature of the Hot stream.

For the Hot stream:

T_{mean} = (60.5 + 48.7) / 2 = 54.6 °C

From table 1 and 2 at T_{mean} = 54.6 °C

ρ_{hot} = 0.986 kg $litre^{-1}$

Cp = 4.182 kJ kg^{-1} k^{-1}

Hence the power emitted from the hot stream $\dot{Q}$ e

$$\dot{Q}e = \frac{V_{hot}}{60}\ \rho_{hot}\ Cp_{Hot}\ (T1 - T2)\ 1000 \quad \text{Watts}$$

$$= \frac{0.98}{60} \times 0.986 \times 4.182 \times (60.5 - 48.7) \times 1000$$

$$= 795 \text{ Watts}$$

For the Cold stream Tmean

T_{mean} = (23.1 + 14.7) / 2 = 18.9 °C

From table 1 and 2 at T_{mean} = 18.9 °C

ρ_{Cold} = 0.998 kg $litre^{-1}$

Cp_{Cold} = 4.182 kJ kg^{-1} k^{-1}

Hence the power absorbed by the cold stream $\dot{Q}$ a

$$\dot{Q}a = \frac{V_{cold}}{60}\ \rho_{cold}\ Cp_{Cold}\ (T4 - T3) \times 1000 \quad \text{Watts}$$

$$= \frac{0.95}{60} \times 0.998 \times 4.182 \times (23.1 - 14.7) \times 1000$$

$$= 555 \quad \text{Watts}$$

Reduction in Hot fluid temperature

Δt hot = T1 – T2

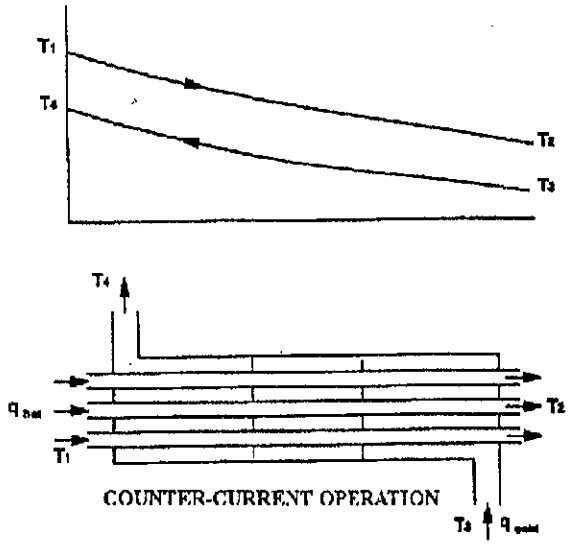
= 60.3 – 48.7

= 11.8 K

Increase in Cold fluid temperature Δt cold $= T4 - T3$
$= 23.1 - 14.7$
$= 8.4$ K

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

$$\eta_{Hot} = \frac{T1 - T2}{T1 - T3} \times 100\%$$
$$= \frac{60.5 - 48.7}{60.5 - 14.7} \times 100\%$$
$$= 25.8\%$$

The temperature efficiency of the cold stream from the above diagram

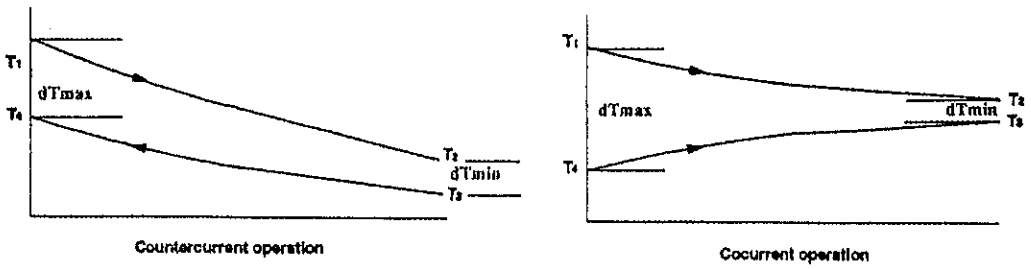
$$\eta_{Cold} = \frac{T4 - T3}{T1 - T3} \times 100\%$$
$$= \frac{23.1 - 14.7}{60.5 - 14.7} \times 100\%$$
$$= 18.3\%$$

The mean temperature efficiency

$$\eta_{Mean} = \frac{\eta_{Hot} + \eta_{Cold}}{2}$$
$$= \frac{25.8 + 18.3}{2}$$
$$= 22.1\%$$

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 text books.



