6 Laboratory Teaching Exercises

6.1 Nomenclature

Name	Symbol	SI unit
Outside diameter	D (e.g. D_{hot})	m
Heat transfer area	A (e.g. A_{hot})	m^2
Wall thickness (distance)	Δx (e.g. Δx_{int})	m
Voltage to heating element	V	V
Current to heating element	I	A
Electrical power to heating element	Q	W
Heat transfer rate per unit time (heat flow)	Q	W
Temperature measured	T*i* (e.g. T1)	°C
Temperature at hot interface	$T_{hotface}$	°C
Temperature at cold interface	$T_{coldface}$	°C
Temperature difference	ΔT_i (e.g. ΔT_{hot})	°C
Temperature gradient	Grad (e.g. $Grad_{hot}$)	W/m°C
Thermal conductivity	k (e.g. k_{hot})	W/m°C
Overall heat transfer coefficient	U	Wm^{2}°C
Resistance to heat flow	R	m^{2}°C/W
Flow of cooling water (if SFT2 is fitted)	Fw	l/min
Time	t	secs

Subscripts

hot	heating section
cold	cooling section
int	intermediate section
red	section with reduced cross sectional area
ins	insulator
hotface	joint between heating section and intermediate section or insulator
coldface	joint between cooling section and intermediate section or insulator
a, b, i, j etc	temperature sensor positions

Note: the electrical power Q supplied to the heated section by the heating element is assumed to be the same as the heat transfer rate per unit time Q along the bar, i.e. there is no heat loss to the surroundings. In practice some heat loss will occur. At low heater power (low temperature at the top of the bar) the heat loss will be negligible. As the heater power is increased (higher temperature at the top of the bar) the heat loss will increase resulting in increased values for calculated conductivity. It will therefore be necessary to estimate the heat loss and apply a correction to obtain accurate values for conductivity when operating at higher temperatures.

6.2 HT11C Laboratory Teaching Exercise A

Objective
To measure the temperature distribution for steady-state conduction of energy through a uniform plane wall and demonstrate the effect of a change in heat flow

Method
By measuring the change in temperature with distance, resulting from the linear conduction of heat along a simple bar at different rates of heat flow through the bar.

Equipment Required
HT10XC Heat Transfer Service Unit

HT11C Computer Compatible Linear Heat Conduction Accessory
(Or HT11 Linear Heat Conduction Accessory)

Optional Equipment
Windows™-compatible PC running Windows™ 98, 2000 or XP
(SFT2 Flow sensor if using HT11)

Equipment set-up
Before proceeding with the exercise, ensure that the equipment has been prepared as follows:

- Locate the HT11C Linear Heat Conduction accessory (1) alongside the HT10XC Heat Transfer Service Unit (20) on a suitable bench.

- Clamp the heated (6 and 7) and cooled (8) section of the HT11C together having lightly coated the mating faces with thermal paste (See Operation section page 3-3).

- Connect the eight thermocouples on the HT11C (3) to the appropriate sockets on the front of the service unit (30). Ensure that the labels on the thermocouple leads (T1-T8) match the labels on the sockets.

Note: readings from thermocouples T4 and T5 will not be used in this exercise.

- Set the VOLTAGE CONTROL potentiometer (23) on the HT10XC service unit to minimum (anticlockwise) and the selector switch to MANUAL then connect the power lead form the HT11C to the socket marked OUTPUT 2 at the rear of the service unit (33).

- Connect the cold water flow control valve (11) to the socket marked AUXILARY OUTPUT (34) on the rear of the HT10XC console.

- Connect the cold water flow rate sensor (9) to the socket marked Fw (36) on the front of the HT10XC console.

- Set the AUXILIARY CONTROL knob (26) on the service unit to minimum (anticlockwise) then connect the power lead from the cold water flow control valve (11) to the AUXILIARY POWER socket on the rear of the service unit (34) (Not relevant if using HT11).

- Ensure that a cold water supply is connected to the inlet of the pressure regulating valve on HT11C (13).

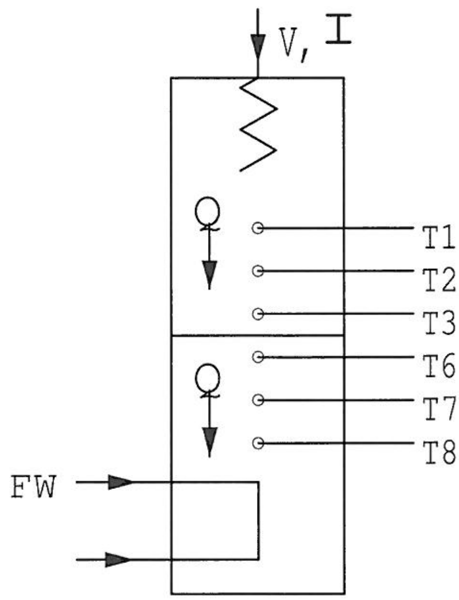
- Ensure that the flexible cooling water outlet tube is directed to a suitable drain.

- Ensure that the service unit is connected to an electrical supply.

- Switch on the MAINS switch on the service unit (21).

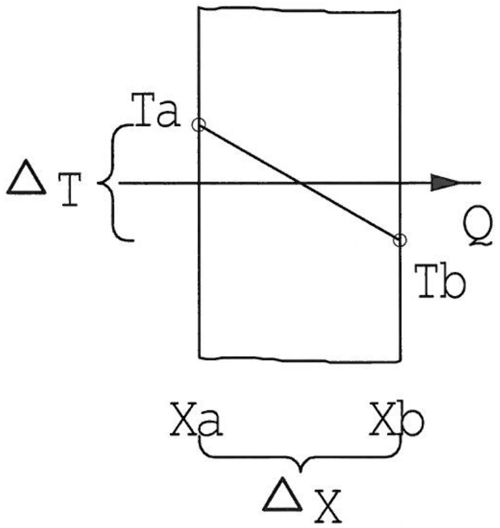
- If using a computer for remote data logging and/or operation, connect the USB socket on the HT10XC (29) to the computer using the USB cable provided, and set the selector switch on the console (22) to REMOTE. (If not using a computer, leave the selector switch set to MANUAL).

