Saturation Pressure

Instruction Manual

TH3

ISSUE 15

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United Kingdom	International
(0) 1425 478781 (calls charged at local rate)	+44 (0) 1425 478781 (international rates apply)
Email: support@armfield.co.uk	
Fax: +44 (0) 1425 470916	

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General Overview

The TH range is designed to introduce the fundamental principles of thermodynamics to the student. The range of equipment starts at basic concepts such as temperature and pressure measurement and leads on to introducing the relationships between these fundamentals, the first and second law of thermodynamics, the principles of reversibility, entropy, enthalpy etc.

The equipment allows the student to gain a true understanding of these principles. The small scale of the equipment allows the relevant teaching exercises to be carried out in a relatively short period of time.

This instruction manual describes the operation of the TH3 'Saturation Pressure' apparatus that has been designed by Armfield to introduce students to the concept of saturation pressure and how different techniques can be employed to measure this variable.

The electrical output from the sensors are available as a voltage signal for direct connection to a PC via an optional interface device (a PC interface and Windows based Educational Software is available to support the TH3 Saturation Pressure apparatus).

Equipment Diagrams

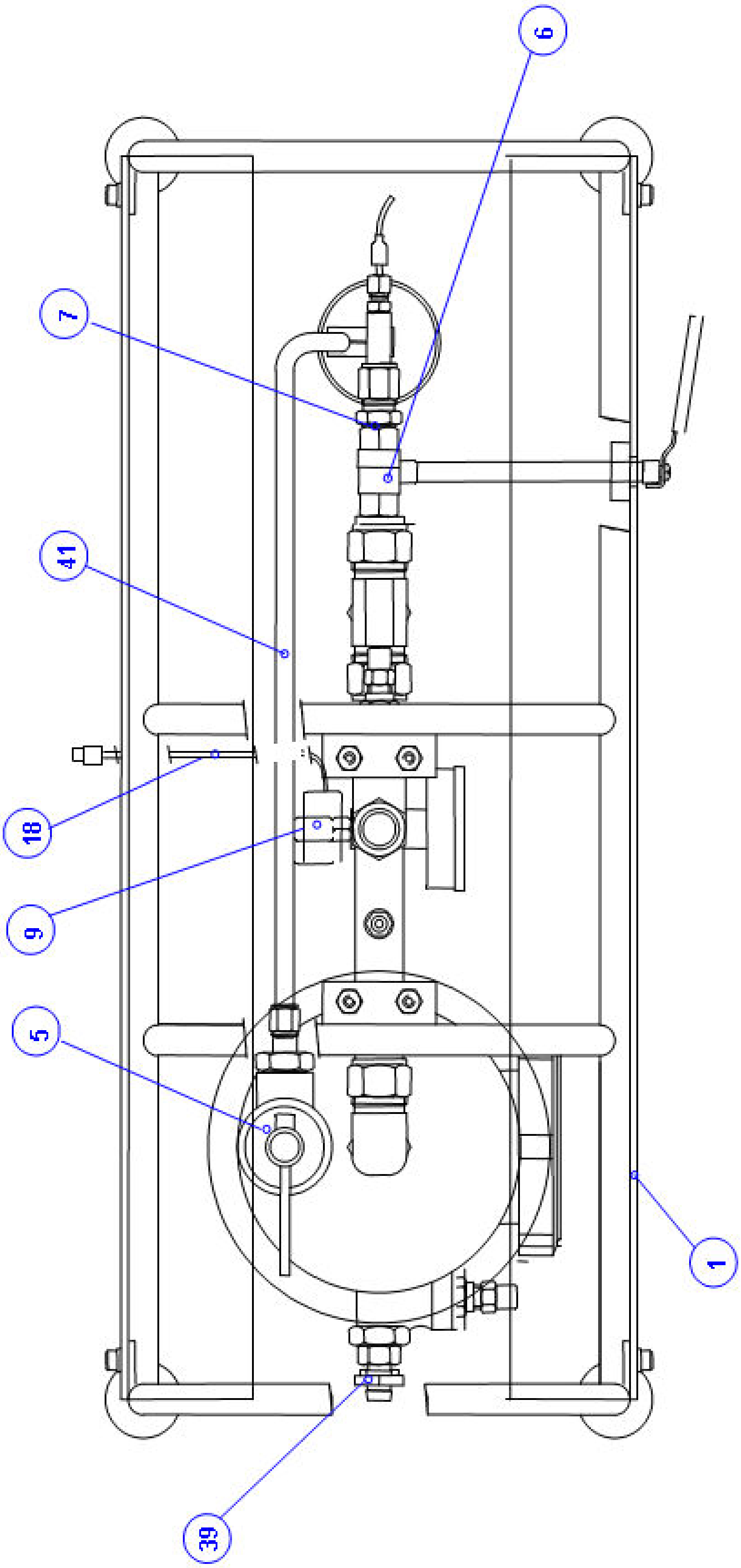


Figure 1: Top View of TH3 Saturation Pressure Apparatus

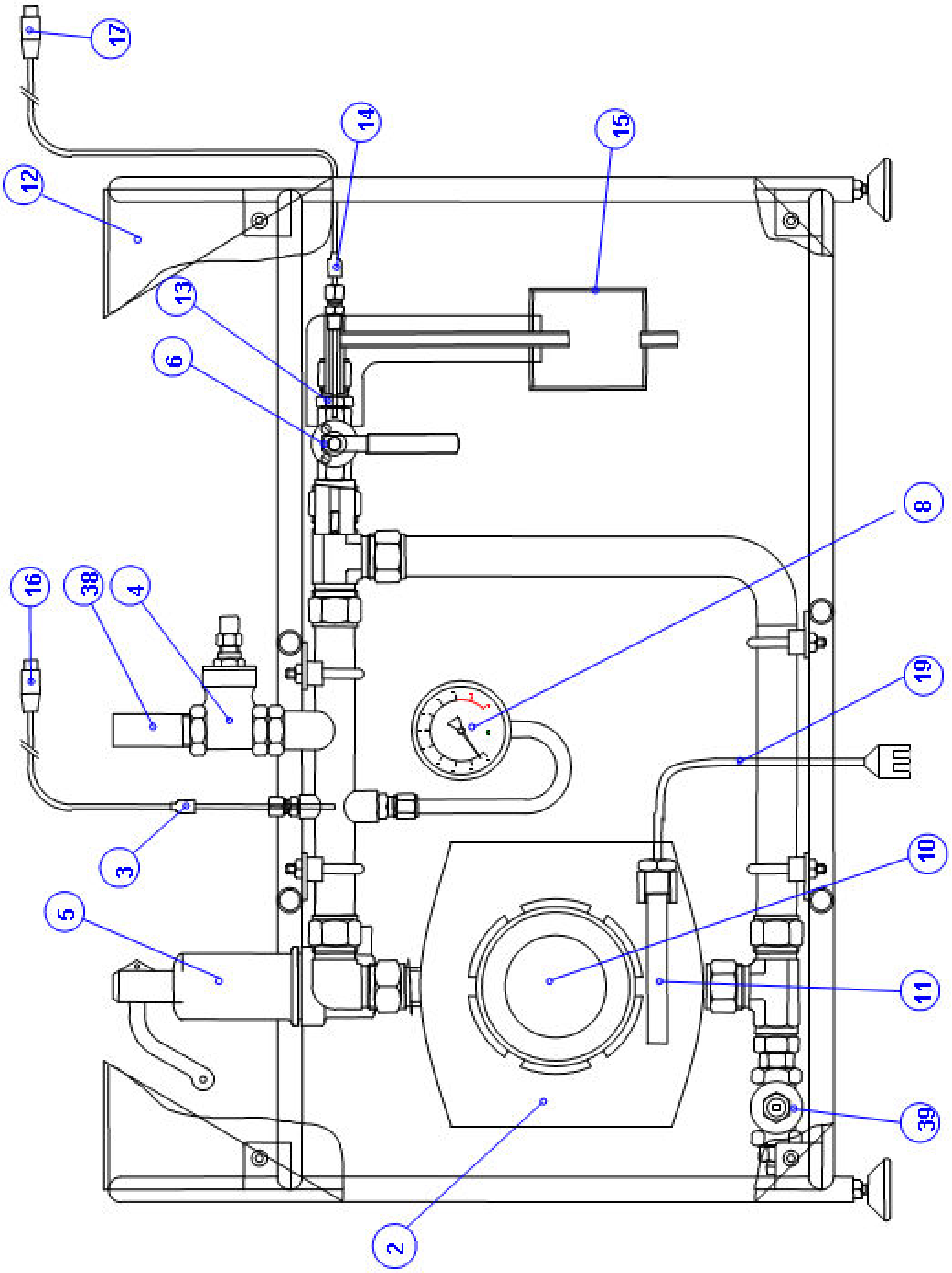


Figure 2: Side View of TH3 Saturation Pressure Apparatus

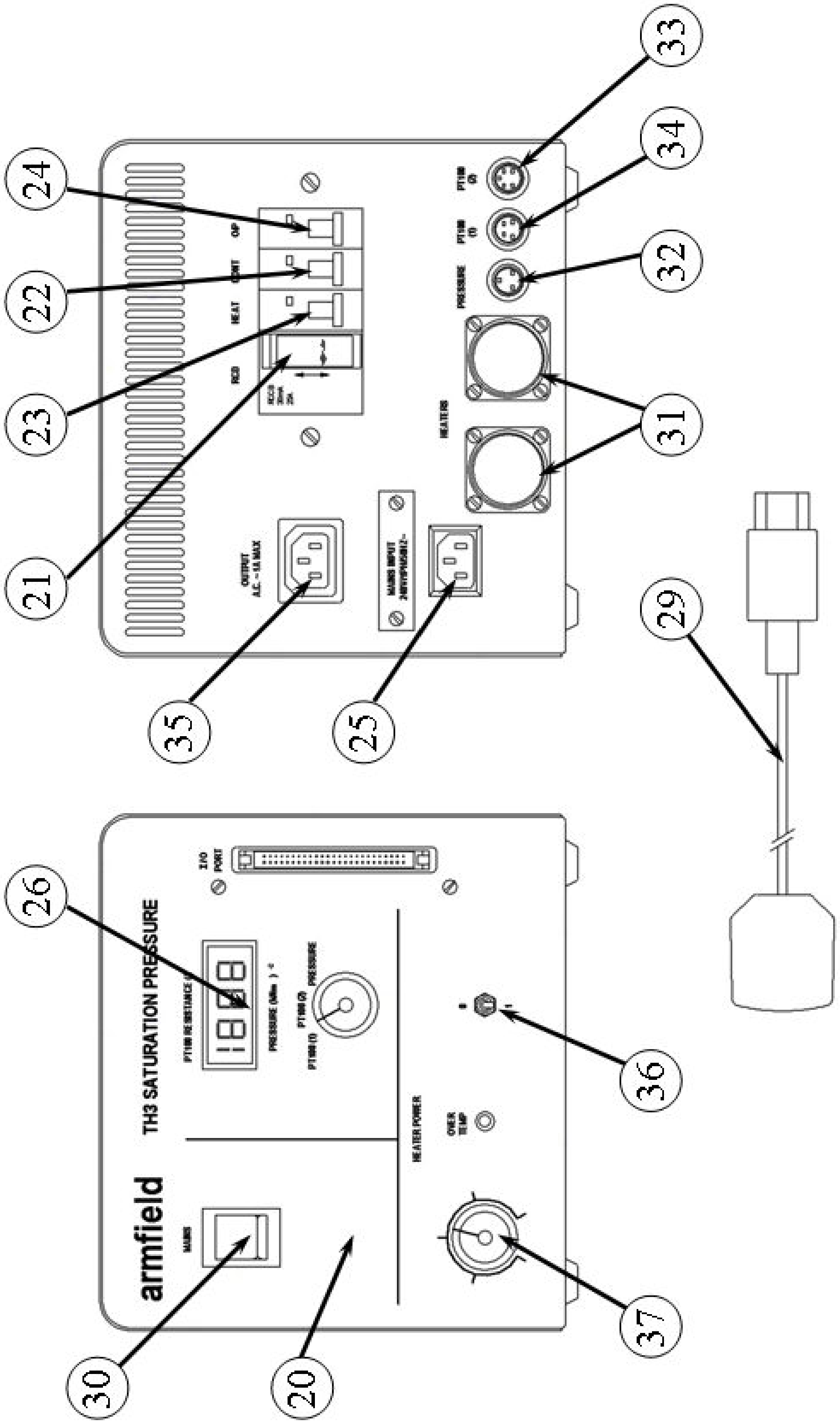


Figure 3: Front and Rear View of Electrical Console for TH3 Saturation Pressure Apparatus

Certificate of Conformity

Our Ref: EES/AK/Dec

PRESSURE EQUIPMENT REGULATIONS

CERTIFICATE OF CONFORMITY

Supplier: Armfield Limited

Product Code: TH3-A/B/G (Saturation Pressure Apparatus)

Declaration:

We certify that the boiler vessel and pipework installed on the above Armfield product has been designed, manufactured and hydraulically pressure tested in accordance with the Pressure Equipment Regulations 1999 (Statutory Instruments, 1999 No 2001) Category 1.

The boiler vessel has been classified Category 1 as follows:

Type of equipment: Steam Generator

Volume of vessel: 2.4 litres

Maximum allowable pressure: 8 bar gauge

Classification chart: 5

PS.V: 19.2 (<50)

Conformity assessment module: A

The detailed design of the pressure vessel is in accordance with BS5500:1997 (British Standard Specification for unfired fusion welded pressure vessels).

The following information is duplicated on a plate attached to the boiler vessel:

Manufactured by: See plate on equipment

Armfield index no: See plate on equipment

Maximum working pressure (PS): 8 bar gauge

Maximum working temperature (Tmax): 180°C

Hydraulic test pressure: 12 bar gauge

Date of manufacture: See plate on equipment

For and on behalf of Armfield Ltd.

