



# **Computer Compatible Linear Heat Conduction Accessory**

## **Instruction Manual**

**HT11C**

**ISSUE 6**

**October 2012**

# Table of Contents

Copyright and Trademarks .....	1
General Overview .....	2
HT10XC and accessories layout diagram.....	3
Equipment Diagrams.....	4
Important Safety Information.....	7
Introduction.....	7
Water Borne Hazards.....	7
Electrical Safety.....	7
Hot Surfaces.....	8
Hot Liquids.....	8
Description .....	9
Overview.....	9
Heating section.....	9
Heating element .....	9
Cooling section .....	9
Cooling water.....	9
Cooling water flow measurement .....	9
Intermediate sections .....	9
Thermal properties of insulators .....	10
Section construction .....	10
Thermocouples.....	11
Thermal paste.....	11
Measurement of temperature gradient .....	11
Installation .....	12
Advisory.....	12
Electrical Supply .....	12
Installing the optional PC software .....	12
Installing the Equipment .....	13
Operation .....	16

Operating the optional PC software.....	16
Operating the Equipment.....	16
Equipment Specifications.....	19
Overall Dimensions .....	19
USB Channel Numbers .....	19
Environmental Conditions.....	19
Routine Maintenance .....	20
Responsibility .....	20
General.....	20
Draining the cooling water pipework.....	20
Storing the intermediate sections .....	20
Cleaning the contact surfaces .....	20
Cleaning the pressure regulator filter .....	20
Adjusting the clamps and bars .....	20
RCD Test.....	21
Laboratory Teaching Exercises.....	22
Index to Exercises .....	22
Nomenclature .....	22
Exercise A - Steady State Conduction through a Uniform Plane Wall .....	24
Exercise B - Use of the Fourier Rate Equation .....	30
Exercise C - Overall Heat Transfer Coefficient for Differing Materials in Series .....	36
Exercise D - Determination of Thermal Conductivity (Constant of Proportionality)...	42
Exercise E - Relationship of Temperature Gradient to Cross-Sectional Area.....	48
Exercise F - Effect of Contact Resistance on Thermal Conduction .....	55
Exercise G - Application and Thermal Conductivity of Insulators .....	61
Exercise H - Unsteady State Conduction of Heat .....	67
Project Work.....	72
Contact Details for Further Information .....	74



## Disclaimer

This document and all the information contained within it is proprietary to Armfield Limited. This document must not be used for any purpose other than that for which it is supplied and its contents must not be reproduced, modified, adapted, published, translated or disclosed to any third party, in whole or in part, without the prior written permission of Armfield Limited.

Should you have any queries or comments, please contact the Armfield Customer Support helpdesk (Monday to Thursday: 0830 – 1730 and Friday: 0830 - 1300 UK time). Contact details are as follows:

United Kingdom	International
(0) 1425 478781 (calls charged at local rate)	+44 (0) 1425 478781 (international rates apply)
Email: <a href="mailto:support@armfield.co.uk">support@armfield.co.uk</a>	
Fax: +44 (0) 1425 470916	

## Copyright and Trademarks

Copyright © 2012 Armfield Limited. All rights reserved.

Any technical documentation made available by Armfield Limited is the copyright work of Armfield Limited and wholly owned by Armfield Limited.

Brands and product names mentioned in this manual may be trademarks or registered trademarks of their respective companies and are hereby acknowledged.

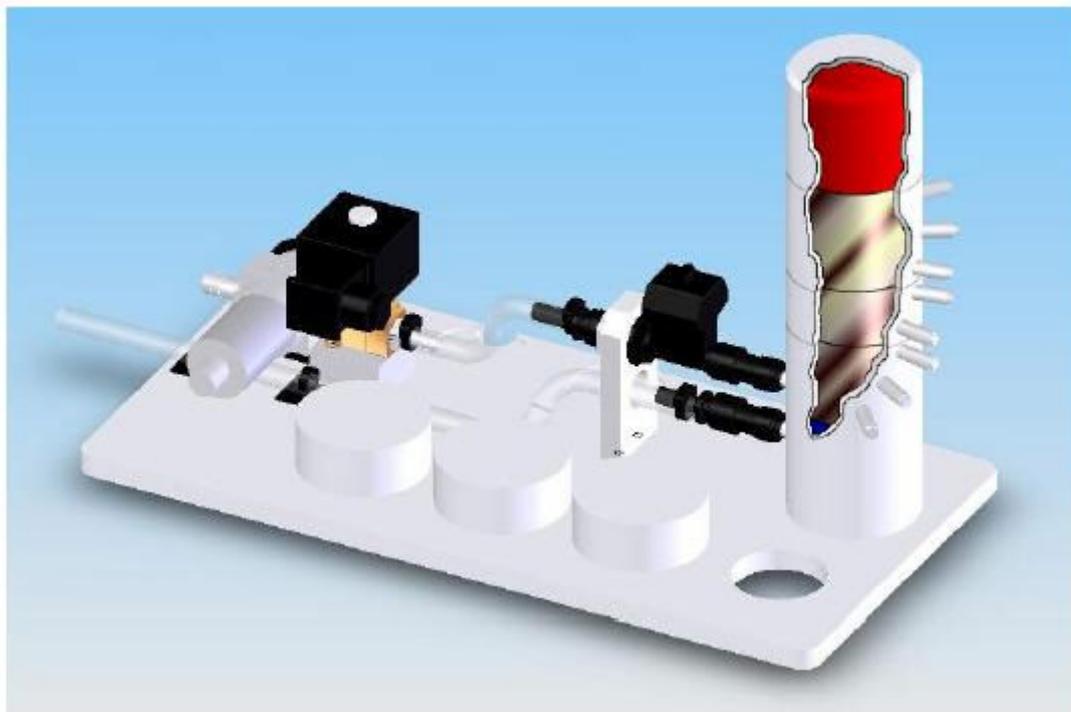
## General Overview

This instruction manual should be used in conjunction with the product manual supplied with the HT10XC 'Computer Compatible Heat Transfer Service Unit'.

The Armfield Computer Compatible Linear Heat Conduction accessory HT11C has been designed to demonstrate the application of the Fourier Rate equation to simple steady-state conduction in one dimension. The unit can be configured as a simple plane wall of uniform material and constant cross sectional area or composite plane walls with different materials or changes in cross sectional area to allow the principles of heat flow by linear conduction to be investigated. Measurement of the heat flow and temperature gradient allows the thermal conductivity of the material to be calculated. The design allows the conductivity of thin samples of insulating material to be determined.

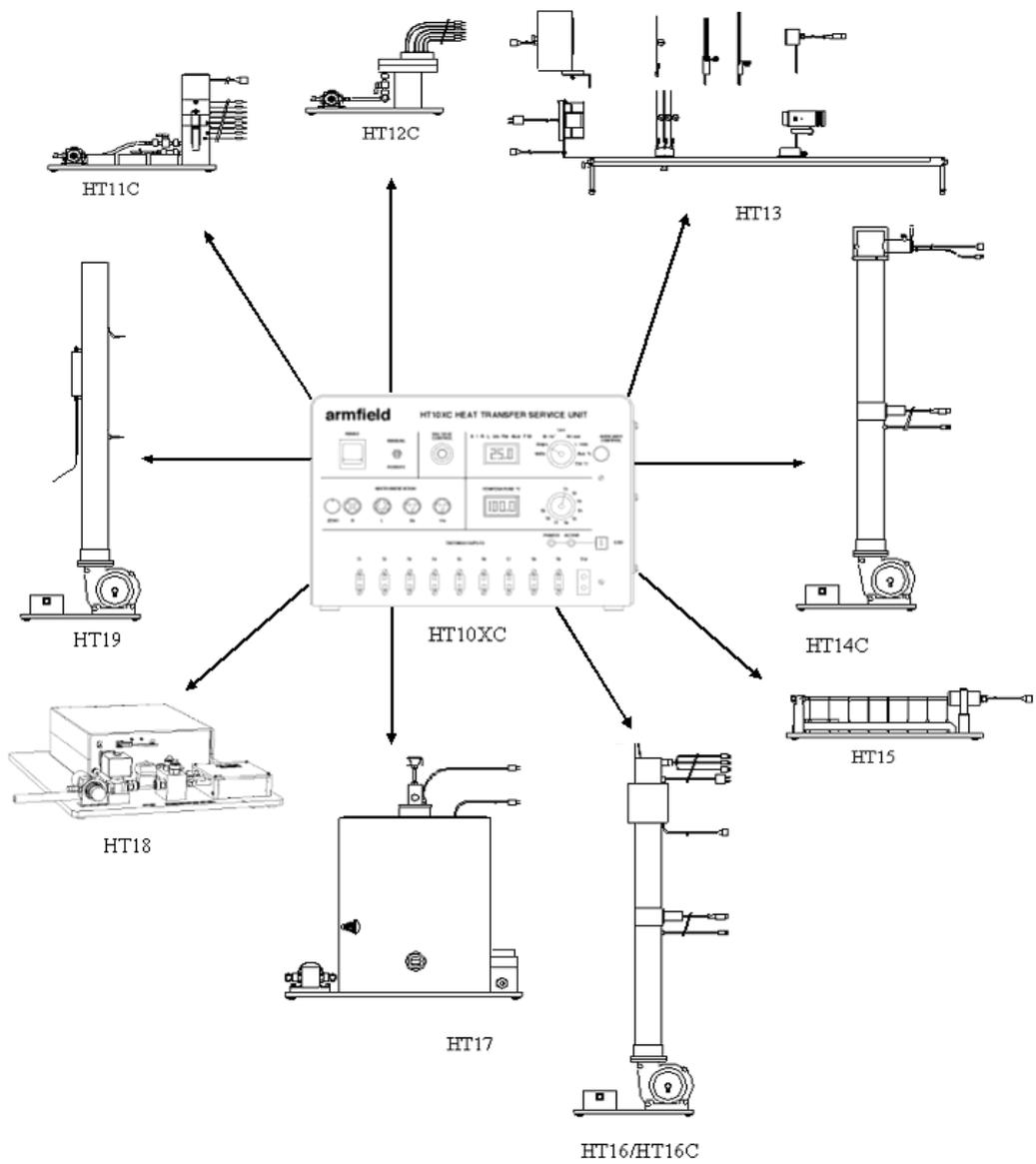
This instruction manual describes the operation of the HT11C Computer Compatible Linear Heat Conduction accessory, which must be used in conjunction with the HT10XC Heat Transfer Service Unit (supplied separately) and may be operated remotely from a Windows™ -compatible PC via the USB interface device included within the console. Details of the service unit are given in a separate instruction manual which is supplied with the unit. This manual describes the operation of the HT11C accessory and includes a set of Laboratory Teaching Exercises.

The HT11C is one of a range of seven small scale heat transfer laboratory teaching accessories which demonstrate the basic modes of heat transfer (conduction, convection and radiation). These accessories may be individually connected to a common bench top service unit (HT10XC) which provides the necessary electrical supplies and measurement facilities for investigation and comparison of the different heat transfer characteristics.



