## 6.6 HT11C Laboratory Teaching Exercise E

**Objective**
To demonstrate that temperature gradient is inversely proportional to the cross-sectional area for one-dimensional flow of heat in a solid material of constant thermal conductivity.

**Method**
By measuring the temperature distribution for steady-state conduction of energy through a plane wall of reduced cross-sectional area at different rates of heat flow.

**Equipment Required**
HT10XC Heat Transfer Service Unit

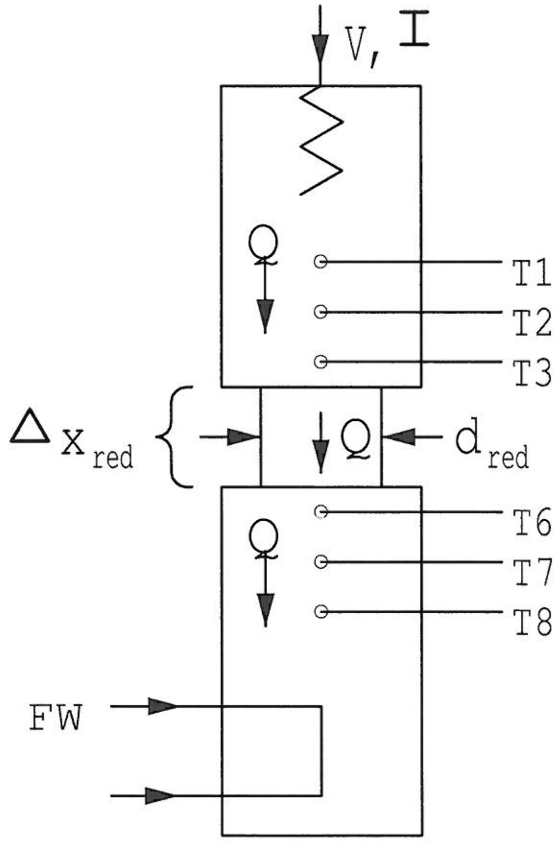
HT11C Computer Compatible Linear Heat Conduction Accessory
(Or HT11 Linear Heat Conduction Accessory)

**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 of reduced diameter (no thermocouples fitted) between the heated and cooled section of the HT11C having lightly coated the mating faces with thermal paste (See 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).

- 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).

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

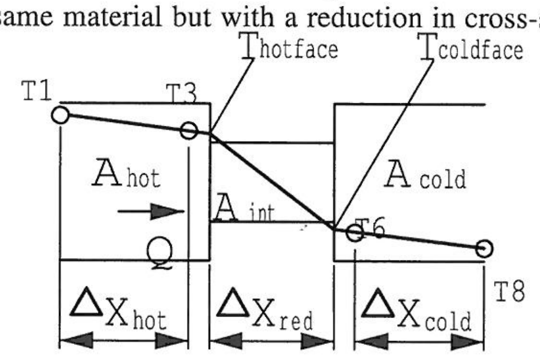
- Connect the cold water flow rate sensor (9) to the socket marked Fw (36) on the front of the HT10XC console.

- 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 the HT11, the cold water flow rate is controlled using the manual control valve next to the test section column).

**Theory/Background**

The heated and cooled sections are clamped tightly together with a section of reduced diameter in between. The end faces are in good thermal contact and create a compound bar of the same material but with a reduction in cross-sectional area in the intermediate section.




From Fourier's Law:

$$Q = kA\frac{\Delta T}{\Delta x}$$

or

$$\Delta T = \frac{Q\Delta x}{kA}$$ ie. $\Delta T$ is inversely proportional to A.

For the heated section

$$\Delta T_{hot} = \frac{Q\Delta x_{hot}}{k_{hot} A_{hot}}$$

For the intermediate section (reduced cross section):

$$\Delta T_{red} = \frac{Q \Delta x_{red}}{k_{red} A_{red}}$$

For the cooled section:

$$\Delta T_{cold} = \frac{Q \Delta x_{cold}}{k_{cold} A_{cold}}$$

Since the result will be the same for $\Delta T_{cold}$ and $\Delta T_{hot}$ (same cross section) results will be calculated for the hot section only.

**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 upper display selector switch to display the flow rate in L/min on the panel display on the console and control the valve setting using the AUXILIARY CONTROL knob).

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 display 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 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 T3 | $\Delta x_{hot} = 0.030$ | (m) |
| Distance between hotface and coldface | $\Delta x_{red} = 0.030$ | (m) |
| Distance between thermocouple T6 and T8 | $\Delta x_{cold} = 0.030$ | (m) |
| Diameter of bar (heated section) | $D_{hot} = \cancel{0.25}$ | (m) 0.025 |
| Diameter of bar (reduced section) | $D_{red} = \cancel{0.13}$ | (m) 0.013 |
| Diameter of bar (cooled section) | $D_{cold} = \cancel{0.25}$ | (m) 0.025 |

**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:

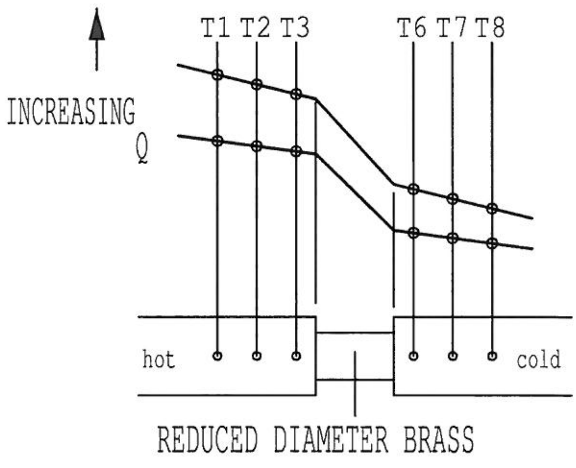
| | | |
|---|---|---|
| Heat flow (Power to heater) | $Q = VI$ | (Watts) |
| Temperature difference in heated section | $\Delta T_{hot} = T1 - T3$ | (°C) |
| Temperature gradient in heated section | $Grad_{hot} = \dfrac{\Delta T_{hot}}{\Delta x_{hot}}$ | (°C) |

| | | |
|---|---|---|
| Temperature at hotface of reduced section | $T_{hotface} = T3 - \frac{(T2 - T3)}{2}$ | (°C) |
| Temperature at coldface of reduced section | $T_{coldface} = T6 + \frac{(T6 - T7)}{2}$ | (°C) |
| Temperature difference in reduced section | $\Delta T_{red} = T_{hotface} - T_{coldface}$ | (°C) |
| Temperature gradient in reduced section | $Grad_{red} = \frac{\Delta T_{red}}{\Delta x_{red}}$ | (°C) |
| Cross sectional area (heated) | $A_{hot} = \frac{\pi D_{hot}^2}{4}$ | ($m^2$) |
| Ratio of temperature gradients | $= \frac{Grad_{red}}{Grad_{hot}}$ | |
| Ratio of cross sections | $= \frac{A_{red}}{A_{hot}}$ | |

Estimate the cumulative influence of the experimental errors on your calculated values for Q, A's, $T_{hotface}$, $T_{coldface}$, $\Delta T$'s, Grads and Ratios and measured values for Ds and $\Delta x$'s.