E E Sansom

Technical Director Date: 14 June 2004

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 **TH3 Saturation Pressure Apparatus** 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.

Before proceeding to install, commission or operate the equipment described in this instruction manual we wish to alert you to potential hazards so that they may be avoided.

Although designed for safe operation, any laboratory equipment may involve processes or procedures that are potentially hazardous. The major potential hazards associated with this particular equipment are listed below.

- INJURY THROUGH MISUSE
- INJURY FROM ELECTRIC SHOCK
- INJURY FROM INCORRECT HANDLING
- BURNS FROM COMPONENTS AT HIGH TEMPERATURES
- SCALDING FROM BOILING WATER AND STEAM
- DAMAGE TO CLOTHING
- RISK OF INFECTION DUE TO LACK OF CLEANLINESS

Accidents can be avoided provided that equipment is **regularly maintained** and **staff** and **students** are made aware of potential hazards. A list of general safety rules is included in this manual, to assist **staff** and **students** in this regard. The list is not intended to be fully comprehensive but for guidance only.

Please refer to the notes below regarding the Control of Substances Hazardous to Health Regulations.

The COSHH Regulations

The Control of Substances Hazardous to Health Regulations (1988)

The COSHH regulations impose a duty on employers to protect employees and others from substances used at work, which may be hazardous to health. The regulations require you to make an assessment of all operations that are liable to expose any person to hazardous solids, liquids, dust, vapours, gases or microorganisms. You are also required to introduce suitable procedures for handling these substances and keep appropriate records.

Since the equipment supplied by Armfield Limited may involve the use of substances which can be hazardous (for example, cleaning fluids used for maintenance or chemicals used for particular demonstrations) it is essential that the laboratory supervisor or some other person in authority is responsible for implementing the COSHH regulations.

Parts of the above regulations are to ensure that the relevant Health and Safety Data Sheets are available for all hazardous substances used in the laboratory. Any person using a hazardous substance must be informed of the following:

Physical data about the substance

Any hazard from fire or explosion

Any hazard to health

Appropriate First Aid treatment

Any hazard from reaction with other substances

How to clean/dispose of spillage

Appropriate protective measures

Appropriate storage and handling

Although these regulations may not be applicable in your country, it is strongly recommended that a similar approach is adopted for the protection of the students operating the equipment. Local regulations must also be considered.

Description

Where necessary, refer to the drawings in the Equipment Diagrams section.

Overview

The equipment is a bench top unit designed to introduce students to the characteristics of saturated water vapour, ie. how the temperature of water behaves at its boiling point with variation in the absolute pressure.

The equipment consists of a rectangular pipe loop incorporating a boiler (2) in one vertical limb. Pure water in the boiler is heated to its boiling point using a pair of cartridge heaters (11) that are located near the bottom. A sight glass (10) on the front of the boiler allows the internal processes to be observed, namely boiling patterns at the surface of the water while heating or reducing the system pressure and cessation of boiling/condensation during cooling. The sight glass also allows the water level in the boiler to be monitored. Saturated steam leaving the top of the boiler passes around the pipe loop before condensing and returning to the base of the boiler for re-heating. The operating range of the boiler and loop is 0 to 7 bar gauge.

The top limb of the pipe loop incorporates a PRT temperature sensor (3) and an electronic pressure sensor (9) to measure the properties of the saturated steam. A filling point (38) on the top limb allows the loop to be filled with pure water and allows all air to be vented safely before sealing the loop for pressurised measurements using the filling valve (4).

A vapour offtake, with isolating valve (6), allows steam from within the loop to be passed through a Throttling Calorimeter (7), the purpose of which is to demonstrate how the dryness fraction of the saturated steam in the loop can be determined.

The steam expands to atmospheric pressure as it passes along a labyrinth (13) and a second PRT temperature sensor (14) installed inside the calorimeter is used to measure the temperature of the steam after it has expanded to atmospheric pressure. A container (15) below the calorimeter collects condensing vapour and allows it to be drained safely from the apparatus.

In normal use the power control on the electrical console is adjusted to produce the required rate of climb in steam temperature for saturation pressure measurements or to produce a steady stream of steam to the Throttling Calorimeter at the required system pressure.

The apparatus is designed for safe operation with the following safety features:

A pressure relief valve (5) is incorporated at the outlet from the boiler. The relief valve is designed to operate if the pressure rises above the above 8 bar working pressure in the boiler. The outlet from the relief valve is vented through a pipe (41) into the container below the calorimeter to prevent injury to the operator.

The apparatus is pressure tested prior to despatch.

A Bourdon gauge (8), marked with the maximum working pressure, gives an approximate indication of the steam pressure in the loop and remains operational when power is disconnected from the electrical console.

The boiler and pipe loop are mounted in a support frame (1) that incorporates clear plastic shields (12) at the front and the back to provide protection against inadvertent contact with the exposed hot surfaces on the apparatus. These shields must be fitted when the equipment is in use.

All power supplies, signal conditioning circuitry etc are contained in a simple electrical console (20) with appropriate current protection devices and an RCD (21) for operator protection. The electrical console is designed to stand alongside the pipe loop on the bench top.

All circuits inside the console are protected against excessive current by miniature circuit breakers as follows:

> CONT (22) This breaker protects the power supply and circuits inside the console.
>
> HEAT (23) This breaker protects the heaters inside the boiler.
>
> O/P (24) This breaker protects the electrical output marked OUTPUT (35) at the rear of the console. The socket is used to power the IFD interface used for data logging.

Readings from the sensors are displayed on a common digital meter (26) on the electrical console. A selector switch (27) and all corresponding signals are connected to an I/O port (28) for connection to a PC using an optional parallel interface with educational software package. Alternatively, the signals can be connected to a user supplied chart recorder if required.

Before use, the boiler vessel and pipe loop must be filled with pure water (demineralised or distilled) via the filling point on the top of the pipe loop. To obtain accurate results when operating the equipment, it is essential to boil the water thoroughly before closing the filling valve to expel all traces of air from the system. Full details are given in **Commissioning** and the Operation section.

Note: An accurate Barometer (not supplied) will be required to determine the absolute pressure.

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.

Where necessary, refer to the drawings in the Equipment Diagrams section.

Electrical Supply

Refer to Figure 3 in the Equipment Diagrams.

Initially fill with pure water (3 litres) and replenish as consumed.

Before connecting the TH3 to the mains electrical supply ensure that the apparatus has been assembled as described in the Assembly section of this instruction manual.

Before connecting the appropriate electrical supply check the following:

> Ensure that the mains on/off switch (30) on the front of the console is in the OFF position.

Electrical Supply for Version TH3-A

The equipment requires connection to a single phase, fused electrical supply. The standard electrical supply for this equipment is 220/240V, 50Hz. Check that the voltage and frequency of the electrical supply agree with the label attached to the supply cable on the equipment. Connection should be made as follows:

GREEN/YELLOW - EARTH

BROWN - LIVE (HOT)

BLUE - NEUTRAL

Fuse rating - 5 AMP

Electrical Supply for Version TH3-B

The equipment requires connection to a single phase, fused electrical supply. The standard electrical supply for this equipment is 120V, 60Hz. Check that the voltage and frequency of the electrical supply agree with the label attached to the supply cable on the equipment. Connection should be made as follows:

GREEN/YELLOW - EARTH

BROWN - LIVE (HOT)

BLUE - NEUTRAL

Fuse rating - 10 AMP

Electrical Supply for Version TH3-G

The equipment requires connection to a single phase, fused electrical supply. The standard electrical supply for this equipment is 220-240V, 60Hz. Check that the voltage and frequency of the electrical supply agree with the label attached to the supply cable on the equipment. Connection should be made as follows:

GREEN/YELLOW - EARTH

BROWN - LIVE (HOT)

BLUE - NEUTRAL

Fuse rating - 5 AMP

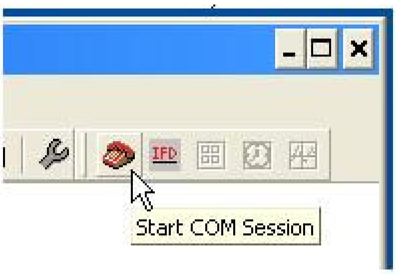
Installing the optional PC software

If it is required to operate TH3 using the optional software supplied with TH306IFD then it will be necessary to install the software from the CD-ROM supplied with TH306IFD 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

Remove the TH3 apparatus and console (20) from the box, and remove all packaging, taking care not to discard any components.

Place the TH3 apparatus on a solid work surface away from flammable substances, with the Bourdon pressure gauge dial (8) facing towards the operator. Place the console to the right of the apparatus.

Plug the mains cable (29) into the socket marked INPUT (25) on the rear of the console, and connect to the mains electrical supply. Do not switch on the mains supply at this stage.

Plug the heater cables (19) into the HEATER sockets (31) on the rear of the console.

Plug the pressure transducer cable (18) into the PRESSURE socket (32) on the rear of the console.

Plug the cable from the platinum resistance thermometer T1 (16) into the PT100(1) socket on the rear of the console (34).

Plug the cable from the platinum resistance thermometer T2 (17) into the PT100(2) socket on the rear of the console (33).

Attach a length of tubing/place a cup (not provided) beneath the container (15), to catch any water dripping from it.

Commissioning

The following procedure should be followed to verify the operation of the TH3.

Check that the RCD (21) and three circuit breakers (22, 23 and 24) on the rear of the console are all in the up position (ON).

Check that he mains switch (30) on the front of the console is switched off. Check that the heater switch (36) is off (0) and the heater power control (37) is set to minimum.

Check that the drain valve (39) is closed using the tool supplied.

Check that the calorimeter isolating valve (6) is closed – lever vertical.

Open the filler valve (38) on the top of the apparatus using the tool supplied.

Slowly fill the system with pure water (preferably deionised or demineralised) until the level reaches ¾ of the way up the sight glass (10) on the front of the boiler. Approximately 1.75 litres of water will be required. It may be helpful to use a funnel (not supplied) when filling the apparatus. Do not close the filler valve at this point.

Switch on the electrical supply to the console then check the operation of the RCD by pressing the TEST button on the RCD. The RCD must trip when the button is pressed. If the RCD does not trip or it trips before pressing the test button then it must be checked by a competent electrician before the equipment is used.

Switch on the mains power switch (30) on the console. The digital display should be illuminated.

Use the selector switch to check that initial readings for PT100(1), PT100(2) and Pressure P are sensible. P should read approximately 0 kN/m^2. The actual values for PT100(1) and PT100(2) will depend on the ambient temperature but a typical reading will be 109 Ohms at 20ºC (Refer to Data Sheet 1 for corrections to the resistance bridge, then to Data Sheet 2 for a full table of temperature vs. resistance values).

Close the isolating valve (6) to the calorimeter. Switch on the heater switch (36) then set the power control (37) to maximum and allow the water to heat. When the water is boiling, with steam escaping from the filler valve, gradually reduce the heater power to maintain a trickle of steam. This will allow all air to be removed from the system without excessive loss of water or rise in system pressure.

Confirm that the pressure in the system remains at approximately 0 kN/m^2. Wait until the reading from PT100(1) is approximately 138.0 Ohms indicated, 138.5 Ohms corrected resistance, corresponding to the boiling point of water at a temperature of 100ºC (Actual readings will depend on the actual atmospheric pressure).

When all air has been expelled from the system and the reading from temperature sensor PT100(1) is sensible close the filler valve using the tool supplied, taking care to avoid the escaping steam. Increase the power control to maximum and allow the pressure/temperature in the system to rise. Observe that the readings for pressure P and temperature corresponding to resistance reading PT100(1) both increase together. When the pressure indicated is approximately 4 bar gauge (400 kN/m^2) check that the reading from PT100(1) is approximately 154 Ohms indicated, 158 Ohms corrected corresponding to a temperature of 152ºC. Open the isolating valve (6) to the throttling calorimeter. Wait for the reading from PT100(2) to stabilise then confirm that the reading is typically 140-142 Ohms, the actual reading depending on the actual quality of the steam and the atmospheric pressure. Close the calorimeter isolating valve and continue heating to confirm that the relief valve operates at no more than 8 bar gauge (800 kN/m^2).

Switch off the heater power, open the calorimeter isolating valve and allow the system to cool to atmospheric pressure/temperature with steam gradually escaping into the container below the throttling calorimeter.

DO NOT attempt to open the filler valve or drain valve until the system pressure has reduced to atmospheric pressure (the reading on the Bourdon gauge must be zero before opening the filler or drain valve).

Commissioning of the TH3 Saturation Pressure Apparatus is complete and the equipment is ready for performing the Laboratory Teaching Exercises.

Electrical Wiring Diagram

Click on the relevant link to invoke the Wiring Diagram:

Wiring Diagram CDM27764H

Printed Versions of this Instruction Manual

Please note, all wiring diagrams are appended at the rear of this manual. If viewing this Instruction Manual via Help Text in Armfield Software refer to the printed version of the manual for these diagrams.

Operation

Where necessary, refer to the drawings in the Equipment Diagrams section.

Operating the optional PC Software

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

Operating the Equipment

The following procedure should be followed to fill the TH3 apparatus before use

Check that the mains switch (30) on the front of the console is switched off.

Check that the drain valve (39) is fully closed using the tool supplied.

Close the calorimeter isolating valve (6) - lever on valve vertical.

Open the filler valve (38) on the top of the apparatus, using the tool supplied.

Slowly fill the system with pure water (preferably deionised or demineralised) until the level reaches ¾ of the way up the sight glass (10) in the side of the boiler (2). This requires approximately 1¾ litres of water. It may be helpful to use a funnel (not supplied) during this procedure.

Do not close the filler valve at this point.

The following procedure should be followed to expel air from the TH3 apparatus before use

Air remaining in the pipework or expelled from the water when boiled for the first time will affect the accuracy of the measurements taken and can cause significant errors. To avoid this, the following procedure should be carried out:

Switch on the electrical console, switch on the heater (36) and set the power control (37) to maximum. Allow the water to heat until it is boiling.