The HT11C Computer Compatible Linear Heat Conduction Accessory

# HT10XC and accessories layout diagram



HT10XC and Accessories

## Equipment Diagrams

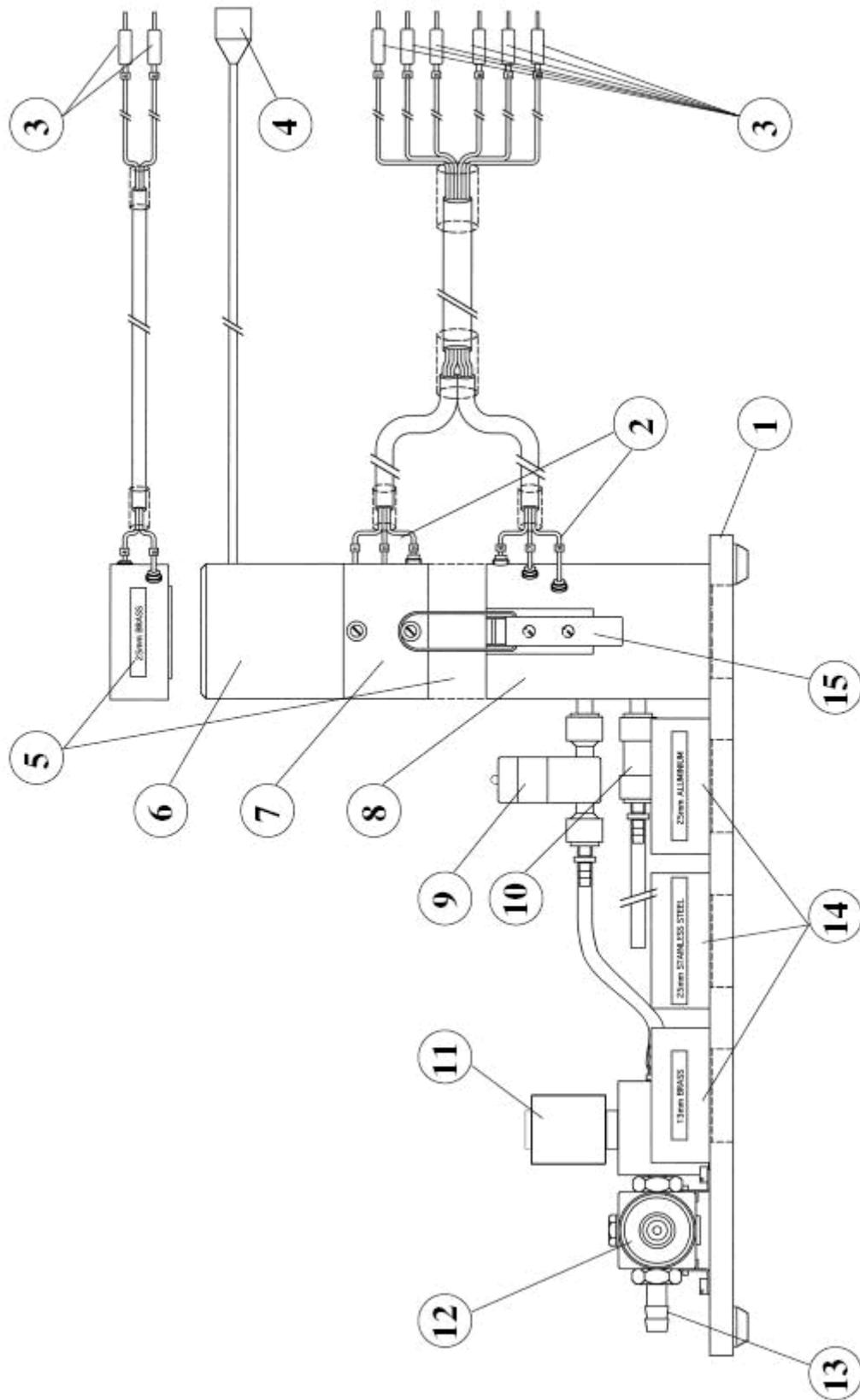


Figure 1: Side View of HT11C Computer Compatible Linear Heat Conduction Accessory

