P.A. HILTON LTD.

EXPERIMENTAL

OPERATING
&
MAINTENANCE MANUAL

BENCH TOP COOLING TOWER

H891

H891M/E/1

NOV 1988

POLICY STATEMENT

After Sales Service

We, P. A. Hilton Ltd., attach considerable importance in being able to retain the confidence and goodwill of our clients in offering an effective after sales service. Every effort is made to answer clients correspondence promptly and to provide a rapid follow up of spares and replacement parts by maintaining comprehensive stocks of components usually available ex-stock.

Should our clients encounter any difficulty in operating or maintaining a Hilton product we would ask that as a first step they contact the Hilton representative in their country or, in the absence of a local representative, write direct to P. A. Hilton Ltd.

In the extreme case a problem may arise in the operation of equipment which could seriously disrupt a teaching or research schedule. In such circumstances rapid advice from the manufacturers is desirable and we wish our clients to know that Hiltons' will accept from them a transfer charge telephone call from anywhere in the world.

We ask our clients to treat this service as an emergency service only and to use it sparingly and wisely. Please do be aware of the time differences that may exist and, before making a telephone call, make notes of the problem you wish to describe. English is a preferred language. Our telephone number is "ROMSEY 388382" and the telephone is normally manned 24 hours every day. Advance notice of an impending telephone call by cable would be appreciated.

Each product manufactured by P. A. Hilton Ltd., is tested under operating conditions in our permanent installations before despatch. Visitors to Horsebridge Mill are encouraged to operate and evaluate our equipment with initial guidance from an Hilton engineer.

Paul A. Hilton.

Gerald A. Hewett.

Finish and Materials in the construction of Hilton products

All components parts used in the construction of Hilton products are finished or manufactured in materials resistant to corrosive attack.

Stainless steels are widely used and other ferrous components are either electro-plated nickel or zinc, or electro-statically coated with an attractive and durable epoxy-resin.

Pipe fittings are manufactured in brass, bronze or stainless steel whilst connecting pipes are copper, plastic or electro-plated steel according to the application.

INSTALLATION AND ASSEMBLY AND OPERATING INSTRUCTIONS ARE SUPPLIED WITH THE EQUIPMENT.

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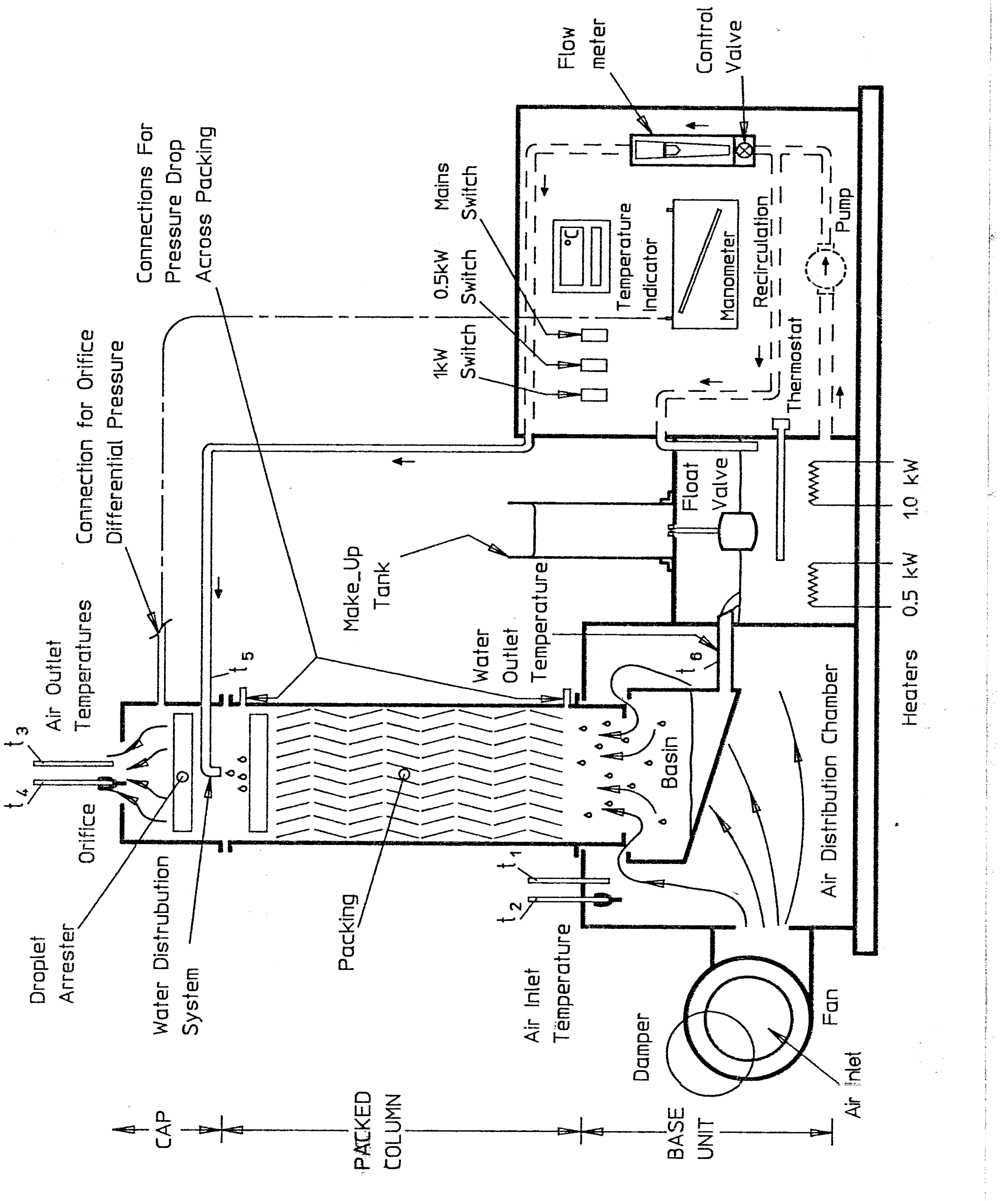
INDEX

Appendix

Addendum

H891 Bench Top Cooling Tower – Basic Unit



SYMBOLS AND UNITS

Symbol	Quantity	Fundamental Unit
C_p	Specific Heat Capacity $\frac{dh}{dt}$	$J\ kg^{-1}\ K^{-1}$
h	Specific Enthalpy	$J\ kg^{-1}$
H	Enthalpy	J
$\dot{H}$	Enthalpy Rate	W
KE	Kinetic Energy	J
m	Mass	kg
$\dot{m}$	Mass Rate	$kg\ s^{-1}$
M	Molecular Mass	$kg(kg\ mole)^{-1}$
p	Pressure	$N\ m^{-2}$
$\mathcal{P}$	Power	W
q	Heat Transfer per Unit Mass	$J\ kg^{-1}$
$\dot{Q}$	Heat Transfer Rate	W
R	Specific Gas Constant	$J\ kg^{-1}\ K^{-1}$
Ro	Universal Gas Constant	$J(kg\ mole)^{-1}\ K$
t	Temperature (Customary)	$^{\circ}C$
T	Temperature (Absolute)	K
v	Specific Volume	$m^3\ kg^{-1}$
y	Time Interval	s
x	Orifice Differential	$mm\ H_2O$
ω	Specific Humidity	$kg\ kg^{-1}$
ϕ	Relative Humidity	-
Δ	Finite Change	-

Presentation of Numerical Data

In this manual, numerical quantities obtained during experiments, etc., are expressed in a non-dimensional manner. That is, the physical quantity involved has been divided by the units in which it has been measured.