- If using a computer, start the HT11C software and select 'Exercise A'. The software includes full instructions on how to use the software and perform the exercise, and should be used in preference to this manual when undertaking the teaching exercises.



Theory/Background

Provided that the heated and cooled sections are clamped tightly together, so that the two end faces are in good thermal contact, the two sections can be considered to be one continuous wall of uniform cross section and material.



According to Fourier's law of heat conduction:

If a plane wall of thickness (Δx) and area (A) supports a temperature difference (ΔT) then the heat transfer rate per unit time (Q) by conduction through the wall is found to be:

$$Q \propto A\frac{\Delta T}{\Delta x}$$

$$Q = C\frac{\Delta T}{\Delta x}$$ where C is a constant which will be investigated in a later exercise

The object of this exercise is to show that for a simple plane wall where the material and cross section are constant:

$$Q \propto \frac{\Delta T}{\Delta x}$$

Procedure

Refer to the Operation section (page 3-1) if you need details of the instrumentation and how to operate it.

Check that the panel displays on the service console are illuminated (24 and 27). If the panel displays do not illuminate check the RCD (35) at the rear of the service unit; the switch should be up.

If using a computer, check that the software indicates IFD OK in the bottom right hand corner of the software window.

Turn on the cooling water and adjust the flow control valve (NOT the pressure regulator) to give approximately 1.5 litres/min. If using the software, the flow rate should be controlled using the control box on the software mimic diagram window. The flow rate may be monitored on the software screen. (If not using the software, use the selector switch (25) to display the flow rate on the panel display on the console (L/min) and the AUXILIARY CONTROL knob to control the setting. If using the HT11, the cold water flow rate is controlled using the manual control valve next to the test section column).

Set the heater voltage to 9 volts:

- If using the computer, enter the voltage in the display box for the heater, or use the control box arrows.
- If using the console, adjust the voltage control potentiometer to give a reading of 9 volts on the top panel display with the selector switch set to position V.

Allow the HT11C to stabilise. If using a computer, monitor the temperatures on the software mimic diagram screen. (If operating using the console, use the lower selector switch (28) on the console to set the console display (27) to each temperature sensor in turn.

When the temperatures are stable, select the icon in the software to record the following: T1, T2, T3, T6, T7, T8, V I, Fw

(If operating the equipment using the console then these values should be recorded manually. Fw is not available if using the HT11 unless the optional SFT2 flow sensor is fitted).

Set the heater voltage to 12 volts.

Allow the HT11C to stabilise then repeat the above readings.

Set the heater voltage to 17 volts.

Allow the HT11C to stabilise then repeat the above readings.

Set the heater voltage to 21 volts.

Allow the HT11C to stabilise then repeat the above readings.

Results and Calculations

For this exercise the raw data is tabulated under the following headings:

Heater Voltage	V	Volts
Heater Current	I	Amps
Heated section high temperature	T1	(°C)
Heated section mid temperature	T2	(°C)
Heated section low temperature	T3	(°C)
Cooled section high temperature	T6	(°C)
Cooled section mid temperature	T7	(°C)
Cooled section low temperature	T8	(°C)
Cooling water flow rate	Fw	(l/min)

You should also estimate and record the experimental errors for these measurements

For this exercise the following constants are applicable:

Distance between thermocouples T1 and T3 $\Delta x_{13} = 0.03$ (m)
Distance between thermocouples T6 and T8 $\Delta x_{68} = 0.03$ (m)

Note: The distance between each thermocouple is 0.015m
The distance between thermocouple T3 or T6 and the end face is 0.0075m

For each set of readings the derived results are tabulated under the following headings:

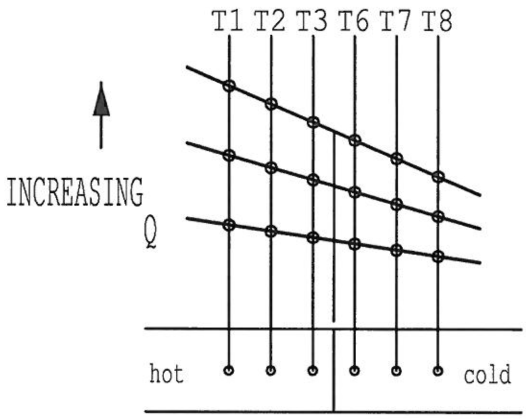
Heat flow (power to heater)	$Q = VI$	(Watts)
Temperature difference in heated section	$\Delta T_{hot} = T1 - T3$	(°C)
Temperature difference in cooled section	$\Delta T_{cold} = T6 - T8$	(°C)

Estimate the cumulative influence of the experimental errors on your calculated values for Q, ΔT_{hot} and ΔT_{cold} and measured values for Δx_{13} and Δx_{68}.

Compare the changes in temperature (ΔT_{hot} and ΔT_{cold}) in the two sections at the same heat flow.

Compare the changes in temperature in the two sections at different heat flows.

Plot a graph of temperature against position along the bar and draw the best straight line through the points. Your graph should be similar to the diagram below.



Observe that each temperature profile is a straight line and that the gradient of the line increases with increase in heat flow. Calculate the gradient of each line and show that

$\frac{Q}{\text{gradient}}$ is a constant (C).

Conclusions

You have demonstrated how heat flow through a plane wall creates a temperature difference and the temperature changes linearly with distance. For a wall of constant conductivity and constant cross sectional area the temperature gradient is directly proportional to the rate of heat flow.

Comment on the changes in ΔT_{hot} and ΔT_{cold} when the heat flow through the bar is changed. The consequence of these changes will be investigated in a later exercise.

Comment on the effect of measurement accuracy and heat loss from the equipment on your results.

Note: Exercise HT11CB should be carried out on completion of this exercise.

6.3 HT11C Laboratory Teaching Exercise B

Objective
To understand the use of the Fourier Rate Equation in determining rate of heat flow through solid materials for one-dimensional steady flow of heat.

Method
To demonstrate Fourier's Law for the linear conduction of heat along a simple bar, by measuring the change in temperature with distance, at different rates of heat flow through the bar and using the measurements to calculate the conductivity of the bar.