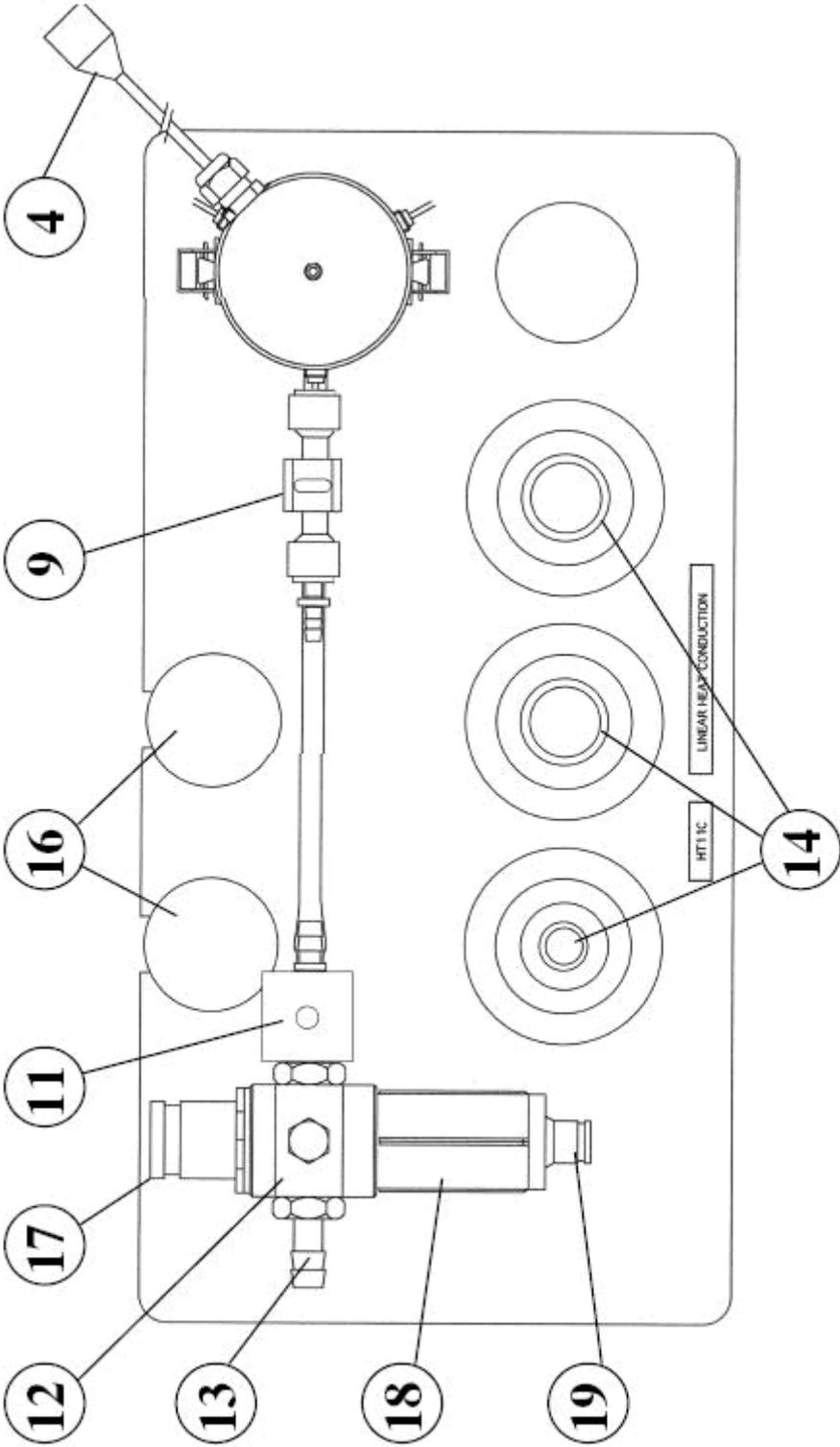


Figure 2: Top View of HT11C Computer Compatible Linear Heat Conduction Accessory

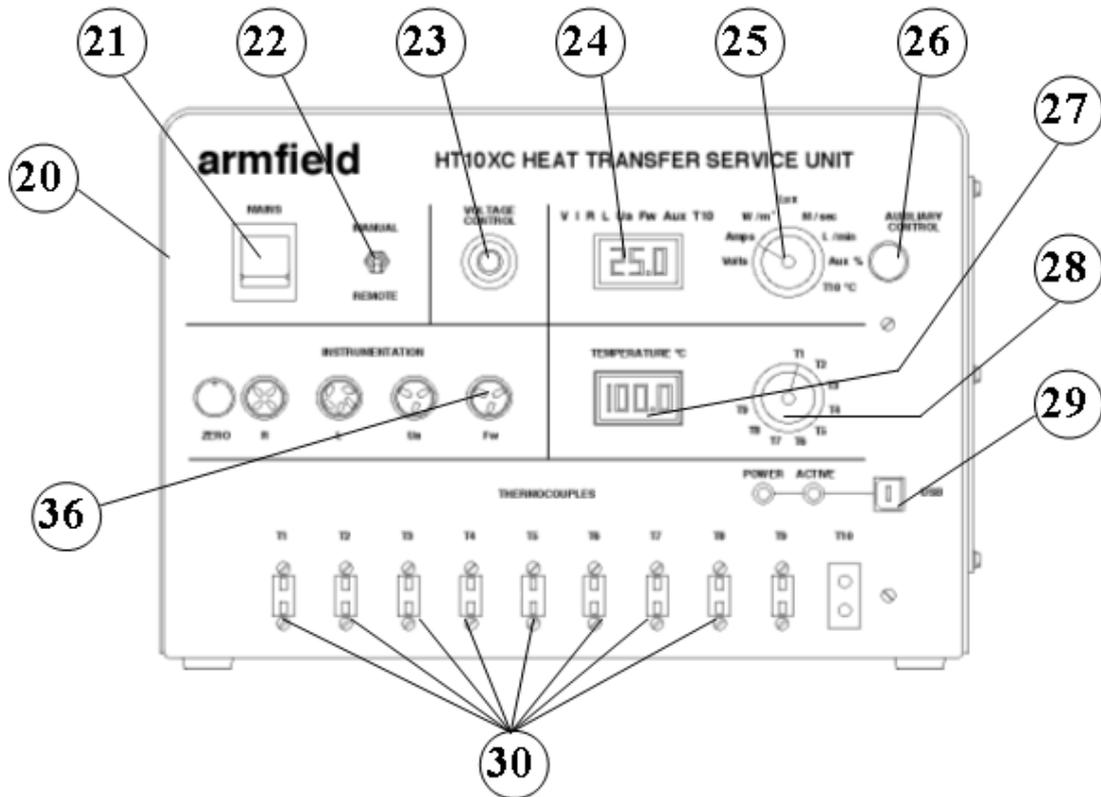


Figure 3: Front View of HT10XC

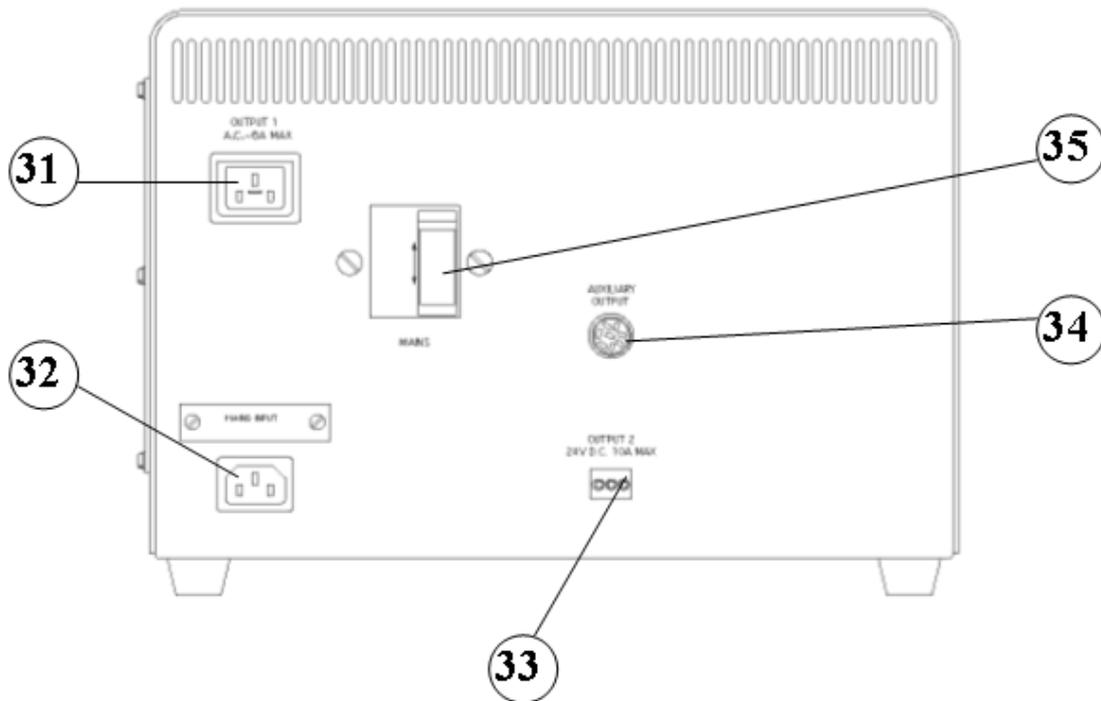


Figure 4: Rear View of HT10XC

# Important Safety Information

## Introduction

All practical work areas and laboratories should be covered by local safety regulations **which must be followed at all times**.

It is the responsibility of the owner to ensure that all users are made aware of relevant local regulations, and that the apparatus is operated in accordance with those regulations. If requested then Armfield can supply a typical set of standard laboratory safety rules, but these are guidelines only and should be modified as required. Supervision of users should be provided whenever appropriate.

Your **Computer Compatible Linear Heat Conduction Accessory** has been designed to be safe in use when installed, operated and maintained in accordance with the instructions in this manual. As with any piece of sophisticated equipment, dangers exist if the equipment is misused, mishandled or badly maintained.

## Water Borne Hazards

The equipment described in this instruction manual involves the use of water, which under certain conditions can create a health hazard due to infection by harmful micro-organisms.

For example, the microscopic bacterium called *Legionella pneumophila* will feed on any scale, rust, algae or sludge in water and will breed rapidly if the temperature of water is between 20 and 45°C. Any water containing this bacterium which is sprayed or splashed creating air-borne droplets can produce a form of pneumonia called Legionnaires Disease which is potentially fatal.

*Legionella* is not the only harmful micro-organism which can infect water, but it serves as a useful example of the need for cleanliness.

Under the COSHH regulations, the following precautions must be observed:

- Any water contained within the product must not be allowed to stagnate, i.e. the water must be changed regularly.
- Any rust, sludge, scale or algae on which micro-organisms can feed must be removed regularly, i.e. the equipment must be cleaned regularly.
- Where practicable the water should be maintained at a temperature below 20°C. If this is not practicable then the water should be disinfected if it is safe and appropriate to do so. Note that other hazards may exist in the handling of biocides used to disinfect the water.
- A scheme should be prepared for preventing or controlling the risk incorporating all of the actions listed above.

Further details on preventing infection are contained in the publication "The Control of Legionellosis including Legionnaires Disease" - Health and Safety Series booklet HS (G) 70.

## Electrical Safety

The equipment described in this Instruction Manual operates from a mains voltage electrical supply. It must be connected to a supply of the same frequency and voltage

as marked on the equipment or the mains lead. If in doubt, consult a qualified electrician or contact Armfield.

The equipment must not be operated with any of the panels removed.

To give increased operator protection, the unit incorporates a Residual Current Device (RCD), alternatively called an Earth Leakage Circuit Breaker, as an integral part of this equipment. If through misuse or accident the equipment becomes electrically dangerous, the RCD will switch off the electrical supply and reduce the severity of any electric shock received by an operator to a level which, under normal circumstances, will not cause injury to that person.

At least once each month, check that the RCD is operating correctly by pressing the TEST button. The circuit breaker **MUST** trip when the button is pressed. Failure to trip means that the operator is not protected and the equipment must be checked and repaired by a competent electrician before it is used.

## Hot Surfaces

This apparatus is capable of producing temperatures that could cause **burns / serious burns**.

- Allow time for the equipment to cool before handling any of the components.
- Do not touch any surfaces with a 'Hot Surfaces' warning label.
- Do not allow the apparatus to come into contact with flammable materials or liquids.
- Do not cover or store the equipment until it has cooled.
- Any safety guards are there for operator protection- they must not be removed except as described in this manual, and nothing should be inserted through the guards.
- Always operate the apparatus according to the Operational Procedures described in this manual.
- The apparatus should not be left unattended while switched on.

## Hot Liquids

This apparatus contains fluid at temperatures capable of causing serious scalds / scalds.

- Always allow time for the apparatus to cool before disconnecting any tubing.
- Avoid skin contact with hot fluids. Take particular care if refilling of the apparatus or manual collection of the hot fluid is required during use.
- Always operate the apparatus according to the Operational Procedures described in this manual.
- Use only those fluids described in this manual when setting up and operating this equipment.

## Description

Where necessary, refer to the drawings in the [Equipment Diagrams](#) section.

## Overview

The Computer Compatible Linear Heat Conduction accessory comprises heating and cooling sections which can be clamped together directly or clamped with interchangeable intermediate sections as required. Each interchangeable section contains a different specimen of metal conductor which allows a plane wall of the same material, a plane wall of different cross section or composite walls with different materials to be created for evaluation. The temperature difference created by the application of heat to one end of the resulting wall, and cooling at the other end, results in the flow of heat linearly through the wall by conduction.

## Heating section

The heating section (7) is manufactured from 25 mm diameter cylindrical brass bar with a cartridge type electric heating element (6) installed at one end.

## Heating element

The heating element (6) is operated at low voltage for increased operator safety and is protected by a thermostat to prevent damage from overheating. The heating element is rated to produce 60 Watts nominally at 24 VDC. The power supplied to the heating element can be varied and measured using the HT10XC. The lead from the heating element (4) is connected to the DC outlet socket marked OUTPUT 2 on the HT10XC (33).

## Cooling section

The cooling section (8) is manufactured from 25 mm diameter cylindrical brass bar to match the heating section and cooled at one end by water passing through galleries in the section.

## Cooling water

A proportioning solenoid valve (11) allows the flow of cooling water to be varied, if required, over the operating range of 0 - 1.5 litres/min. The valve should be connected to the socket marker AUXILIARY OUTPUT (34) on the rear of the HT10XC console. The cold water supply is connected to the serrated ferrule (13) on the side of the pressure regulator using reinforced flexible tubing (not supplied).

## Cooling water flow measurement

The HT11C includes a turbine-type flow sensor (9) for measurement of the cooling water flow rate directly in litres per minute. The flow sensor should be connected to the socket marked Fw (36) on the front of the HT10XC console.

## Intermediate sections

Four intermediate sections (5 and 14) are supplied, each incorporating a different metal specimen as follows:

### Brass specimen

30 mm long brass section (5) of the same diameter as the heating and cooling sections (25 mm diameter) and fitted with two thermocouples at the same intervals (15 mm). When this section is clamped between the heating and cooling sections a

long plane wall of uniform material and cross section is created with temperatures measured at eight positions.

The thermal conductivity of the Brass specimen is typically in the range 110 to 128 W/m°C over the range of operating temperatures in the HT11C.

### **Stainless Steel specimen**

30 mm long stainless steel specimen (14) of the same diameter as the heating and cooling sections (25 mm diameter) to demonstrate the effect of a change in thermal conductivity. The specimen does not incorporate thermocouples.

The thermal conductivity of the Stainless Steel specimen is approximately 25 W/m°C at the typical operating temperatures in the HT11C.

**Note:** The poor conductivity of the stainless steel specimen means that operation with high settings of the voltage control will cause the thermal trip to operate. Stabilisation of the temperature readings will take considerably longer than when using the brass or aluminium specimens.

### **Aluminium Alloy specimen**

30 mm long Aluminium Alloy specimen (14) of the same diameter as the heating and cooling sections (25 mm diameter) to demonstrate the effect of a change in thermal conductivity. The specimen does not incorporate thermocouples.

The thermal conductivity of the Aluminium Alloy specimen is approximately 180 W/m°C at the typical operating temperatures in the HT11C.

### **Brass specimen with reduced diameter**

30 mm long brass specimen (14) reduced in diameter to 13 mm to demonstrate the effect of a change in cross sectional area. The specimen does not incorporate thermocouples.

The thermal conductivity of the reduced diameter Brass specimen is typically in the range 110 to 128 W/m°C over the range of operating temperatures in the HT11C.

**Note:** The reduced area of heat flow in this specimen means that operation with high settings of the voltage control will cause the thermal trip to operate. Stabilisation of the temperature readings will take considerably longer than when using the standard brass specimen.

### **Thermal properties of insulators**

The heat conducting properties of insulators (16) may be found by simply inserting the paper or cork specimens supplied between the heating and cooling sections. The specimens must be extremely thin to compensate for their poor conductivity.

**Note:** The very poor conductivity of the insulators means that the voltage control must be set to extremely low settings (typically 1.5 Volts) to prevent the thermal trip from operating. Stabilisation of temperatures will take considerably longer than when using specimens with high conductivity.

### **Section construction**

The heating section, cooling section and all intermediate sections are located co-axially inside plastic housings which provide an air gap and insulate the section to minimise heat loss to the surroundings and prevent burns to the operator. The plastic

housings incorporate shallow shoulders to ensure that each section aligns concentrically with the adjacent section. This means that the interchangeable sections can only be installed one way round. A pair of toggle clamps (15) ensures that the sections are held tightly together when in use. Two alternative studs are located on the heated section to allow the clamp to operate with or without an intermediate section installed.

### Thermocouples

Three thermocouples (T1, T2 and T3) are positioned along the heated section at uniform intervals of 15mm. Three thermocouples (T6, T7 and T8) are positioned along the cooling section at uniform intervals of 15mm. Two thermocouples (T4 and T5) are positioned along the brass intermediate section, also at 15mm intervals. These thermocouples measure the temperature gradient along the section to which they are attached.