As an example:

Pressure $\frac{p}{10^3\ Nm^{-2}}$	150	

This indicates that $\frac{p}{10^3\ Nm^{-2}} = 150$

or $\underline{p = 150 \times 10^3\ N\ m^{-2}}$

alternatively $\underline{p = 150\ kN\ m^{-2}}$

Suffixes

A	Air at entry to base of column
B	Air at exit from top of column
C	Water at entry to top of column
D	Water at exit from basin
E	Water in make-up tank
d	Dry Bulb
w	Wet Bulb
s	Water Vapour (steam)
a	Air (dry)
t	Total
f	Saturated Liquid

Temperatures

1	Dry bulb temperature of air entering base of column
2	Wet bulb temperature of air entering base of column
3	Dry bulb temperature of air at exit from column
4	Wet bulb temperature of air at exit from column
5	Water temperature on entering column
6	Water temperature on leaving column
7	Water in make-up tank

USEFUL INFORMATION

1. Orifice Constant: $\dot{m}_a = 0.0137\sqrt{\frac{x}{v_B}} = 0.0137\sqrt{\frac{x}{(1+\omega_B)va_B}}$

where m_a = Dry air mass flow rate ($kg\ s^{-1}$)
x = Orifice differential ($mm\ H_2O$)
v_B = Specific volume of steam and air mixture leaving top of column ($m^3\ kg^{-1}$)
va_B = Specific volume of dry air leaving top of column ($m^3\ kg^{-1}$)
ω_B = Specific humidity of air leaving top of the column ($kg\ kg^{-1}$)

2. Energy Transferred to Water by Pump: 0.1kW

3. Water Capacity of System: 3.0 litre (excluding make-up tank)

4. Dimensions of Column: 150mm x 150mm x 600mm high.

5. Packing Data

	A	B	C
Number of Decks	8	8	8
Number of Plates per Deck	7	10	18
Total Surface Area of Packing m^2	0.83	1.19	2.16
Height of Packing m	0.48	0.48	0.48
Packing "Density" $\frac{\text{Area}}{\text{Vol}}$ m^{-1}	77	110	200

6. Constants and Conversion Factors
Specific heat capacity of water (Cp_w): $4.18\ kJ\ kg^{-1}\ K^{-1}$
Specific heat capacity of air (Cp_a): $1.005\ kJ\ kg^{-1}\ K^{-1}$
$1\ bar = 10^5\ N\ m^{-2} = 100\ kN\ m^{-2}$
$1\ kW = 3412\ Btu\ h^{-1}$
For air, $R = 0.2871\ kJ\ kg^{-1}\ K^{-1}$
For steam (H_2O), $M = 18\ kg(kg\ mole)^{-1}$
Universal Gas Constant (Ro) $= 8.3143\ kJ(kg\ mole)^{-1}\ K^{-1}$

7. Note: The heating elements are rated (subject to a manufacturing tolerance) at 240V. At other voltages, the nominal rating should be multiplied by $\left(\frac{\text{local voltage}}{240}\right)^2$.

BENCH TOP COOLING TOWER H890

INTRODUCTION

The Hilton Bench Top Cooling Tower H890 has been specifically designed to give students an appreciation of the construction, design and operational characteristics of a modern evaporative cooling system. The unit is also an excellent example of an "open system" through which two streams of fluid flow (water and air) and in which there is a mass transfer from one stream to the other.

The Bench Top Cooling Tower is completely self-contained and includes both the simulated heating load and the circulating pump. It has much the same configuration as a full size forced draught cooling tower, has the same characteristics, and stabilises quickly.

Convincing energy and mass balances are obtained, and students can quickly investigate the effects of

Air flow rate
Water flow rate
Water temperature
Cooling load
and Packing density

on the performance of a cooling tower.

DESCRIPTION

(Please refer to the schematic diagram on Page 1)

Water Circuit

Warm water is pumped from the load tank through the control valve and water flow meter to the column cap. After its temperature is measured, the water is uniformly distributed over the top packing deck and, as it spreads over the plates, a large thin film of water is exposed to the air stream. During its downward passage through the packing, the water is cooled, largely by the evaporation of a small portion of the total flow.

The cooled water falls from the lowest packing deck into the basin, where its temperature is again measured and then passes into the load tank where it is re-heated before recirculation.

Due to evaporation, the level of the water in the load tank tends to fall. This causes the float operated needle valve to open and transfer water from the make-up tank into the load tank. Under steady conditions, the rate at which the water leaves the make-up tank is equal to the rate of evaporation plus any small airborne droplets in the air discharge.

Air Circuit

Air from the atmosphere, enters the fan at a rate which is controlled by the intake damper setting. The fan discharges into the distribution chamber and the air passes wet and dry bulb sensors before entering the packed column. As the air flows through the packings, its moisture content increases and the water is cooled. On leaving the top of the column the air passes through the droplet arrester which traps most of the entrained droplets and returns them to the packings. The air is then discharged to the atmosphere via the air measuring orifice and further wet and dry bulb sensors.

Flow through the column may be observed through the transparent casing.

Three sets of different packings, each in its own casing, are available.These may be interchanged quickly and without using tools.

A fourth empty column is available for use where students wish to investigate locally made packings.

Additional Facility

The Bench Top Cooling Tower may be used to demonstrate industrial practice in which a cooling tower is used to cool water from a process.

To do this, a small pump is installed to circulate cooled water from the load tank drain point, through the process requiring cooling, and then back to the water distributor at the top of the cooling tower.

The Hilton Refrigeration Laboratory Unit R712 is suitable for connecting in this manner.

See Page 42, Use of Bench Top Cooling Tower H891 in Conjunction with other Hilton Equipment.

SPECIFICATION

Base Unit:	All components are mounted on a robust G.R.P. base plate with integral instrument panel. Components include: (i) Air distribution chamber. (ii) A tank with heaters to simulate cooling loads of 0.5, 1.0 and 1.5kW. (iii) A make-up tank with gauge mark and float operated control valve. (iv) A centrifugal fan with intake damper to give 0.06kg s^{-1} max. air flow. (v) A bronze and stainless steel glandless pump. (vi) A water collecting basin. (vii) An electrical control panel.
Packed Column:	Four packed columns (A, B, C and D), each 150mm x 150mm x 600mm high, and fabricated from clear P.V.C., are available. Columns A, B and C have pressure tapping points and each contain eight decks of inclined, wettable, laminated plastic plates, retained by water distribution troughs. Column A has 7 plates per deck (giving 77m^2 per m^3) Column B has 10 plates per deck (giving 110m^2 per m^3) Column C has 18 plates per deck (giving 200m^2 per m^3) Column D has no packings.
Column Cap:	This fits on top of the chosen column and includes: (i) An 80mm dia. sharp edged orifice and pressure tapping. (ii) A droplet arrester. (iii) A water distributor.

INSTRUMENTATION

Temperature Indicator	6 point digital temperature indicator with Type K thermocouple sensors to measure terminal water temperatures, and wet and dry bulb air temperatures.
Inclined Tube Manometer	0 to 40mm H_2O, to measure orifice differential pressure, or packing resistance.
Variable Area Flow Meter	0 to 50gm s^{-1}, with control valve, for water flow rate to packings

DIMENSIONS

Net Weight	24kg
Height	725mm
Width	710mm
Depth	240mm

SAFETY

(i) Thermostat in load tank.
(ii) All heaters fitted with thermal cut-outs.
(iii) Fan intake fitted with mesh guard.
(iv) All electrical circuits protected by circuit breakers.
(v) R.C.C.B. fitted.

SOFTWARE

Detailed Instruction Manual
Large plastic coated psychrometric chart.

SPARES

Sufficient for at least two years of normal usage.

PRECAUTIONS AND WARNINGS

1. Whenever possible, distilled or demineralised water should be used for filling and topping up of this unit. (This is to eliminate problems with scale and unsightly stains resulting from water impurities.)

2. The water and air stream temperature must not be allowed to exceed 50°C.

3. The make-up tank must always be refilled before the depth of water falls below 50mm.

4. The make-up tank should be allowed to fall to about 50mm whenever the unit is inoperative for more than two hours. (This is to ensure that any leakage past the float valve does not result in an overflow from the load tank.)

5. The system should be completely drained and refilled with fresh water:
   (i) After approximately 20 hours operation (more frequently in dusty conditions).
   (ii) When the unit is to be inoperative for several days. This is to prevent the growth of algae and the formation of sludge.

6. The pump must not be switched on unless the system is filled with water. (See "Preparation 3 to 7" on Page 8 for method of priming pump.)

7. The two wet bulb reservoirs must be filled with distilled water.

8. If the water level in the load tank falls below the arrowed position, switch off the heaters and investigate the cause.

PROTECTION DEVICES

Water Level

A sight glass fitted to the load tank indicates the water level within the tank. During operation, this level must not be allowed to fall below the minimum water level indicated.