Equipment Required
HT10XC Heat Transfer Service Unit

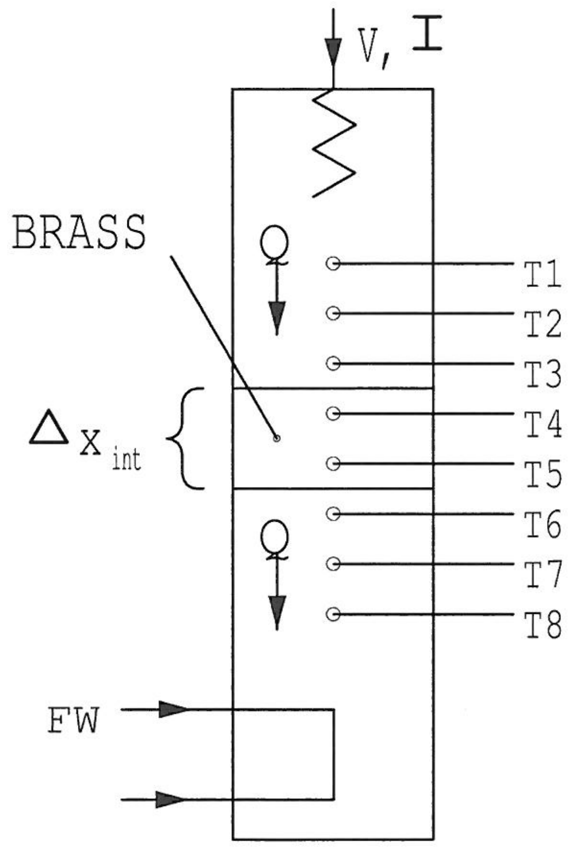
HT11C Computer Compatible Linear Heat Conduction Accessory
(Or HT11 Linear Heat Conduction Accessory)

Optional Equipment
Windows™-compatible PC running Windows™ 98, 2000 or XP
(SFT2 Flow sensor if using HT11)

Equipment set-up
Before proceeding with the exercise, ensure that the equipment has been prepared as follows:-

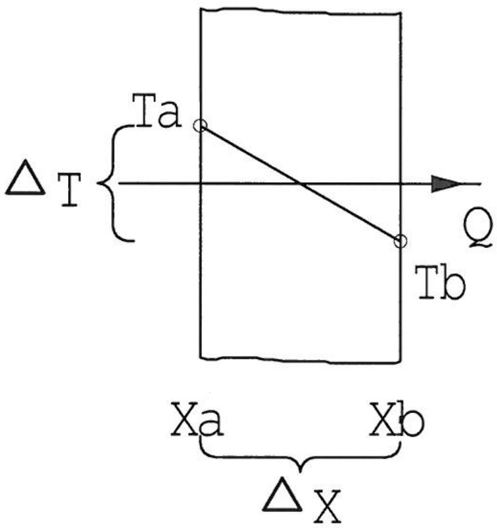
- Locate the HT11C Linear Heat Conduction accessory (1) alongside the HT10XC Heat Transfer Service Unit (20) on a suitable bench.
- Clamp the intermediate Brass section (instrumented with two thermocouples) between the heated and cooled section of the HT11C having lightly coated the mating faces with thermal paste (See Operation page 3-3). Take care to locate the shallow shoulders on the sections before clamping.
- Connect the eight thermocouples on the HT11C (3) to the appropriate sockets on the front of the service unit (30). Ensure that the labels on the thermocouple leads (T1-T8) match the labels on the sockets.
- Set the VOLTAGE CONTROL potentiometer (23) on the HT10XC service unit to minimum (anticlockwise) and the selector switch (22) to MANUAL then connect the power lead form the HT11C to the socket marked OUTPUT 2 at the rear of the service unit (33).

- Connect the cold water flow control valve (11) to the socket marked AUXILARY OUTPUT (34) on the rear of the HT10XC console.
- Connect the cold water flow rate sensor (9) to the socket marked Fw (36) on the front of the HT10XC console.
- Set the AUXILIARY CONTROL knob (26) on the service unit to minimum (anticlockwise) then connect the power lead from the cold water flow control valve (11) to the AUXILIARY POWER socket on the rear of the service unit (34) (Not relevant if using HT11).
- Ensure that a cold water supply is connected to the inlet of the pressure regulating valve on HT11C (13).
- Ensure that the flexible cooling water outlet tube is directed to a suitable drain.
- Ensure that the service unit is connected to an electrical supply.
- Switch on the MAINS switch on the service unit (21).
- If using a computer for remote data logging and/or operation, connect the USB socket on the HT10XC (29) to the computer using the USB cable provided, and set the selector switch on the console (22) to REMOTE. (If not using a computer, leave the selector switch set to MANUAL).
- If using a computer, start the HT11C software and select 'Exercise B'. The software includes full instructions on how to use the software and perform the exercise, and should be used in preference to this manual when undertaking the teaching exercises.



Theory/Background

Provided that the heated, intermediate and cooled sections are clamped tightly together, so that the end faces are in good thermal contact, the three sections can be considered to be one continuous wall of uniform cross section and material.



According to Fourier's law of heat conduction:

If a plane wall of thickness (Δx) and area (A) supports a temperature difference (ΔT) then the heat transfer rate per unit time (Q) by conduction through the wall is found to be:

$$Q \propto A \frac{\Delta T}{\Delta x} \text{ where } \Delta x = (x_b - x_a)$$

If the material of the wall is homogeneous and has a thermal conductivity k (the constant of proportionality) then:

$$Q = -kA \frac{\Delta T}{\Delta x} \text{ where } \Delta T = (Ta - Tb)$$

It should be noted that heat flow is positive in the direction of temperature fall hence the negative sign in the equation.

For convenience the equation can be rearranged to avoid the negative sign as follows:

$$Q = kA\frac{\Delta T}{\Delta x} \text{ where } \Delta T = (Ta - Tb)$$

Note: In this exercise the HT11C is configured as a simple plane wall where k and A are constant therefore the object is to show that the Fourier equation can be used to relate Q, ΔT and Δx. The effect of a change in k or change in A will be investigated in later exercises.