Confirm that the ratio of the temperature gradients is the inverse of the ratio of the cross sectional areas.

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:



Using the graph obtained determine the ratio of the temperature gradient in the heated/cooled sections to the temperature gradient in the reduced diameter section. Determine the ratio for each setting of heat flow and show that the gradients are in inverse proportion to the cross-sectional areas.

**Conclusions**

You have demonstrated how the cross sectional area affects the temperature gradient and confirmed that the Fourier rate equation predicts that the temperature difference is inversely proportional to the cross-sectional area.

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.

**Note:** Exercise HT11CF should be carried out on the completion of this exercise.

## 6.7 HT11C Laboratory Teaching Exercise F

**Objective**
To demonstrate the effect of contact resistance on thermal conduction between adjacent materials.

**Method**
By measuring the temperature gradient across the joints in a compound bar when the joints are assembled without thermal paste or not clamped together.

**Equipment Required**
HT10XC Heat Transfer Service Unit

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

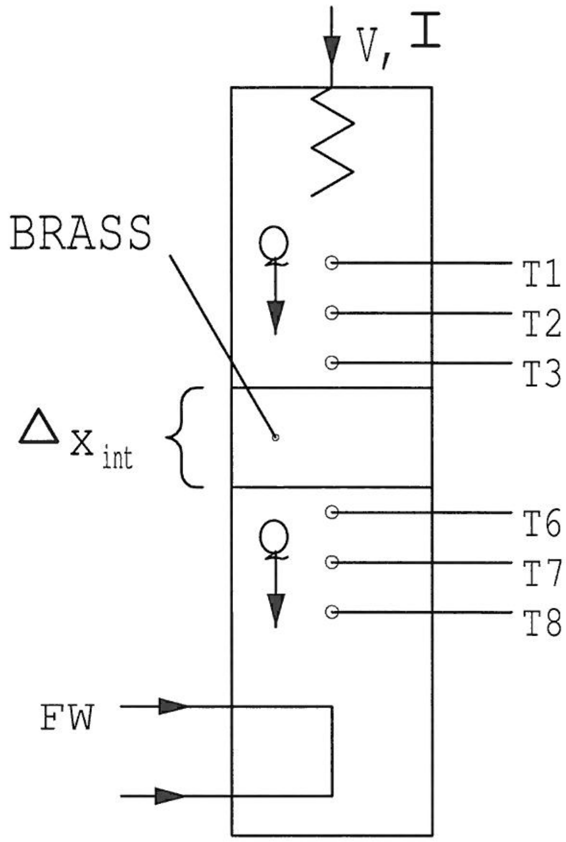
**Optional Equipment**
Windows™-compatible PC running Windows™ 98, 2000 or XP
(SFT2 Flow sensor if using HT11)

**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.

- Unclamp the heating and cooling sections of the HT11C and carefully remove any thermal paste from the mating surface using a soft cloth. Similarly clean any thermal paste from the face of the intermediate brass section (instrumented with two thermocouples) which mates with the heated section. Lightly coat the mating faces between the cooling section and the intermediate brass section with thermal paste.

- Locate the intermediate brass section between the heated and cooled section of the HT11C. Take care to locate the shallow shoulders on the sections but do not clamp the sections together.




- 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.

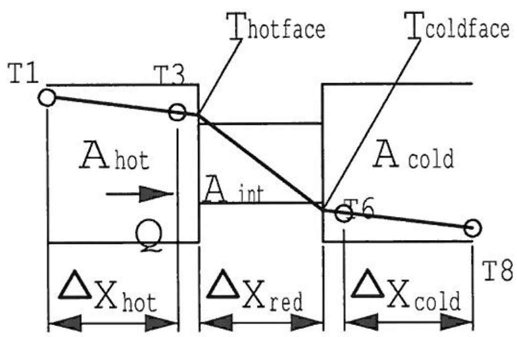
- Set the VOLTAGE CONTROL potentiometer (23) to minimum (anticlockwise) and the selector switch (22) to MANUAL then connect the heater lead from the HT11C to the socket marked OUTPUT 2 at the rear of the service unit (33).

- 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.

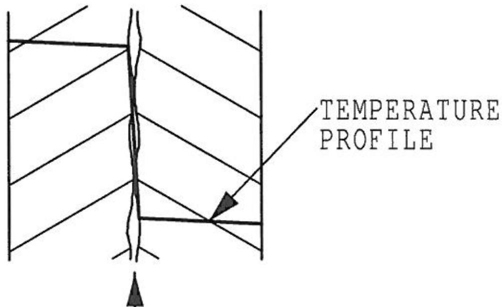
- Set the AUXILIARY CONTROL knob (26) on the service unit to minimum (anticlockwise) then connect the power lead from the cold water flow control valve (11) to the AUXILIARY POWER socket on the rear of the service unit (Not relevant if using HT11).

- 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**

When two surfaces are in contact, paths of thermal conduction exist only across those points where physical contact occurs on the microscopic scale. The degree of thermal contact depends on the respective surface finishes, the alignment between the surfaces and the degree of pressure applied.




Air trapped in the gaps between each surface acts as an insulator resulting in a temperature gradient in the conduction path. This can be reduced by the use of thermal paste which fills the air spaces and provides thermal contact.

The thermal paste itself has limited heat conduction and a thick layer of paste will itself create a resistance to heat flow.

**Procedure**

(Refer to the Operation section on page 3-3 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 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.

Leave the Heater Voltage at 17 Volts. Clamp the sections together on the HT11C.