Water Temperature

The water temperature must not exceed 50°C and a thermostat is fitted in the load tank to switch off the heaters should this temperature be exceeded. The heater switch neon indicators will not illuminate when the thermostat operates.

Heating Elements

All heating elements are provided with automatically re-set thermal protection devices which will operate in the unlikely event of the element overheating.

INSTALLATION AND ASSEMBLY

1. Unpack the cooling tower and examine it for damage during transit. If any damage is observed, notify the insurers immediately.

2. Check that the local electrical supply (or if used, the transformer output) agrees with the label on the side of the electrical panel.

3. Place the base unit on a strong table close to a suitable power supply and where there is a good air circulation.

4. Fit the 75mm dia. clear plastic tube into the grey socket on top of the load tank and push it fully home.

   (Notes: (i) The tube and 'O' ring should be moistened to reduce friction.
   (ii) The gauge mark should be to the top front of the tube.)

5. Ensure that the knitted nylon "splash preventers" are uniformly positioned in the basin. (The basin is accessible through the square hole in the top of the base unit.)

6. Fit the chosen packed column onto the screwed studs on the base unit and lightly tighten the four knurled nuts.

   (Note: The pressure tappings are on the front face of the column.)

7. Place the column cap on the four screwed studs at the top of the column and lightly tighten the knurled nuts.

   (Note: When viewed from the front, the water connection is to the right of the cap. Ensure that the three water distribution pipes are aligned with the three troughs in the top of the column.)

8. Connect the plastic water supply pipe from the base unit to the union on the right-hand side of the cap, taking care not to damage the thermocouples in the sleeve attached to the pipe.

9. Fit the "rod" thermocouple sensor into the union on the top of the water connections to the cap. Fit the two clear plastic air temperature outlet sensors to the clips on the column cap so that the sensing ends are in the air stream. The wick of the wet bulb sensor must be placed in the water reservoir formed in the column cap. Fill the reservoir with distilled water.

10. Fill the reservoir of the air inlet wet bulb temperature sensor with water, and then fit both wet and dry bulb sensors in the holes formed in the top of the air distribution chamber.

11. Connect the orifice tapping on the cap to the left-hand connection on the manometer.

12. 220/240V Units
    Connect the three core electrical cable provided to the local power supply via a suitable fused connection (for a 2kW load).

The BROWN cable is	LIVE
" BLUE " "	NEUTRAL
" GREEN/YELLOW "	EARTH (GROUND)

110/120V (Nominal) Units
The transformer supplied is suitable for input voltages of between 110 and 130 volts (110 to 130V in 5 volt steps).

Before connection to the transformer, the local mean supply voltage should be measured. When this has been determined, the live input of the supply should be connected to the terminal having the nearest voltage label. The Neutral of the supply is connected to the 0V terminal and the Earth or Ground of the supply connected to the terminal labelled 'E'.

The supply cable, cable gland, and switched and fused outlet should be suitable for supplying 30A and be to a standard corresponding to the local regulations.

The 220/240V socket outlet on the transformer should be connected to the plug on the power supply cable emerging from the rear of the unit.

The BROWN cable is	LIVE
" BLUE " "	NEUTRAL
" GREEN/YELLOW "	EARTH (GROUND)

The transformer should be placed in a protected position close to the unit and power supply, but where air can circulate freely.

PREPARATION FOR USE

1. Ensure that the drain cock at rear of load tank is closed, that all switches are off and that the water control valve (at the bottom of the water flow meter) is fully open.

2. Check that the unit is level.

3. Remove the column (with cap in situ), then carefully pour 3.0 litre water through the square opening into the basin.

4. Refit the column and lightly tighten the knurled nuts.

5. Switch on the mains so that the circulating pump runs. If the water flow is less than 40 g s^{-1}, or if the pump is noisy, switch off. It is probable that air is present in the pump.

   To clear, raise the left hand end of the unit by about 500mm for about 30 sec. Repeat until a satisfactory flow is achieved.

   (Note: The pump must not be allowed to run for a long period until the air has been eliminated.)

6. Wetting of the distribution trough may be expedited by removing the cap, then moistening the sides with the aid of a tooth brush.

7. Pour water into the make-up tank to the gauge mark.

9. Remove the plugs from the manometer and check the fluid level. Using the plastic tube supplied, connect the orifice pressure tapping point in the cap to the left-hand connection on the manometer.

10. Fully open the fan inlet shutter and check that the manometer is operating correctly. (The differential pressure should be about 16mm H_2O.)

11. Allow the unit to run for a few minutes for the float valve to adjust the level in the load tank. Top up the make-up tank as required.

12. Check the levels in the wet bulb thermometer reservoirs.

The unit is now ready for use and may be set to the desired conditions.

Note

When the water flow rate is reduced there will be a reduction in the quantity of water held by the packings and the level in the load tank will rise accordingly, closing the float valve.

Although evaporation will eventually restore the correct level in the load tank, the process can be accelerated by draining off water from the load tank drain until the level in the make up tank is seen to fall.

SHUTTING DOWN

1. Reduce the level in the make-up tank to about 50mm by running normally.

2. Switch off both heaters.

3. After about two minutes switch off all power supplies.

4. If the unit is to be idle for several days it should be completely drained.

CARE AND MAINTENANCE

Sludge in Load Tank

In dusty conditions a certain amount of sludge may collect in the basin and load tank.

If this cannot be removed by filling and draining two or three times, the column and load tank lid should be removed. The sludge can then be loosened with a small brush and washed away.

CAUTION: When the make-up tank is removed, care must be taken to prevent damage to the float and needle valve, and when the tank is replaced, the screws should be only lightly tightened.

Pump Filter

If after venting air from the pump (See Page 8) the water flow rate is less than 40 gm s^{-1}, it is probable that the intake filter is blocked.

To clean the pump filter:

(i) Remove the make-up tank lid taking care not to damage the float valve.
(ii) Using a tooth brush and fresh water, clean the filter.
(iii) Drain water from the system and refill with clean water.
(iv) Replace the make-up tank and lightly tighten the screws.

In extreme circumstances it may be necessary to undo the hex nut which secures the filter and remove the filter for cleaning. Note the nut should be only lightly tightened.

Columns and Packings

To protect these from dust and damage when not in use, these should be kept in a cupboard or in the boxes provided.

External

If the external surfaces require cleaning, a mild detergent and water only should be used. The surface of the P.V.C. is relatively soft and will be damaged by abrasive cleaning materials.

Ensure that no detergent is allowed to enter the water circulation system as it may be extremely difficult to remove.

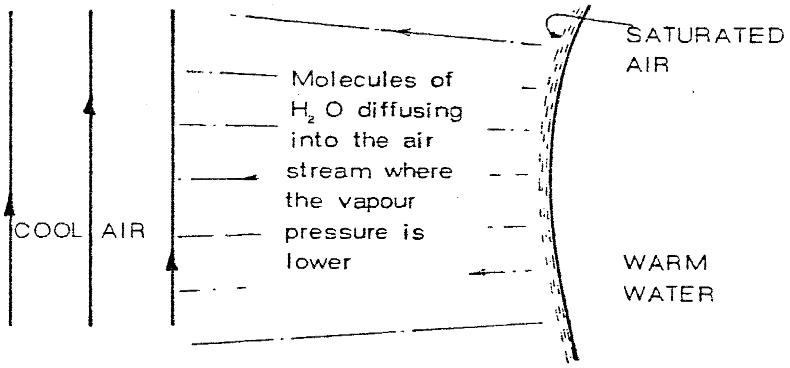
THEORY

Cooling Tower Terms

Cooling Range	The difference between the water temperature at entry to and exit from the tower.
Cooling Load	The rate at which heat is removed from the water. This may be expressed in kW, Btu/h or k Cal/h.
Make-Up	The quantity of fresh water which must be supplied to the water circuit to make good the losses due to evaporation and other causes.
Drift or Carry Over	Droplets of water which are entrained by the air stream leaving the tower.
Packing or Fill	The material over which the water flows as it falls through the tower, so that a large surface area is presented to the air stream.
Approach to Wet Bulb	The difference between the temperature of the water leaving the tower and the wet bulb temperature of the air entering. $T_6 - T_2$
Drain Down	Water deliberately removed from the water system to prevent the excessive concentration of dissolved solids due to evaporation and sludge due to impurities from the atmosphere.