Procedure
Refer to the Operation section (page 3-1) if you need details of the instrumentation and how to operate it.

Check that the panel displays on the service console are illuminated. If the panel displays do not illuminate check the RCD and circuit breakers at the rear of the service unit (35); all switches at the rear should be up.

If using a computer, check that the software indicates IFD OK in the bottom right hand corner of the software window.

Turn on the cooling water and adjust the flow control valve (NOT the pressure regulator) to give approximately 1.5 litres/min. If using the software, the flow rate should be controlled using the control box on the software mimic diagram window. The flow rate may be monitored on the software screen. (If not using the software, use the selector switch to display the flow rate on the panel display on the console and control the valve setting using the AUXILIARY CONTROL knob. If using the HT11, the cold water flow rate is controlled using the manual control valve next to the test section column).

Set the heater voltage to 12 volts:
- If using the computer, enter the voltage in the display box for the heater, or use the control box arrows.
- If using the console, adjust the voltage control potentiometer to give a reading of 12 volts on the top panel display with the selector switch set to position V.

Allow the HT11C to stabilise. If using a computer, monitor the temperatures on the software mimic diagram screen. (If operating the equipment manually from the console, use the lower selector switch on the console to set the console display to each temperature sensor in turn).

When the temperatures are stable, select the GO icon to record the following: T1, T2, T3, T4, T5, T6, T7, T8, V, I, Fw.

(If operating the equipment using the console then these values should be recorded manually. Fw is not available if using the HT11 unless the optional SFT2 flow sensor is fitted).

Set the Heater Voltage to 17 Volts.

Allow the HT11C to stabilise then repeat the above readings.

Results and Calculations
For this exercise the raw data is tabulated under the following headings:

Heater Voltage	V	Volts
Heater Current	I	Amps
Heated section high temperature	T1	(°C)
Heated section mid temperature	T2	(°C)
Heated section low temperature	T3	(°C)
Intermediate section high temperature	T4	(°C)
Intermediate section low temperature	T5	(°C)
Cooled section high temperature	T6	(°C)
Cooled section mid temperature	T7	(°C)
Cooled section low temperature	T8	(°C)
Cooling water flowrate	Fw	(l/min)

You should also estimate and record the experimental errors for these measurements.

For this exercise the following constants are applicable:

Distance between thermocouples T1 and T3	$x_{13} = 0.03$	(m)
Distance between thermocouples T4 and T5	$x_{45} = 0.015$	(m)
Distance between thermocouples T6 and T8	$x_{68} = 0.03$	(m)
Diameter of bar	$D = 0.025$	(m)

Note: The distance between each thermocouple is 0.015 m
The distance between thermocouple T3, T4, T5 or T6 and the end face is 0.0075 m

For each set of readings the derived results are tabulated under the following headings:

Heat flow (Power to heater)	$Q = V\,I$	(Watts)
Cross sectional area of bar	$A = \dfrac{\pi D^2}{4}$	(m^2)
Temperature difference in heated section	$\Delta T_{hot} = T1 - T3$	(°C)
Conductivity in heated section	$k_{hot} = \dfrac{x_{13} Q}{\Delta T_{hot} A_{hot}}$	(W/m°C)
Temperature difference in intermediate section	$\Delta T_{int} = T4 - T5$	(°C)
Conductivity in intermediate section	$k_{int} = \dfrac{x_{45} Q}{\Delta T_{int} A_{int}}$	(W/m°C)
Temperature difference in cooled section	$\Delta T_{cold} = T6 - T8$	(°C)

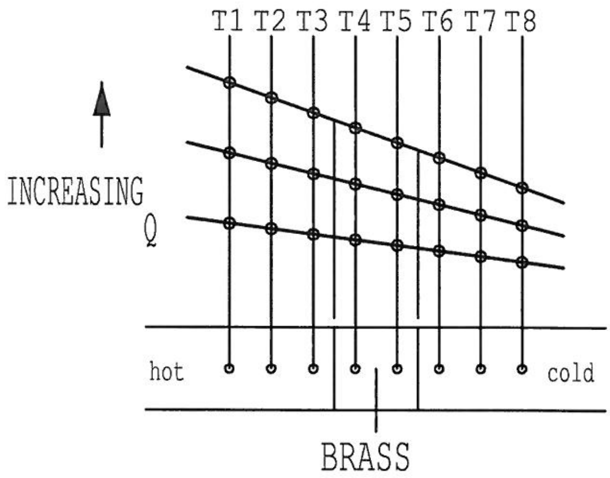
Conductivity in cooled section $$k_{cold} = \frac{x_{68} Q}{\Delta T_{cold} A_{cold}} \quad (W/m°C)$$

Estimate the cumulative influence of the experimental errors on your calculated values for Q, ΔT, ΔT_{hot}, ΔT_{int}, ΔT_{cold}, k_{hot}, k_{int} and k_{cold} and measured values for D, Δx_{18}, Δx_{13}, Δx_{45} and Δx_{68}.

Compare the calculated value for the thermal conductivity of Brass in the three sections at the same heat flow.

Compare the calculated value for the thermal conductivity of Brass in the three sections at different heat flows.

Plot a graph of temperature against position along the bar and draw the best straight line through the points. Your graph should be similar to the diagram below:



Observe that each temperature profile is a straight line and that the gradient of the line increases with increase in heat flow.

Calculate the average conductivity of the brass bar using the gradient of each straight line and the corresponding heat flow through the bar. Compare the value obtained with the values previously obtained for each individual section of the bar and comment on any difference.

Your results should give values in the range 110 - 128 W/m°C for the thermal conductivity of Brass, assuming no heat loss from the equipment. As a small amount of heat loss is inevitable as the temperature of the bar increases, the calculated value for the conductivity will increase at higher operating temperatures.

Conclusions

You have demonstrated how the Fourier rate equation can be used to relate temperature difference, heat flow and distance in a solid material of constant cross-sectional area and thermal conductivity. Increased heat flow produces an increased temperature gradient.