When the water is boiling, with steam escaping from the filler valve, gradually reduce the heater power to maintain a trickle of steam. This will allow all air to be removed from the system without excessive loss of water or rise in system pressure.

Confirm that the pressure in the system remains at approximately 0 kN/m^2. Wait until the reading from PT100(1) is approximately 138.0 Ohms indicated, 138.5 Ohms corrected resistance, corresponding to the boiling point of water at a temperature of 100ºC (Actual readings will depend on the actual atmospheric pressure).

When all air has been expelled from the system and the reading from temperature sensor PT100(1) is sensible close the filler valve (38) using the tool supplied, taking care to avoid the escaping steam. Increase the power control to maximum and allow the pressure/temperature in the system to rise as required for the exercise being performed.

The following procedure should be followed to drain the TH3 apparatus after use

IMPORTANT: Allow the apparatus to cool to room temperature before attempting to drain the water.

Open the calorimeter isolating valve (6) and check that the internal and external pressures have equalised (the internal pressure should be approximately 0 kN/m^2 or 0 bar gauge). The Bourdon gauge (8) provides a convenient visual indication of the internal pressure and must read zero before opening the drain valve.

Attach a length of tubing (not provided) to the drain valve near the base of the boiler (39), and place the other end of the tube in a suitable container or drain.

Open the filler valve (38) using the tool supplied.

Open the drain valve (39) using the tool supplied, and allow the water to drain from the system.

NOTE: If deionised or demineralised water has been used for filling, the apparatus need not be drained except for storage.

Equipment Specifications

USB Channel Numbers

The channel numbers for the USB port are listed below for information:

Pin No	Channel No	Signal Function
Analog Outputs (0-5 V dc exported from socket):		
1	Ch 0 Signal	PRT100(1) (0V = 0 Ohms, 5V = 164.8 Ohms)
2	Ch 0 Return	
3	Ch 1 Signal	Not used on TH3
4	Ch 1 Return	
5	Ch 2 Signal	Not used on TH3
6	Ch 2 Return	
7	Ch 3 Signal	Not used on TH3
8	Ch 3 Return	
9	Ch 4 Signal	Not used on TH3
10	Ch 4 Return	
11	Ch 5 Signal	Pressure 0V = 0 Kn/m^2, 5V = 1378 Kn/m^2
12	Ch 5 Return	
13	Ch 6 Signal	PRT100(2) (0V = 0 Ohms, 5V = 164.8 Ohms)
14	Ch 6 Return	
15	Ch 7 Signal	Not used on TH3
16	Ch 7 return	
17-21	Not used	
Analog Inputs (0-5V dc input from socket):		

22-25	Not used	
Digital Outputs (0-5V dc):		
26-37	Not Used	
Digital Inputs (0-5V dc):		
38-50	Not used	

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 ±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

In addition to regular maintenance the following notes should be observed:

1. The TH3 should be disconnected from the electrical supply when not in use.

2. Water should be drained from the apparatus after use to minimise fouling.

> **Note:** If it is necessary to change the pressure sensor then any offset in the output from the sensor should be eliminated by adjusting VR14 on the PCB inside the console to give a reading of 0 kN/m^2 on the display with the system open to atmosphere.

If recalibration of the PT100 bridge circuits is necessary then calibration should be carried out with the system boiling at atmospheric pressure. Adjust VR10 for PT100(1) or VR11 for PT100(2) until the display reads the correct resistance- use Data Sheet 7, Data Sheet 2 and then Data Sheet 1 to obtain the resistance corresponding to the boiling point of water at the local atmospheric pressure (a barometer will be required).

Laboratory Teaching Exercises

Index to Exercises

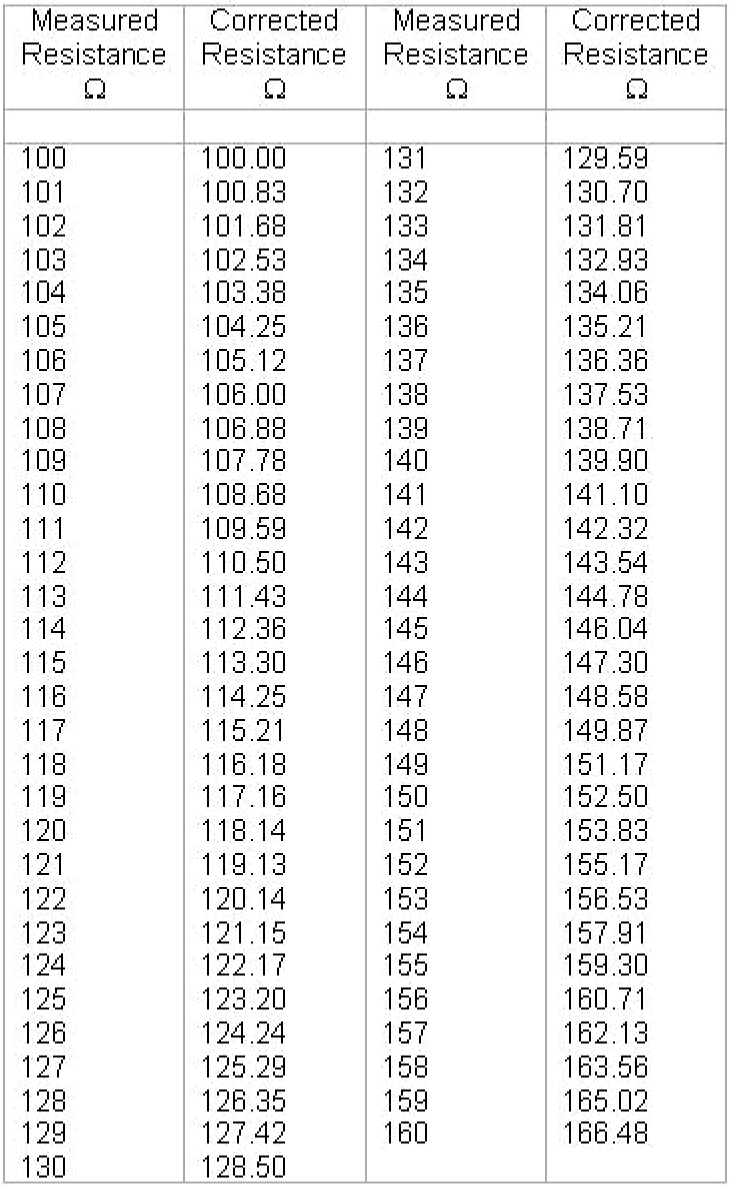
Nomenclature

The following nomenclature has been used for the theory and calculations presented in this manual:

Name	Symbol	Unit	Type	Definition
Measured resistance	R_{m1}	Ω	Recorded	Indicated resistance of the platinum resistance thermometer within the pipe loop.
Measured resistance	R_{m2}	Ω	Recorded	Indicated resistance of the platinum resistance thermometer in the steam offtake pipe.
Corrected resistance	R_{c1}	Ω	Referenced	Actual resistance of the platinum resistance thermometer in pipe loop after correction for bridge circuit.
Corrected resistance	R_{c1}	Ω	Referenced	Actual resistance of the platinum resistance thermometer in steam offtake pipe after correction for bridge circuit.
Temperature	T_1	^{o}C	Referenced	Temperature corresponding to indicated resistance of the platinum resistance thermometer within the pipe loop.
Temperature	T_2	^{o}C	Referenced	Temperature corresponding to indicated resistance of the platinum resistance thermometer in the steam offtake pipe.
Pressure	P_1	kN/m^2	Recorded	Pressure reading from electronic pressure sensor.
Elapsed time	t	s	Recorded	Time elapsed since the test run was started.

Absolute temperature	T_{abs}	K	Referenced or calculated	Absolute temperature at the point of measurement, as found from the platinum resistance thermometer reading. May be referenced directly from the table provided, or calculated as: $T_{abs} = T_{(1\ or\ 2)} + 273.15$
Actual temperature	T_{act}	K	Referenced	True absolute temperature at the point of measurement, referenced from the graph of the vapour point of water using the absolute pressure P_{abs}.
Atmospheric pressure	P_{atm}	kN/m²	Recorded	Ambient pressure of the surroundings of the apparatus.
Absolute pressure	P_{abs}	kN/m²	Calculated	Absolute pressure corresponding to the pressure indicated by the electronic pressure sensor. Calculated as: $P_{abs} = P_1 + P_{atm}$
Enthalpy of fluid before throttling	h_1	kJ/kg	Referenced	Enthalpy of steam in the pipe loop. Referenced using the absolute temperature corresponding to T_1.
Enthalpy of fluid after throttling	h_2	kJ/kg	Referenced	Enthalpy of steam after passing through the throttling calorimeter. Referenced using the absolute temperature corresponding to T_2.

Data Sheet 1



Measured Resistance Ω	Corrected Resistance Ω	Measured Resistance Ω	Corrected Resistance Ω
100	100.00	131	129.59
101	100.83	132	130.70
102	101.68	133	131.81
103	102.53	134	132.93
104	103.38	135	134.06
105	104.25	136	135.21
106	105.12	137	136.36
107	106.00	138	137.53
108	106.88	139	138.71
109	107.78	140	139.90
110	108.68	141	141.10
111	109.59	142	142.32
112	110.50	143	143.54
113	111.43	144	144.78
114	112.36	145	146.04
115	113.30	146	147.30
116	114.25	147	148.58
117	115.21	148	149.87
118	116.18	149	151.17
119	117.16	150	152.50
120	118.14	151	153.83
121	119.13	152	155.17
122	120.14	153	156.53
123	121.15	154	157.91
124	122.17	155	159.30
125	123.20	156	160.71
126	124.24	157	162.13
127	125.29	158	163.56
128	126.35	159	165.02
129	127.42	160	166.48
130	128.50		

Resistance Bridge Correction Chart

The bridge will be balanced when the PT100 has a resistance of 100Ω. At any other value of resistance there will be an imbalance in the bridge resulting in an error in the reading. This chart can be used to correct for this error.

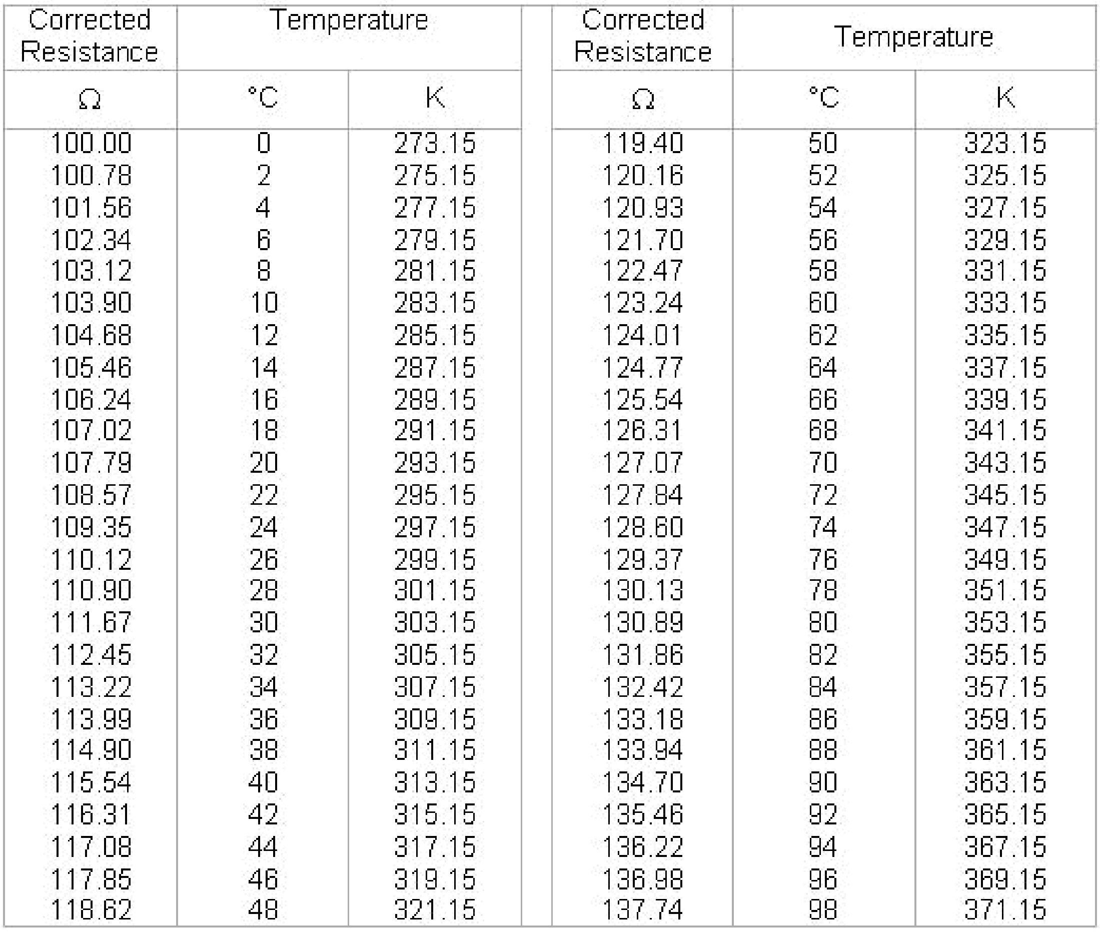
Use of the chart

Take a reading for the resistance of the PT100 from the display on the front of the console.

Find the closest value to this reading from the ‘Measured resistance’ column of the table, then read the corresponding ‘Corrected resistance’.