Basic Principles

Consider the surface of a warm water droplet or film in contact with an air stream.



Assuming that the water is hotter than the air, it will be cooled:

(i) By radiation - This effect is likely to be very small at normal conditions and may be neglected.

(ii) By conduction and convection - This will depend on the temperature difference, the surface area, air velocity, etc.

(iii) By evaporation - This is by far the most important effect. Cooling takes place as molecules of H_2O diffuse from the surface into the surrounding air. These molecules are then replaced by others from the liquid (evaporation) and the energy required for this is taken from the remaining liquid.

Evaporation from a Wet Surface

The rate of evaporation from a wet surface into the surrounding air is determined by the difference between the vapour pressure at the liquid surface, i.e. the saturation pressure corresponding with the surface temperature, and the vapour pressure in the surrounding air. The latter is determined by the total pressure of the air and its absolute humidity.

In an enclosed space, evaporation can continue until the two vapour pressures are equal, i.e. until the air is saturated and at the same temperature as the surface. However, if unsaturated air is constantly circulated, the wet surface will reach an equilibrium temperature at which the cooling effect due to the evaporation is equal to the heat transfer to the liquid by conduction and convection from the air, which under these conditons, will be at a higher temperature.

The equilibrium temperature reached by the surface under adiabatic conditions, i.e. in the absence of external heat gains or losses, is the "wet bulb temperature", well known in connection with hygrometry.

In a cooling tower of infinite size and with an adequate air flow, the water leaving will be at the wet bulb temperature of the incoming air.

For this reason, the difference between the temperature of the water leaving a cooling tower and the local wet bulb temperature is an indication of the effectiveness of the cooling tower.

The "Approach to Wet Bulb" is one of the important parameters in the testing, specification, design and selection of cooling towers.

Conditions within a cooling tower packing are complex due to the changing air temperature, humidity and water temperature as the two fluids pass through the tower - usually in a contra flow fashion.

Cooling Tower Performance

The following factors affect the performance of a cooling tower:

(i) The air flow rate
(ii) The water flow rate
(iii) The water temperature
(iv) The air temperature and humidity at inlet (particularly the wet bulb temperature)
(v) The type of packing used
(vi) The area and volume of the packing

The Bench Top Cooling Tower enables these factors to be varied so that an overall appreciation of cooling tower characteristics can be obtained.

THERMODYNAMIC PROPERTIES

Water

The specific enthalpy of saturated water is assumed to be zero at the triple point (0.01°C and 0.00611 bar (611 N m^{-2}), which is taken as datum.

Thermodynamic tables give the specific enthalpy of saturated water (h_f) at a range of temperatures above the datum condition, e.g. from tables (Ref.7, Page 47) at 20°C, the value of h_f is 83.9 kJ kg^{-1}, the saturation pressure is 0.02337 bar (2.337 kN m^{-2}) and the specific volume is 0.001m^3 kg^{-1}.

Water in the Bench Top Cooling Tower is at atmospheric pressure, usually about 1.013 bar (101.3 kN m-2), and if the water is at say 20°C it must be "compressed liquid", as its pressure is above the saturation pressure.

The specific enthalpy of compressed liquid is given by $h = h_f + v_f(p - p_{sat})$

so that water at 20°C and 101.3 kN m^{-2} has a specific enthalpy of

$$\begin{aligned} h &= 83.9 \times 10^3 + 0.001(101300 - 2337) \text{ J kg}^{-1} \\ h &= 83.9 \times 10^3 + 99 \text{ J kg}^{-1} \\ h &\simeq 84 \text{ kJ kg}^{-1} \end{aligned}$$

It will be seen that at the conditions likely to be encountered in a cooling tower, $h \simeq h_f$ at the given temperature, i.e. the correction for pressure is insignificant.

Specific Heat Capacity (Cp)

If water is cooled from say 50°C to 20°C at atmospheric pressure, its specific enthalpy will fall from 209.3 to 83.9 kJ kg^{-1}, i.e. a decrease of 125.4 kJ kg^{-1}.

This is an average change $\frac{\Delta h}{\Delta t}$ of $\frac{125.4}{30} = 4.18 \text{ kJ kg}^{-1} \text{ K}^{-1}$.

The rate of change of enthalpy with respect to temperature, (i.e. $\frac{dh}{dt}$) is given symbol Cp (often called the specific heat at constant pressure).

Over the range of temperatures likely to be used in the Bench Top Cooling Tower, we may therefore use for water,

$$\left.\begin{aligned} \boxed{\Delta h = Cp\,\Delta t} \\ \text{and } h = Cp\,t \end{aligned}\right) \text{ where } Cp = 4.18 \text{ kJ kg}^{-1}$$

Dalton's and Gibbs Laws

Air is a mixture of "dry air" (oxygen, nitrogen and other gases) and water vapour.

The behaviour of such a mixture is set out in the laws of Dalton and Gibbs from which the following may be deduced:

(i) The total pressure of the air is equal to the sum of the pressures which the "dry air" and the water vapour each and alone would exert if they were to occupy the volume of the mixture at the temperature of the mixture.

(ii) The dry air and the water vapour respectively obey their normal property relationships at their partial pressures.

(iii) The enthalpy of the mixture may be found by adding together the enthalpies which the dry air and water vapour each would have as the sole occupant of the space occupied by the mixture and at the same temperature.

The "water vapour", "steam" or "moisture" content of the air is denoted by its "HUMIDITY".

"Absolute or Specific Humidity" (ω) is the ratio $\frac{\text{Mass of Water Vapour}}{\text{Mass of Dry Air}}$ (I)

"Relative Humidity" (ϕ) is the ratio

$$\frac{\text{Partial Pressure of Water Vapour in the Air}}{\text{Saturation Pressure of Water Vapour at the same Temperature}} \qquad \text{(II)}$$

"Percentage Saturation" is the ratio

$$\frac{\text{Mass of Water Vapour in a given volume of Air}}{\text{Mass of same volume of Saturated Water Vapour at the same Temperature}} \qquad \text{(III)}$$

It can be shown that at the conditions within a cooling tower, i.e. at high humidities, there is very little difference between the "Relative Humidity" and the "Percentage Saturation" and for convenience, they will be regarded as equal in the following.

Hygrometers are instruments for measuring the H_2O content of the atmosphere.

Many different types of hygrometer are available but the Bench Top Cooling Tower uses the well known "wet" and "dry" bulb type for which a large amount of data is available.

In this hygrometer, the wet bulb thermometer bulb is enclosed by a water wetted fabric sleeve. Evaporation from this sleeve causes the temperature indicated by the wet bulb thermometer to be lower than that indicated by the "dry" bulb thermometer. (See Page 11)

Observation of these temperatures in conjunction with published tables or charts enables the humidity and other properties of the air to be determined.

Alternatively, the pressure of the water vapour in the atmosphere may be obtained by substitution in the equation (due originally to Regnault, August and Apjohn),

$$p_s = p_{sat_W} - 6.666 \times 10^{-4}\, p_t(t_D - t_W)$$

where, p_s is the pressure of the water vapour in the air/(mbar)

p_{sat_W} is the saturation pressure of water vapour at the temperature of the wet bulb/(mbar)

p_t is the total air pressure (normally atmospheric pressure)/(mbar)

t_D is the temperature of dry bulb/°C

t_W is the (sling) temperature of wet bulb/°C

Effect of Air Velocity on the Indicated Wet Bulb Temperature

The "sling" wet bulb temperature used by the psychrometric charts and tables is that indicated by a wet bulb sensor placed in an air stream having a velocity of 3.5m s^{-1} or more.

At high relative humidities, there is little error if the sensor is placed in a stream having a lower velocity, but at low relative humidities an appreciable error may occur.

At outlet from the Bench Top Cooling Tower the sensors are placed in air with a very high relative humidity and where the air velocity is high. The wet bulb temperature indicated will therefore be accurate.

The wet bulb sensor in the air chamber is in a region where the velocity is lower and where the relative humidity is much lower. It is therefore advisable to confirm the wet bulb reading as follows:

(i) Ease the bung securing the wet bulb sensor from the top of the air chamber.

(ii) Draw the sensor upward until the air escapes between the socket and the sleeve. The air velocity over the sleeve will now be about 10m/s and the "sling" temperature will quickly be indicated by the sensor.