Comment on the effect of measurement accuracy and heat loss from the equipment on your calculated results and any differences between the results for each section.

The consequence of a change in thermal conductivity or a change in cross sectional area will be investigated in later exercises.

Note: Exercise HT11CC should be carried out on completion of this exercise.

6.4 HT11C Laboratory Teaching Exercise C

Objective
To measure the temperature distribution for steady-state conduction of energy through a composite plane wall and determine the Overall Heat Transfer Coefficient for the flow of heat through a combination of different materials in series.

Note: The poor conductivity of the stainless steel specimen used in this exercise results in a much longer time for the temperature distribution to stabilise. If the long duration of this is not acceptable exercise (typically 60 minutes at one power setting) then omit this exercise and perform exercise D instead to demonstrate the conductivity of a different material (Aluminium) with faster response.

Method
By measuring the temperature distribution along a composite bar of different solid materials (conductors) for one-dimensional steady flow of heat and using the Fourier Rate Equation applied to each material to determine the Overall Heat Transfer Coefficient.

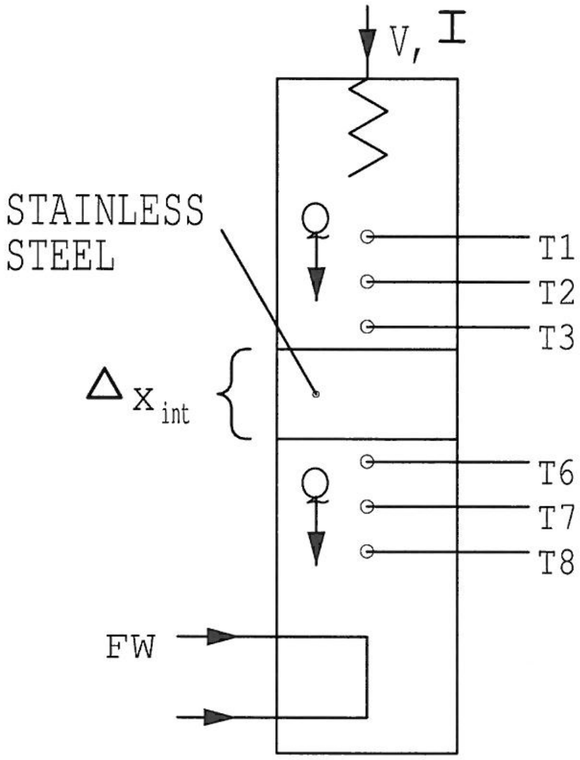
Equipment Required
HT10XC Heat Transfer Service Unit

HT11C Computer Compatible Linear Heat Conduction Accessory
(Or HT11 Linear Heat Conduction Accessory)

Optional Equipment
Windows™-compatible PC running Windows™ 98, 2000 or XP
(SFT2 Flow sensor if using HT11)

Equipment set-up
Before proceeding with the exercise ensure that the equipment has been prepared as follows:-

- Locate the HT11C Linear Heat Conduction accessory (1) alongside the HT10XC Heat Transfer Service Unit (20) on a suitable bench.
- Clamp the intermediate Stainless Steel section (no instrumentation) between the heated and cooled section of the HT11C having lightly coated the mating faces with thermal paste (See Operation page 3-3). Take care to locate the shallow shoulders on the sections before clamping.



- Connect the eight thermocouples on the HT11C (3) to the appropriate sockets on the front of the service unit (30). Ensure that the labels on the thermocouple leads (T1 - T8) match the labels on the sockets.

Note: Readings from thermocouples T4 and T5 will not be used in this exercise.

- Set the VOLTAGE CONTROL potentiometer (23) to minimum (anticlockwise) and the selector switch (22) to MANUAL then connect the heater lead from the HT11C (4) to the socket marked OUTPUT 2 at the rear of the service unit (33).

- Connect the cold water flow control valve (11) to the socket marked AUXILARY OUTPUT (34) on the rear of the HT10XC console.

- Connect the cold water flow rate sensor (9) to the socket marked Fw (36) on the front of the HT10XC console.

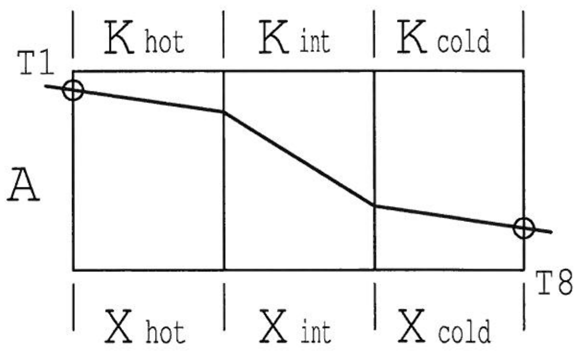
- Set the AUXILIARY CONTROL knob (26) on the service unit to minimum (anticlockwise) then connect the power lead from the cold water flow control valve (11) to the AUXILIARY POWER socket on the rear of the service unit (34) (Not relevant if using HT11).

- Ensure that a cold water supply is connected to the inlet of the pressure regulating valve on HT11C (13).

- Ensure that the flexible cooling water outlet tube is directed to a suitable drain.
- Ensure that the service unit is connected to an electrical supply.
- Switch on the MAINS switch on the service unit (21).
- If using a computer for remote data logging and/or operation, connect the USB socket on the HT10XC (29) to the computer using the USB cable provided, and set the selector switch on the console (22) to REMOTE. (If not using a computer, leave the selector switch set to MANUAL).

Theory/Background

The heated, intermediate and cooled sections are clamped tightly together, so that the end faces are in good thermal contact, and create a composite bar with a Stainless steel section sandwiched between two Brass sections.