Each type K thermocouple is fitted with a miniature plug (3) for direct connection to the front panel of the service unit HT10XC (26). The thermocouple beads are located on the centreline of each section in holes at different angular positions to minimise the disturbance to heat flow along the sections.

### Thermal paste

A tube of thermal paste is provided. The paste is applied between the adjacent faces to minimise the temperature gradient across the joints. The effect of poor thermal contact between the sections can be demonstrated by taking equivalent readings with no paste applied then with the sections unclamped.

### Measurement of temperature gradient

When the Brass Specimen, which incorporates thermocouples, is clamped between the heated and cooled sections the two thermocouples installed in the specimen assume the identities T4 and T5 to provide a continuous plane wall with eight thermocouples T1 - T8.

When the non-instrumented specimens or insulated disks are installed between the heated and cooled sections, the temperature at the interfaces must be calculated from the temperature measurements taken in the appropriate section. The thermocouples in each section are located 15mm apart. T3 and T6 are located 7.5mm away from the end surface.

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

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

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

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

Details of connections between the HT11C and the HT10XC service unit are given in the Installation section.

## Installation

### Advisory

Before operating the equipment, it must be unpacked, assembled and installed as described in the steps that follow. Safe use of the equipment depends on following the correct installation procedure.

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

Where necessary, refer to the drawings in the [Equipment Diagrams](#) section.

### Electrical Supply

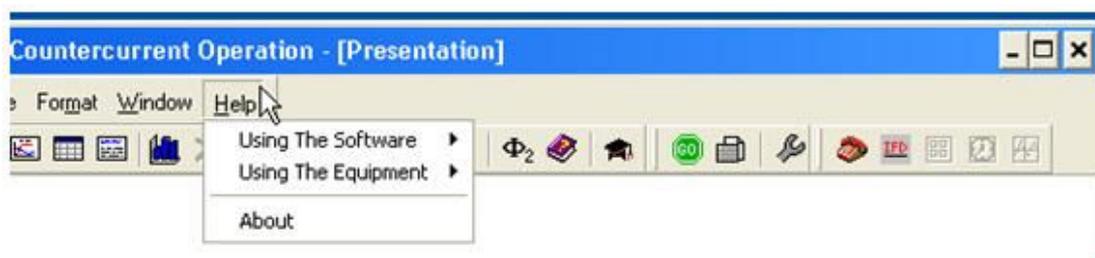
	HT11C-A	HT11C-B	HT11-G
<b>Green/yellow lead</b>	Earth (Ground)	Earth (Ground)	Earth (Ground)
<b>Brown lead</b>	Live (Hot)	Live (Hot)	Live (Hot)
<b>Blue lead</b>	Neutral	Neutral	Neutral
<b>Fuse rating</b>	13A	15A	13A
<b>Voltage</b>	220-240V	110-120V	220V
<b>Frequency</b>	50Hz	60Hz	60Hz

### Installing the optional PC software

If it is required to operate HT11C using the optional software supplied with HT10XC then it will be necessary to install the software from the CD-ROM supplied with HT10XC onto an appropriate PC (PC not supplied).

For instructions on how to install and run the software insert the CD-ROM into the optical drive on the PC (PC not supplied) then choose 'Help' from the menu.

After installing and running the software on the PC, instructions on how to operate the software can be obtained by choosing the 'Help' tab in the top right hand corner of the screen as shown below:



Note that when operating the software for the first time it will be necessary to enable the USB virtual COM port by choosing the Red telephone icon (Start COM session).



Full instructions about enabling the port are included in the Help menus.

## Installing the Equipment

To install the equipment:

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 H10XC 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.

- To install the optional software:
  - The HT10XC Heat Transfer Service Unit includes Windows™ based software that allows remote operation of the HT11C from any compatible PC running Windows™ 98 or later. The PC should have an available USB port and be situated within cable length of the HT10XC.
  - For information about using the software associated with this product refer to the section Operating the Software in the HT10XC Instruction Manual or refer to Operating the Software via Help in the top menu bar of 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 for further information.

## Operation

Where necessary, refer to the drawings in the [Equipment Diagrams](#) section.

The apparatus must be set up in accordance with the Installation section. Additionally, ensure that you have read the Important Safety Information.

### Operating the optional PC software

Details about operating the optional HT11C software can be obtained by choosing the 'Help' tab in the top right hand corner of the screen as shown below:



### Operating the Equipment

#### Setting the Heater Voltage

The heater is designed to be operated remotely from a PC. The manual/remote selector switch (22) on the front panel of the HT10XC (20) should be set to REMOTE for normal operation. The heater voltage may then be set using the voltage control box on the mimic diagram software screen.

The heater may also be operated manually, using the front panel controls. To control the heater manually, set the selector switch (22) to the MANUAL position. The voltage supplied to the heater may then be adjusted using the multi-turn potentiometer (23) marked VOLTAGE CONTROL.

The range of the output voltage is continuously adjustable from 0 Volts to 24 Volts DC using the multi-turn potentiometer. Ensure that the clamp on the side of the knob is released before turning the knob.

#### Measuring the Power to the Heater

While adjusting the heater voltage the actual voltage supplied to the heater can be monitored on the software mimic diagram.

If operating the equipment using the console, with the selector switch (22) set to MANUAL, the heater voltage may be monitored by setting the top measurement selector switch (25) to position V. The reading is displayed directly in Volts on the top panel display (24).

The current drawn by the heater in the accessory can be monitored by setting the top measurement selector switch (25) to position I. The reading is displayed directly in Amps on the top panel display (24).

As the electrical supply to the heater is Direct Current the power supplied to the heater is simply obtained from the product of the Voltage and Current, i.e.

$$\text{Heater Power } Q = \text{Voltage } V \times \text{Current } I$$

E.g. If  $V = 15.0$  Volts and  $I = 2.00$  Amps then  $Q = 2 \times 15 = 30.0$  Watts

**Note:** The heating section of HT11C incorporates a thermostat to limit the maximum operating temperature. If the heater voltage is set too high, resulting in excessive temperature, the current to the heater will be disconnected until the thermostat resets when the temperature falls. If the display shows no current when voltage is applied to the heating element check that temperature T1 is below 100°C.

If temperature T1 is excessive ensure that cooling water is flowing through the cooling section to drain and check that the heating and cooling sections are clamped tightly together. If temperature T1 does not reduce set the Heater Voltage to zero and allow the thermostat to reset.

If temperature T1 is not excessive but the display shows no current when voltage is applied to the heating element check the following:

Check that the RCD at the rear of the service unit is latched (up).

Check that the heater lead (4) on the HT11C is connected to the socket marked Output 2 at the rear of the service unit.

### Temperature Measurement

The outputs of the either thermocouples T1 to T8 are displayed on the mimic diagram of the HT11C software. All temperatures on the HT11C are indicated with a resolution of one decimal place.

They may also be monitored on the HT10XC console, with the selector switch (22) set to MANUAL, by setting the temperature selector switch (28) to the required position and read the corresponding value on the lower panel display (27).

### Setting the Cold Water Pressure Regulator

Before using the cooling water system it will be necessary to adjust the pressure regulating valve.

Ensure that the cold water pressure regulating valve (12) is fully off by pulling the knob (17) outwards from the body of the regulator, then turning the knob fully anticlockwise. Ensure that the drain/vent (19) on the transparent filter bowl (18) is closed by turning it fully clockwise.

Connect the cold water flow control valve (11) to the socket marked AUXILIARY 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.

Open the cold water flow control valve (11) fully using the flow control box on the mimic diagram software screen\*. Gradually open the pressure regulating valve by turning the knob clockwise until the cold water flow through the cooling section is approximately 1.5 litres/ min.

\*If using the HT11 instead of the HT11C, the cold water flow is regulated using a manual valve situated next to the test section column. If operating the equipment manually via the console, the flow rate can controlled using the AUXILIARY CONTROL knob (26). The flow rate can be read on the top panel display (24) with the selector switch (25) set to position Fw.

(If using the HT11 without the optional flow sensor SFT2 then the actual flow can be checked using a stopwatch and measuring cylinder).

When the flow rate is acceptable push the knob down to lock the setting of the pressure regulator.

If it is required to reduce the cooling water flow rate adjust the flow rate using the flow control valve (11) by adjusting the valve setting within the software (or, if operating manually, using the AUXILIARY CONTROL knob (26). Do not use the pressure regulating valve to adjust the flow of cooling water.

### **Measuring the Cold Water Flow Rate**

The HT11C includes a flow meter and corresponding measurement channel in the HT11C software, which allows the cold water flow rate to be measured and logged. Provided that the pressure regulator is set as instructed above, the flow of cooling water should remain constant provided that the flow control valve is left fully open.

(If the HT11 accessory is used with the HT10XC, the cold water flow rate can only be easily monitored if the optional flow sensor SFT2 is fitted. If a flow rate must be obtained then it is possible to perform a timed volume collection using a measuring cylinder and a stopwatch).

### **Applying the Thermal Paste (Conductive compound)**

The end faces of the heating section, cooling section and appropriate intermediate section should be coated with the thermal paste supplied to minimise temperature gradients across the joints. The paste should be applied sparingly and smeared as thinly as possible over the entire contact area before clamping the sections together. To ensure an even spread of the paste twist the sections by a few degrees clockwise then anticlockwise while holding them together, then operate the clamps simultaneously.

## Equipment Specifications

### Overall Dimensions

Height - 282mm

Width - 427mm

Depth - 210mm

### USB Channel Numbers

Refer to the HT10XC Instruction Manual for details about the USB channel numbers.

### Environmental Conditions

This equipment has been designed for operation in the following environmental conditions. Operation outside of these conditions may result reduced performance, damage to the equipment or hazard to the operator.

- a. Indoor use;
- b. Altitude up to 2000m;
- c. Temperature 5°C to 40°C;
- d. Maximum relative humidity 80% for temperatures up to 31°C, decreasing linearly to 50% relative humidity at 40°C;
- e. Mains supply voltage fluctuations up to  $\pm 10\%$  of the nominal voltage;
- f. Transient over-voltages typically present on the MAINS supply;

**NOTE:** The normal level of transient over-voltages is impulse withstand (over-voltage) category II of IEC 60364-4-443;

- g. Pollution degree 2.

Normally only nonconductive pollution occurs.

Temporary conductivity caused by condensation is to be expected.

Typical of an office or laboratory environment

## **Routine Maintenance**

### **Responsibility**

To preserve the life and efficient operation of the equipment it is important that the equipment is properly maintained. Regular maintenance of the equipment is the responsibility of the end user and must be performed by qualified personnel who understand the operation of the equipment.

### **General**

The equipment should be disconnected from the electrical supply when not in use.

The cooling water supply should be disconnected from the inlet on the HT11C when not in use.

### **Draining the cooling water pipework**

Water should be drained from the cooling section of the HT11C after use to minimise build up of scale or fouling inside the cooling section. The water can be drained by simply disconnecting the top flexible tube from the inlet to the flow control valve and allowing the water to flow out through the outlet tube under gravity, ensuring that the valve is fully open. To remove the ferrule from the control valve depress the collar on the valve while pulling the ferrule. To reassemble simply push the ferrule fully into the control valve.