(iii) Compare the "sling" reading with that previously indicated - any discrepancy can be allowed for in subsequent observations at the same conditions.

The application of the foregoing Laws and relationships and the evaluation of properties is best illustrated by a worked example as follows.

WORKED EXAMPLE

Properties of Air

Determine the specific enthalpy (relative to 0.01°C), specific volume and "moisture" content of air at a total pressure of 1.013 bar (101.3 kN m^{-2}) and having dry and wet bulb (sling) temperatures of 20°C and 14°C respectively.

From Thermodynamic Tables, $p_{sat_w} = 15.97$ mbar.

Using the Regnault/August/Apjohn expression,

$$\begin{aligned} p_s &= 15.97 - 6.6666 \times 10^{-4} \times 1013(20 - 14) \text{ mbar} \\ &= \underline{\underline{11.92}} \text{ mbar} \end{aligned}$$

The saturation pressure at 20°C is 23.37 mbar.

$$\begin{aligned} \text{Thus, the Relative Humidity} &= \frac{11.92}{23.37} \\ &= \underline{\underline{51\%}} \end{aligned}$$

From the foregoing or from the tables (Ref. 6, Page 47) we see that the relative humidity is 51% and that the steam pressure is 11.92mbar.

From Thermodynamic Tables (Ref. 3, Page 47) the saturation temperature of water vapour at 11.92 mbar is approximately 9.5°C. The water vapour is therefore superheated. Its enthalpy may be obtained from tables or charts, if available, or calculated from

$$\begin{aligned} h &= h_g + Cp_{steam} \times \text{degrees of superheat} \qquad (Cp \text{ for steam} \simeq 1.9 \text{ kJ kg}^{-1}) \\ &= 2517.4 + 1.9(20 - 9.5) \text{ kJ kg}^{-1} \\ &= \underline{\underline{2537}} \text{ kJ kg}^{-1} \end{aligned}$$

The specific volume of water vapour at this condition may be found from tables or charts, if available, or may be calculated with sufficient accuracy from the gas equation,

$$\begin{aligned} v &= \frac{RT}{p} \quad \text{where} \quad R = \frac{Ro}{M} \\ v &= \frac{Ro\ T}{MT} \\ &= \frac{8.3143 \times 10^3 \times 293}{18 \times 0.01192 \times 10^5} \text{ m}^3 \text{ kg}^{-1} \\ &= \underline{\underline{113.52}} \text{ m}^3 \text{ kg}^{-1} \end{aligned}$$

Thus, a volume of 113.52 m^3 of air will contain 1 kg water vapour having an enthalpy of 2537 kJ kg^{-1}.

The mass of "dry air" in the same volume may also be found from the gas equation provided the air pressure is known.

From Dalton's Law,

$$\begin{aligned} p_t &= p_a + p_s \\ p_a &= p_t - p_s \\ &= 1.013 - 0.01192 \text{ bar} \\ p_a &= 1.001 \text{ bar} \end{aligned}$$

$$\begin{aligned} \dot{m} &= \frac{p_a V}{R_a T} \\ &= \frac{1.001 \times 10^5 \times 113.52}{287.1 \times 293} \\ &= \underline{\underline{135}} \text{ kg} \end{aligned}$$

The enthalpy of this (relative to 0.01°C) is given by

$$\begin{aligned} H &= m\,Cp(t - 0.01) \\ &= 135 \times 1.005(20 - 0.01) \text{ kJ} \\ &= \underline{\underline{2714}} \text{ kJ} \end{aligned}$$

Thus 113.52 m^3 of "air" will contain, 1 kg water vapour having an enthalpy 2537 kJ

$\underline{135}$ kg "dry air" " " " $\underline{2714}$ kJ

i.e. $\underline{\underline{136}}$ kg air " " " $\underline{\underline{5251}}$ kJ

(Gibbs Law)

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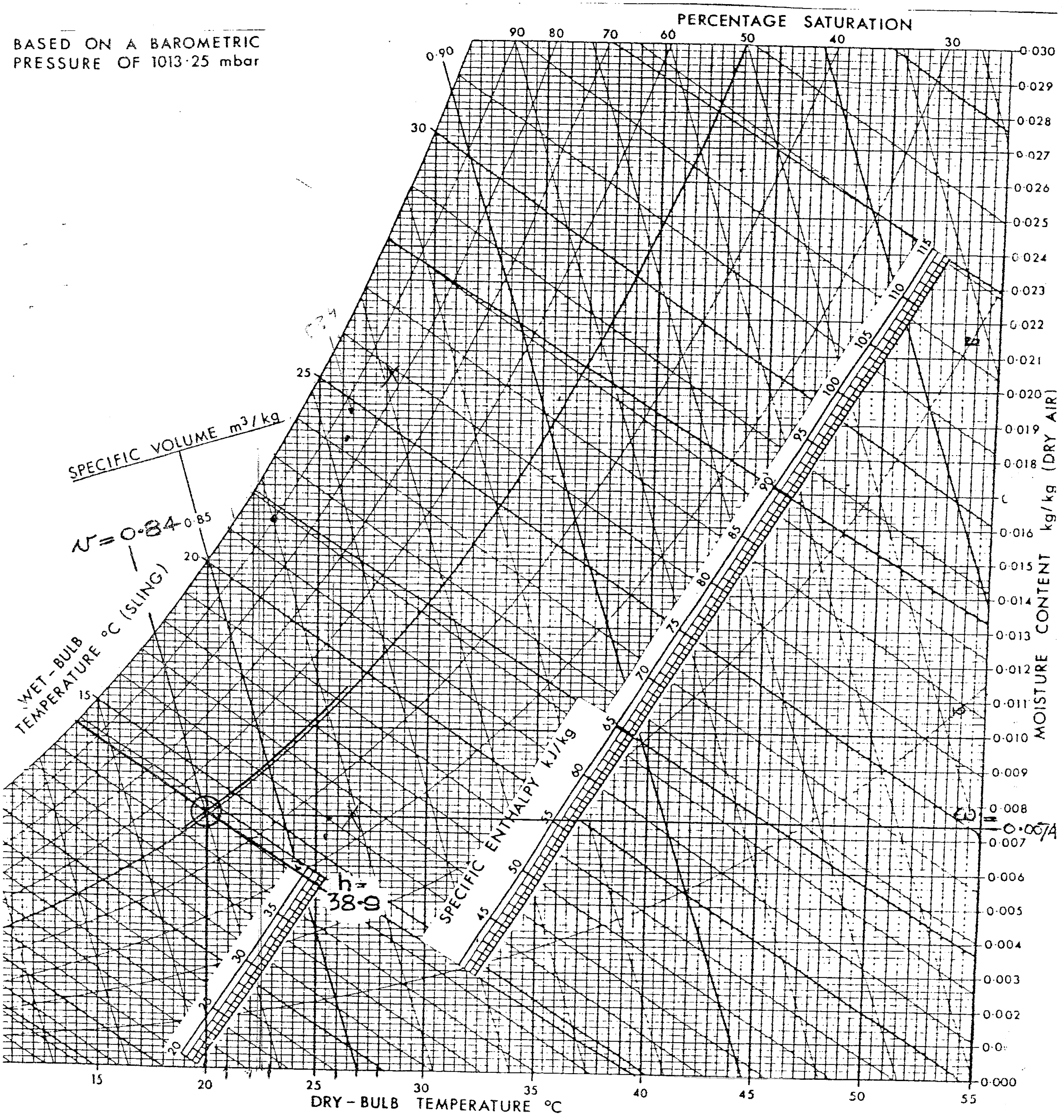
PSYCHROMETRIC CHART

BASED ON A BAROMETRIC PRESSURE OF 1013·25 mbar



The specific enthalpy of this mixture is, $\frac{5251}{136}$ kJ kg^{-1}

or 38.6 kJ kg^{-1}

It is often convenient to express the enthalpy of the dry air/water vapour mixture (relative to 0.01°C) per kg of dry air.