The LMTD is defined as

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

Hence from the above diagrams of temperature distribution

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

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.

Hence for the Counter-current example

$$\text{LMTD} = \frac{(60.5 - 23.1) - (48.7 - 14.7)}{\ln\left(\frac{(60.5 - 23.1)}{(48.7 - 14.7)}\right)}$$

$$= \frac{3.4}{\ln(1.1)}$$

$$= \frac{3.4}{0.0953}$$

$$= 35.67\ \text{K}$$

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)
$\dot{Q}$ 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

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

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)
n	Number of heat transfer tubes (Non dimensional)

Hence for the heat exchanger from the **USEFUL DATA** section on page C7.

$$d_m = \frac{(0.00635) + (0.00635 - (2 \times 0.0006))}{2}$$

$$= \frac{0.00635 + 0.00515}{2}$$

$$= 0.00575 \text{ m}$$

$$A = \pi \times 0.00575 \times 0.144 \times 7$$

$$= 0.0182 \text{ m}^2$$

Hence for the test conditions the overall heat transfer coefficient:-

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

$$= \frac{795}{0.0182 \text{ x } 35.67}$$

$$= 1224.6 \text{ Wm}^{-2}\text{K}^{-1}$$

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 $\dot{Q}$ e

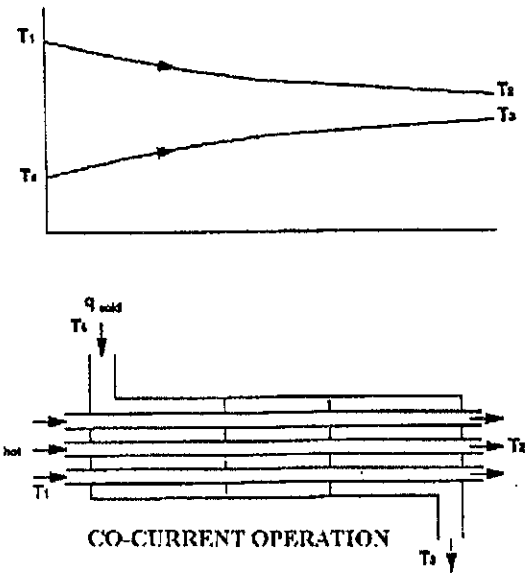
$$\dot{Q}e = \frac{V_{hot}}{60} \rho_{hot} \, Cp_{Hot} (T1 - T2) \; 1000 \quad \text{Watts}$$

The power absorbed by the cold stream $\dot{Q}$ a

$$\dot{Q}a = \frac{V_{cold}}{60}\ \rho_{cold}\ Cp_{Cold}\left(T3 - T4\right)\ 1000 \quad \text{Watts}$$

Reduction in Hot fluid temperature $\Delta t\ hot = T1 - T2\ K$

Increase in Cold fluid temperature $\Delta t\ cold = T3 - T4\ K$



The temperature efficiency of the hot stream from the above diagram

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

The temperature efficiency of the cold stream from the above diagram

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

The mean temperature efficiency

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

The logarithmic mean temperature difference LMTD

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

The Overall heat transfer coefficient U

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

In order to see the effect of the volume flow rate on the overall heat transfer coefficient the data should be plotted with overall heat transfer coefficient on the Y(vertical) axis and the Hot flow rate on the X (horizontal) axis.
If the optional Computer Interface HC100 and software is being used and the suggested procedure followed then the nominal flow rate column will group the data and allow the effect of varying hot flow rate to be seen.