### **Storing the intermediate sections**

After use the intermediate sections should be located in the recesses on the baseplate to avoid damage to the contact surfaces. The shallow lip on one side of the section should be located in the recess.

### **Cleaning the contact surfaces**

Any build up of thermal paste or other contamination on the contact surfaces of the heating section, cooling section and intermediate sections can be removed by carefully polishing the surfaces using a proprietary liquid metal polish applied to a clean, soft cloth.

**Note:** Correct operation of the equipment depends on the contacting surfaces remaining flat and square. It is therefore important to take care not to damage the surfaces or round the corners by applying too much force or using a coarse abrasive cleaner.

### **Cleaning the pressure regulator filter**

The pressure regulator incorporates an integral filter to prevent particles or fibres in the water from entering the delicate regulator. The transparent bowl allows the condition of the filter element to be inspected. Any contamination in the bowl or on the filter should be removed by unscrewing the transparent bowl and rinsing the bowl and element in clean water before reassembling.

### **Adjusting the clamps and bars**

With prolonged use the clamps or the position of the brass bars inside the heating and/or cooling sections may require adjustment to ensure good thermal contact between the end faces (poor contact may be indicated by a large temperature gradient across the junction).

### **Adjusting the clamps**

Clamp the heating and cooling sections together by operating the clamping levers simultaneously. The clamp levers should be tight to operate and the two sections should be held firmly together. If the clamping action is too light then length of the metal wire clasps should be reduced by increasing the curvature (the wire can be easily bent by supporting the centre of the clasp in one hand and applying pressure to the free end using the other hand).

When correctly adjusted equal pressure should be required to operate both clamp levers.

### **Adjusting the bars**

The position of the brass bars may be checked and adjusted as follows:

Check the position of the brass end face in the heating (top) section. It should be flush with the plastic insulator which surrounds it. If the position is not correct partially unscrew the M4 securing screw on the side of the insulated housing using an M2 hexagonal key (Allen key measuring 2mm across the flats). Adjust the position of the brass bar by turning the M6 adjusting screw on the top of the insulated housing using an M3 hexagonal key (Allen key measuring 3mm across the flats) while keeping the brass bar pressed against the adjusting screw. When the face is flush tighten the securing screw on the side of the insulated housing to retain the position.

The brass end face in the cooling (bottom) section should be recessed approximately 1mm below the outer diameter of the plastic insulator which surrounds it.

Clamp the heating section to the cooling section. If correctly adjusted there should be a visible gap of approximately 0.5mm but no more than 1mm between the end faces of the plastic insulators (outer diameters only).

If the gap is too large or too small, partially unscrew the M4 securing screw on the side of the insulated housing using an M2 hexagonal key. Adjust the position of the brass bar by turning the M6 adjusting screw, accessible through a hole in the underside of the base plate using an M3 hexagonal key while keeping the brass bar pressed against the adjusting screw. When the face is correctly positioned tighten the securing screw on the side of the insulated housing to retain the position.

As a final check, lightly smear the metal contact surfaces with thermal paste before clamping the heating section and the cooling section together. Release the two sections and check that the thermal paste has been uniformly displaced.

### **RCD Test**

Test the RCD (35) by pressing the TEST button at least once a month. If the RCD button does not trip when the Test button is pressed then the equipment must not be used and should be checked by a competent electrician.

# Laboratory Teaching Exercises

## Index to Exercises

[Exercise A - Steady State Conduction through a Uniform Plane Wall](#)

[Exercise B - Use of the Fourier Rate Equation](#)

[Exercise C - Overall Heat Transfer Coefficient for Differing Materials in Series](#)

[Exercise D - Determination of Thermal Conductivity \(Constant of Proportionality\)](#)

[Exercise E - Relationship of Temperature Gradient to Cross-Sectional Area](#)

[Exercise F - Effect of Contact Resistance on Thermal Conduction](#)

[Exercise G - Application and Thermal Conductivity of Insulators](#)

[Exercise H - Unsteady State Conduction of Heat](#)

[Project Work](#)

## Nomenclature

Name	Symbol	SI Unit
Outside diameter	$D$ (e.g. $D_{\text{hot}}$ )	m
Heat transfer area	$A$ (e.g. $A_{\text{hot}}$ )	$\text{m}^2$
Wall thickness (distance)	$\Delta x$ (e.g. $\Delta x_{\text{int}}$ )	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. $T_1$ )	$^{\circ}\text{C}$
Temperature at hot interface	$T_{\text{hotface}}$	$^{\circ}\text{C}$
Temperature at cold interface	$T_{\text{coldface}}$	$^{\circ}\text{C}$
Temperature difference	$\Delta T_i$ (e.g. $\Delta T_{\text{hot}}$ )	$^{\circ}\text{C}$
Temperature gradient	Grad (e.g. $\text{Grad}_{\text{hot}}$ )	$\text{W}/\text{m}^{\circ}\text{C}$
Thermal conductivity	$k$ (e.g. $k_{\text{hot}}$ )	$\text{W}/\text{m}^{\circ}\text{C}$
Overall heat transfer coefficient	$U$	$\text{Wm}^2\text{C}$

Resistance to heat flow	R	m <sup>2</sup> C/W
Flow of cooling water (if SFT2 is fitted)	F <sub>w</sub>	l/min
Time	t	secs

<b>Subscripts</b>	
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.

# Exercise A - Steady State Conduction through a Uniform Plane Wall

## 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:

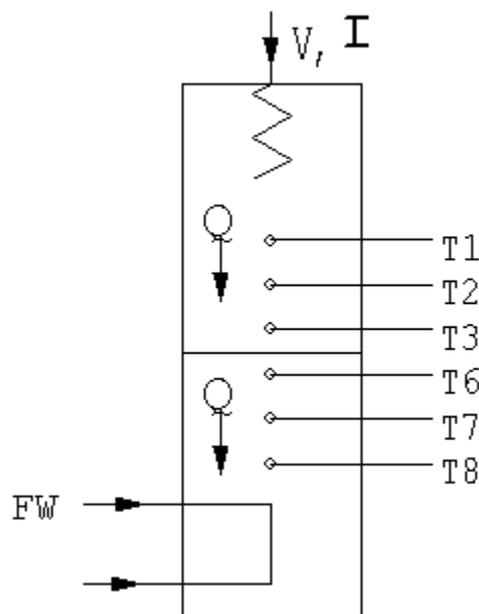
- Locate the HT11C Linear Heat Conduction accessory (1) alongside the HT10XC Heat Transfer Service Unit (20) on a suitable bench.
- Clamp the heated (6 and 7) and cooled (8) section of the HT11C together having lightly coated the mating faces with thermal paste (see [Applying the Thermal Paste](#) in Operating the Equipment).
- 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 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 AUXILIARY 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

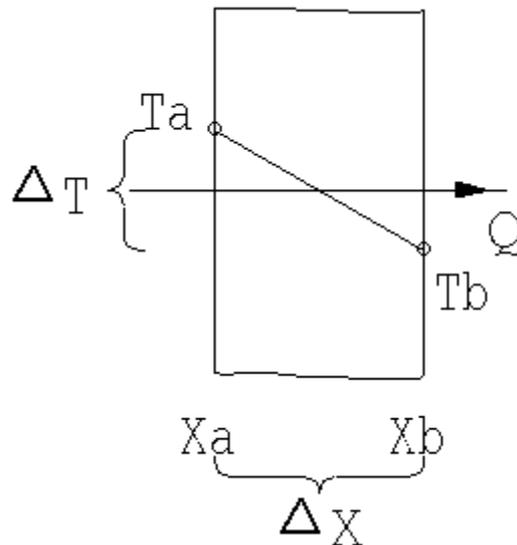
valve (11) to the AUXILIARY POWER socket on the rear of the service unit (34) (Not relevant if using HT11).

- 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 ( $\Delta x$ ) and area (A) supports a temperature difference ( $\Delta T$ ) then the heat transfer rate per unit time (Q) by conduction through the wall is found to be:

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

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

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 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:

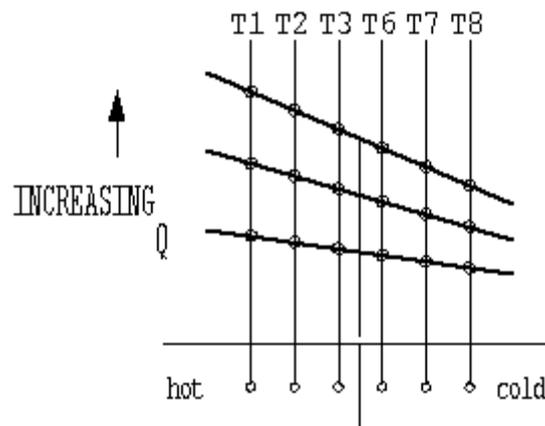
Heat flow (power to heater)	$Q = VI$	(Watts)
Temperature difference in heated section	$\Delta T_{hot} = T1 - T3$	(°C)
Temperature difference in cooled section	$\Delta T_{cold} = T6 - T8$	(°C)

Estimate the cumulative influence of the experimental errors on your calculated values for  $Q$ ,  $\Delta T_{hot}$  and  $\Delta T_{cold}$  and measured values for  $\Delta x_{13}$  and  $\Delta x_{68}$ .

Compare the changes in temperature ( $\Delta T_{hot}$  and  $\Delta T_{cold}$ ) 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  $\Delta T_{\text{hot}}$  and  $\Delta T_{\text{cold}}$  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 B should be carried out on completion of this exercise.

## Exercise B - Use of the Fourier Rate Equation

### 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)

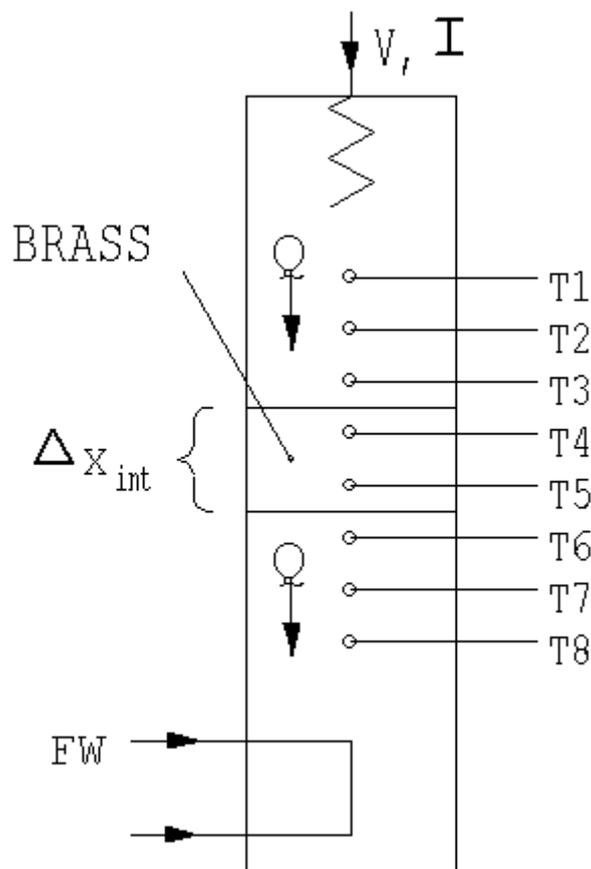
### Equipment set-up

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 [Applying the Thermal Paste](#) in Operating the Equipment). 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 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 AUXILIARY 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

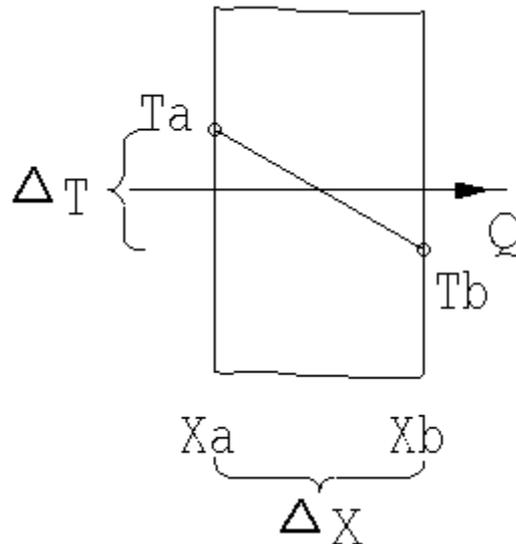
valve (11) to the AUXILIARY POWER socket on the rear of the service unit (34) (Not relevant if using HT11).