For continuity, the steady heat flow through the successive sections must be the same so Fourier's Law can be applied to the three sections as follows:

$$\frac{Q}{A} = \frac{k_{hot}\Delta T_{hot}}{\Delta x_{hot}} = \frac{k_{int}\Delta T_{int}}{\Delta x_{int}} = \frac{k_{cold}\Delta T_{cold}}{\Delta x_{oold}}$$

from which it follows that:

$$(T_1 - T_8) = (\Delta T_{hot} + \Delta T_{int} + \Delta T_{cold}) = \frac{Q}{A}\left(\frac{x_{hot}}{k_{hot}} + \frac{x_{int}}{k_{int}} + \frac{x_{cold}}{k_{cold}}\right)$$

or

$$\frac{Q}{A} = U(T_1 - T_8) \text{ where } \frac{1}{U} = \frac{x_{hot}}{k_{hot}} + \frac{x_{int}}{k_{int}} + \frac{x_{cold}}{k_{cold}} = R$$

where U is the Overall Heat Transfer Coefficient and 1/U is the resistance to heat flow R.

Note: In this exercise the HT11C is configured as a composite plane wall where k varies but A remains constant. The effect of a change in cross-sectional area will be investigated in a later exercise.

Procedure

(Refer to the Operation section on page 3-1 if you need details of the instrumentation and how to operate it.)

Switch on the MAINS switch (21). (If the panel displays do not illuminate check the RCD at the rear of the service unit (35), the switch should be up.)

If using a computer, check that the software indicates IFD OK in the bottom right hand corner of the software window.

Turn on the cooling water and adjust the flow control valve (NOT the pressure regulator) to give approximately 1.5 litres/min. If using the software, the flow rate should be controlled using the control box on the software mimic diagram window. The flow rate may be monitored on the software screen. (If not using the software, use the selector switch to display the flow rate on the panel display on the console and control the valve setting using the AUXILIARY CONTROL knob. If using the HT11, the cold water flow rate is controlled using the manual control valve next to the test section column).

Set the heater voltage to 9 volts:

- If using the computer, enter the voltage in the display box for the heater, or use the control box arrows.
- If using the console, adjust the voltage control potentiometer to give a reading of 9 volts on the top panel display with the selector switch set to position V.

Allow the HT11C to stabilise. If using a computer, monitor the temperatures on the software mimic diagram screen. (If operating the equipment manually from the console, use the lower selector switch on the console to set the console display to each temperature sensor in turn).

When the temperatures are stable record the following: When the temperatures are stable, select the GO icon to record the following: T1, T2, T3, T6, T7, T8, V, I, Fw.

(If operating the equipment using the console then these values should be recorded manually. Fw is not available if using the HT11 unless the optional SFT2 flow sensor is fitted).

Set the Heater Voltage to 12 Volts.

Allow the HT11C to stabilise then repeat the above readings.

Results and Calculations

For this exercise the raw data is tabulated under the following headings:

Heater Voltage	V	Volts
Heater Current	I	Amps
Heated section high temperature	T1	(°C)
Heated section mid temperature	T2	(°C)
Heated section low temperature	T3	(°C)
Cooled section high temperature	T6	(°C)
Cooled section mid temperature	T7	(°C)
Cooled section low temperature	T8	(°C)
Cooling water flowrate	Fw	(l/min) If sensor SFT2 is fitted

You should also estimate and record the experimental errors for these measurements.

For this exercise the following constants are applicable:

Distance between thermocouple T1 and the hotface	x_{hot} = 0.0375	(m)
Distance between hotface and coldface	x_{int} = 0.030	(m)
Distance between the coldface and thermocouple T8	x_{cold} = 0.0375	(m)
Diameter of bar	D = 0.025	(m)

Note:
The distance between each thermocouple is 0.015m
The distance between thermocouple T3 or T6 and the end face is 0.0075m
The conductivity of the Brass sections is approximately 121 W/m°C
The conductivity of the Stainless Steel section is approximately 25 W/m°C

For each set of readings the derived results are tabulated under the following headings:

Heat flow (Power to heater) $Q = V\,I$ (Watts)

Cross sectional area $A = \frac{\pi D^2}{4}$ (m^2)

Temperature difference across composite wall $\Delta T_{18} = T1 - T8$ (°C)

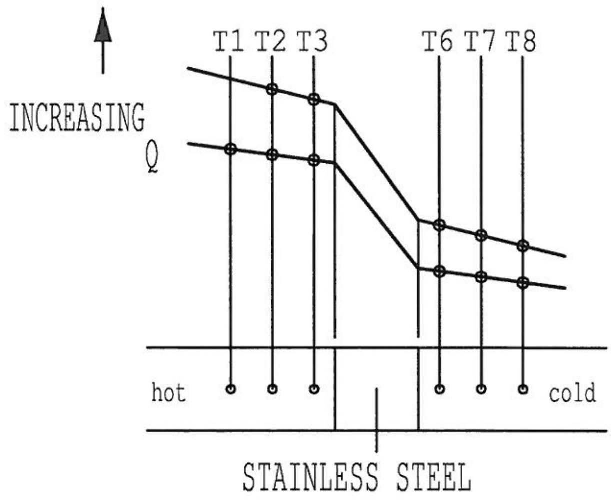
Resistance to heat flow $R = \frac{1}{U} = \frac{\Delta x_{hot}}{k_{hot}} + \frac{\Delta x_{int}}{k_{int}} + \frac{\Delta x_{cold}}{k_{cold}}$

Overall Heat Transfer Coefficient $U = \frac{Q}{A(T1 - T8)}$

Estimate the cumulative influence of the experimental errors on your calculated values for Q, ΔT_{18}, R and U and measured values for Δx_{hot}, Δx_{int}, Δx_{cold} and D.

Compare the two values obtained for the Overall Heat Transfer Coefficient U and U = 1/R and comment on any difference in the values obtained.

Plot a graph of temperature against position along the bar and draw the best straight line through the points for the heated section and cooled section. Extrapolate each line to the joint with the intermediate section then join these two points to give the gradient through the intermediate section. Your graph should be similar to the diagram below:



Observe that the temperature gradient increases in the Stainless Steel section because of the reduced thermal conductivity of the material (increased resistance to heat flow).

Your results should give values of approximately 25 W/m°C for the thermal conductivity of Stainless steel, assuming no heat loss from the equipment. As a small amount of heat loss is inevitable as the temperature of the bar increases, the calculated value for the conductivity will increase at higher operating temperatures.

What was the effect of varying the heater power (heat flow through the composite bar)?