If the optional Computer Interface HC100 and software is being used then the user can return to the H100C Shell and Tube Heat Exchanger Main Menu by clicking the End and Back keys.
Once back at the main menu the user can opt to record more data in another experiment on the same heat exchanger or review the data recorded during the preceding experiment. Alternatively the user can return to the H100 Main Menu by continuing to click the Back key and the select to use another optional heat exchanger if available.

6. To investigate the effect of driving force (difference between hot stream and cold stream temperature) with counter-current and co-current flow

The following procedure demonstrates the effect of changing the temperature difference (or driving force) between the hot and cold streams. The effect of this on the overall heat transfer coefficient and temperature efficiencies may be investigated for both counter-current and co-current flows.

I It is assumed that the basic INSTALLATION AND COMMISSIONING procedures for the Heat Exchanger Service Unit H100 have been completed as detailed in the main manual on pages 5 to 7.

Procedure

Install the Concentric tube Heat Exchanger H100C as detailed in **INSTALLATION / Heat Exchanger Installation H100C** on page C5 and connect the cold water circuit to give **Counter-Current** flow as detailed in the same section.

Follow the **OPERATING PROCEDURE** detailed in the main manual on page 16 onwards in order to establish the following operating conditions.

Fill the hot water circuit, set the cold water pressure regulator, and turn on the power to the unit. Then set the hot water temperature controller to 40°C and turn on the circulating pump.

Set the cold water flow rate V_{cold} to 1 litre min^{-1} and the hot water flow rate V_{hot} to 2.0 litre min^{-1}.

If the optional Computer Interface HC100 and software is being used:

It is assumed that the Installation and commissioning of both the hardware and software has been carried out according to the procedures on page 5 of the main manual. Ensure that the power lead to the Hilton data logger is connected, that the serial lead from the computer to the data logger is connected and that the ribbon cable from the interface to the base unit is also connected.

It is assumed that the computer is already running in Windows™ mode. Click on the H100 icon to start the software.

Language Screen:

The first screen will show the language section. If this option has been purchased then the preferred language may be selected.

H100 Main Menu:

The next screen is the main menu for the H100 series of optional units. Select ***the H100C Shell and Tube heat exchanger*** *(Note that only one option can be selected and that if the wrong unit is selected the procedure may be repeated).*

It is assumed that the data is to be captured on disc and therefore this option should be selected in the lower box. When all selections have been made click OK.

Communications Test:

As the user has selected to collect data the next screen carries out a communications test with the H100 base unit. Select the serial port of the computer that the unit is connected to and then click the Go button with the mouse pointer.

Assuming communications is confirmed the next screen will show the H100C Shell and Tube Heat Exchanger Main Menu.

If communications fails for any reason check the parameters indicated on the screen and repeat the test. If communications cannot be established for any reason the Cancel button may be used and the cause investigated.

H100C Shell and Tube Heat Exchanger Main Menu:

This lists the optional experiments that may be carried out with the H100C Shell and Tube Heat Exchanger. To continue with the above experiment select 6 ***To investigate the effect of driving force (difference between hot stream and cold stream temperature) with counter-current and co-current flow*** *and then click OK.*

H100C Experiment Number 6:

Assuming that the above procedure is being followed select the ***Counter-Current*** *flow option initially and check the Instructions on the screen have been observed. If data is to be recorded to disc then select the Store data on disc for later review option. Then click OK.*

If the user DOES select to record data to disc then a file name will be requested. Note that a partially fixed file name is used together with a fixed file suffix. This enables the software to recognise data during the review option that is compatible with the review mode selected. The user is required to enter the remaining digits that will be of relevance to them in the future. Once a valid file name is entered the Recording data screen is displayed.

Recording data:

The next screen shows four tabs Flow, Temperature and Data Point. The Flow and Temperature graphs may be used to set the hot and cold stream flow rates to the desired values and the temperature graph used to determine when the unit has reached a stable condition.

Once stable conditions have been established the Data point tab may be clicked and the Record button clicked to record and display a captured data point.

Note that data may be sent to a printer (If a printer is connected) if required The option of Raw (end results not calculated) or Calculated data may be selected for the printing option. The results shown in the table are updated each time the record button is clicked. NOTE that if no changes are made to the H100C settings of flow rate and hot stream temperature the captured results will all be similar.