In this case,

$$h = \frac{5251}{135} \text{ kJ (kg dry air)}^{-1}$$

$$h = 38.9 \text{ kJ (kg dry air)}^{-1}$$

The Specific Volume of the mixture is obtained from $v = \frac{V}{m}$

$$v = \frac{113.52}{136} \text{ m}^3 \text{ kg}^{-1}$$

$$v = 0.835 \text{ m}^3 \text{ kg}^{-1}$$

Again, it is sometimes useful to quote the specific volume of the dry air,

$$v = \frac{113.52}{135} \text{ m}^3\text{(kg dry air)}^{-1}$$

$$= 0.841 \text{ m}^3\text{(kg dry air)}^{-1}$$

The ratio, $\frac{\text{Mass of Water Vapour}}{\text{Mass of Dry Air}}$, is called specific humidity (ω)

$$\omega = \frac{1}{135.0} \text{ kg kg}^{-1}$$

$$\omega = 0.00740 \text{ kg kg}^{-1}$$

Psychrometric Chart

The foregoing is rather tedious and it is usually far more convenient to use a psychrometric chart (Page 15) for the appropriate atmospheric pressure.

Using the information given on Page 14, i.e. Dry Bulb 20°C, Wet Bulb 14°C, Total Pressure 101.36 kN m^{-2}, the specific enthalpy, specific volume and specific humidity can be readily obtained as shown. (These figures should be compared with those found on Pages 14 and 16

Specific Volume of Air - Effect on Orifice Calibration

The values of specific volume given on a psychrometric chart are for 1 kg of DRY air at the stated total pressure.

However, associated with 1 kg of dry air is ω kg of water vapour, giving a total mass of $1 + \omega$ kg.

The specific volume of the air and steam mixture is thus $\frac{v_a}{1 + \omega}$.

The air mass flow rate through the orifice is given by

$$\dot{m} = 0.0137 \sqrt{\frac{x}{v_B}}$$

where v_B is the true specific volume.

Thus,

$$\dot{m} = 0.0137 \sqrt{\frac{x(1 + \omega_B)}{v_{a_B}}}$$

The mass flow rate of dry air, $= \frac{1}{1 + \omega} \times$ Mass flow rate of air and steam mixture

$$\therefore \quad \dot{m}_a = \frac{1}{1 + \omega} \times 0.0137 \sqrt{\frac{x(1 + \omega_B)}{v_{a_B}}}$$

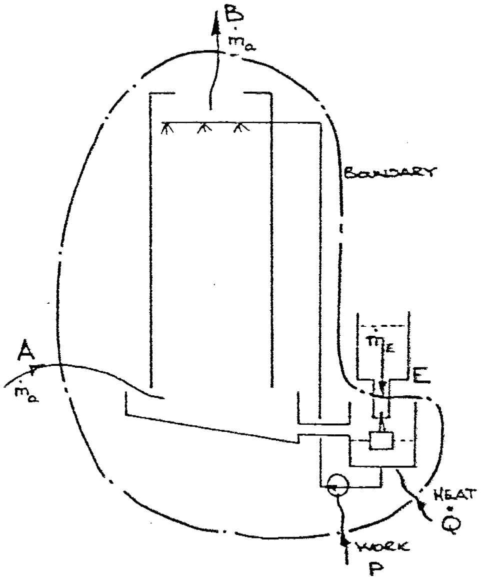
$$\dot{m}_a = 0.0137 \sqrt{\frac{x}{v_{a_B}(1 + \omega_B)}}$$

However, at the conditions likely to be encountered, ω_B is unlikely to exceed 0.025 and the error involved if ω_B is neglected is very small.

Note: A range of psychrometric charts for different atmospheric pressures is available (Ref. 7, Page 47). However, errors in using the standard chart (1.013 bar) are likely to be small over the variation of atmospheric pressures normally experienced at altitudes up to 500m above sea level.

Application of Steady Flow Energy Equation

Before the equation can be applied the system must be defined.



SYSTEM. F.

For the System F, indicated by the chain line,

- Heat is transferred at the load tank, i.e. the process load, and possibly a small quantity to surroundings.
- Work is transferred at the pump.
- Low humidity air enters at A.
- High humidity air leaves at B.
- Make-up (equal to the increase of moisture in the air stream) enters at E.

From the steady flow equation, $\dot{Q} - P = \dot{H}_{Exit} - \dot{H}_{Entry}$

$$\dot{Q} - P = (\dot{m}_a h_{da} + \dot{m}_s h_s)_B - (\dot{m}_a h_{da} + \dot{m}_s h_s)_A - \dot{m}_E h_E \qquad \text{(IV)}$$

(Note: The pump power P is -ve since it is a work input.)

The specific enthalpies of air, water vapour and water can be evaluated as previously described (Pages 13 to 16), although this is tedious.

However, if the enthalpy of the air includes the enthalpy of the steam associated with it, and this quantity is expressed per unit mass of dry air, (See Page 14), the equation may be written

$$\dot{Q} - P = \dot{m}_a(h_B - h_A) - \dot{m}_E h_E \qquad \text{(V)}$$

N.B. (a) The mass flow rate of dry air ($\dot{m}_a$) through a cooling tower is a constant, whereas the mass flow rate of moist air increases due to the evaporation of some of the water.

(b) The term $\dot{m}_E h_E$ is usually small compared with the other terms and is often neglected.

Mass Balance

By conservation of mass, under steady state conditions, the mass flow rate of DRY air and of H_2O (as liquid or vapour) must be the same at inlet and outlet to any system.

Thus,
$$(\dot{m}_a)_A = (\dot{m}_a)_B$$

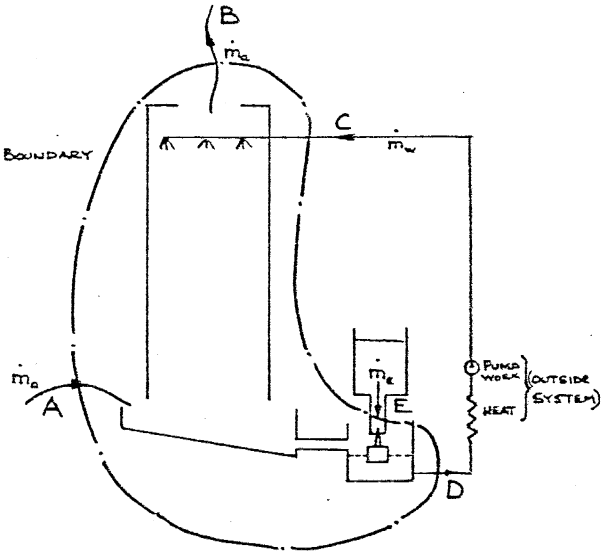
and
$$(\dot{m}_s)_A + \dot{m}_E = (\dot{m}_s)_B$$
$$\dot{m}_E = (\dot{m}_s)_B - (\dot{m}_s)_A$$

The ratio of steam to air (ω) is known for the initial and final state points on the psychrometric charts.

Thus,
$$(\dot{m}_s)_B = \dot{m}_a \omega_B$$
$$(\dot{m}_s)_A = \dot{m}_a \ A$$

and
$$\underline{\underline{\dot{m}_E = \dot{m}a(\omega_B - \omega_A)}}$$

The system may be re-defined thus,



SYSTEM G

In this case the process heat and pump work does not cross the boundary of the system, but we now have warm water entering the system at C and cool water leaving at D.

Applying the Steady Flow Energy Equation, $\dot{Q} - P = \dot{H}_{exit} - \dot{H}_{inlet}$

$P = 0$; $\dot{Q}$ may have a small value due to heat transfer between the unit and its surroundings.

$$\dot{Q} = \dot{m}_a h_B + \dot{m}_w h_D - (\dot{m}_a h_A + \dot{m}_w h_C + \dot{m}_E h_E)$$

$$\dot{Q} = \dot{m}_a(h_B - h_A) + \dot{m}_w(h_D - h_C) - \dot{m}_E h_E$$
$$= \dot{m}_a(h_B - h_A) + \dot{m}_w\, Cp(t_D - t_C) - \dot{m}_E h_E$$

As stated earlier, the term $\dot{m}_E h_E$ is usually small compared with the other terms.

SUMMARY OF EXPERIMENTS USING THE BENCH TOP COOLING TOWER

1. Observation of the processes within a forced draught cooling tower.

2. Determination of all "end state" properties of air and H_2O from tables or charts, and the application of the steady flow equation to selected systems to draw up energy and mass balances.