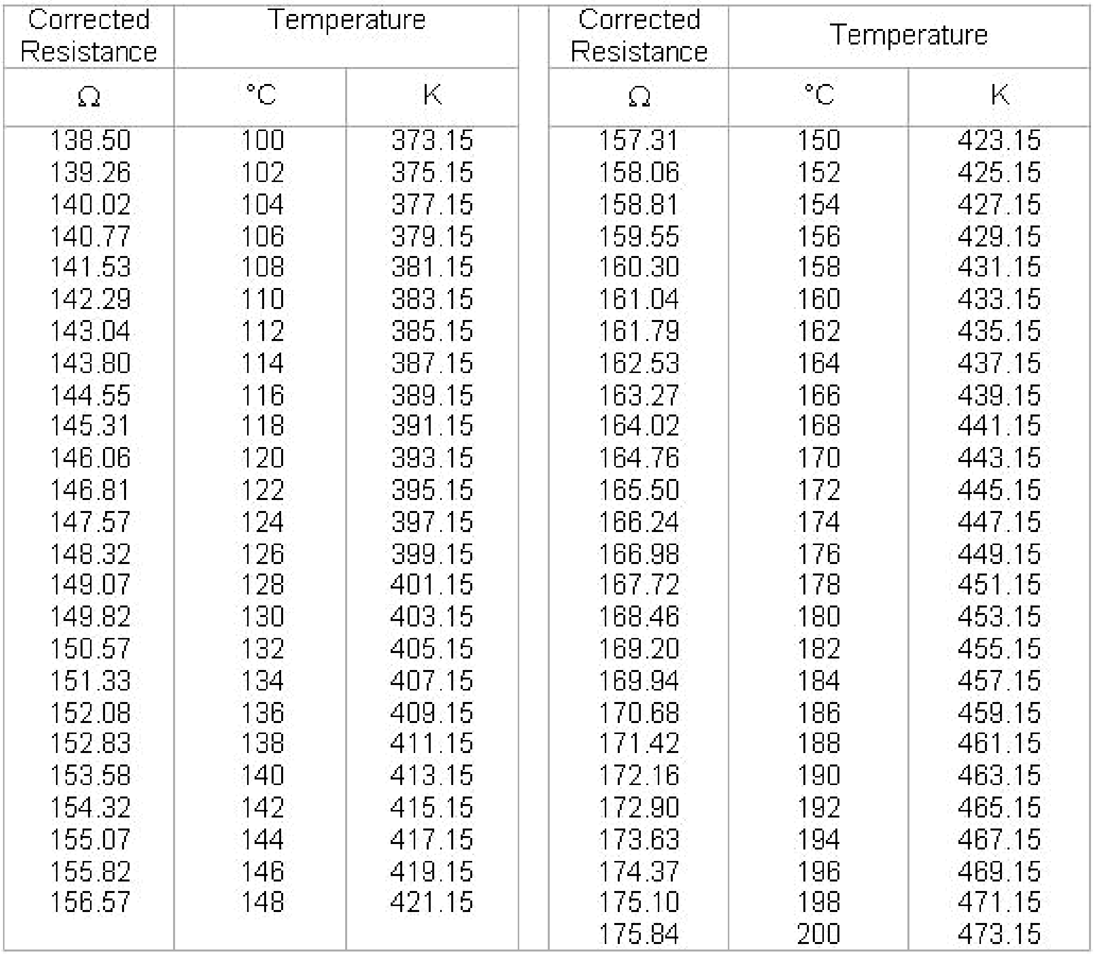
Values may be interpolated for improved accuracy.

Data Sheet 2



Corrected Resistance	Temperature			Corrected Resistance	Temperature	
Ω	°C	K		Ω	°C	K
100.00	0	273.15		119.40	50	323.15
100.78	2	275.15		120.16	52	325.15
101.56	4	277.15		120.93	54	327.15
102.34	6	279.15		121.70	56	329.15
103.12	8	281.15		122.47	58	331.15
103.90	10	283.15		123.24	60	333.15
104.68	12	285.15		124.01	62	335.15
105.46	14	287.15		124.77	64	337.15
106.24	16	289.15		125.54	66	339.15
107.02	18	291.15		126.31	68	341.15
107.79	20	293.15		127.07	70	343.15
108.57	22	295.15		127.84	72	345.15
109.35	24	297.15		128.60	74	347.15
110.12	26	299.15		129.37	76	349.15
110.90	28	301.15		130.13	78	351.15
111.67	30	303.15		130.89	80	353.15
112.45	32	305.15		131.86	82	355.15
113.22	34	307.15		132.42	84	357.15
113.99	36	309.15		133.18	86	359.15
114.90	38	311.15		133.94	88	361.15
115.54	40	313.15		134.70	90	363.15
116.31	42	315.15		135.46	92	365.15
117.08	44	317.15		136.22	94	367.15
117.85	46	319.15		136.98	96	369.15
118.62	48	321.15		137.74	98	371.15

PT100 Platinum Resistance Thermometer Reference Chart



Corrected Resistance	Temperature		Corrected Resistance	Temperature	
Ω	°C	K	Ω	°C	K
138.50	100	373.15	157.31	150	423.15
139.26	102	375.15	158.06	152	425.15
140.02	104	377.15	158.81	154	427.15
140.77	106	379.15	159.55	156	429.15
141.53	108	381.15	160.30	158	431.15
142.29	110	383.15	161.04	160	433.15
143.04	112	385.15	161.79	162	435.15
143.80	114	387.15	162.53	164	437.15
144.55	116	389.15	163.27	166	439.15
145.31	118	391.15	164.02	168	441.15
146.06	120	393.15	164.76	170	443.15
146.81	122	395.15	165.50	172	445.15
147.57	124	397.15	166.24	174	447.15
148.32	126	399.15	166.98	176	449.15
149.07	128	401.15	167.72	178	451.15
149.82	130	403.15	168.46	180	453.15
150.57	132	405.15	169.20	182	455.15
151.33	134	407.15	169.94	184	457.15
152.08	136	409.15	170.68	186	459.15
152.83	138	411.15	171.42	188	461.15
153.58	140	413.15	172.16	190	463.15
154.32	142	415.15	172.90	192	465.15
155.07	144	417.15	173.63	194	467.15
155.82	146	419.15	174.37	196	469.15
156.57	148	421.15	175.10	198	471.15
			175.84	200	473.15

PT100 Platinum Resistance Thermometer Reference Chart (cont.)

Use of the chart

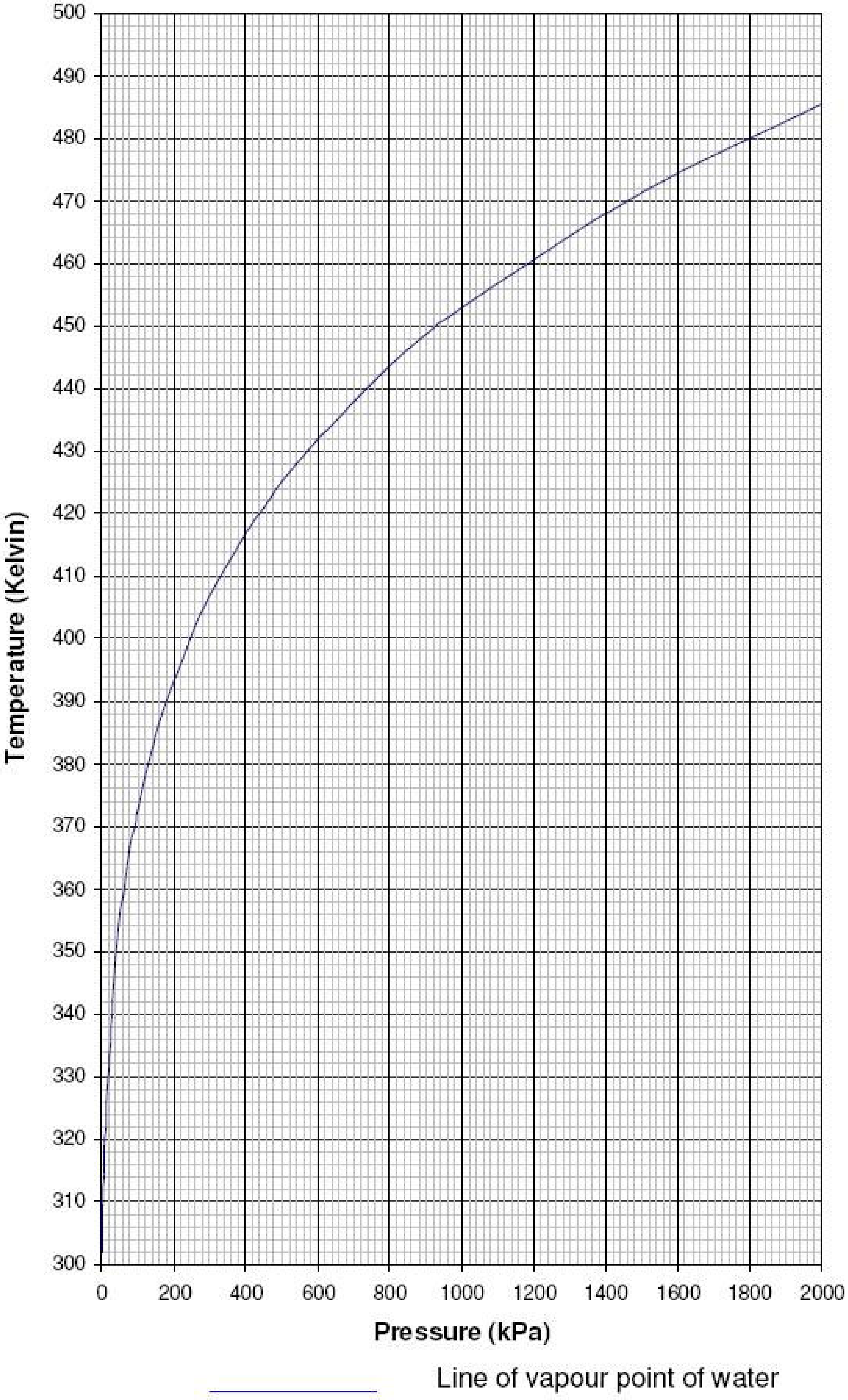
Take a reading for the resistance of the PT100 from the display on the front of the console.

Find the corrected value for the resistance from the Resistance Bridge Correction Chart (Data Sheet 1).

Find the closest value to the corrected resistance from the ‘Measured Resistance’ column of the above table.

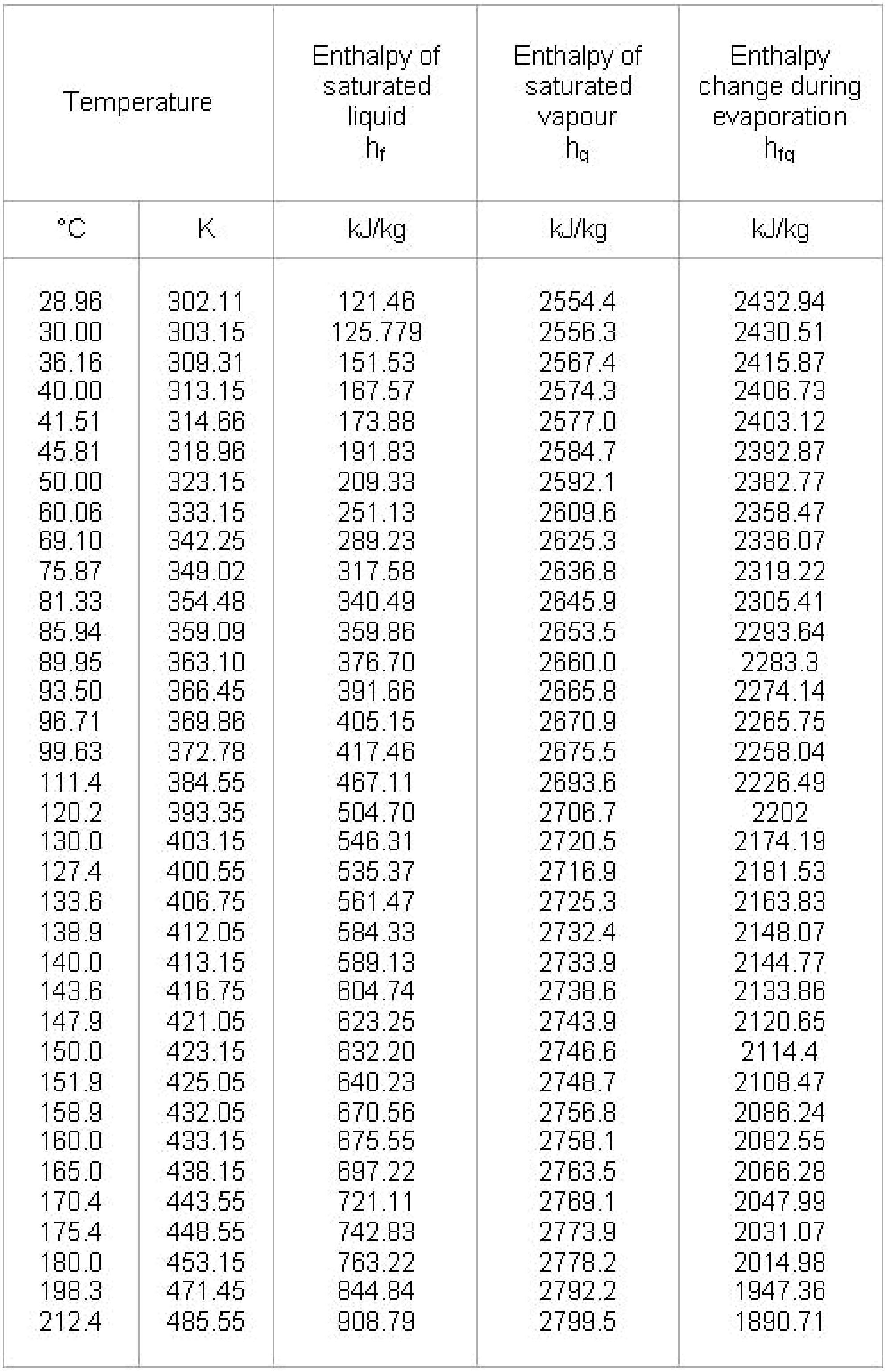
Read along the column to find the reading in degrees Celsius and the corresponding reading in degrees Kelvin.