The software should be utilised to automate the data recording procedures detailed as follows in the manual procedure.

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}

Repeat the above procedure with the hot water temperature controller set to 50°, 60° and 70 °C.

If the optional Computer Interface HC100 and software is being used:

All of the observations may be carried out without leaving the experiment 6 Recording data screens. The water flow rate tab and temperature tabs should be used to check the required flow rates and temperature stability and the Recording data procedures used to collect each data point.

This completes the Counter-current observation procedures

If the optional Computer Interface HC100 and software is being used then the user can return to the H100C Shell and Tube Heat Exchanger Main Menu by clicking the End and Back keys.

Next connect the cold water circuit to give **Co-Current flow** as detailed in the **INSTALLATION / Heat Exchanger Installation H100C** on page C5. Note that there is no need to disconnect the hot water circuit or to turn off the hot water pump during this operation.

Follow the **OPERATING PROCEDURE** detailed in the main manual on page 16 onwards in order to establish the following operating conditions.

Fill the hot water circuit, set the cold water pressure regulator, and turn on the power to the unit. Then set the hot water temperature controller to **40°C** and turn on the circulating pump.

Set the cold water flow rate V_{cold} to 1 litre min^{-1} and the hot water flow rate V_{hot} to 2.0 litre min^{-1}.

If the optional Computer Interface HC100 and software is being used:

Select H100C Experiment Number 6:

*Assuming that the above procedure is being followed select the **Co-Current** flow option and check the Instructions on the screen have been observed. If data is to be recorded to disc then select the Store data on disc for later review option. Then click OK.*

If the user DOES select to record data to disc then a file name will be requested. Note that a partially fixed file name is used together with a fixed file suffix. This enables the software to recognise data during the review option that is compatible with the review mode selected. The user is required to enter the remaining digits that will be of relevance to them in the future. Once a valid file name is entered the Recording data screen is displayed.

Recording data:

The next screen shows four tabs Flow, Temperature and Data Point. The Flow and Temperature graphs may be used to set the hot and cold stream flow rates to the desired values and the temperature graph used to determine when the unit has reached a stable condition.

Once stable conditions have been established the Data point tab may be clicked and the Record button clicked to record and display a captured data point.

Note that data may be sent to a printer (If a printer is connected) if required The option of Raw (end results not calculated) or Calculated data may be selected for the printing option. The results shown in the table are updated each time the record button is clicked. NOTE that if no changes are made to the H100C settings of flow rate and hot stream temperature the captured results will all be similar.

The software should be utilised to automate the data recording procedures detailed as follows in the manual procedure.

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}

Repeat the above procedure with the hot water temperature controller set to 50°, 60° and 70° C.
If the optional Computer Interface HC100 and software is being used:
All of the observations may be carried out without leaving the experiment 6 Recording data screens. The water flow rate tab and temperature tabs should be used to check the required flow rates and temperature stability and the Recording data procedures used to collect each data point.

This completes the Co-current observation procedures

If the optional Computer Interface HC100 and software is being used then the user can return to the H100C Shell and Tube Heat Exchanger Main Menu by clicking the End and Back keys.
Once back at the main menu the user can opt to record more data in another experiment on the same heat exchanger or review the data recorded during the preceding experiment. Alternatively the user can return to the H100 Main Menu by continuing to click the Back key and the select to use another optional heat exchanger if available.

OBSERVATIONS
Flow Direction: Counter-Current

Sample No.	T1	T2	T3	T4	V_{hot}	V_{cold}
----	°C	°C	°C	°C	L min^{-1}	L min^{-1}
1	38.4	35.4	14.6	18.9	1.94	0.99
2	48.5	44.2	14.5	21.5	2	1.01
3	59.5	52.7	14.4	24.4	2.04	1.02
4	69	60.1	14.3	27.4	1.92	1.03
5	73	60.9	14.4	27.7	2.01	1.02