- 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 ( $\Delta x$ ) and area ( $A$ ) supports a temperature difference ( $\Delta T$ ) 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:

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

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:

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

**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  $Q$ ,  $\Delta T$  and  $\Delta x$ . The effect of a change in  $k$  or change in  $A$  will be investigated in later exercises.

### Procedure

Refer to the Operation section 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  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:

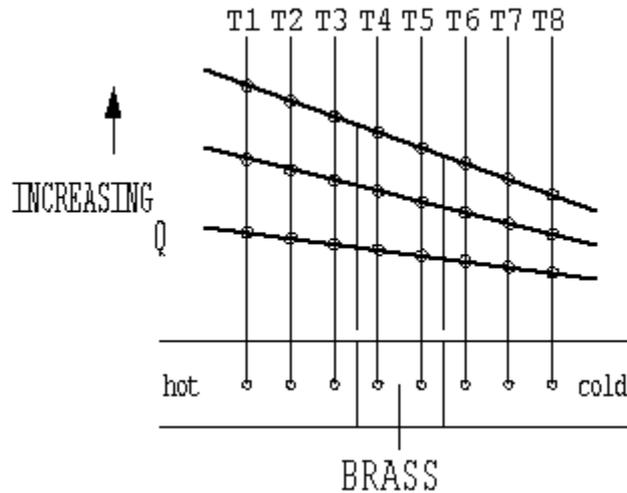
Heat flow (Power to heater)	$Q = VI$	(Watts)
Cross sectional area of bar	$A = \frac{\pi D^2}{4}$	(m <sup>2</sup> )
Temperature difference in heated section	$\Delta T_{hot} = T1 - T3$	(°C)
Conductivity in heated section	$k_{hot} = \frac{x_{13}Q}{\Delta T_{hot} A_{hot}}$	(W/m°C)
Temperature difference in intermediate section	$\Delta T_{int} = T4 - T5$	(°C)
Conductivity in intermediate section	$k_{int} = \frac{x_{45}Q}{\Delta T_{int} A_{int}}$	(W/m°C)
Temperature difference in cooled section	$\Delta T_{cold} = T6 - T8$	(°C)
Conductivity in cooled section	$k_{cold} = \frac{x_{68}Q}{\Delta T_{cold} A_{cold}}$	(W/m°C)

Estimate the cumulative influence of the experimental errors on your calculated values for  $Q$ ,  $\Delta T$ ,  $\Delta T_{hot}$ ,  $\Delta T_{int}$ ,  $\Delta T_{cold}$ ,  $k_{hot}$ ,  $k_{int}$  and  $k_{cold}$  and measured values for  $D$ ,  $\Delta x_{18}$ ,  $\Delta x_{13}$ ,  $\Delta x_{45}$  and  $\Delta x_{68}$ .

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 C should be carried out on completion of this exercise.

## Exercise C - Overall Heat Transfer Coefficient for Differing Materials in Series

### 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

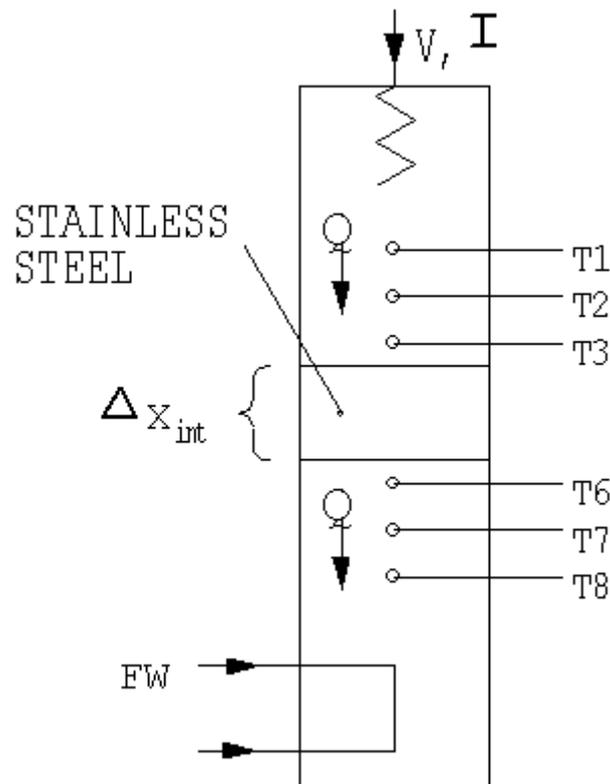
Windows™-compatible PC running Windows™ 98, 2000 or XP

(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 [Applying the Thermal Paste](#) in Operating the Equipment). 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.

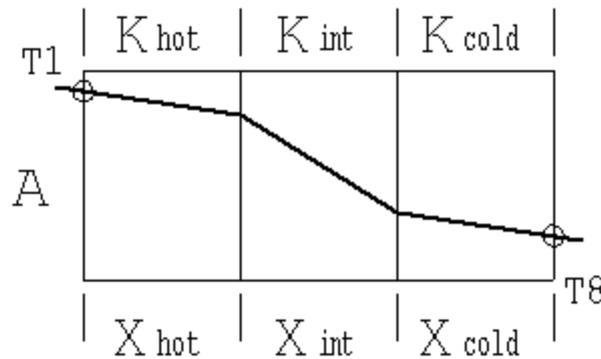
**Note:** Readings from thermocouples T4 and T5 will not be used in this exercise.

- 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 AUXILIARY 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:

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

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

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

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 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  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<sup>2</sup>)

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

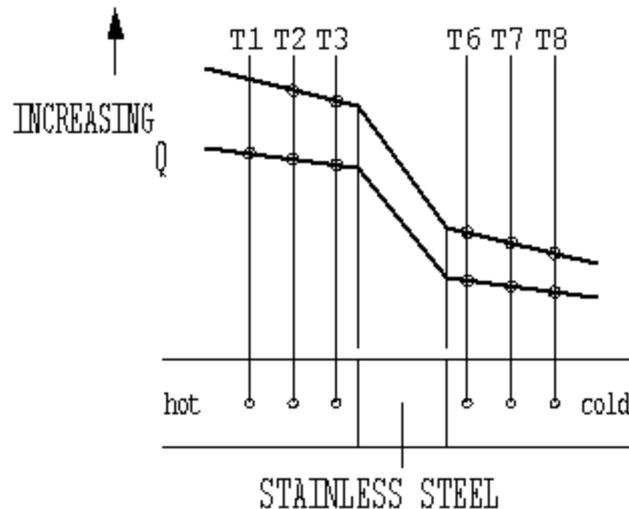
Resistance to heat flow  $R = \frac{1}{U} = \frac{\Delta x_{hot}}{k_{hot}} + \frac{\Delta x_{int}}{k_{int}} + \frac{\Delta x_{cold}}{k_{cold}}$

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

Estimate the cumulative influence of the experimental errors on your calculated values for Q,  $\Delta T_{18}$ , R and U and measured values for  $\Delta x_{hot}$ ,  $\Delta x_{int}$ ,  $\Delta x_{cold}$  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  $25 \text{ W/m}^\circ\text{C}$  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 D should be carried out on completion of this exercise.

## **Exercise D - Determination of Thermal Conductivity (Constant of Proportionality)**

### **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**

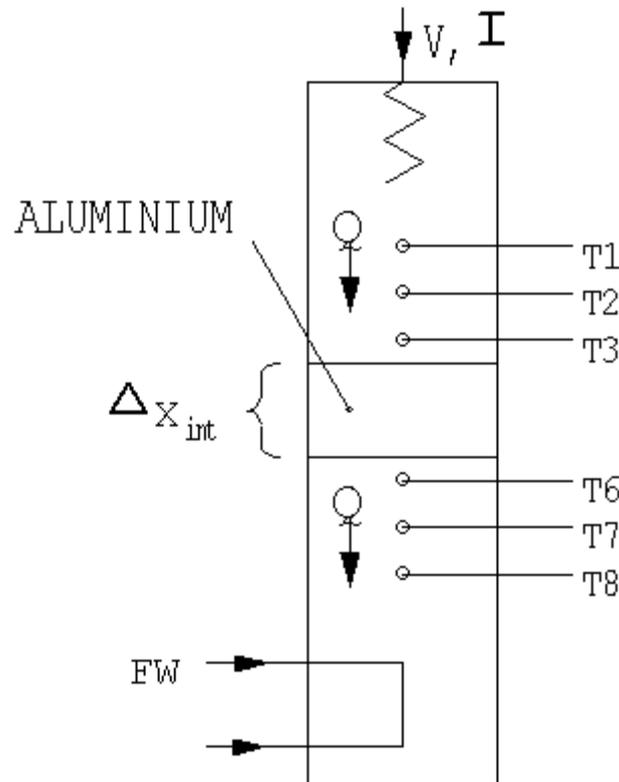
Windows™-compatible PC running Windows™ 98, 2000 or XP

(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 [Applying the Thermal Paste](#) in Operating the Equipment).
- 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.

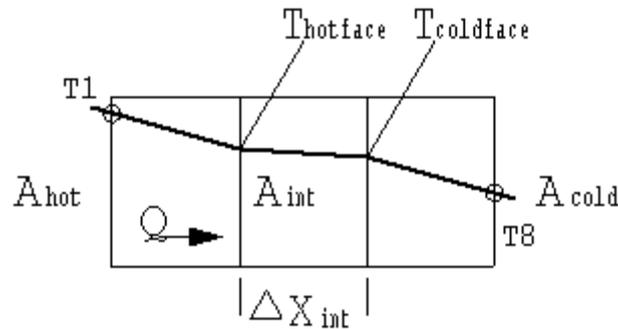
**Note:** Readings from thermocouples T4 and T5 will not be used in this exercise.