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) 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:

Diameter of bar $D= 0.025$ (m)

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

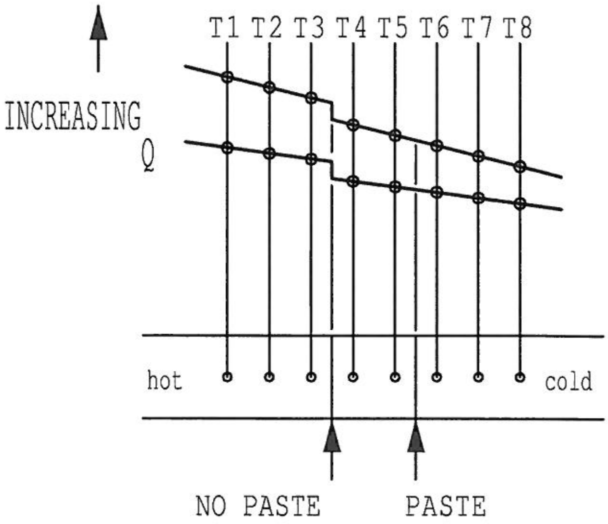
For each set of readings the derived results are tabulated under the following headings:

Heat flow (power to heater) $Q = VI$ (Watts)

Estimate the cumulative influence of the experimental errors o your calculated value for Q.

The effect of the contact resistance is best analysed graphically as follows:

Plot a graph of temperature against position along the bar and draw the best straight line through each of the three sections. Extrapolate each line to the joint with the intermediate section. your graph should be similar to the diagram below:




Observe that a step change in temperature occurs at both joints due to the poor thermal contact.

Observe that the step is greatest where the joint is dry and no pressure is applied.

Observe that the step is minimal where the joint was smeared with thermal paste and clamped tightly together.

Observe that the step in temperature due to poor contact increases when the flow of heat increases.

## Conclusions

You have demonstrated how surface contact affects the flow of heat across a joint by conduction.

Thermal compound can be applied to the adjoining faces to reduce the resulting temperature gradient by the coating must be thin and adequate pressure must be applied to the joint to minimise the 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.

**Note:** Exercise HT11CG should be carried out on completion of this exercise.

## 6.8 HT11C Laboratory Teaching Exercise G

**Objective**
To understand the application of poor conductors (insulators), and determine the thermal conductivity k (the constant of proportionality) of an insulator.

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

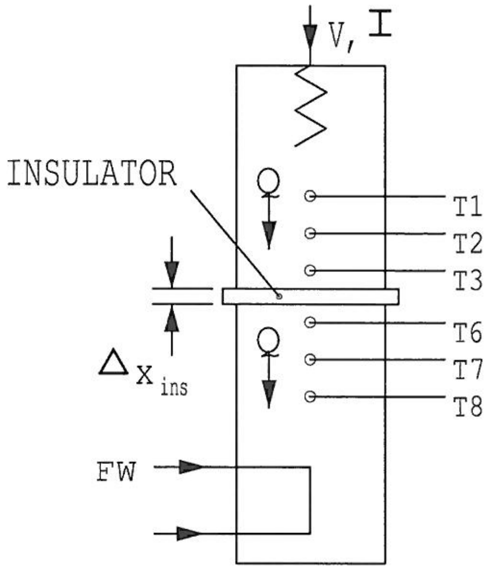
**Equipment Required**
HT10XC Heat Transfer Service Unit

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.
- Measure and record the thickness $\Delta x_{ins}$ (m) of the cork disk. If using the software, record the value by entering it on the mimic diagram screen.
- Clamp the thin cork disk between the heated and cooled section of the HT11C.




- 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 sued 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 to the socket marked OUTPUT 2 at the rear of the service unit (33).

- 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).

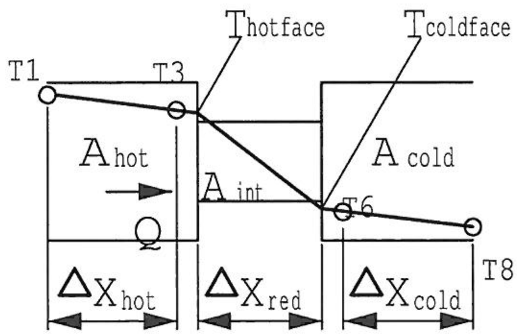
- Connect the cold water flow control valve (11) to the socket marked AUXILARY OUTPUT (34) on the rear of the HT10XC console.

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

- 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.

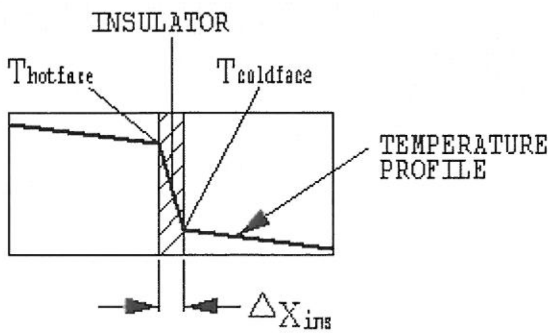
- Ensure that the service unit is connected to an electrical supply.
- Switch on the MAINS switch on the service unit (21).
- If using a computer for remote data logging and/or operation, connect the USB socket on the HT10XC (29) to the computer using the USB cable provided, and set the selector switch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




**Theory/Background**

Materials such as paper and cork have very low values of thermal conductivity which means that only a small amount of heat will pass through the material even though a high temperature difference may exist across its two faces. Such materials are known as insulators and are practically utilised in situations where it is required to reduce heat loss from a hot body to its surroundings.

The heated and cooled sections are clamped tightly together with the cork disk in between to create a composite bar with the insulated disk of unknown thermal conductivity sandwiched between two brass sections.




Fourier's Law can be used in the same way as it was used in exercise HT11CD.

Because of the low value of k for an insulator the dimension x must be small and only a small amount of heat (low power) must flow through the specimen to prevent a large temperature difference which will trip the thermostat.

$$Q = k_{ins} \frac{\Delta T_{ins}}{\Delta x_{ins}} \text{ where } \Delta T_{ins} = (T_{hotface} - T_{coldface})$$

$$\text{therefore } k_{ins} = \frac{Q}{A_{ins}(T_{hotface} - T_{coldface})}$$

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 1.5 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 1.5 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 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).

**Note:** T4 and T5 are not used in this exercise.

Set the Heater Voltage to 2 Volts.

Allow the HT11C to stabilise then repeat the above readings.

If time permits replace the cork disk with the paper disk and repeat the exercise.