Calculated Data

Sample No.	Δt_{hot}	Δt_{cold}	$\dot{Q}_e$	$\dot{Q}_a$	η_{Cold}	η_{Hot}	η_{Mean}
---	K	K	W	W	%	%	%
1	3.0	4.3	402	297	18.1	12.6	15.3
2	4.3	7.0	592	492	20.6	12.6	16.6
3	6.8	10.0	953	710	22.2	15.1	18.6
4	8.9	13.1	1178	938	23.9	16.3	20.1
5	12.1	13.3	1662	943	22.7	20.6	21.7

Sample No.	LMTD	U
—	K	$W\ m^{2}K^{-1}$
1	20.1	1096.7
2	28.3	1149.3
3	36.7	1426.7
4	43.7	1481.2
5	45.9	1989

If the optional Computer Interface HC100 and software is being used then it will be seen that the tabular displays are similar to those used on screen.
Similar observations may be obtained for the Co-current configuration. The calculation procedures are shown below.

CALCULATIONS

Counter-Current Flow

For sample No 1 above:
It is necessary to convert the volume flow rates to mass flow rates using the conversion factors in table 1 and 2 on page C7. The water density ρ (kg litre^{-1}) and specific heat capacity Cp (kJ kg^{-1} K^{-1}) is dependant upon the temperature and the mean fluid temperature Tmean

$$T_{mean} = \frac{T_{inlet} + T_{outlet}}{2}$$

Is used to calculate the relevant temperature of the Hot stream.
For the Hot stream:
T_{mean} = (38.4 + 35.4) / 2 = 36.9 °C
From table 1 and 2 at T_{mean} = 36.9 °C

ρ_{hot} = 0.993 kg litre^{-1}
Cp = 4.178 kJ kg^{-1} k^{-1}

Hence the power emitted from the hot stream $\dot{Q}e$

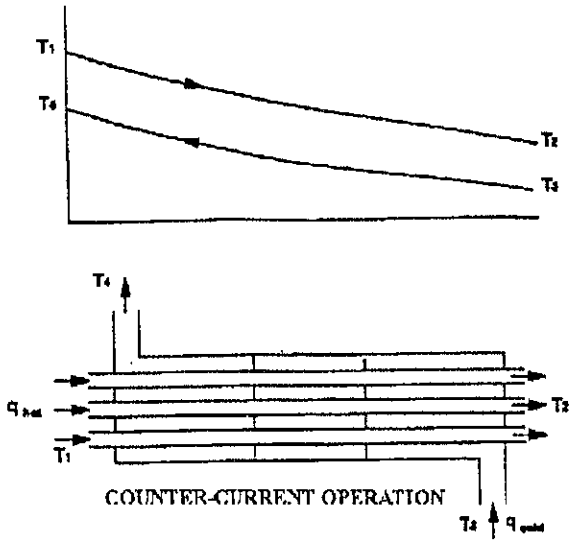
$$\dot{Q}e = \frac{V_{hot}}{60}\ \rho_{hot}\ Cp_{Hot}\left(T1 - T2\right) \times 1000 \quad \text{Watts}$$

$$= \frac{1.94}{60} \times 0.993 \times 4.178 \times (38.4 - 35.4) \times 1000$$

$$= 402 \text{ Watts}$$

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

$$\eta_{Hot} = \frac{T1 - T2}{T1 - T3} \times 100\%$$
$$= \frac{38.4 - 35.4}{38.4 - 14.6} \times 100\%$$
$$= 12.6\%$$

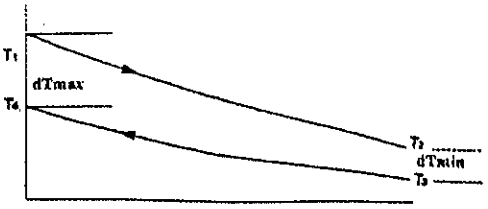
The temperature efficiency of the cold stream from the above diagram

$$\eta_{Cold} = \frac{T4 - T3}{T1 - T3} \times 100\%$$
$$= \frac{18.9 - 14.6}{38.4 - 14.6} \times 100\%$$
$$= 18.06\%$$

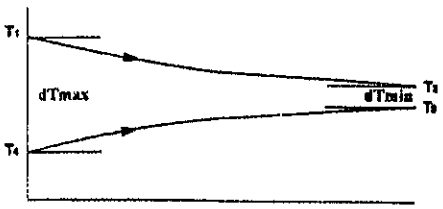
The mean temperature efficiency

$$\eta_{Mean} = \frac{\eta_{Hot} + \eta_{Cold}}{2}$$
$$= \frac{12.6 + 18.06}{2}$$
$$= 15.3\%$$

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.