Conclusions

You have demonstrated how the Fourier rate equation can be used to determine an Overall Heat Transfer Coefficient for heat flow through a composite plane wall of constant cross sectional area but differing thermal conductivity.

Comment on the effect of measurement accuracy and heat loss from the equipment on your calculated results and any differences between the results for each section.

The consequence of a change in cross sectional area will be investigated in a later exercise.

Note: Exercise HT11CD should be carried out on completion of this exercise.

6.5 HT11C Laboratory Teaching Exercise D

Objective
To determine the thermal conductivity k (the constant of proportionality) of a metal specimen (good conductor)

Method
By measuring the temperature difference across a metal specimen resulting from a known steady flow of heat through the specimen and using the Fourier Rate Equation to calculate the thermal conductivity of the specimen.

Equipment Required
HT10XC Heat Transfer Service Unit

HT11C Computer Compatible Linear Heat Conduction Accessory
(Or HT11 Linear Heat Conduction Accessory)

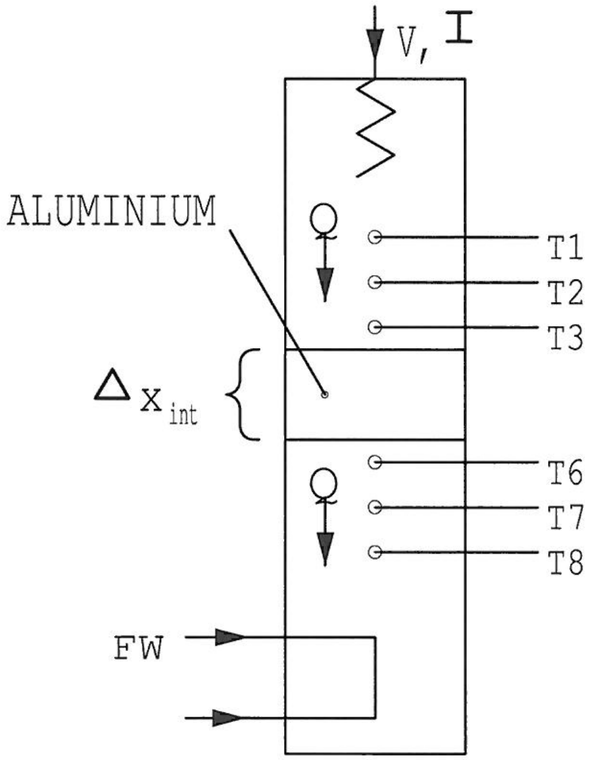
Optional Equipment
Windows™-compatible PC running Windows™ 98, 2000 or XP
(SFT2 Flow sensor if using HT11)

Equipment set-up
Before proceeding with the exercise ensure that the equipment has been prepared as follows:-

- Locate the HT11C Linear Heat Conduction accessory (1) alongside the HT10XC Heat Transfer Service Unit (20) on a suitable bench.

- Clamp the intermediate Aluminium section (no instrumentation) between the heated and cooled section of the HT11C having lightly coated the mating faces with thermal paste (See Operation section page 3-3).

- Take care to locate the shallow shoulders on the sections before clamping.



- Connect the eight thermocouples on the HT11C (3) to the appropriate sockets on the front of the service unit (30). Ensure that the labels on the thermocouple leads (T1 - T8) match the labels on the sockets.

Note: Readings from thermocouples T4 and T5 will not be used in this exercise.

- Set the VOLTAGE CONTROL potentiometer (23) to minimum (anticlockwise) and the selector switch (22) to MANUAL then connect the heater lead from the HT11C (4) to the socket marked OUTPUT 2 at the rear of the service unit (33).

- Connect the cold water flow control valve (11) to the socket marked AUXILARY OUTPUT (34) on the rear of the HT10XC console.

- Connect the cold water flow rate sensor (9) to the socket marked Fw (36) on the front of the HT10XC console.

- Set the AUXILIARY CONTROL knob (26) on the service unit to minimum (anticlockwise) then connect the power lead from the cold water flow control valve (11) to the AUXILIARY POWER socket on the rear of the service unit (Not relevant if using HT11).

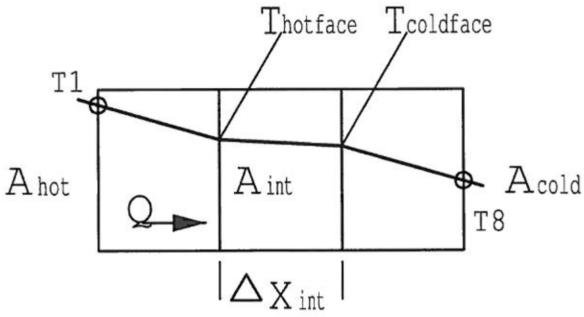
- Ensure that a cold water supply is connected to the inlet of the pressure regulating valve on HT11C (13).

- Ensure that the flexible cooling water outlet tube is directed to a suitable drain.

- Ensure that the service unit is connected to an electrical supply.
- Switch on the MAINS switch on the service unit (21).
- If using a computer for remote data logging and/or operation, connect the USB socket on the HT10XC (29) to the computer using the USB cable provided, and set the selector switch on the console (22) to REMOTE. (If not using a computer, leave the selector switch set to MANUAL).

Theory/Background

The heated, intermediate and cooled sections are clamped tightly together, so that the end faces are in food thermal contact, and create a composite bar with a metal specimen of unknown thermal conductivity sandwiched between two brass sections.



From Fourier's Law:

$Q = k_{int} A_{int} \frac{\Delta T_{int}}{\Delta x_{int}}$ where $\Delta t_{int} = (T_{hotface} - T_{coldface})$ and Δx_{int} is the length of the intermediate specimen (= 0.03m)

therefore $k_{int} = \frac{Q \Delta x_{int}}{A_{int} (T_{hotface} - T_{coldface})}$

Thermocouples T3 and T6 are located 7.5mm from the endfaces compared with a distance of 15mm between adjacent thermocouples (half the distance), therefore:

In the case of the heated section the temperature of the end face (hotface) will be lower than T3 and can be calculated as follows:

$$T_{hotface} = T3 - \frac{(T2 - T3)}{2}$$

In the case of the cooled section the temperature of the end face (coldface) will be higher than T6 and can be calculated as follows:

$$T_{coldface} = T6 + \frac{(T6 - T7)}{2}$$

Procedure

(Refer to the Operation section on page 3-1 if you need details of the instrumentation and how to operate it.)