**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 |
| Thickness of insulated disk | x | (m) |

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

For this exercise the following constants are applicable:

Diameter of insulator in contact with the bar $D_{ins} = 0.025$ (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

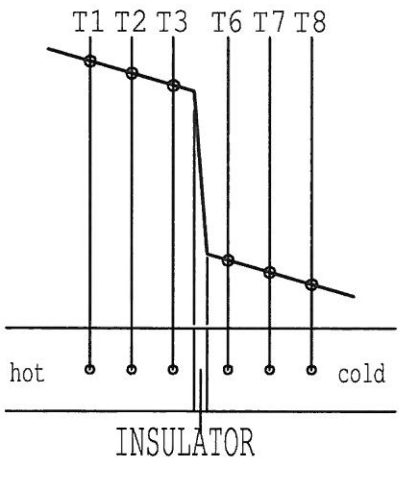
For each set of readings the derived results are tabulated under the following headings:

Heat flow (power to heater) $Q = VI$ (Watts)

| | | |
|---|---|---|
| Cross sectional area | $A = \dfrac{\pi D_{ins}^{\ 2}}{4}$ | ($m^2$) |
| Temperature at hotface of insulator | $T_{hotface} = T3 - \dfrac{(T2 - T3)}{2}$ | (°C) |
| Temperature at coldface of insulator | $T_{coldface} = T6 + \dfrac{(T6 - T7)}{2}$ | (°C) |
| Temperature difference across insulator | $\Delta T_{ins} = T_{hotface} - T_{coldface}$ | (°C) |
| Thermal conductivity of insulated disk | $k_{ins} = \dfrac{Q \Delta x_{ins}}{A_{ins} \Delta T_{ins}}$ | W/m°C |

Estimate the cumulative influence of the experimental errors of your calculated value for Q, $A_{ins}$, $T_{hotface}$, $T_{coldface}$,, $\Delta T_{ins}$, $\Delta x_{ins}$ and $k_{ins}$.

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 insulator then join these two points to give the gradient through the insulator. Your graph should be similar to the diagram below:




Observe that the temperature gradient in the two brass sections is the same and extremely small because of the low heat flow.

Observe the extremely large temperature gradient across the insulated disk compared to the brass sections. Only very low heat flow is possible through the disk because of the very low thermal conductivity of the material (large resistance to heat flow).

Measure the temperature gradient across the insulated disk then calculate the conductivity of the disk using the average gradient. Compare the value obtained with that previously calculated. Note that 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 HT11CH).

## Conclusions

You have demonstrated how the Fourier rate equation can be used to calculate the thermal conductivity of a material (insulator) if the temperature difference and 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.

**Note:** Exercise HT11CH should be carried out on completion of this exercise.

## 6.9 HT11C Laboratory Teaching Exercise H

**Objective**
To observe unsteady state conduction of heat.

**Method**
By monitoring the transient changes in temperature along a bar when a step change is applied to the heat flow through the bar. Note that this experiment requires continuous recording of sensor outputs, and thus can only be performed using a connected PC.

**Equipment Required**
HT10XC Heat Transfer Service Unit

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

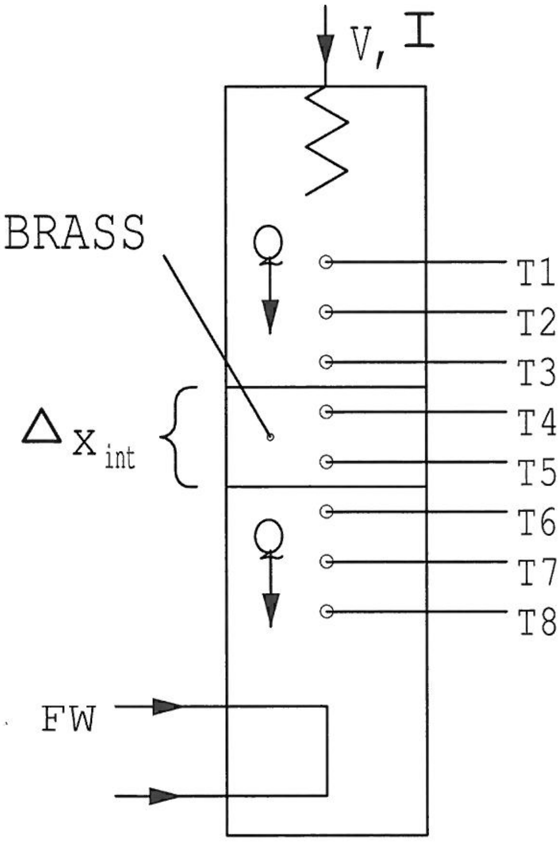
Windows™-compatible PC running Windows™ 98, 2000 or XP

**Optional Equipment**
(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 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) to minimum (anticlockwise) and the selector switch (22) to MANUAL then connect the heater lead from the HT11C to the socket marked OUTPUT 2 at the rear of the service unit (33).

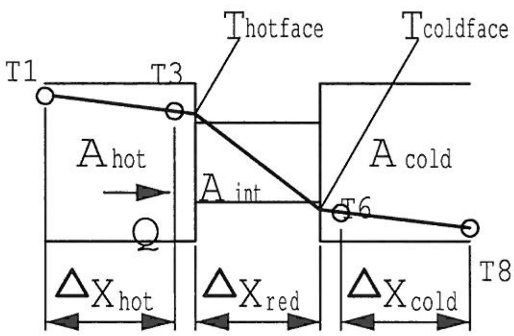
- Set the AUXILIARY CONTROL knob (26) on the service unit to minimum (anticlockwise) then connect the power lead from the cold water flow control valve (11) to the AUXILIARY POWER socket on the rear of the service unit (Not relevant if using HT11).

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

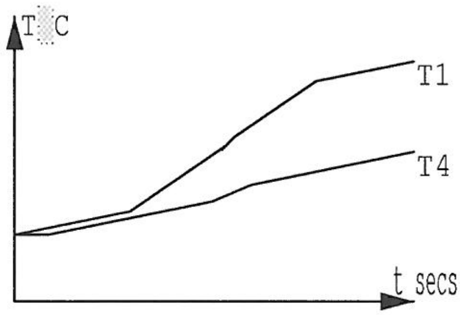
- Connect the cold water flow rate sensor (9) to the socket marked Fw (36) on the front of the HT10XC console.

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

**Theory/Background**




This exercise is qualitative only and intended to show the transient/time-dependent behaviour of a system where temperature varies with time and position. This condition, referred to as unsteady-state, exists when the bar on the HT11C is first heated and continues until it reaches equilibrium. Similarly the condition exists if a step change is applied such as reducing the heater power or reducing the flow of cooling water.