Countercurrent operation



Cocurrent operation

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

The LMTD is defined as

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

Hence from the above diagrams of temperature distribution

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

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.

Hence for the Counter-current example

$$\begin{aligned}\mathrm{LMTD} &= \frac{(38.4 - 18.9) - (35.4 - 14.6)}{\ln\left(\dfrac{(38.4 - 18.9)}{(35.4 - 14.6)}\right)} \\ &= \frac{-1.3}{\ln(0.9375)} \\ &= \frac{-1.3}{-0.0645} \\ &= 20.14\,\mathrm{K}\end{aligned}$$

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

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

Where

A	Heat transfer area of heat exchanger (m^2)
$\dot{Q}e$	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

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

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)
n	Number of heat transfer tubes (Non dimensional)

Hence for the heat exchanger from the **USEFUL DATA** section on page C7.

$$d_m = \frac{(0.00635) + (0.00635 - (2 \times 0.0006))}{2}$$

$$= \frac{0.00635 + 0.00515}{2}$$

$$= 0.00575\ \text{m}$$

$$A = \pi \times 0.00575 \times 0.144 \times 7$$

$$= 0.182\ \text{m}^2$$

Hence for the test conditions the overall heat transfer coefficient:-

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

$$= \frac{402}{0.0182 \times 20.14}$$

$$= 1096.7\ \text{Wm}^{-2}\text{K}^{-1}$$

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 $\dot{Q}e$

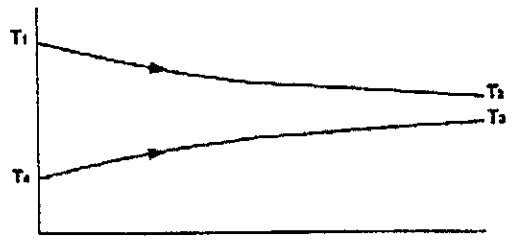
$$\dot{Q}e = \frac{V_{hot}}{60}\ \rho_{hot}\ Cp_{Hot}\,(T1 - T2)\ \ 1000 \quad \text{Watts}$$

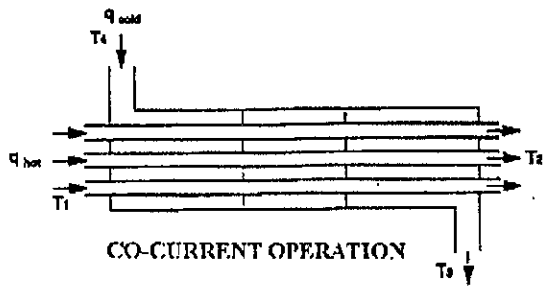
The power absorbed by the cold stream $\dot{Q}$ a

$$\dot{Q}a = \frac{V_{cold}}{60}\ \rho_{cold}\ Cp_{Cold}\left(T3 - T4\right)\ 1000 \quad \text{Watts}$$