Data Sheet 3



Vapour Point of Saturated Water

Data Sheet 4



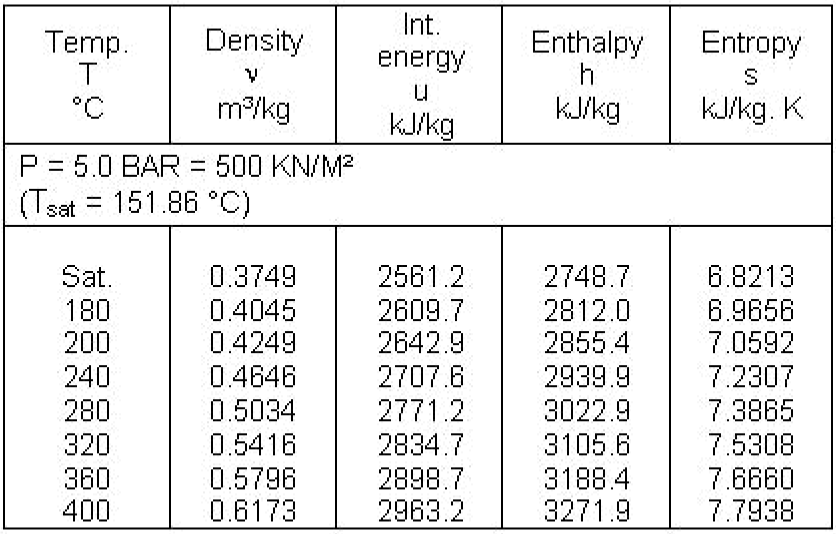
Temperature		Enthalpy of saturated liquid h_f	Enthalpy of saturated vapour h_g	Enthalpy change during evaporation h_{fg}
°C	K	kJ/kg	kJ/kg	kJ/kg
28.96	302.11	121.46	2554.4	2432.94
30.00	303.15	125.779	2556.3	2430.51
36.16	309.31	151.53	2567.4	2415.87
40.00	313.15	167.57	2574.3	2406.73
41.51	314.66	173.88	2577.0	2403.12
45.81	318.96	191.83	2584.7	2392.87
50.00	323.15	209.33	2592.1	2382.77
60.06	333.15	251.13	2609.6	2358.47
69.10	342.25	289.23	2625.3	2336.07
75.87	349.02	317.58	2636.8	2319.22
81.33	354.48	340.49	2645.9	2305.41
85.94	359.09	359.86	2653.5	2293.64
89.95	363.10	376.70	2660.0	2283.3
93.50	366.45	391.66	2665.8	2274.14
96.71	369.86	405.15	2670.9	2265.75
99.63	372.78	417.46	2675.5	2258.04
111.4	384.55	467.11	2693.6	2226.49
120.2	393.35	504.70	2706.7	2202
130.0	403.15	546.31	2720.5	2174.19
127.4	400.55	535.37	2716.9	2181.53
133.6	406.75	561.47	2725.3	2163.83
138.9	412.05	584.33	2732.4	2148.07
140.0	413.15	589.13	2733.9	2144.77
143.6	416.75	604.74	2738.6	2133.86
147.9	421.05	623.25	2743.9	2120.65
150.0	423.15	632.20	2746.6	2114.4
151.9	425.05	640.23	2748.7	2108.47
158.9	432.05	670.56	2756.8	2086.24
160.0	433.15	675.55	2758.1	2082.55
165.0	438.15	697.22	2763.5	2066.28
170.4	443.55	721.11	2769.1	2047.99
175.4	448.55	742.83	2773.9	2031.07
180.0	453.15	763.22	2778.2	2014.98
198.3	471.45	844.84	2792.2	1947.36
212.4	485.55	908.79	2799.5	1890.71

Enthalpy of Saturated Water

Data Sheet 5

Enthalpy of superheated water vapour

The properties of superheated water are normally given in standard text books in a similar manner to the example given below. The enthalpy of superheated water vapour may be determined by finding the table for the pressure closest to the measured pressure, and then cross-referencing the appropriate column with the temperature closest to the measured temperature. For greater accuracy, intermediate values may be interpolated from the given data.



Temp. T °C	Density v m³/kg	Int. energy u kJ/kg	Enthalpy h kJ/kg	Entropy s kJ/kg. K
P = 5.0 BAR = 500 KN/M² (T_{sat} = 151.86 °C)				
Sat.	0.3749	2561.2	2748.7	6.8213
180	0.4045	2609.7	2812.0	6.9656
200	0.4249	2642.9	2855.4	7.0592
240	0.4646	2707.6	2939.9	7.2307
280	0.5034	2771.2	3022.9	7.3865
320	0.5416	2834.7	3105.6	7.5308
360	0.5796	2898.7	3188.4	7.6660
400	0.6173	2963.2	3271.9	7.7938

For use with this equipment, the required information from these tables has been extracted, and is given in the following table. The enthalpy of superheated water vapour may be found by cross-referencing the values closest to the measured pressure and temperature.

Temp. °C														
95	2667	2667	2666											
100	2678	2677	2676											
110	2698	2697	2696	2695	2694	2693								
120	2718	2717	2717	2715	2715	2714	2711							
130	2738	2737	2737	2736	2735	2734	2732	2727						
140	2757	2757	2757	2756	2755	2754	2752	2748	2739					
150	2777	2777	2776	2776	2775	2774	2773	2770	2760	2753				
160	2797	2797	2796	2796	2795	2794	2793	2789	2782	2774	2766			
165	2807	2806	2806	2805	2805	2804	2803	2799	2792	2785	2778	2770		
170	2817	2816	2816	2815	2815	2814	2813	2810	2803	2796	2789	2782	2774	
180	2836	2836	2836	2835	2835	2834	2833	2830	2824	2818	2812	2805	2799	2791
190	2856	2856	2856	2855	2855	2854	2853	2850	2845	2839	2833	2828	2821	2815
200	2876	2876	2875	2875	2874	2874	2873	2871	2866	2862	2855	2851	2845	2840
210	2896	2895	2895	2895	2894	2894	2893	2891	2886	2881	2877	2872	2867	2862
220	2915	2915	2915	2914	2914	2914	2913	2911	2907	2902	2898	2894	2889	2884
230	2935	2935	2935	2934	2934	2934	2933	2931	2927	2923	2919	2915	2911	2907
240	2955	2955	2955	2954	2954	2953	2953	2951	2948	2944	2940	2936	2933	2929
250	2975	2975	2974	2974	2974	2973	2973	2971	2968	2965	2962	2958	2955	2951
260	2995	2994	2994	2994	2994	2993	2993	2991	2988	2985	2982	2979	2975	2972
270	3015	3014	3014	3014	3014	3013	3013	3012	3009	3006	3003	3000	2997	2994
280	3035	3034	3034	3034	3034	3033	3033	3032	3029	3026	3023	3021	3018	3015
290	3055	3054	3054	3054	3054	3053	3053	3052	3049	3047	3044	3042	3039	3036
300	3075	3074	3074	3074	3074	3074	3073	3072	3070	3067	3065	3062	3060	3057
320	3115	3115	3115	3114	3114	3114	3114	3113	3111	3108	3106	3104	3102	3099
340	3155	3155	3155	3155	3155	3155	3154	3153	3151	3149	3147	3145	3143	3141
360	3196	3196	3196	3196	3196	3195	3195	3195	3193	3191	3189	3187	3185	3183
380	3237	3237	3237	3237	3237	3236	3236	3236	3234	3233	3231	3228	3227	3225
400	3278	3278	3278	3278	3278	3278	3277	3277	3275	3274	3272	3270	3269	3267
Press. kN/m²	90	95	100	110	120	130	150	200	300	400	500	600	700	800

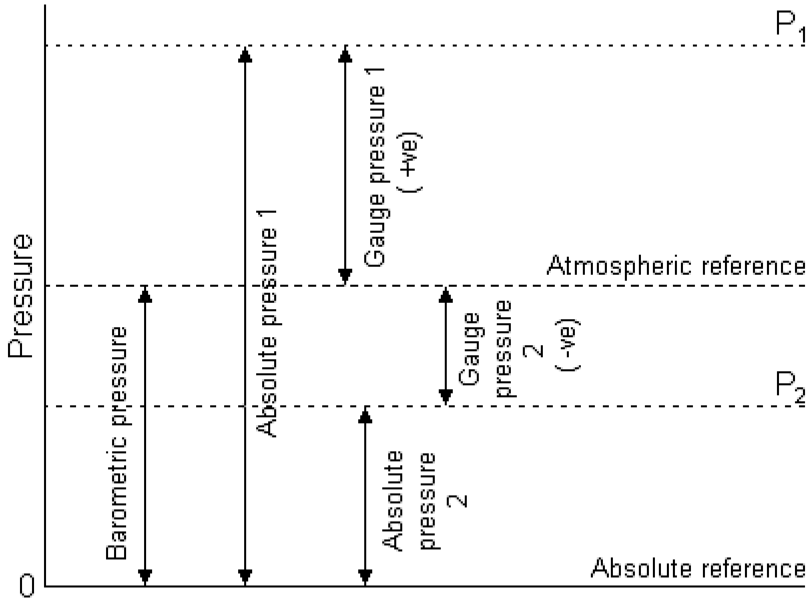
Data Sheet 6

Relative and absolute scale values

As with the measurement of any physical property, the measurement of pressure and temperature rely upon comparison with some fixed reference point. In the measurement of pressure, an obvious reference point is that of the ambient pressure of the surroundings. Pressure scales have been based around a zero point of the pressure of the atmosphere at sea level. Pressures lower than atmospheric pressure are assigned negative values; pressures higher than atmospheric pressure have positive values.

Gauges for measuring pressure give readings relative to this zero point, by comparing the pressure of interest to the pressure of the surrounding air. Pressures measured using such a gauge are given relative to a fixed value, and are sometimes termed *gauge pressure*. These measure pressure difference between the pressure to be measured and the barometric (ambient) pressure. This may then need adjusting, to take into account any difference between barometric pressure and the pressure at sea level.

Many calculations using equations derived from fundamental physical laws require absolute pressure values. Absolute pressure is the pressure relative to a total absence of pressure (ie. a total vacuum). On an absolute pressure scale, all pressures have a positive value. The following chart illustrates the difference between gauge pressure, barometric pressure, and absolute pressure.



As for pressure, temperature scales have also been based around a comparison with fixed reference points. For example, the ice point of water is assigned a value of 0° on the Celsius scale. Temperatures measured on the Celsius scale are therefore given relative to a fixed value. Absolute temperature scales take as a zero point the theoretical temperature at which an ideal gas has a zero volume and no internal energy, equal to –273.15°C. One such scale is the Kelvin scale, which has the same scale interval as the Celsius scale.

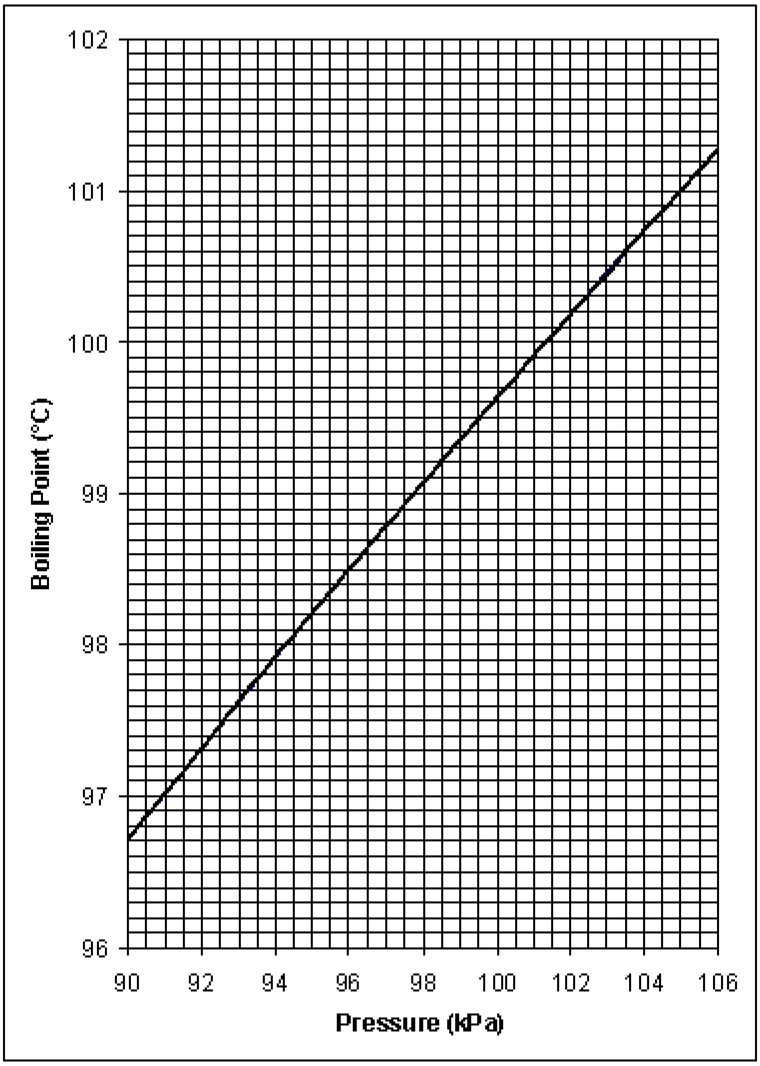
If two different scales have the same scale interval, then the number of intervals of difference between two temperatures will be identical. For example, the difference between 25°C (298.15 K) and 27°C (300.15 K) is 2 for both the Celsius and Kelvin scales. When performing calculations involving temperature difference, it is good practice to first convert all values into the same scale required for the answer. This avoids possible confusion.

Most industrial pressure instruments read gauge pressure, especially where the working pressure of a vessel is being monitored. These must be converted to absolute pressure before the experimental pressure data is used for calculations. This means that there must be some sensor, such as a barometer, to measure the ambient pressure of the location.