3. Investigation of the effect of cooling load on "Approach to Wet Bulb".

4. Investigation of the effect of air velocity on
   (i) "Approach to Wet Bulb"
   (ii) The pressure drop through the packing

5. Investigation of the effect of load on cooling range.

6. Investigation of the effect of packing density on the performance of a cooling tower.

7. Investigation of locally designed and manufactured packings.

1. Observation of the Processes within a Forced Draught Cooling Tower.

The Bench Top Cooling Tower behaves in a similar manner and has similar components to a full size cooling tower and may be used to introduce students to their characteristics and construction.

The Bench Top Cooling Tower should be set to operate with moderate air and water flows and with either 1.0 or 1.5kW cooling load (See "Preparation for Use", Page 7).

After conditions have stabilised the following may be observed:

Water System

(i) The warm water enters the top of the tower and is fed into troughs from which it flows via notches onto the packings. The troughs are designed to distribute the water uniformly over the packings with minimum splashing.

(ii) The packings have an easily wetted surface and the water spreads over this to expose a large surface to the air stream.

(iii) The cooled water falls from the lowest packing into the basin and may then be pumped to a process requiring cooling (or in the Bench Top Cooling Tower, to the simulated load in the load tank).

(iv) Due to evaporation from the water, "make-up" must be supplied to maintain the quantity of water in the cooling system. The falling level in the load tank may be observed.

(v) Droplets of water (resulting from splashing, etc.) may become entrained in the air stream and then lost from the system. This loss does not contribute to the cooling, but must be made good by "make-up". To minimise this loss, a "droplet arrester", or "eliminator" is fitted at the tower outlet. This component causes droplets to coalesce, forming drops which are too large to be entrained and these fall back into the packings.

Air System

(vi) Under the action of the fan, air is driven upward through the wet packings. It will be seen that the change of dry bulb temperature is smaller than the change of wet bulb temperature, and that at air outlet there is little difference between wet and dry bulb temperatures. This indicates that the air leaving is almost saturated, i.e. Relative Humidity → 100%. This increase in the moisture content of the air is due to the conversion of water into steam and the "latent heat" for this accounts for most of the cooling effect.

(viii) If the cooling load is now switched off and the unit allowed to stabilise, it will be found that the water will leave the basin close to the wet bulb temperature of the air entering. According to the local atmospheric conditions, this can be several degrees below the incoming air (dry bulb) temperature.

With no load, the water would be cooled to the incoming wet bulb temperature, but this condition cannot be attained since the pump transfers about 100W to the water.

This is an interesting and instructive demonstration for students and explains the importance of "Approach to Wet Bulb" as a cooling tower parameter.

2. Determination of all "end state" properties of the air and H_2O from charts and tables, and the application of the steady flow equation to selected systems to draw up energy and mass balances.

The Bench Top Cooling Tower should be prepared, started and allowed to stabilise under the following suggested conditions:

Orifice differential	16mm H_2O
Water flow rate	40gm s^{-1}
Cooling load	1.0kW

(Note: Stability is reached when there is no further appreciable change in temperature, or flow rate.)

At regular intervals over a measured period of say 10 minutes, all temperatures and flow rates should be noted and the mean values entered on the observation sheet.

At the commencement of this period, fill the make-up tank to the gauge mark with distilled water. At the end of this period, refill the tank from a known quantity of distilled water in a measuring cylinder. By difference, determine the quantity of make up which has been supplied in the time interval.

The observation may be repeated at other water, or air flow rates and with another load.

Typical observations, and specimen calculations are given on Pages 22 to 26.

HILTON BENCH TOP COOLING TOWER

OBSERVATION SHEET

Date:

Investigation:

Atmospheric Pressure: 1010 mbar

TEST No.	1	2	3	4	5	6
Packing Installed	B					
Packing Density m^{-1}	110					
Air Inlet Dry Bulb $\frac{t_1}{^\circ C}$	20.8					
Air Inlet Wet Bulb $\frac{t_2}{^\circ C}$	17					
Air Outlet Dry Bulb $\frac{t_3}{^\circ C}$	22.9					
Air Outlet Wet Bulb $\frac{t_4}{^\circ C}$	22.7					
Water Inlet Temperature $\frac{t_5}{^\circ C}$	29.5					
Water Outlet Temperature $\frac{t_6}{^\circ C}$	23.1					
Water Make-Up Temperature (Assumed same as ambient dry bulb temperature t_1) $\frac{t_7}{^\circ C}$	20.8					
Orifice Differential $\frac{x}{mm\ H_2O}$	16					
Water Flow Rate $\frac{\dot{m}_w}{gm\ s^{-1}}$	42					
Cooling Load $\frac{\dot{Q}}{kW}$	1.0					
Make-Up Quantity $\frac{m_E}{kg}$	0.26					
Time Interval $\frac{y}{s}$	600					
Pressure Drop Across Packing $\frac{\Delta p}{mm\ H_2O}$						

IHVE
PSYCHROMETRIC CHART

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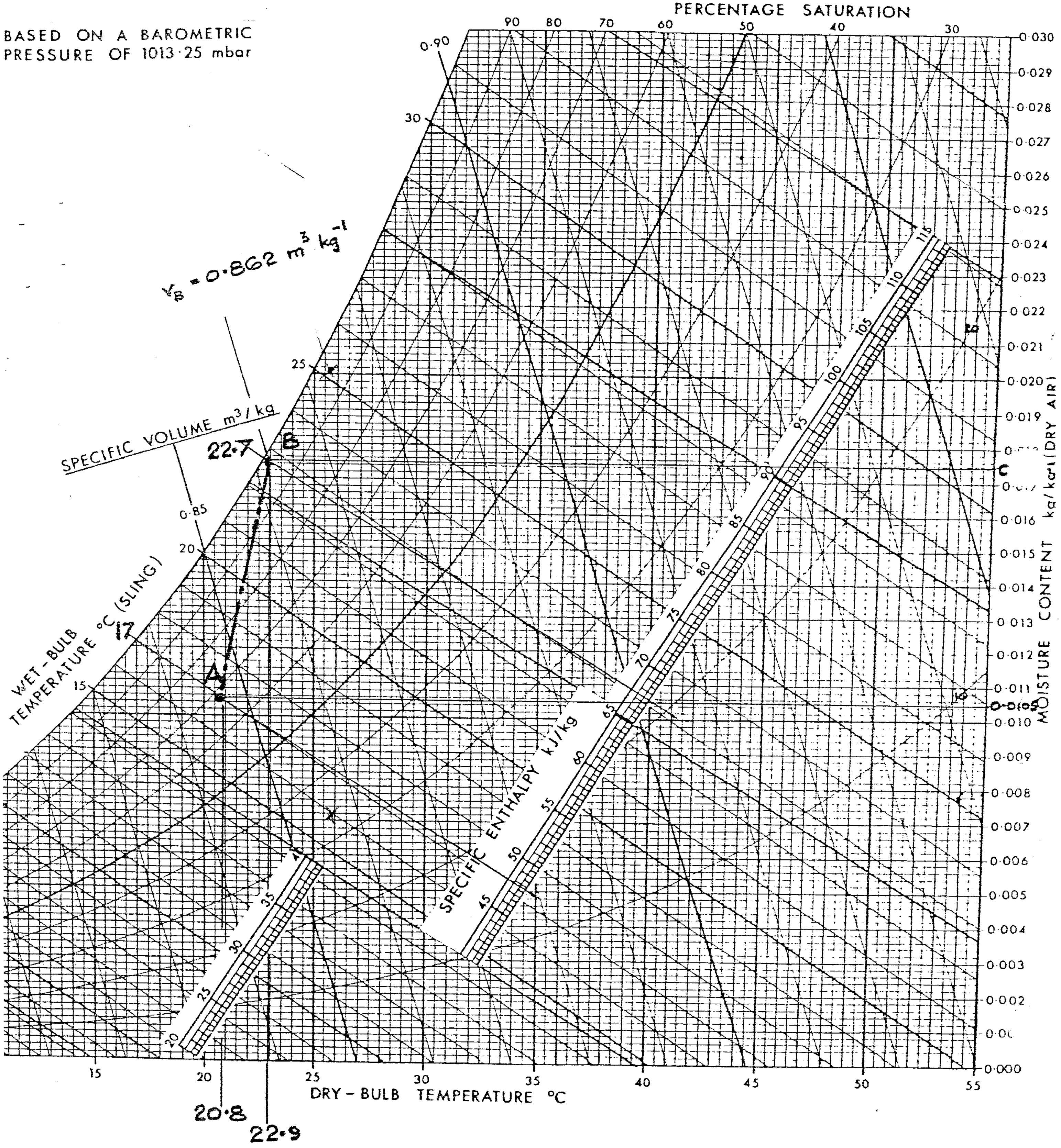
BASED ON A BAROMETRIC
PRESSURE OF 1013·25 mbar