Reduction in Hot fluid temperature $\Delta t\ hot = T1 - T2\ K$

Increase in Cold fluid temperature $\Delta t\ cold = T3 - T4\ K$





The temperature efficiency of the hot stream from the above diagram

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

The temperature efficiency of the cold stream from the above diagram

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

The mean temperature efficiency

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

The logarithmic mean temperature difference LMTD

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

The Overall heat transfer coefficient U

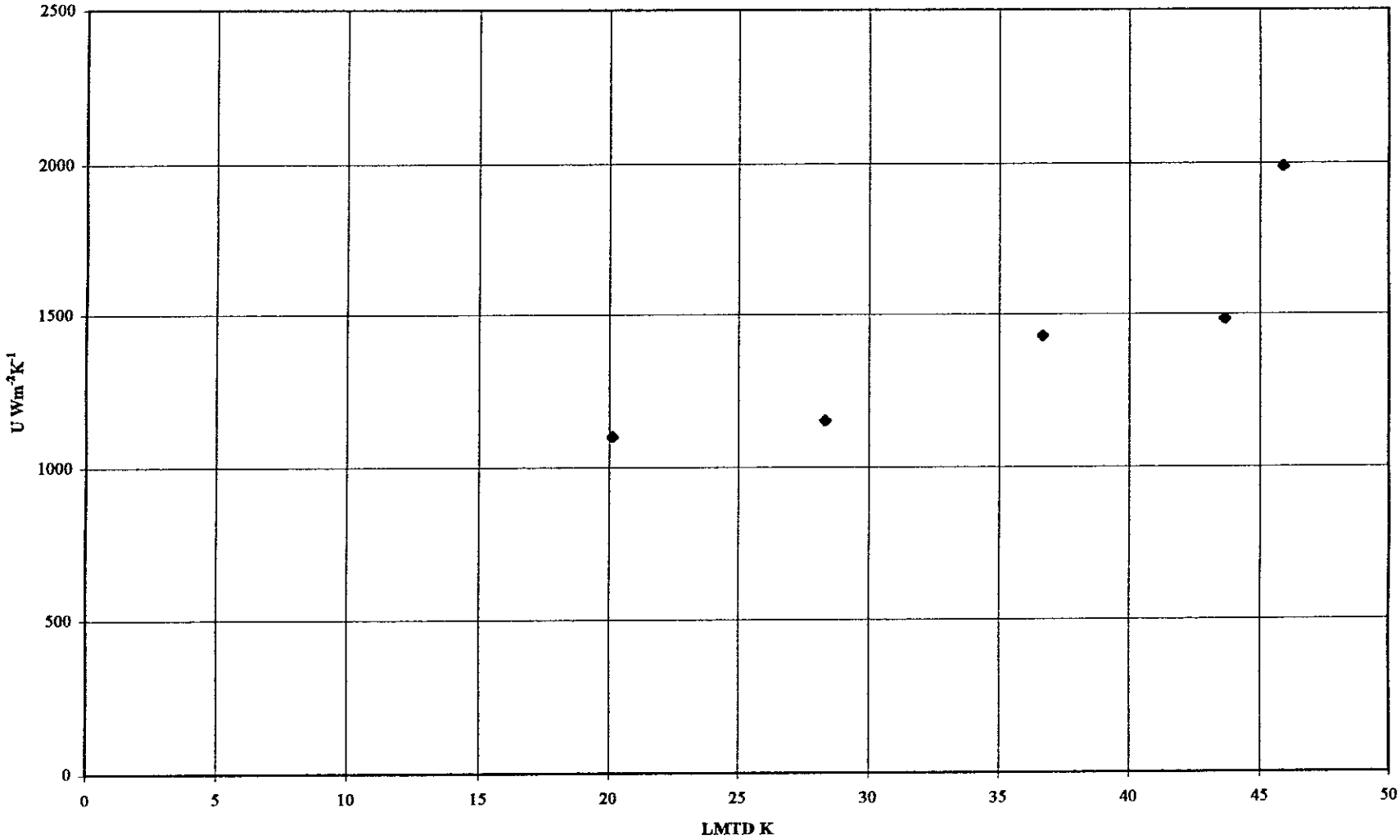
$$U = \frac{\dot{Q}_e}{A \times LMTD}$$

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.
An example of this is given on page C52 for the Counter-current flow configuration.

If the optional Computer Interface HC100 and software is being used then the user can return to the H100A Concentric Tube Heat Exchanger Main Menu by clicking the End and Back keys.
Once back at the main menu the user can opt to record more data in another experiment on the same heat exchanger or review the data recorded during the preceding experiment. Alternatively the user can return to the H100 Main Menu by continuing to click the Back key and the select to use another optional heat exchanger if available.