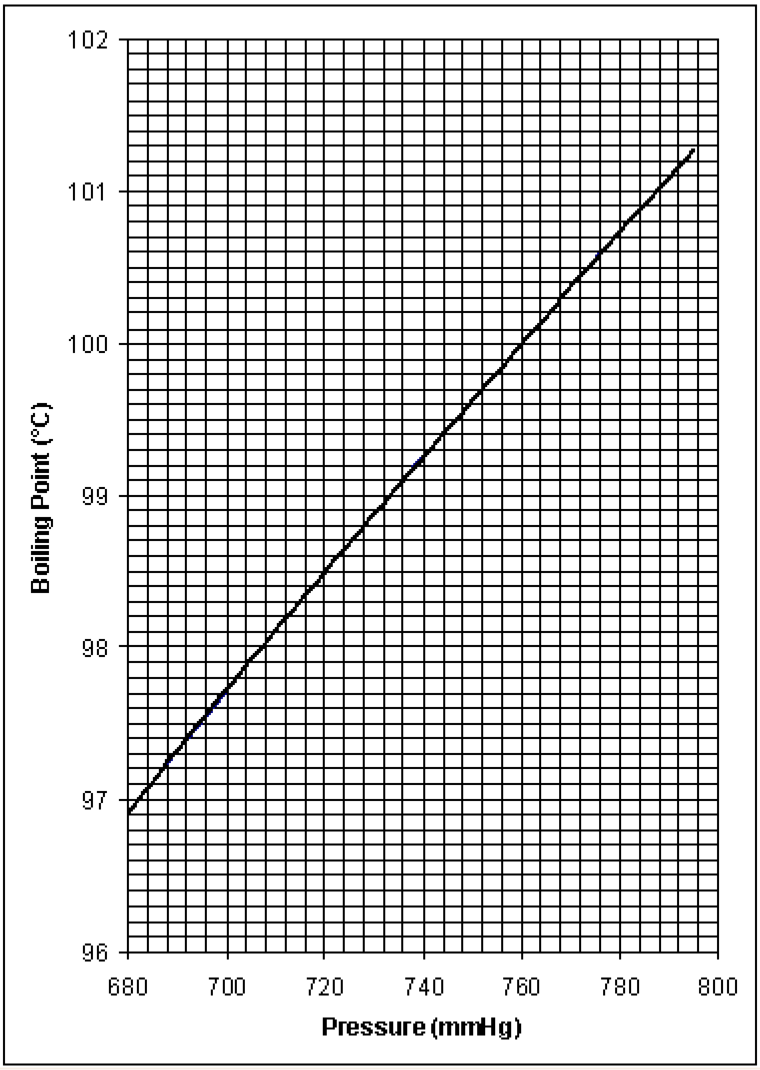
In the case of the TH3, the pressure sensors give a reading relative to ambient pressure. Because of the level of accuracy of the other readings being taken and the magnitude of the experimental errors involved, it is only necessary to determine absolute pressure to ± 0.01 bar. This means that atmospheric pressure also only needs to be determined to the same accuracy. This can be achieved with a simple mercury barometer (not supplied).

The temperature sensors included with the equipment are of the platinum resistance type. The resistance of the sensors may be read from the display on the console. The value can then be compared to the graph provided to determine the temperature. This potentially provides better accuracy than transponder circuitry to convert the values into degrees electronically, as it eliminates zero errors. It also allows a direct conversion from sensor resistance into an absolute temperature scale.

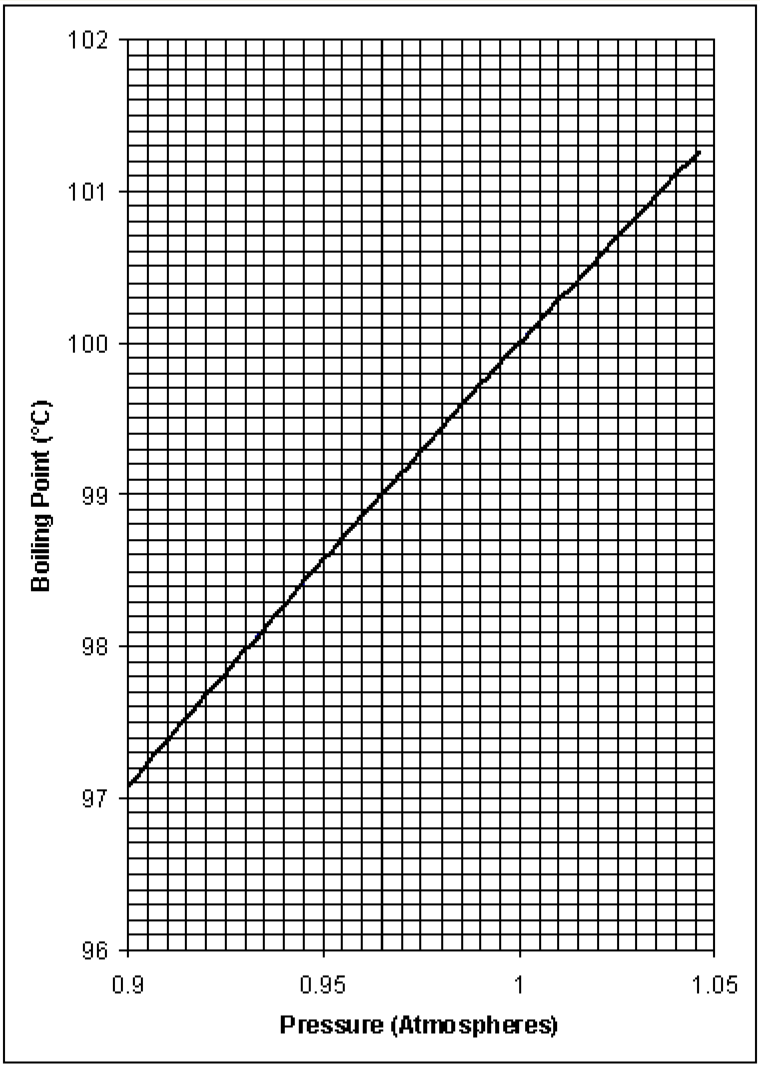
Data Sheet 7



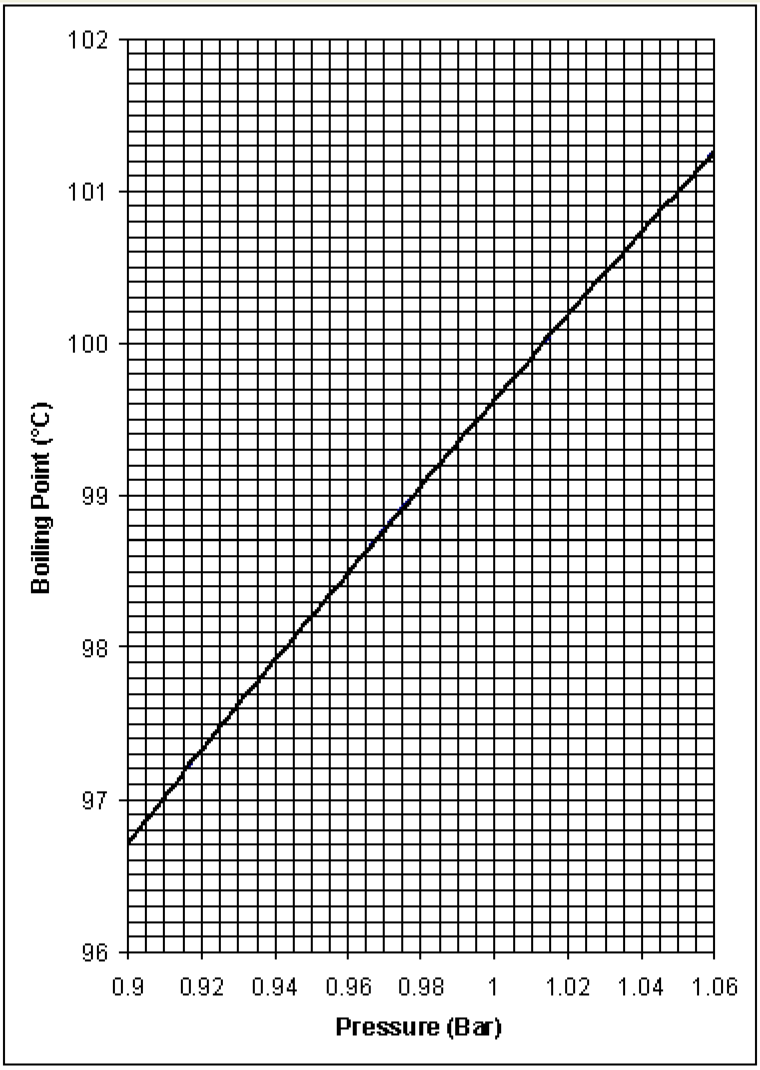
Boiling Point of Water (kPa-°C)



Boiling Point of Water (mm Hg-°C)

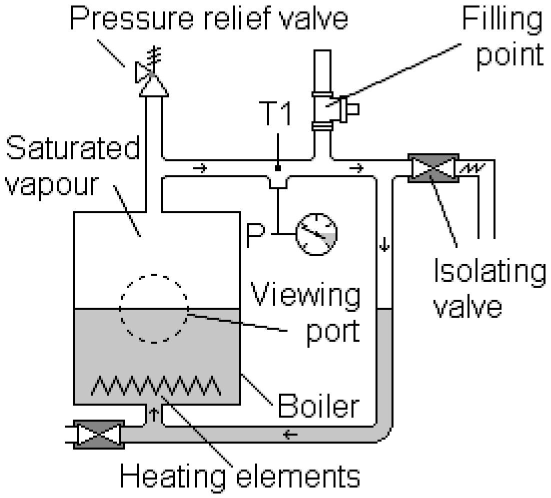


Boiling Point of Water (Atmospheres-°C)



Boiling Point of Water (bar-°C)

Exercise A - Characteristic behaviour of a two phase fluid



Objective

To study the behaviour of water during the transition between liquid and vapour phases.

Method

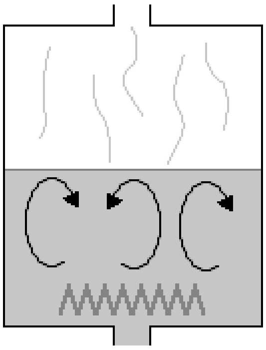
To investigate the behaviour of water, at temperatures around the vapour point, over a range of pressures. To study the change in vapour point with increasing pressures, and to watch the fluid behaviour using a sight glass set into a pressure vessel.

Theory

Boiling regimes

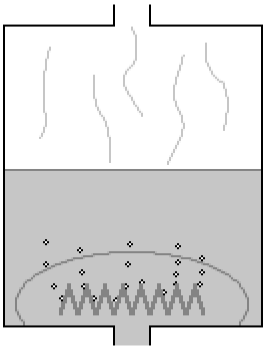
When a body of water is heated at constant volume by means of a hot surface, such as a heater element, various different stages may be observed in the heating process:

At very low heat flux between the heater and the fluid, no boiling occurs. Heat transfer between the element and the fluid is by conduction, and fluid motion occurs through free convection. Phase change occurs only as evaporation at the free surface.



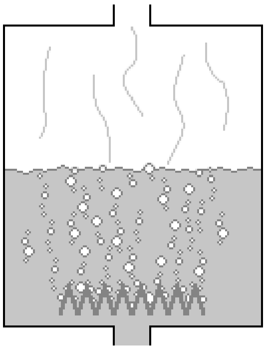
During this stage, slight swirling of the water surface may be seen.

At increased heat flux, phase change will occur at the heater surface, with small bubbles of vapour forming as the layer of fluid surrounding the heater reaches saturation temperature. These rise out of the hot boundary layer between the heater and the main volume of the water, until they reach cooler fluid, where they condense. Final phase change occurs as evaporation at the free surface.



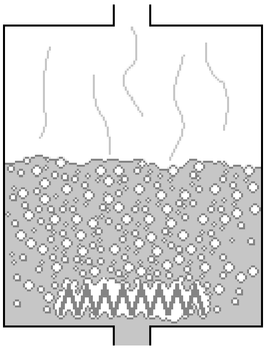
During this stage, small bubbles may occasionally be seen condensing on the sight glass.

As heat flux rises, heat is transferred through the fluid mainly by free convection, until most of the volume reaches saturation temperature or higher. Many bubbles of vapour form on the heater surface, and rise through the fluid to the surface. The bubble movement agitates the fluid, producing increased mixing and consequently better heat transfer from the heater to the fluid. This stage is sometimes termed *nucleate boiling*.



During this stage, vigorous bubbling may be seen through the sight glass.

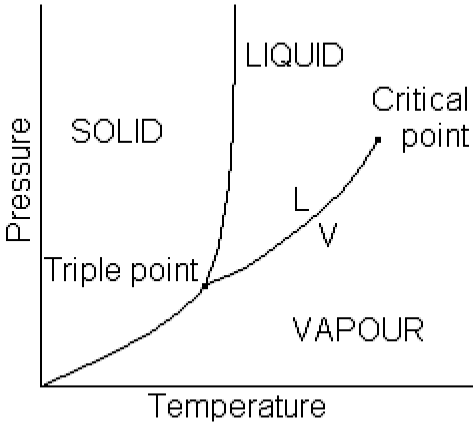
As heating within the vessel is at constant volume, the internal pressure of the system increases during the heating process. As pressure increases, the saturation temperature of water also increases, and the liquid in the system becomes superheated (it remains liquid at a temperature above the boiling point at atmospheric pressure).



If the pressure is now reduced without a corresponding reduction in temperature, for example by bleeding off steam from the system, then the saturation temperature is reduced. The superheated liquid vaporises as the vapour point falls, producing violent frothing.