When heat is applied to one end of the bar the elevated temperature at the heated end causes heat to flow towards the cold end. The result is a gradual rise in the temperature of the bar until the appropriate temperature gradient is established along the bar (as studied in previous exercises.) The changes in temperature cannot occur instantaneously and changes in the middle of the bar will lag the changes at the heated end of the bar despite being smaller in magnitude. Similarly the smaller changes at the cooled end of the bar will lag the changes at the centre of the bar.

**Note:** Unsteady-state heat transfer can be analysed in much greater detail using the Armfield HT17.

**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.)

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. 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 using the HT11, the cold water flow rate is controlled using the manual control valve next to the test section column. Flow rate may only be monitored if the optional flow sensor SFT2 is fitted).

Select the 'Sample' menu and 'Configure…'. Check that Sampling Operation is set to Automatic, the Sample Interval to 30 seconds, and Duration of Sampling to Continuous. Change the values to match if required.

Select the  icon from the menu bar to begin data logging.

Set the heater voltage to 17 volts: enter the voltage in the display box for the heater, or use the control box arrows.

Allow the HT11C to stabilise. Monitor the temperatures on the software mimic diagram screen.

Set the Heater Voltage to 12 Volts.

Allow the HT11C to stabilise.

If time permits reduce the flow of cooling water dramatically by closing the flow control valve (not the pressure regulating valve) but do not stop the flow of water altogether. If using the HT11C, the valve should be controlled using the control box on the mimic diagram screen. The HT11 requires manual control using the valve next to the test section column.

Allow the HT11C to stabilise.

Select the  icon to stop data logging.

**Results and Calculations**

The transient behaviour of the heated bar is best analysed graphically using the recorded graphs of temperature versus time which you have obtained. At any point in time the temperature gradient along the bar can be established by plotting a graph of temperature against position along the bar. Repeating this graph at different time intervals will show the changing gradient along the bar as the bar stabilises in temperature.

You should observe the following features on the graphs obtained.

When the heating element is switched on the temperatures throughout the bar gradually rise until the steady-state linear temperature gradient is achieved.

The rise in temperature at T4 occurs slightly later than the rise at T1 because of the temperature gradient along the bar due to conduction.

When the heat input is reduced the heat flow cannot support the original temperature gradient and temperatures along the bar must reduce until an appropriate temperature gradient is achieved.

When the flow of cooling water is reduced the cold end of the bar cannot be maintained at the original low temperature. As all other conditions are unchanged, the gradient along the bar will remain the same resulting in an offset in all of the temperatures (all temperatures along the bar will rise by the same amount). This effect should be clearly shown on the graphs plotted of temperature versus distance.

**Conclusions**

You have observed how, in a solid, temperature changes with time and position while heat flows from hot boundaries to cold boundaries and temperature gradients are established. This condition of unsteady-state heat transfer exists until a constant temperature gradient has developed and a condition of steady-state is achieved.

**Note:** **R**efer to exercise HT11CI for details on additional project work.

## 6.10 HT11C Laboratory Teaching Exercise I

### PROJECT WORK

The design of the HT11C, with the facility to clamp thin samples of insulating material or 30mm long samples of conducting material between the heated and cooled sections, makes the accessory ideal for student project work. Typical exercises might include:

**Good Conductors:**
Analysis of the thermal conductivity to a range of materials which are good conductors.

Samples should be 30m long and 25mm in diameter to clamp directly between the heated section and cooled section of the HT11C. A simple insulated jacket, eg. a length of pipe insulation, will minimise heat loss from the sample.

**Poor Conductors (insulators):**
Analysis of the thermal conductivity of a range of different materials which are poor conductors.

Samples should be as thin as possible to allow a reasonable heat flow to be measured without excessive temperature gradient which will trip the thermostat in the heated section.

**Surface finish (contact resistance):**
Analysis of the effect of surface finish/roughness on the temperature drop across a joint.

Specimens should be constructed from brass in two halves, 15mm thick with smooth, flat surfaces in contact with each other. Comparison of the temperature gradient with the gradient across a reference specimen in solid brass, at the same heat power, will indicate the effect of the surface finish.

**Heat transfer compounds (contact resistance):**
Analysis of the effectiveness of different jointing compounds to minimise temperature drop across a joint.

Each compound should be applied directly to the interface between the heated and cooled sections. The temperature gradient across the interface, at the same heat power, will indicate the effectiveness of the compound.

If tests have been carried out with samples of different surface finish then the effect of heat transfer compounds on these samples can also be investigated.

**Glued joints (contact resistance):**
Investigation of the conduction across glued joints when using different types of adhesive and different thickness of adhesive.

Specimens should be constructed from brass in two halves, 15mm thick, bonded together using the adhesives to be tested. Comparison of the temperature gradient with the gradient across a reference specimen in solid brass, at the same heat power, will indicate the effectiveness of the bonded joint.

Note: The adhesives used must be capable of withstanding operating temperatures up to 100°C.

In all of the above exercises the temperature at the interface between the heated face and the sample or the cooled face and the sample can be determined as follows:

Thermocouples T3 and T6 are located 7.5mm from the end faces 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:

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

**Designing a model to demonstrate heat transfer by conduction**

An interesting project for students who have completed the previous training exercises is to build and test a heat transfer model of their own design.

The HT10XC service unit provides the necessary power supplies and instrumentation to operate such a model. Provided that the model is constructed with the following principles it can be connected directly to the HT10XC service unit for evaluation:

The heater must operate from a 24 VDC electrical supply at a maximum current of 9 Amps (216 Watts maximum)

The thermocouples must be type K and terminated with a miniature thermocouple plug.