Switch on the MAINS switch (21). (If the panel displays do not illuminate check the RCD at the rear of the service unit (35), the switch should be up.)

If using a computer, check that the software indicates IFD OK in the bottom right hand corner of the software window.

Turn on the cooling water and adjust the flow control valve (NOT the pressure regulator) to give approximately 1.5 litres/min. If using the software, the flow rate should be controlled using the control box on the software mimic diagram window. The flow rate may be monitored on the software screen. (If not using the software, use the selector switch to display the flow rate on the panel display on the console and control the valve setting using the AUXILIARY CONTROL knob. If using the HT11, the cold water flow rate is controlled using the manual control valve next to the test section column).

Set the heater voltage to 9 volts:

- If using the computer, enter the voltage in the display box for the heater, or use the control box arrows.
- If using the console, adjust the voltage control potentiometer to give a reading of 9 volts on the top panel display with the selector switch set to position V.

Allow the HT11C to stabilise. If using a computer, monitor the temperatures on the software mimic diagram screen. (If operating the equipment manually from the console, use the lower selector switch on the console to set the console display to each temperature sensor in turn).

When the temperatures are stable record the following: When the temperatures are stable, select the GO icon to record the following: T1, T2, T3, T6, T7, T8, V, I, Fw.

(If operating the equipment using the console then these values should be recorded manually. Fw is not available if using the HT11 unless the optional SFT2 flow sensor is fitted).

Set the Heater Voltage to 12 Volts.

Allow the HT11C to stabilise then repeat the above readings.

Results and Calculations

For this exercise the raw data is tabulated under the following headings:

Heater Voltage	V	Volts
Heater Current	I	Amps
Heated section high temperature	T1	(°C)
Heated section mid temperature	T2	(°C)
Heated section low temperature	T3	(°C)
Cooled section high temperature	T6	(°C)
Cooled section mid temperature	T7	(°C)
Cooled section low temperature	T8	(°C)
Cooling water flowrate	Fw	(l/min) If sensor SFT2 is fitted

You should also estimate and record the experimental errors for these measurements.

For this exercise the following constants are applicable:

Length of aluminium specimen	Δx_{int} = 0.030	(m)
Diameter of bar	D_{int} = 0.025	(m)

Note:
The distance between each thermocouple is 0.015m
The distance between thermocouple T3 or T6 and the end face is 0.0075m
The conductivity of the Brass sections is approximately 121 W/m°C

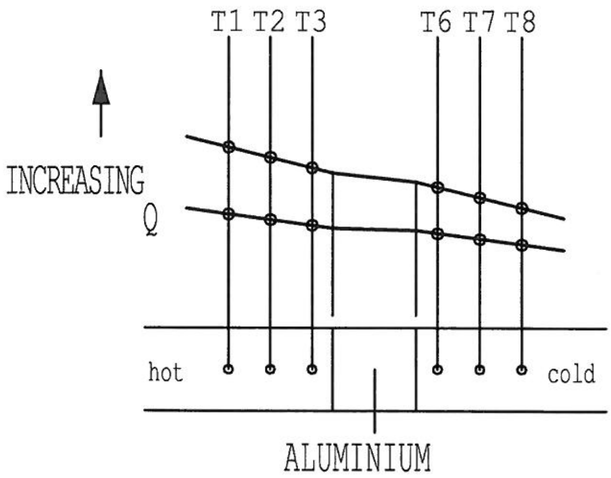
For each set of readings the derived results are tabulated under the following headings:

Heat flow (Power to heater)	$Q = V I$	(Watts)
Cross sectional area	$A = \frac{\pi D_{int}^{2}}{4}$	(m^2)
Temperature at hotface of specimen	$T_{hotface} = T3 - \frac{(T2 - T3)}{2}$	°C
Temperature at coldface of specimen	$T_{coldface} = T6 + \frac{(T6 - T7)}{2}$	°C
Temperature difference across specimen	$\Delta T_{int} = T_{hotface} - T_{coldface}$	°C
Thermal conductivity of specimen	$k_{int} = \frac{Q \Delta x_{int}}{A_{int}(T_{hotface} - T_{coldface})}$	(W/m°C)

Estimate the cumulative influence of the experimental errors on your calculated values for Q, A_{int}, $T_{hotface}$, ΔT_{int} and k_{int} and measured values for D_{int} and x_{int}.

Compare the values obtained for the Thermal Conductivity k_{int} at the different settings of heat flow through the specimen.

Plot a graph of temperature against position along the bar and draw the best straight line through the points for the heated section and cooled section. Extrapolate each line to the joint with the intermediate section then join these two points to give the gradient through the intermediate section. Your graph should be similar to the diagram below:



Observe the temperature gradient decreases in the aluminium section because of the increased thermal conductivity of the material (reduced resistance to heat flow). Measure the temperature gradient through the aluminium section from the graph then calculate the thermal conductivity using the average gradient. Compare the value obtained with that previously calculated.

Your results should give values of approximately 180 W/m°C for the thermal conductivity of Aluminium, assuming no heat loss from the equipment. As a small amount of heat loss is inevitable as the temperature of the bar increases, the calculated value for the conductivity will increase at higher operating temperatures.

Note: The thermal conductivity of an alternative material may be determined by repeating the exercise using a prepared sample of the required material (refer to the project work in exercise FT11H).

Conclusions

You have demonstrated how the Fourier rate equation can be used to calculate the thermal conductivity of a solid material if the temperature difference and rate heat flow through the material is known.

Comment on the effect of measurement accuracy and heat loss from the equipment on your calculated results and any differences between the results for each section.

The thermal conductivity of insulating materials will be investigated in a later exercise.

Note: Exercise HT11CE should be carried out on completion of this exercise.