The pressure – volume – temperature relationship

The relationship between pressure, specific volume and temperature can be found in most standard thermodynamics textbooks. This exercise investigates the pressure-temperature relationship at constant volume. A graph summarising this relationship is given below; the exercise will cover temperatures and pressures occurring along the L-V line. The relationship is covered in greater detail in later exercises.



Equipment Set Up

Check that the calorimeter valve and the drain valve at the base of the boiler are both closed.

Check that the mains power to the console is switched off before filling the boiler.

Open the filling point at the top using the key provided. Fill the equipment using purified or de-ionised water, until the water level is halfway up the sight-glass at the front of the boiler. Do not seal the filling point until instructed later.

Switch on the mains power to the console, and switch on the console itself.

Procedure

Switch on the heater, and turn the heater power control to maximum.

Observe the appearance of the fluid in the boiler through the sight glass as the temperature increases. Allow the water to reach boiling point, indicated by intense movement at the surface and steam escaping from the filling point. Reduce the heater power slightly to maintain a steady but not excessive stream of steam. Wait until the resistance reading (R_{m1}) becomes steady, meaning that all air has been expelled. Note the pressure inside the vessel, as indicated by the pressure sensor P_1, and the resistance indicated by the platinum resistance thermometer R_{m1}. The resistance may be converted into temperature using the tables provided in Data Sheet 1 and Data Sheet 2. Close the filler valve then return the heater to maximum power.

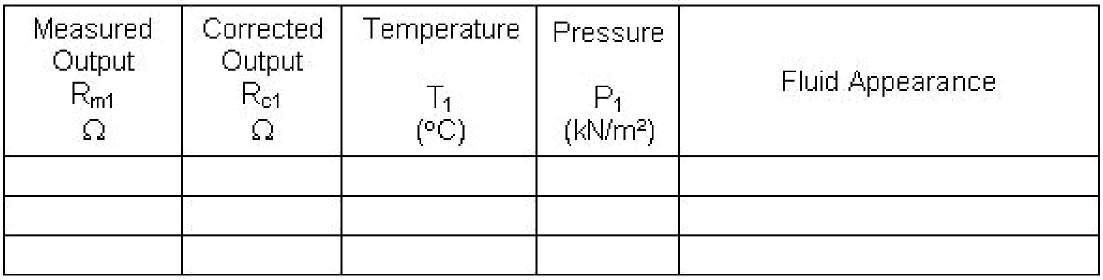
At intervals of approximately five minutes, note the readings for P_1 and R_{m1}. Note the approximate temperature and pressure at which significant changes occur in the appearance of the fluid.

When the system reaches maximum working pressure (7 bar), fully open the calorimeter valve and switch off the heater power. After thirty seconds take readings for pressure (P_1) and resistance (R_{m1}), and continue to do so at thirty-second intervals. Note any changes in fluid appearance as the pressure drops.

LEAVE THE CALORIMETER ISOLATING VALVE OPEN AFTER THE DATA HAS BEEN TAKEN. Leaving the valve closed, after the pressure reaches atmospheric pressure, may result in partial vacuum inside the apparatus as it cools to ambient temperature. This could permanently damage the apparatus.

Results

Tabulate your results under the following headings:



Measured Output R_{m1} Ω	Corrected Output R_{c1} Ω	Temperature T_1 (°C)	Pressure P_1 (kN/m²)	Fluid Appearance

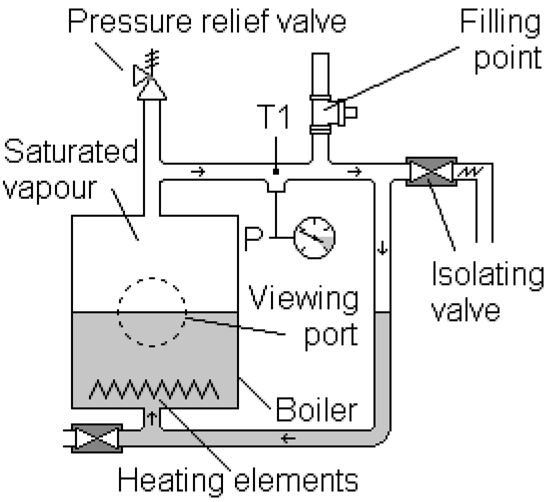
Plot a graph of pressure against temperature.

Conclusion

Describe the behaviour observed as the fluid was heated and then the pressure reduced. Did the fluid show sudden changes in behaviour, or were the transitions gradual?

Comment on the pressure and temperature graph obtained. Does it look similar to the theoretical graph provided?

Exercise B - Principles of saturation pressure measurement



Objective

To obtain an understanding of the principles of saturation pressure measurement.

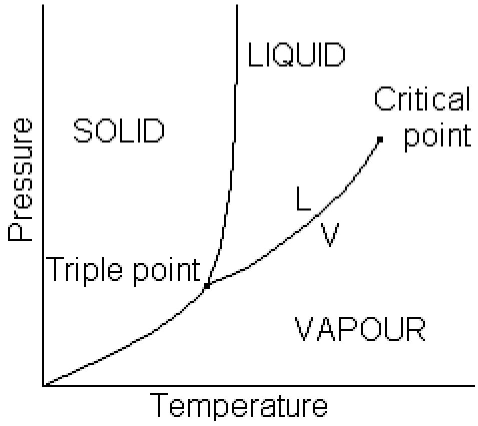
Method

To measure the saturation pressure of water using a pressurised vessel. To examine the effect of unsteady conditions on measurement accuracy.

Theory

It is recommended that students read Data Sheet 6, Relative and absolute scale values, before beginning this experiment.

The properties of water at constant volume can be represented as a function of pressure and temperature as shown in the diagram below.

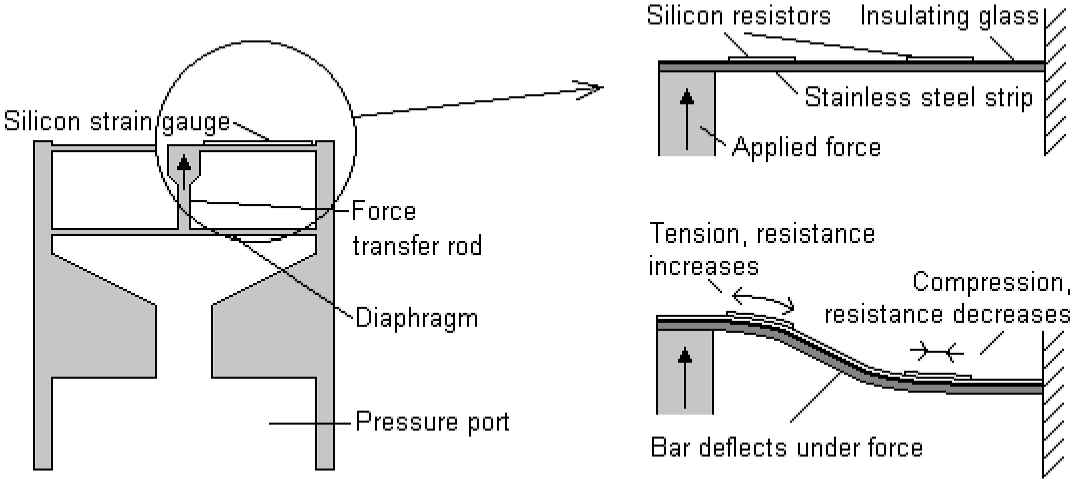


The saturation point of water is the condition at which a phase change occurs from liquid to vapour, or vapour to liquid. It occurs at a very precise set of conditions, which form a line when plotted on a graph such as that shown above (marked L V). Measurement of the saturation point therefore requires accurate measurement of absolute pressure and absolute temperature. Selection of suitable measuring devices must take into account several factors:

- The range of temperatures expected – devices must be able to operate over the full temperature range of the apparatus.
- The range of pressures expected – devices must be able to operate over the full pressure range of the apparatus.
- The type of sensor output required – automated monitoring will generally require an electrical output, for example.
- The response times required – which will partly depend upon the rate of heating and consequently the rate of temperature change.
- The size of sensor required, including any output transducer and display.
- Hot, wet conditions – combination of heat, air and water produces a highly corrosive atmosphere.

The TH3 apparatus uses sensors that are fairly typical of those used in a similar industrial situation:

- Platinum resistance thermometers are used to measure temperature, giving an electrical output in Ohms. These have a wide temperature range and give excellent accuracy. They can operate under a wide range of pressures, but require a protective shield in liquid and corrosive atmospheres. Such shielding does increase the response time of the sensor and the size of the sensor probe.
- An electronic pressure sensor of semiconductor type has been used. In this sensor, one side of a diaphragm is exposed to the pressure to be measured, while the other side is open to atmosphere. The resulting deflection forces a rod into a metallic strip with semiconductor resistance gauges bonded to the surface. The resulting tension or compression in these gauges produces a measurable change in the semiconductor resistance, which can then be converted to a pressure reading by a suitable conditioning circuit.



A Bourdon-type gauge has been included to give a visual indication of the pressure inside the equipment. This is intended as an extra safety measure, indicating when the system is pressurised even if the water is not visibly active. Bourdon gauges can be constructed to cover a wide pressure range, but due to the nature of the display the accuracy of such gauges decreases as the total range of the scale increases.

Temperature changes will affect the accuracy of the sensor, but where temperature variation is pressure-dependent the sensor may be calibrated to compensate. The gauge is relatively bulky and robust, and output purely mechanical.

The accuracy of the measurements taken will be affected by the properties of the sensors chosen. This experiment will investigate the effect of one property, that of response time or thermal lag, on the accuracy of the results.

Equipment Set Up

Check that the calorimeter valve and the drain valve at the base of the boiler are both closed.

Check that the mains power to the console is switched off before filling the boiler.

Open the filling point at the top using the key provided. Fill the equipment using purified or de-ionised water, until the water level is halfway up the sight-glass at the front of the boiler. Do not seal the filling point until instructed later.

Switch on the mains power to the console, and switch on the console itself.

Procedure

Switch on the heater and turn the heater control to maximum.

Allow the water to reach boiling point, indicated by intense movement at the surface and steam escaping from the filling point. Reduce the heater power slightly to maintain a steady but not excessive stream of steam. Wait until the resistance reading (R_{m1}) becomes steady, meaning that all air has been expelled. Note the pressure inside the vessel, as indicated by the pressure sensor P_1, and the resistance indicated by the platinum resistance thermometer R_{m1}. The resistance may be converted into temperature using the tables provided in Data Sheet 1 and Data Sheet 2. Close the filler valve then return the heater to maximum power.

At intervals of two minutes, record the thermometer output and the reading from the electronic pressure sensor.

When the pressure reaches maximum working pressure (7 bar), turn off the heater.

At intervals of five minutes, record the thermometer output and the reading from the electronic pressure sensor.

Continue recording until the readings stabilise, or for as long as possible if the readings have not stabilised within the available time.

The first part of the experiment can be repeated with the heater at lower power settings, to investigate the effect of different heating rates. The cooling rate should remain unchanged, so need not be repeated.

LEAVE THE CALORIMETER ISOLATING VALVE OPEN AFTER THE DATA HAS BEEN TAKEN. Leaving the valve closed, after the pressure reaches atmospheric pressure, may result in partial vacuum inside the apparatus as it cools to ambient temperature. This could permanently damage the apparatus.

Results

Tabulate your results under the following headings:

Barometric pressure: kN/m^2

Elapsed Time t (mins)	Measured Output R_{m1} (Ω)	Corrected Output R_{c1} (Ω)	Absolute Temperature T_{abs} (K)	Pressure P_1 (kN/m^2)	Absolute Pressure P_{abs} (kN/m^2)	Actual Temperature T_{act} (K)

Use the reference tables in Data Sheet 1 and Data Sheet 2 to find the absolute temperature indicated by the Platinum Resistance Thermometer, from the thermometer output in Ohms.

Add the barometric pressure to the readings from the electronic pressure sensor, to give an absolute pressure reading.

Assuming that the measured temperature of the steam is equal to the vapour point of water, the actual temperature may be found from the absolute pressure, using the graph in Data Sheet 3.

Plot a graph of indicated absolute temperature and actual absolute temperature against time.

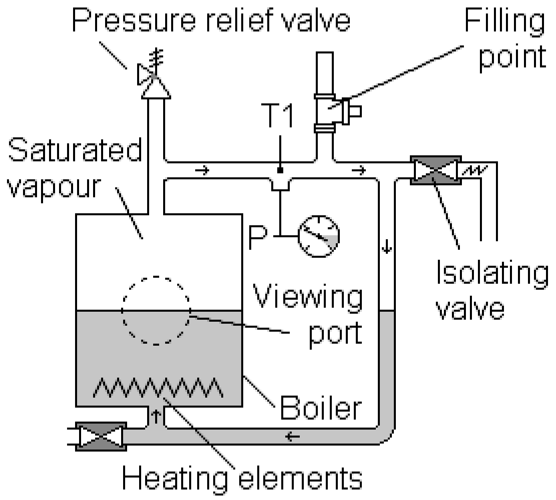
Conclusions

Comment on the shape of the graphs obtained. Discuss any differences between the actual temperature and the temperature indicated by the platinum resistance thermometer output.

Estimate the thermal lag of the thermometer. If results are available, compare the thermal lag at different rates of heating.

What is the significance of these results when measuring saturation pressure? How could the effect of thermal lag be reduced?

Exercise C - Concept of a saturation line



Objective

To study the relationship between pressure and temperature of vaporisation of a fluid.

Method

To heat water contained in a closed system of constant volume, and to measure the resulting changes in temperature and pressure.

Theory

It is commonly understood that the temperature at which water undergoes a liquid-to-vapour phase change varies with pressure. For example, water boils at a lower temperature when at high altitudes, such as encountered on mountains. This relationship between pressure and temperature at which the liquid-to-vapour phase change occurs may be plotted on a graph. The resulting line is termed the *saturation line*. Saturation lines may be obtained for any fluid, although in this experiment water will be used.