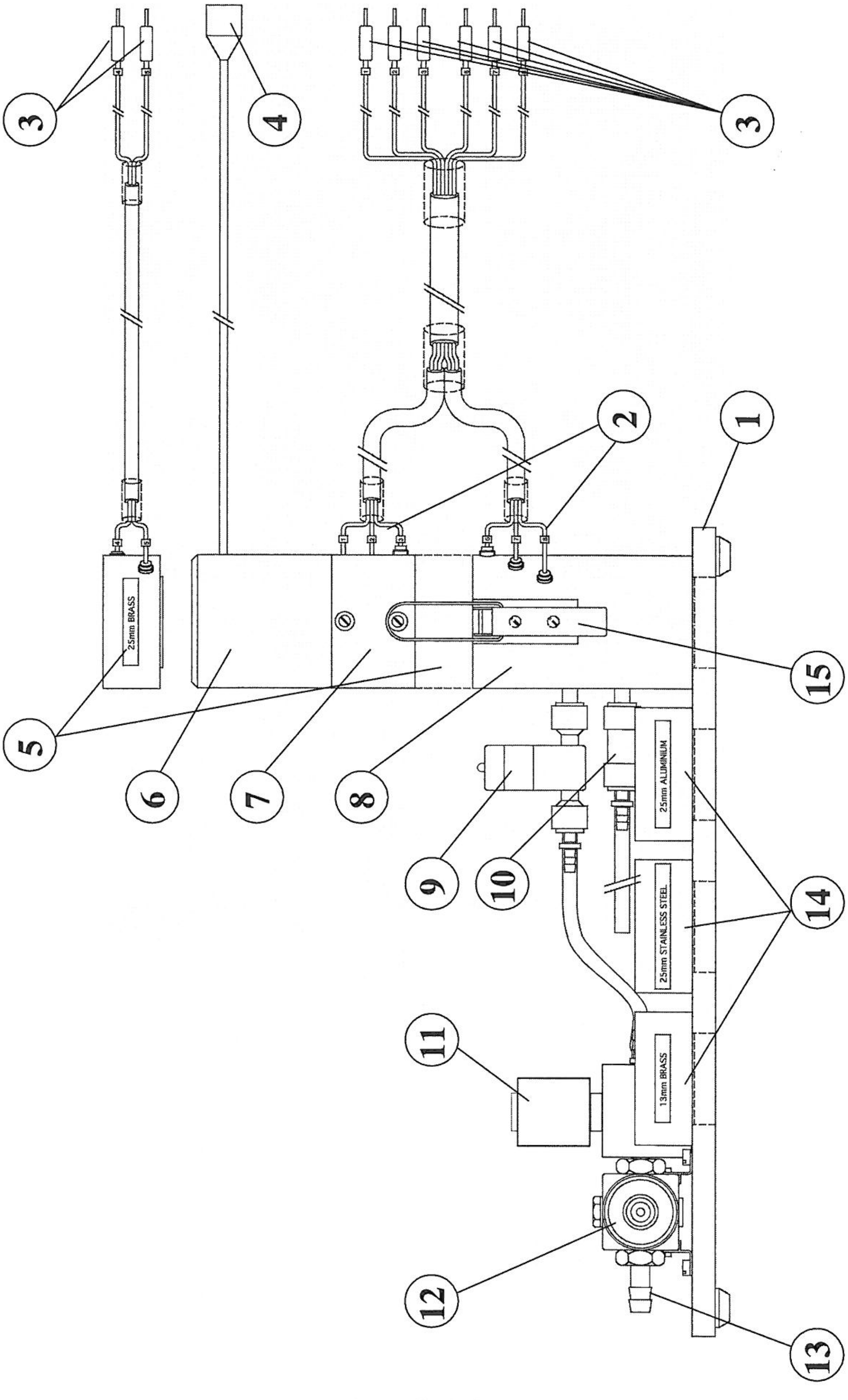
Where appropriate, any of the exercises A to H or the project work suggested above might be applied to the model constructed by the student.

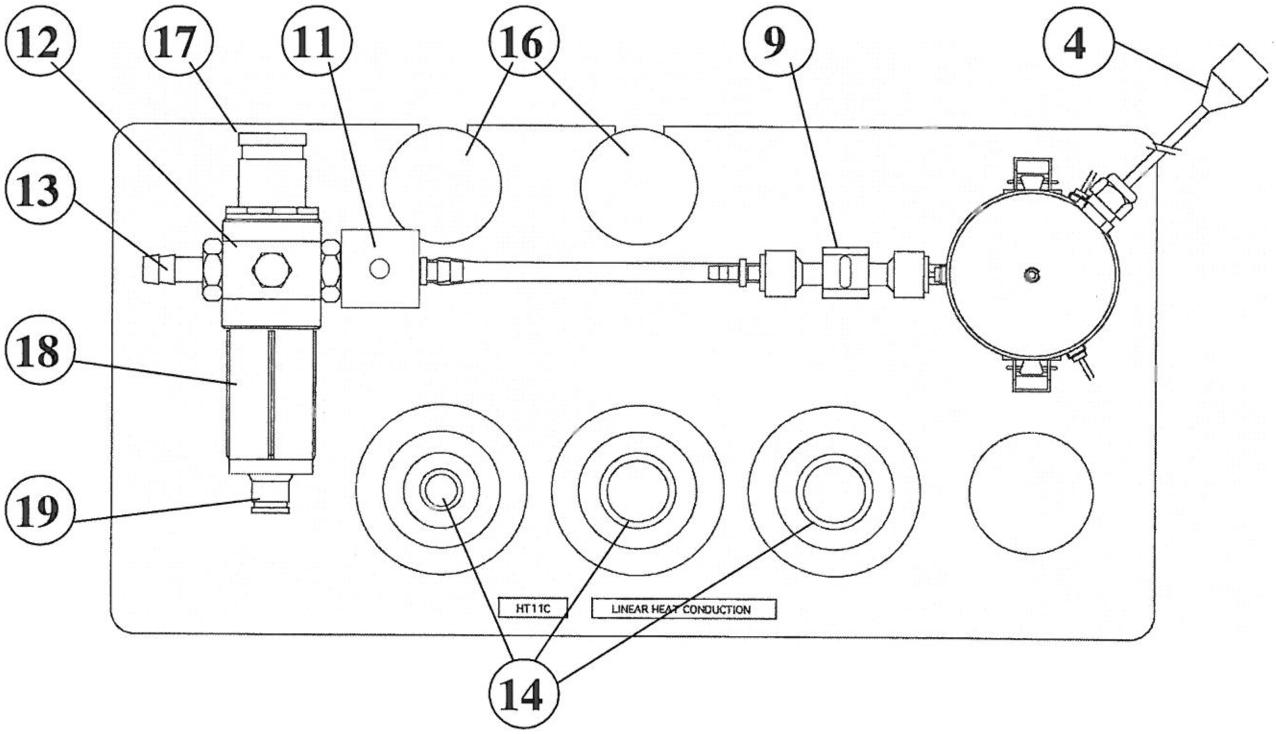
**Note:** When using the HT11C to measure the thermal conductivity of different specimens it is important to estimate the effect of heat loss from the equipment to obtain accurate results. Heat loss at different operating temperatures of the bar can be determined by testing the brass specimen of known conductivity and correcting the heater power to obtain the correct value for the conductivity. These corrected values for heater power can then be applied to obtain accurate values at different operating temperatures. Averaging of temperature gradients along the composite bar will reduce the effect of measurement errors, especially when measured temperature differences are small.