- 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 AUXILIARY 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 good thermal contact, and create a composite bar with a metal specimen of unknown thermal conductivity sandwiched between two brass sections.



From Fourier's Law:

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

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

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 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  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	$\Delta x_{int} = 0.030$	(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.

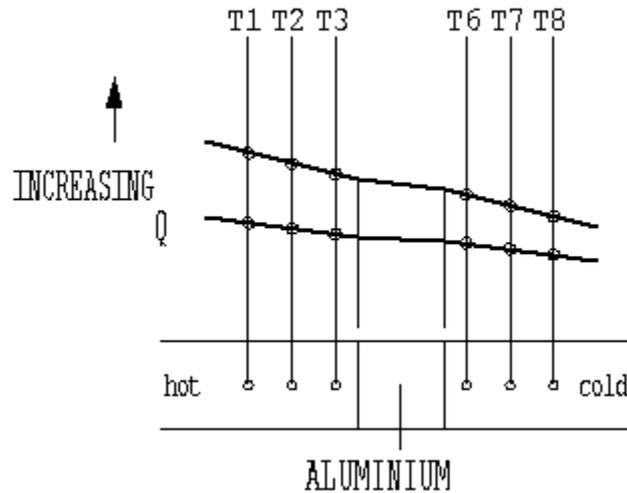
For each set of readings the derived results are tabulated under the following headings:

Heat flow (Power to heater)	$Q = VI$	(Watts)
Cross sectional area	$A = \frac{\pi D_{int}^2}{4}$	(m <sup>2</sup> )
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  $Q$ ,  $A_{int}$ ,  $T_{hotface}$ ,  $\Delta T_{int}$  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  $180 \text{ W/m}^\circ\text{C}$  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 H).

### 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 E should be carried out on completion of this exercise.

## **Exercise E - Relationship of Temperature Gradient to Cross-Sectional Area**

### **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**

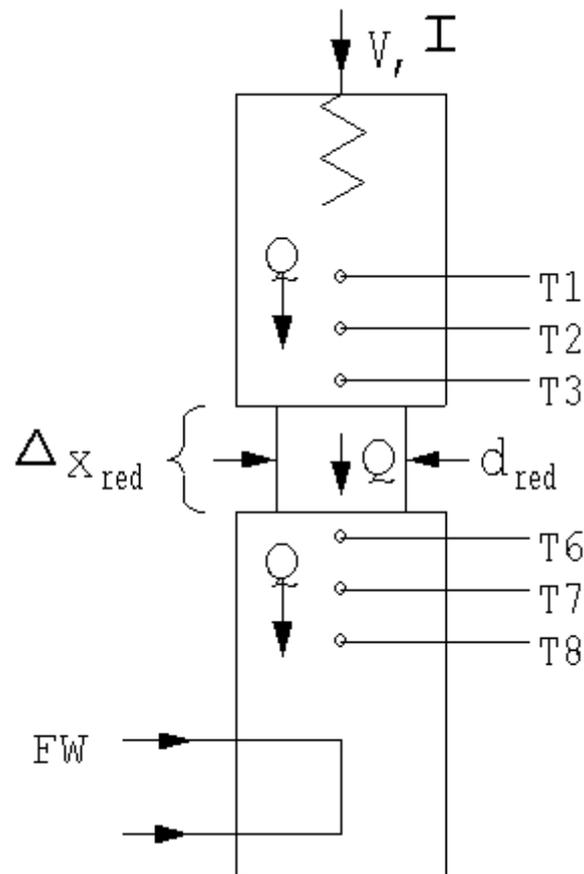
Windows™-compatible PC running Windows™ 98, 2000 or XP

(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 [Applying the Thermal Paste](#) in Operating the Equipment). 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.

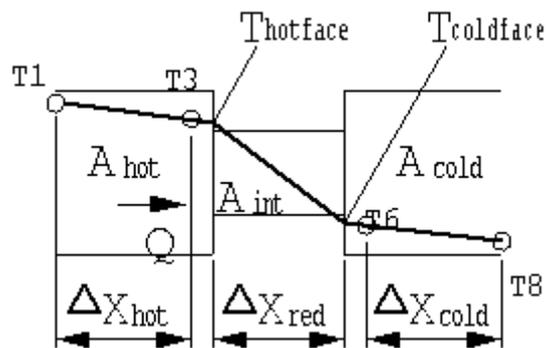
**Note:** Readings from thermocouples T4 and T5 will not be used in this exercise.

- 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 AUXILIARY 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

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

For the heated section:

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

For the intermediate section (reduced cross section):

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

For the cooled section:

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

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

### Procedure

(Refer to the Operation section 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	$\Delta x_{\text{hot}} = 0.030$	(m)
Distance between hotface and coldface	$\Delta x_{\text{red}} = 0.030$	(m)
Distance between thermocouple T6 and T8	$\Delta x_{\text{cold}} = 0.030$	(m)
Diameter of bar (heated section)	$D_{\text{hot}} = 0.25$	(m)
Diameter of bar (reduced section)	$D_{\text{red}} = 0.13$	(m)
Diameter of bar (cooled section)	$D_{\text{cold}} = 0.25$	(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.

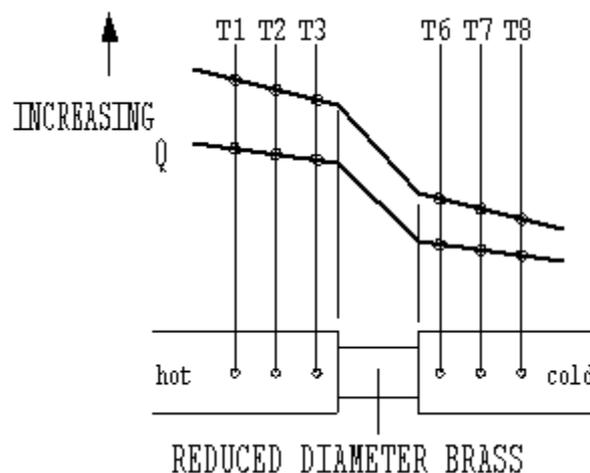
For each set of readings the derived results are tabulated under the following headings:

Heat flow (Power to heater)	$Q = VI$	(Watts)
Temperature difference in heated section	$\Delta T_{\text{hot}} = T1 - T3$	(°C)
Temperature gradient in heated section	$\text{Grad}_{\text{hot}} = \frac{\Delta T_{\text{hot}}}{\Delta x_{\text{hot}}}$	(°C)
Temperature at hotface of reduced section	$T_{\text{hotface}} = T3 - \frac{(T2 - T3)}{2}$	(°C)
Temperature at coldface of reduced section	$T_{\text{coldface}} = T6 + \frac{(T6 - T7)}{2}$	(°C)
Temperature difference in reduced section	$\Delta T_{\text{red}} = T_{\text{hotface}} - T_{\text{coldface}}$	(°C)
Temperature gradient in reduced section	$\text{Grad}_{\text{red}} = \frac{\Delta T_{\text{red}}}{\Delta x_{\text{red}}}$	(°C)
Cross sectional area (heated)	$A_{\text{hot}} = \frac{\pi D_{\text{hot}}^2}{4}$	(m <sup>2</sup> )
Ratio of temperature gradients	$= \frac{\text{Grad}_{\text{red}}}{\text{Grad}_{\text{hot}}}$	
Ratio of cross sections	$= \frac{A_{\text{red}}}{A_{\text{hot}}}$	

Estimate the cumulative influence of the experimental errors on your calculated values for  $Q$ ,  $A$ 's,  $T_{\text{hotface}}$ ,  $T_{\text{coldface}}$ ,  $\Delta T$ 's, Grads and Ratios and measured values for  $D$ s 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 F should be carried out on the completion of this exercise.

## **Exercise F - Effect of Contact Resistance on Thermal Conduction**

### **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**

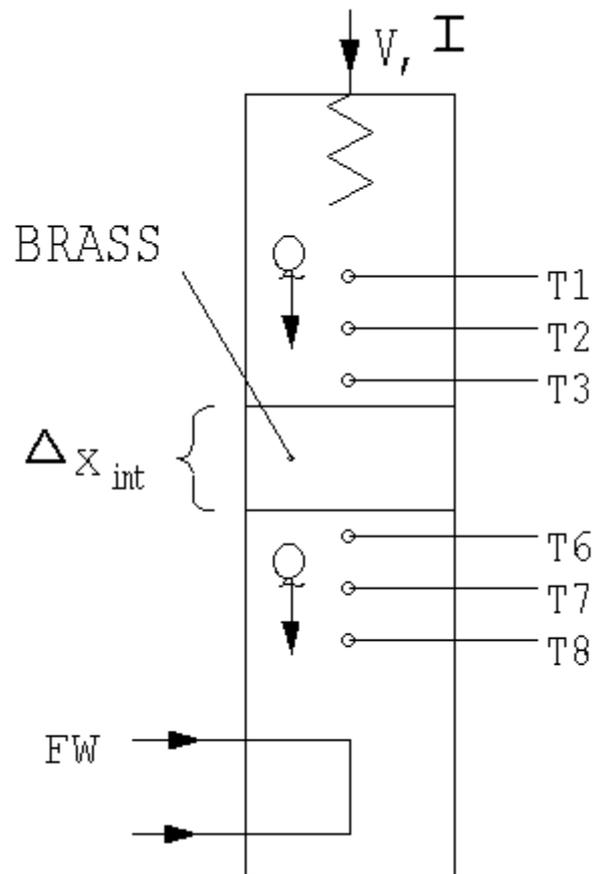
Windows™-compatible PC running Windows™ 98, 2000 or XP

(SFT2 Flow sensor if using HT11)

### **Equipment set-up**

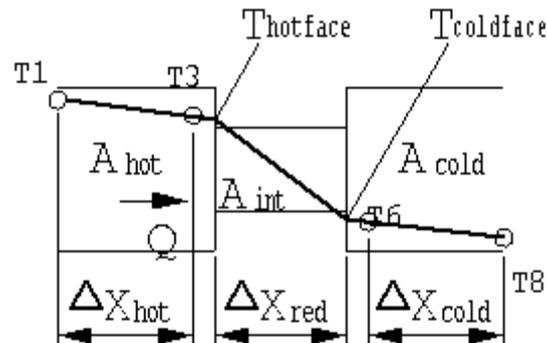
Before proceeding with the exercise ensure that the equipment has been prepared as follows:

- 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 (see [Applying the Thermal Paste](#) in Operating the Equipment).
- 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.