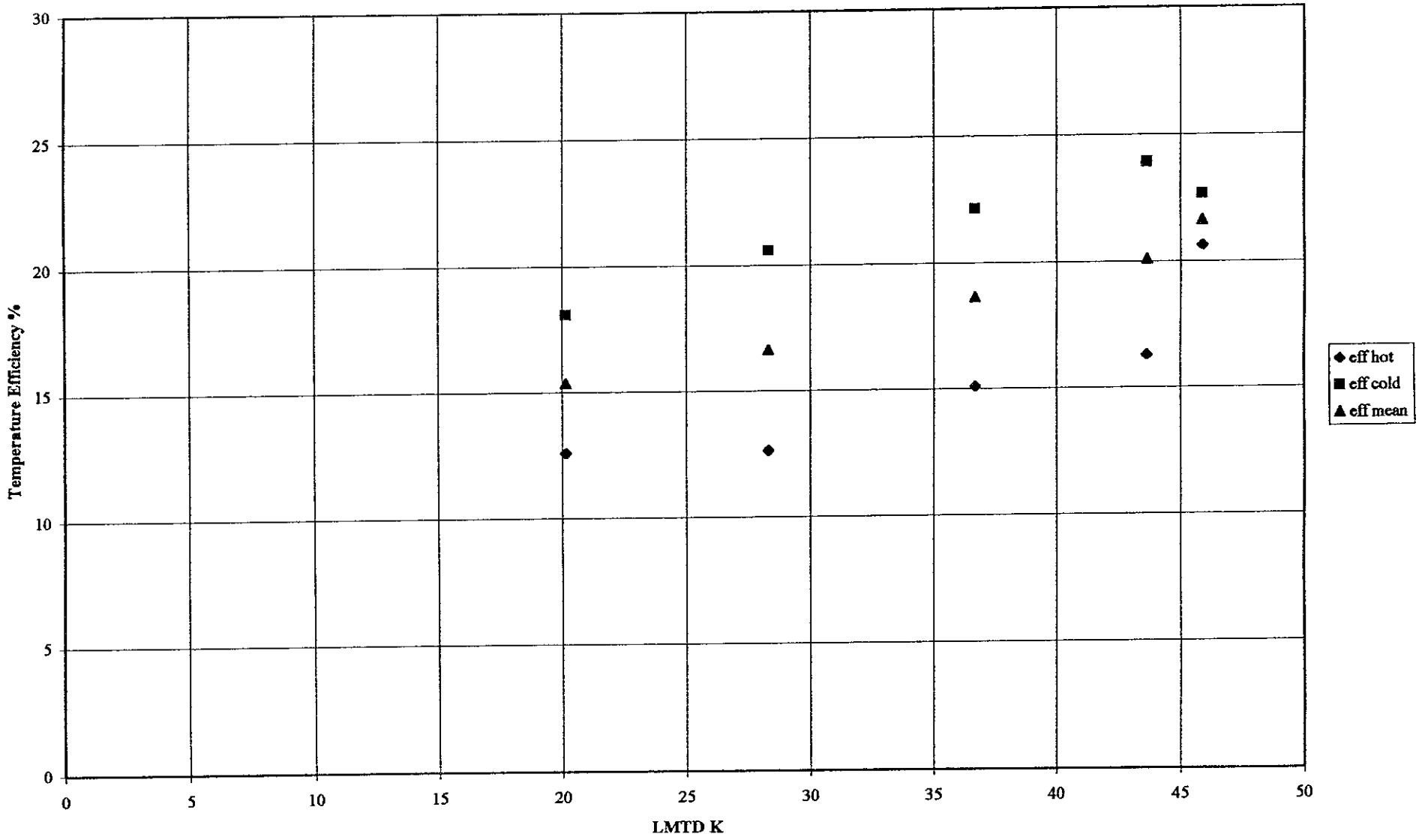
Example Data

Overall Heat Transfer Coefficient v Logarithmic Mean Temperature Difference for a Shell and Tube Heat Exchanger
H100C



Example Data

Temperature Efficiencies v Logarithmic Mean Temperature Difference For a Shell and Tube Heat Exchanger H100C



C53

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