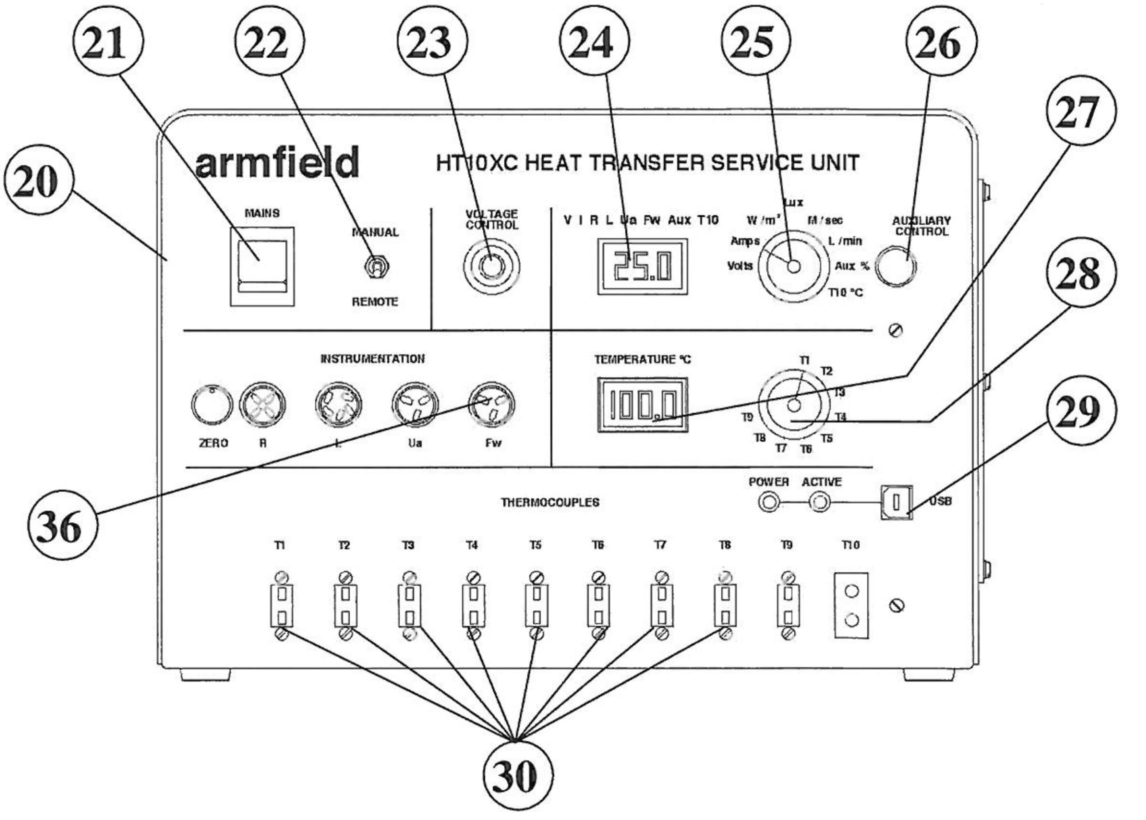
# 7 APPENDIX A: INSTALLATION GUIDE

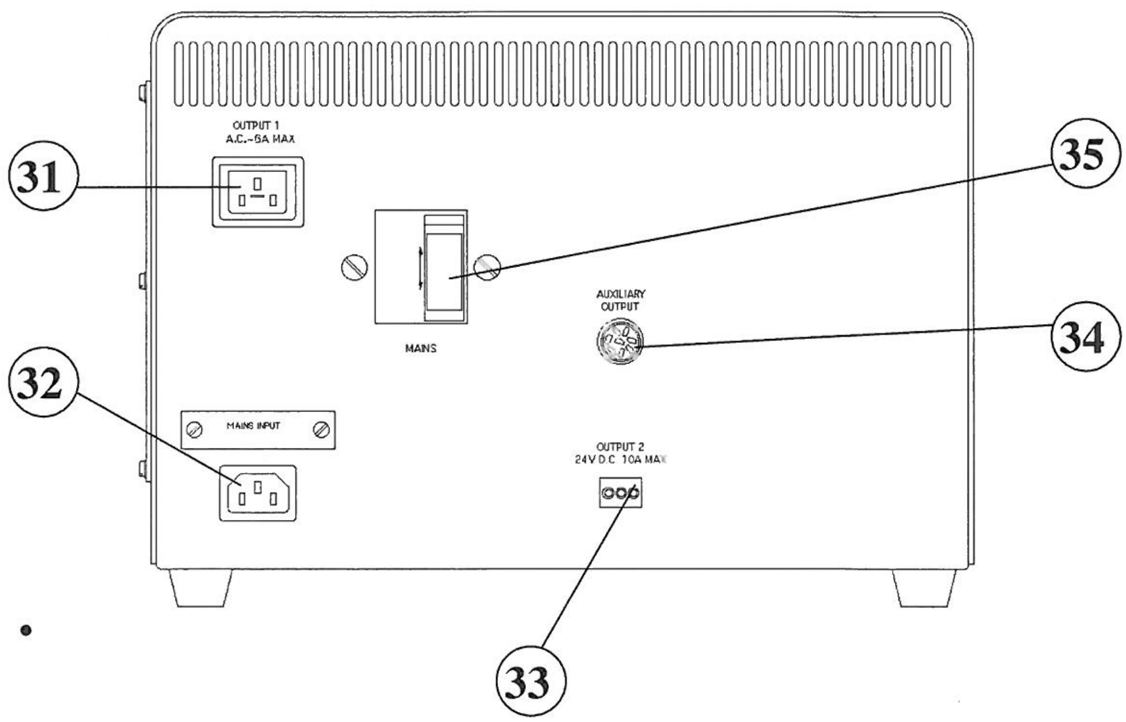
## 7.1 HT11C Installation Guide

**NOTE:** The HT11 'Linear Heat Conduction' accessory must be used in conjunction with the HT10X 'Heat Transfer Service Unit'. This Installation Guide assumes that the HT10XC has already been installed according to the guide included with the HT10XC manual.