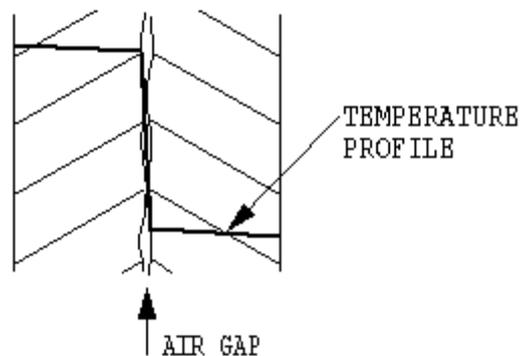
- Connect the eight thermocouples on the HT11C (3) to the appropriate sockets on the front of the service unit (30). Ensure that the labels on the thermocouple leads (T1-T8) match the labels on the sockets.
- Set the VOLTAGE CONTROL potentiometer (23) to minimum (anticlockwise) and the selector switch (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 AUXILIARY 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 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  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

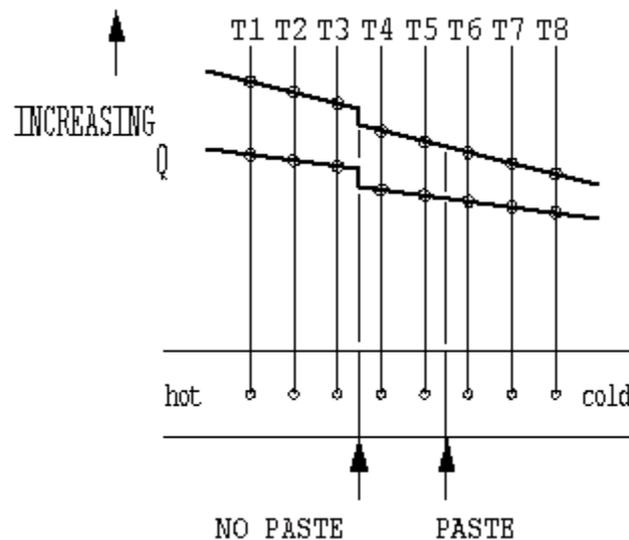
For each set of readings the derived results are tabulated under the following headings:

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

Estimate the cumulative influence of the experimental errors on 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 G should be carried out on completion of this exercise.

## Exercise G - Application and Thermal Conductivity of Insulators

### 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

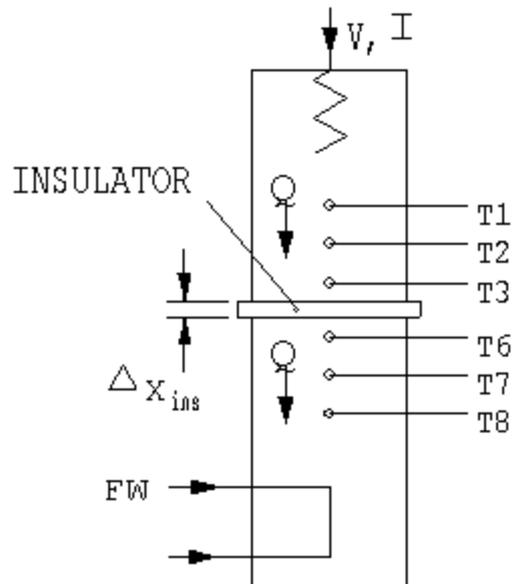
Windows™-compatible PC running Windows™ 98, 2000 or XP

(SFT2 Flow sensor if using HT11)

### Equipment set-up

Before proceeding with the exercise, ensure that the equipment has been prepared as follows:

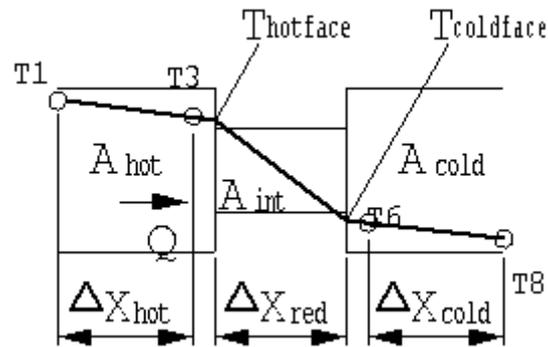
- Locate the HT11C Linear Heat Conduction accessory (1) alongside the HT10XC Heat Transfer Service Unit (20) on a suitable bench.
- Measure and record the thickness  $\Delta x_{\text{ins}}$  (m) of the cork disk. If using the software, record the value by entering it on the mimic diagram screen.
- Clamp 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 used in this exercise.

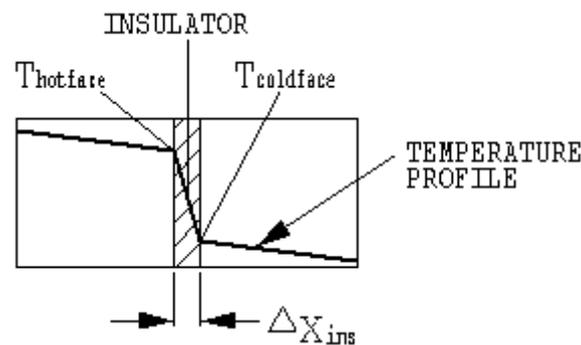
- Set the VOLTAGE CONTROL potentiometer (23) to minimum (anticlockwise) and the selector switch (22) to MANUAL then connect the heater lead from the HT11C to the socket marked OUTPUT 2 at the rear of the service unit (33).
- Set the AUXILIARY CONTROL knob (26) on the service unit to minimum (anticlockwise) 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 AUXILIARY 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 D.

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.

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

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

In the case of the heated section the temperature of the end face (hotface) will be lower than  $T_3$  and can be calculated as follows:

$$T_{hotface} = T_3 - \frac{(T_2 - T_3)}{2}$$

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

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

### Procedure

(Refer to the Operation section 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

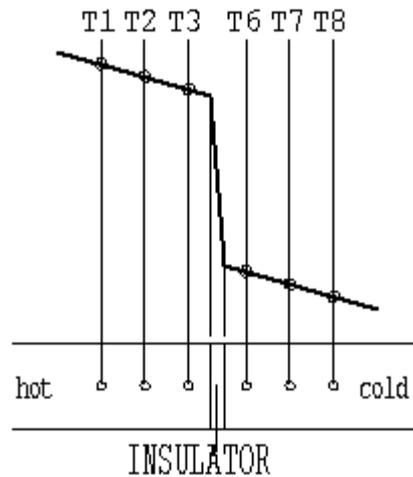
The conductivity of the brass sections is approximately 121 W/m°C

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	$A = \frac{\pi D_{ins}^2}{4}$	(m <sup>2</sup> )
Temperature at hotface of insulator	$T_{hotface} = T3 - \frac{(T2 - T3)}{2}$	(°C)
Temperature at coldface of insulator	$T_{coldface} = T6 + \frac{(T6 - T7)}{2}$	(°C)
Temperature difference across insulator	$\Delta T_{ins} = T_{hotface} - T_{coldface}$	(°C)
Thermal conductivity of insulated disk	$k_{ins} = \frac{Q \Delta x_{ins}}{A_{ins} \Delta T_{ins}}$	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 H).

## 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 H should be carried out on completion of this exercise.

## Exercise H - Unsteady State Conduction of Heat

### 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

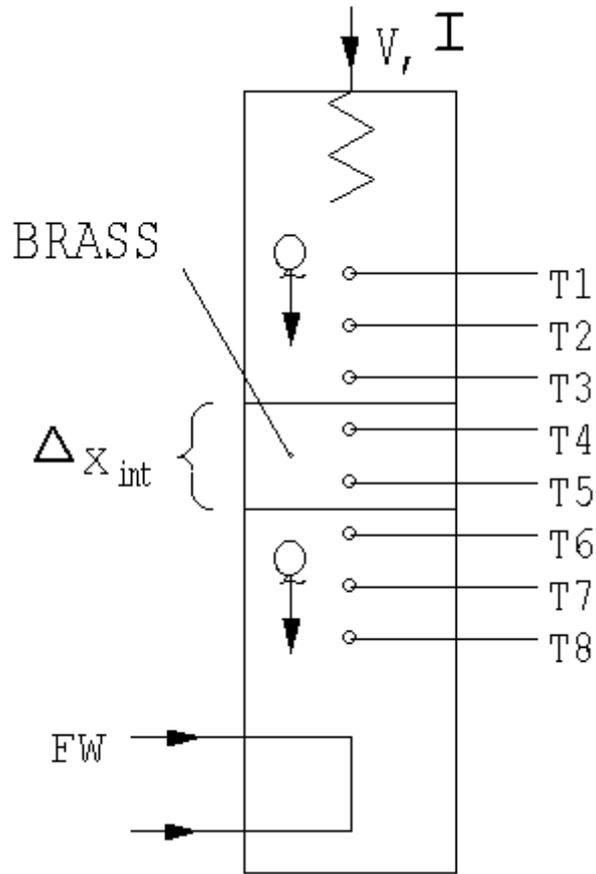
### Optional Equipment

(SFT2 Flow sensor if using HT11)

### Equipment set-up

Before proceeding with the exercise ensure that the equipment has been prepared as follows:

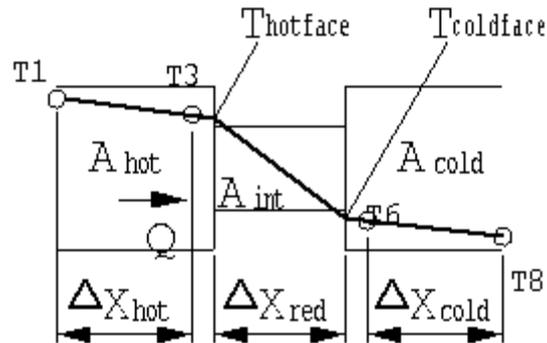
- Locate the HT11C Linear Heat Conduction accessory (1) alongside the HT10XC Heat Transfer Service Unit (20) on a suitable bench.
- Clamp the intermediate brass section (instrumented with two thermocouples) between the heated and cooled section of the HT11C having lightly coated the mating faces with thermal paste (see [Applying the Thermal Paste](#) in Operating the Equipment). Take care to locate the shallow shoulders on the sections before clamping.



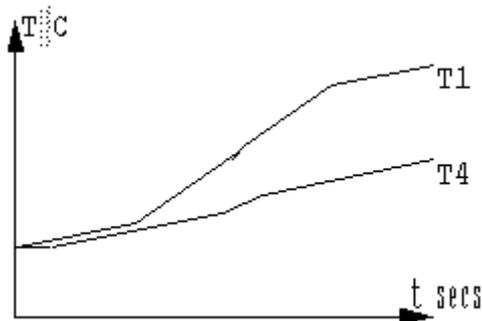
- Connect the eight thermocouples on the HT11C (3) to the appropriate sockets on the front of the service unit (30). Ensure that the labels on the thermocouple leads (T1-T8) match the labels on the sockets.
- Set the VOLTAGE CONTROL potentiometer (23) to minimum (anticlockwise) and the selector switch (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 AUXILIARY 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 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:** Refer to Exercise I for details on additional project work.

## 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 30mm 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:

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

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:

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

### **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.

## Contact Details for Further Information

**Main Office:     Armfield Limited**

Bridge House  
West Street  
Ringwood  
Hampshire  
England BH24 1DY

**Tel:** +44 (0)1425 478781

**Fax:** +44 (0)1425 470916

**Email:** sales@armfield.co.uk  
support@armfield.co.uk

**Web:** <http://www.armfield.co.uk>

**US Office:     Armfield Inc.**

436 West Commodore Blvd (#2)  
Jackson, NJ 08527

**Tel:** (732) 928 3332

**Fax:** (732) 928 3542

**Email:** info@armfieldinc.com