When plotted on a graph of absolute pressure P_{abs} against absolute temperature T_{abs}, the result is a smooth curve. The curve does not have a simple describing equation, but over a limited range of pressure it is possible to obtain a good fit using:

$$P_{abs} = p_0 \, e^{\left(\frac{a}{T}\right)} \qquad \text{Equation (1)}$$

This equation is not derived from any theory or underlying physical laws. It only describes behaviour. For any particular range of pressures, there are particular values of the coefficients a and p_0 which minimise the differences between the measured points and the curve given by the equation. These differences arise both through experimental errors (random, scale and zero errors) and because the real behaviour does not perfectly match the describing equation.

Obtaining best-fit values of the coefficients *a* and p_0 may only be obtained by linearising the curve. The usual method for doing this is to take logarithms of Equation (1):

$$\ln P_{abs} = \ln p_0 + a\left(\frac{1}{T}\right)$$ Equation (2)

Therefore a and ln p_0 are respectively, the gradient and the intercept of a graph of ln P_{abs} vs. (1/T).

At an elementary level, the coefficients may be obtained by drawing a best-fit line to a plot of experimental results. The value of a may be obtained as $a = (\Delta y/\Delta x)$. To obtain a good spread of data, the zero of the x-axis will have been suppressed, so the value of p_0 cannot be read from the graph and must be obtained by substituting the co-ordinates of a point on the line into equation (2).

At a more advanced level, the values of a and p_0 may be obtained by applying linear regression, using either a calculator or a spreadsheet.

Equipment Set Up

Check that the calorimeter valve and the drain valve at the base of the boiler are both closed.

Check that the mains power to the console is switched off before filling the boiler.

Open the filling point at the top using the key provided. Fill the equipment using purified or de-ionised water, until the water level is halfway up the sight-glass at the front of the boiler. Do not seal the filling point until instructed later.

Switch on the mains power to the console and switch on the console itself.

Procedure

Allow the water to reach boiling point, indicated by intense movement at the surface and steam escaping from the filling point. Reduce the heater power slightly to maintain a steady but not excessive stream of steam. Wait until the resistance reading (R_{m1}) becomes steady, meaning that all air has been expelled. Note the pressure inside the vessel, as indicated by the pressure sensor P_1, and the resistance indicated by the platinum resistance thermometer R_{m1}. The resistance may be converted into temperature using the tables provided in Data Sheet 1 and Data Sheet 2.

When heating fluid in the boiler, it takes time heat to conduct through the apparatus to the pipework and the temperature probe. The platinum resistance thermometer must reach the same temperature as the fluid before it will provide an accurate reading. This time delay between the fluid reaching a given temperature and the sensor reaching the same value is known as **thermal lag**.

Close the filler valve then return the heater to maximum power.

Allow the water to heat for two minutes, then switch off the heater power. Watch the platinum resistance thermometer output R_{m1}, and wait until the value stabilises. This allows heat to conduct from the fluid to the rest of the apparatus, and thus reduces the effect of thermal lag.

Take a second set of readings from the platinum resistance thermometer and the electronic pressure sensor.

Heat at maximum power for another two minutes then turn the heater off, wait for the temperature reading to stabilise and repeat the sensor readings

Continue in the same way until the pressure reaches 7 bar. Leave the heater power switched off after taking the final set of readings.

Open the isolating valve to the calorimeter, and allow steam to bleed off. This will reduce both the pressure and temperature. Close the valve again after thirty seconds.

Take a second set of data as the system cools, opening the isolating valve for thirty seconds to allow steam to escape, then closing the valve and allowing time for the sensors to stabilise before recording the sensor outputs.

LEAVE THE CALORIMETER ISOLATING VALVE OPEN AFTER THE DATA HAS BEEN TAKEN. Leaving the valve closed, after the pressure reaches atmospheric pressure, may result in partial vacuum inside the apparatus as it cools to ambient temperature. This could permanently damage the apparatus.

Results

Tabulate your results under the following headings:

Measured Output R_{m1} (Ω)	Corrected Output R_{c1} (Ω)	Pressure P_1 (kN/m²)	Absolute Temperature T_{abs} (K)	Absolute Pressure P_{abs} (kN/m²)	$\frac{1}{T_{abs}}$	ln P_{abs}

Plot a graph of ln P_{abs} vs. 1/T, and use the graph to obtain approximate values of a and p_0.

On the same axes as the previous graph, plot a graph of ln P_{abs} calculated using the equation

$$\ln P_{abs} = \ln p_0 + a\left(\frac{1}{T}\right)$$

and the values for a and p_0 obtained from the graph of ln P_{abs} vs. 1/T.

Conclusions

Compare the two graphs and comment on the accuracy of the describing equation.

It is suggested that students begin Exercise D on completion of this exercise.

Exercise D - Steam tables

Objective

To investigate the accuracy of saturation data obtained using basic equipment.

Method

To compare laboratory data with published steam tables. It is recommended that Exercise C, ‘Concept of a saturation line’, is completed before commencing this experiment. The data from Exercise C may then be used for this exercise.

Theory

Published graphs and tables of the liquid-to-vapour phase change temperature over a range of pressures are available for reference. These may be found in relevant textbooks and may be provided by the manufacturers of equipment involving the use of high-pressure steam. These curves are obtained from very accurate experiments, which eliminate experimental error.

In Exercise C, it was seen that a reasonable fit to the saturation line might be obtained using the equation

$$P_{abs} = p_0 \, e^{\left(\frac{a}{T}\right)}$$

However, the range of values for temperature and pressure obtainable without the use of highly specialised equipment is limited. Estimation of ln p_0 is by extrapolation over a logarithmic scale, and small differences in *a* can lead to a wide range of values of p_0.

The limitations of the method used to obtain the relationship between vapour point and pressure may be seen by comparing experimental values obtained during the laboratory exercise with values taken from published steam tables.

Equipment Set Up and Procedure

If the results from Exercise C are available, these may be used and no equipment is required. If there are no previous results available, follow the equipment set up and procedure instructions for Exercise C.

Results

Tabulate your results under the following headings:

Measured Output R_{m1} (Ω)	Corrected Output R_{c1} (Ω)	Pressure P_1 (kN/m^2)	Absolute Temperature T_{abs} (K)	Absolute Pressure P_{abs} (kN/m^2)	$\frac{1}{T_{abs}}$	ln P_{abs}

Plot a graph of ln P_{abs} vs. 1/T, and use this to obtain approximate values of a and p_0. (This may be omitted if the results from Exercise C are available).

Plot a graph of P_{abs} vs. T from the experimental data.

Plot a graph of P_{abs} vs. T, calculating P_{abs} using the equation.

$$P_{abs} = e^{\ln p_0 + a\left(\frac{1}{T}\right)}$$

and the values for a and p_0 obtained earlier. The axes should cover the temperature range 0° - 200° Celsius.

Compare the graphs of P_{abs} vs. T with the graph provided in Data Sheet 3. This graph is taken from steam tables typical of those published in standard thermodynamics texts.

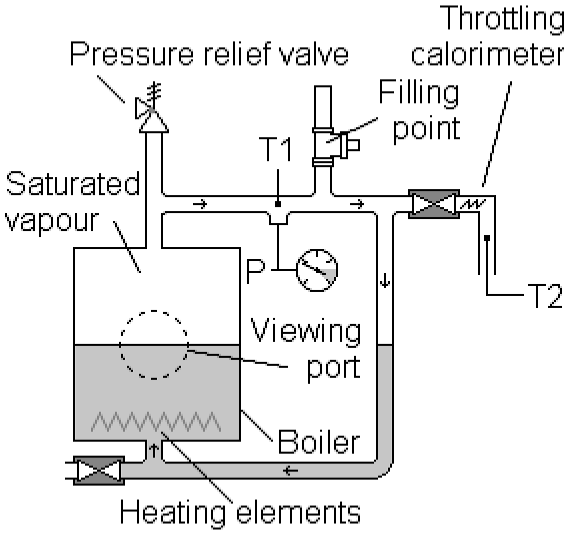
Conclusions

How well does the experimental data compare to the standard graph over the temperature and pressure range covered by the experiment?

How well does the describing equation obtained from the experimental data fit the standard graph?

What are the implications of these results for the design of an automatic monitoring system for liquid-vapour transitions?

Exercise E - Use of the steady flow energy equation



Objective

To determine the quality of steam exiting a pressurised vessel.

Method

To make use of a throttling calorimeter in conjunction with the Steady Flow Energy Equation, in order to calculate the enthalpy of the escaping steam. To determine the quality of the steam using standard reference tables.

Theory

After reaching the saturated liquid stage, heated fluid in the system will form a two-phase liquid-vapour mixture. The ratio of the mass of vapour to the total mass of the mixture is referred to as its *quality*, x. The quality varies from x = 0 (saturated liquid state) to x = 1 (saturated vapour).

From the thermodynamic laws of specific internal energy and enthalpy, it is possible to derive an equation for the specific enthalpy of a two-phase fluid given in terms of the quality:

$$h = h_f + x\,(h_g - h_f) \qquad \text{Equation (1)}$$

where h_f = Enthalpy of vapour

h_g = Enthalpy of liquid

The increase in enthalpy during vaporisation is sometimes termed h_{fg}. Values for the enthalpy of saturated water are provided in Data Sheet 3. A detailed explanation of enthalpy is beyond the scope of this manual.

The thermodynamic laws for conservation of energy in a steady flow process give rise to the Steady Flow Energy Equation:

$$\dot{Q}_{12} + \dot{W}_{12} = \dot{m}\left(h_2 - h_1 + \frac{c_2^{\,2} - c_1^{\,2}}{2} + g\,(z_2 - z_1) \right) \qquad \text{Equation (2)}$$

where $\dot{Q}$ = Rate of change of energy of system

$\dot{W}$ = Rate of doing work by system

$\dot{m}$ = Rate of mass change within system

h_1 = Enthalpy of fluid before throttling

h_2 = Enthalpy of fluid after throttling

c = Velocity of fluid

g = Gravitational constant

z = Potential energy of fluid

Applying this to the throttling process (where heat transfer and changes in potential and kinetic energies are negligible and the system does no work) indicates that the specific enthalpy of the fluid is the same before and after throttling:

$$h_1 = h_2 \qquad \text{Equation (3)}$$

This means that the specific enthalpy of a sample of steam is the same as that of the supply. Substituting back into equation (1) then produces the equation:

$$x = \frac{h_2 - h_f}{h_{fg}} \qquad \text{Equation (4)}$$

The *Two Property Rule* states that the thermodynamic state of a fluid is defined by any two independent properties. Published reference tables are commonly available giving the thermodynamic state of water at given conditions, obtained from accurate experimental data.

The only two intensive properties that can be directly measured in this experiment are temperature and pressure. The sample must be in a state where these two values are independent, ie. superheated steam. This condition is ensured by forcing the sample through a greatly restricted pipe section, producing a large pressure drop, and causing the steam sample to enter the superheated region. In this condition, the measured values of pressure and temperature for the sample may be used in combination with the reference table provided in Data Sheet 4, to determine the steam quality.

Equipment Set Up

Check that the calorimeter valve and the drain valve at the base of the boiler are both closed.

Check that the sensors are correctly connected to the console.

Check that the mains power to the console is switched off before filling the boiler.

Open the filling point at the top using the key provided. Fill the equipment using purified or de-ionised water, until the water level is halfway up the sight-glass at the front of the boiler. Do not seal the filling point until instructed later.

Switch on the mains power to the console and switch on the console itself.

Procedure

Allow the water to reach boiling point, indicated by intense movement at the surface and steam escaping from the filling point. Reduce the heater power slightly to maintain a steady but not excessive stream of steam. Wait until the resistance reading (R_{m1}) becomes steady, meaning that all air has been expelled. Note the pressure inside the vessel, as indicated by the pressure sensor P_1, and the resistance indicated by the platinum resistance thermometer R_{m1}. The resistance may be converted into temperature using the tables provided in Data Sheet 1 and Data Sheet 2.

Close the filling point then set the heater to maximum power. Allow the pressure to rise to 1 bar above atmospheric. Turn the heater control to minimum, and allow the sensors to stabilise.

Take readings for the pressure and temperature inside the boiler, using the reference charts in Data Sheet 1 and Data Sheet 2 to find the temperature corresponding to the reading from the platinum resistance thermometer.

Open the calorimeter valve to bleed off a sample of steam. Wait until the reading for PRT100(2) stabilises then record the pressure and temperature values for the sample, and close the calorimeter valve again.

Increase the pressure and temperature inside the boiler in increments of one bar, to a maximum of seven bar. At each stage, turn the heater control to a minimum and wait for the sensors to stabilise, then take a set of readings.

Switch off the heater.

At maximum pressure, open the calorimeter valve, and allow steam to escape continuously. Take readings in one bar increments as the pressure decreases.

LEAVE THE CALORIMETER ISOLATING VALVE OPEN AFTER THE DATA HAS BEEN TAKEN. Leaving the valve closed, after the pressure reaches atmospheric pressure, may result in partial vacuum inside the apparatus as it cools to ambient temperature. This could permanently damage the apparatus.

Results

Tabulate your results under the following headings:

Corrected Resistance R_{c1} (Ω)	Temperature T_1 (°C)	Absolute Temperature (from T_1) T_{abs} (K)	Pressure P_1 (kN/m^2)	Corrected Resistance R_{c2} (Ω)	Temperature T_2 (°C)	Absolute Temperature (from T_2) T_{abs} (K)	Pressure P_2 (kN/m^2)	Enthalpy of Saturated Liquid (from T_1) h_f (kJ/kg)	Enthalpy of Saturated Vapour (from T_1) h_g (kJ/kg)	Enthalpy of Steam Sample h_2 (kJ/kg)	Quality of Steam Sample x -

Conclusions

Explain the variation in steam quality as pressure and temperature change.

What effect might steam quality have on design considerations for a plant producing or working with superheated water vapour?

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