1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
25mm BRASS
25mm ALUMINIUM
25mm STAINLESS STEEL
13mm BRASS


12
17
11
16
9
4
13
18
19
14
HT11C
LINEAR HEAT CONDUCTION


armfield
HT10XC HEAT TRANSFER SERVICE UNIT
MAINS
MANUAL
REMOTE
VOLTAGE CONTROL
V I R L Ua Fw Aux T10
AUXILIARY CONTROL
INSTRUMENTATION
ZERO
TEMPERATURE °C
POWER
ACTIVE
USB
THERMOCOUPLES
T1 T2 T3 T4 T5 T6 T7 T8 T9 T10
20
21
22
23
24
25
26
27
28
29
30
36


OUTPUT 1
A.C.-6A MAX
MAINS
AUXILIARY OUTPUT
MAINS INPUT
OUTPUT 2
24V D.C. 10A MAX
31
32
33
34
35

Unpack the apparatus and check the items against the included Advice Note.

- The intermediate sections containing specimens of different metal conductors (14) and insulators (16) should be located in the machined recesses on the PVC base (1). The shallow shoulder on one side of each intermediate section should be located in the recess to prevent the section from moving on the baseplate.
- Position the accessory on a suitable bench top alongside the H10X service unit (20).
- Connect the miniature thermocouple plug from each of the eight temperature sensors (3) to the appropriate socket on the front of the service unit (30), ensuring that the numbers on the plugs and sockets are compatible.
- Set the Voltage Control potentiometer (23) on the front of the service unit to zero (turn the adjusting knob fully anticlockwise).
- Set the Auxiliary Control potentiometer (26) on the front of the service unit to zero (turn the adjusting knob fully anticlockwise).
- Set the Remote/Manual selector switch (22) to the MANUAL position.
- Connect the power lead from the heating section of the HT11C to the variable DC outlet socket marked OUTPUT 2 at the rear of the service unit (33).
- Connect the power lead from the cold water flow control valve on the HT11C to the socket marked Auxiliary Output on the rear of the HT10XC console (34) (This step is not relevant if using the Ht11 instead of the HT11C).
- Connect the lead from the cold water flow rate sensor (9) to the socket marked Fw (36) on the front of the HT10XC console.
- Connect a supply of clean cold water (minimum 1.5 l/min supply at maximum pressure 1 bar) to the inlet on the HT11C (13) using suitable flexible tubing. Secure the tubing to the inlet connection on the pressure regulator with a suitable clip.
- Direct the cooling water outlet tube to a suitable drain.

HT11 Only: If using the HT11 instead of the HT11C, and the optional flow sensor SFT2 is available, connect the flow sensor to the outlet tubing on the HT11 using the quick release connector. Connect the electrical lead from the flow sensor to the socket marked Fw on the front of the service unit.

- Switch the MAINS switch on the HT10XC console (21) to the OFF position.
- Set the Voltage Control potentiometer on the front of the HT10XC (23) to zero (turn the adjusting knob fully anticlockwise).
- Set the Manual/Remote selector switch (22) to MANUAL.

- Turn off the cold water pressure regulating valve: pull the knob (17) away from the body of the regulator (12), then turn the knob fully anticlockwise. Close the drain/vent (19) on the transparent filter bowl (18) by turning it fully clockwise.

- Ensure that the RCD/RCCB at the rear of the service unit (35) is in the ON (up) position.

- Check that the HT10XC is connected to a suitable mains electricity supply. Switch on the mains electricity supply and the water supply to the HT11C.

- Set the mains on/off switch on the service unit front panel (21) to the ON position.

- Check that both digital display displays on the console (24 and 27) are illuminated (as no power is supplied to the accessory at this stage the temperature display should indicate approximately ambient temperature).

- Set the top selector switch (25) to L/min in order to monitor the cold water flow rate. Fully open the cold water flow control valve (11) by turning the Auxiliary Control knob on the console (26) fully clockwise.

- Gradually open the pressure regulating valve (12) by turning the knob (17) clockwise until the cold water flow through the cooling section is approximately 1.5 litres/min as displayed on the upper display panel (24). When the flowrate is acceptable push the knob on the regulator in to lock the setting of the pressure regulator.
  **Note:** If using the HT11 instead of the HT11C, the cold water flow rate is controlled by manually adjusting the valve next to the test section column. The HT11 cold water flow rate may only be monitored using the console if the optional flow sensor SFT2 is used. When setting the pressure regulator on the HT11 without the SFT2, the flow rate may be measured by a timed collection of cold water outflow using a measuring beaker and a stopwatch.

- Ensure that the exposed metal end faces on the heating and cooling sections are clean (refer to the Routine Maintenance section for information on cleaning) then clamp the two sections together using the toggle clamps (15) by operating the two clamping levers simultaneously.

- Set the temperature selector switch (28) to position T1 to indicate the temperature at the heated end of the bar. Check that the temperature indicated (27) is approximately ambient temperature.

- Set the top measurement selector switch (25) to position V to indicate the voltage supplied to the heating element on HT11C. Adjust the Voltage Control potentiometer (23) to give a reading of approximately 12 Volts on the top panel display (24). (Ensure that the clamp on the side of the knob is released before turning the knob.)

- Check that the reading of temperature T1 gradually increases. Check that temperature T1 stabilises. Check that the temperatures indicated decrease towards the cooled end of the bar, i.e. T1>T2, T2>T3, T3>T6, T6>T7 and T7>T8 by selecting each position in turn on the selector switch (28).

- Turn off the power to the heater by setting the potentiometer (23) to zero.

- Allow the bar to cool then turn off the cooling water by turning the auxiliary control knob (26) fully anticlockwise.

  **Note:** Although a thermostat is incorporated to protect the heating element from over heating it is good practice to turn off the power first followed by the cooling water.

- If required, install the HT11C software:
  - Insert the software CD-ROM into the CD or DVD drive on the PC
  - The CD should autorun. If autorun fails to initiate, select 'Run...' from the 'Start' menu, and type 'D:\setup.exe' where 'D' is the letter of your CD-ROM drive. (ignore the '' marks).
  - Follow the instructions on the screen
  - You will need to restart the PC before running the software

- You may now connect the HT10XC console to the PC using the USB cable provided to connect the console socket (29) to a free USB port.
  **Note:** The software must be installed BEFORE connecting the console in order to provide the operating system with the correct USB driver. If the console is been connected before installing the software, Windows may install the wrong driver. If this happens, ask your system administrator to delete the installed USB driver for the HT10XC console, then re-install the software before reconnecting the console.

**The basic operation of the 'Linear Heat Conduction' accessory and 'Heat Transfer Service Unit' has been confirmed. Refer to the Operation section in the manual for further information.**