Specimen Calculations

Using the wet and dry bulb temperatures, points A and B may be plotted on the psychrometric chart, (See Page 23) and the following values read off:

$$h_A = 47.8 \text{ kJ kg}^{-1}$$
$$\omega_A = 0.0105 \text{ kg kg}^{-1}$$
$$h_B = 67.4 \text{ kJ kg}^{-1}$$
$$\omega_B = 0.0175 \text{ kg kg}^{-1}$$
$$v_{a_B} = 0.862 \text{m}^3 (\text{kg dry air})^{-1}$$

From the orifice calibration (Page 16):

$$\dot{m}_a = 0.0137 \sqrt{\frac{x}{(1 + \omega_B) v_{a_B}}}$$

$$= 0.0137 \sqrt{\frac{16}{(1 + 0.0175) \times 0.862}} \text{ kg s}^{-1}$$

$$\dot{m}_a = \underline{\underline{0.0585}} \text{ kg s}^{-1}$$

Make-up rate,

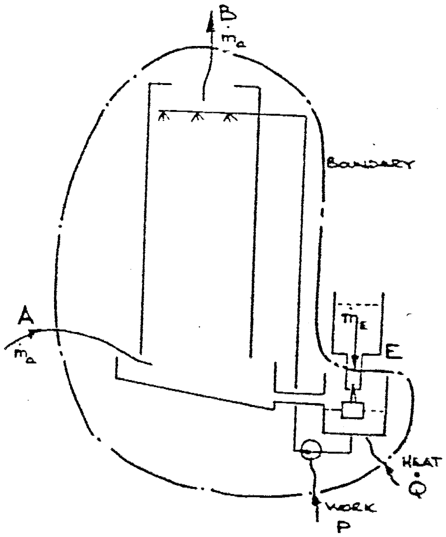
$$m_E = \frac{m_E}{y}$$

$$= \frac{0.26}{600} \text{ kg s}^{-1}$$

$$= \underline{\underline{0.433}} \times 10^{-3} \text{ kg s}^{-1}$$

Specific enthalpy of make-up, (h_f at 20.8°C)

$$h_E = \underline{\underline{86.9}} \text{ kJ kg}^{-1}$$



SYSTEM. F

Applying the Steady Flow Equation to the system indicated by the chain line (System F):

$$\underline{\underline{\dot{Q} - P = \Delta\dot{H} + \Delta\dot{KE}}}$$

Now,

$$\begin{aligned} \dot{Q} - P &= 1.0 - -0.1 \text{ kW} \\ &= \underline{\underline{1.1}} \text{ kW} \end{aligned}$$

(Pump power is approximately 100W, negative)

$$\begin{aligned} \Delta\dot{H} &= \dot{H}_{Exit} - \dot{H}_{Entry} \\ &= \dot{m}_a h_B - \dot{m}_a h_A - \dot{m}_E h_E \\ &= \dot{m}_a (h_B - h_A) - \dot{m}_E h_E \\ &= 0.0585(67.4 - 47.8) - 0.433 \times 10^{-3} \times 86.9 \text{ kW} \\ &= 1.146 - 0.038 \text{ kW} \\ &= \underline{\underline{1.108}} \text{ kW} \end{aligned}$$

The small discrepancy may be attributed to errors and heat transfer to or from the surroundings and to manufacturing tolerances in the rating of heating elements.

Mass Balance

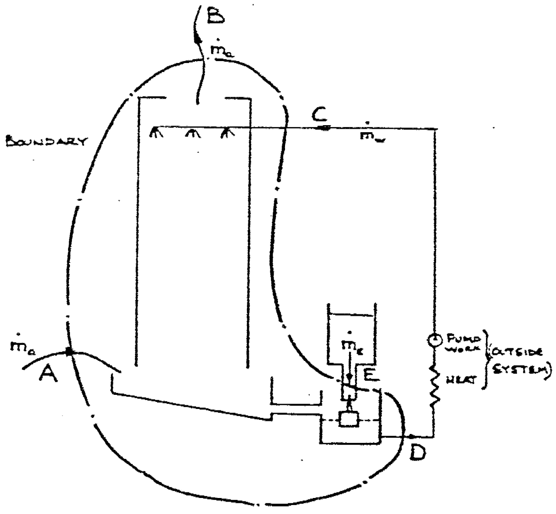
$$\dot{m}_E = \dot{m}_{s_B} - \dot{m}_{s_A}$$

$$\dot{m}_E = \dot{m}_a(\omega_B - \omega_A)$$

$$\dot{m}_E = \underline{\underline{0.433 \times 10^{-3}}} \text{ kg s}^{-1}$$

$$\begin{aligned} \dot{m}_a(\omega_B - \omega_A) &= 0.0585(0.0175 \times 0.0105) \\ &= \underline{\underline{0.409 \times 10^{-3}}} \text{ kg s}^{-1} \end{aligned}$$

The discrepancy may be attributed to carry over and errors.



SYSTEM G

Applying the Steady Flow Equation to the system indicated by the chain line (System G):

$$\dot{Q} - P = \Delta\dot{H} + \Delta\dot{KE}$$

$$\underline{\underline{\dot{Q} - P = 0}}$$

$$\Delta\dot{H} = \dot{H}_{Exit} - \dot{H}_{Entry}$$

$$= (\dot{m}_a h_B + \dot{m}_w h_D) - (\dot{m}_a h_A + \dot{m}_w h_A + \dot{m}_w h_C - \dot{m}_E h_E)$$

$$= \dot{m}_a (h_B - h_A) + \dot{m}_w (h_D - h_C) - \dot{m}_E h_E$$

$$= \dot{m}_a (h_B - h_A) + \dot{m}_w Cp_w (t_D - t_C) - \dot{m}_E h_E$$

$$= 0.0585(67.4 - 47.8) + 0.042 \times 4.18(23.1 - 29.5) - 0.433 \times 10^{-3} - 81.8$$

$$= \underline{\underline{-0.011}}\ \text{kW}$$

The discrepancy (0.011 kW) may be attributed to errors and heat transfers not taken into account.

The mass balance will be as given earlier.

3. Effect of Cooling Load on "Wet Bulb Approach"

The Bench Top Cooling Tower should be prepared, started and allowed to stabilise under the following suggested conditions:

Water flow rate	40 gm s^{-1}
Air flow manometer differential	16mm H_2O
Cooling load	0

Observations as set out on Page 28 should then be made.

While keeping the water and air flows constant, the load should be increased to 0.5 kW, and when conditions have stabilised, the observations should be repeated.

Similar tests should be made with cooling loads of 1.0 and 1.5 kW.

The four tests may then be repeated at another constant air flow.

Typical observations, calculations, results and graphs are shown on Pages 28 to 30.

HILTON BENCH TOP COOLING TOWER

OBSERVATION SHEET

Date: Investigation: Atmospheric Pressure: 1020 mbar

TEST No.		1	2	3	4	5	6
Packing Installed		B	B	B	B		
Packing Density	m^{-1}	110	110	110	110		
Air Inlet Dry Bulb	$\frac{t_1}{°C}$	20.0	20.2	21.2	21.4		
Air Inlet Wet Bulb	$\frac{t_2}{°C}$	15.7	15.7	16.4	16.4		
Air Outlet Dry Bulb	$\frac{t_3}{°C}$						
Air Outlet Wet Bulb	$\frac{t_4}{°C}$						
Water Inlet Temperature	$\frac{t_5}{°C}$						
Water Outlet Temperature	$\frac{t_6}{°C}$	16.7	19.9	23.2	25.2		
Water Make-Up Temperature (Assumed same as ambient dry bulb temperature t_1)	$\frac{t_7}{°C}$						
Orifice Differential	$\frac{x}{mm\ H_2O}$	16	16	16	16		
Water Flow Rate	$\frac{\dot{m}_w}{gm\ s^{-1}}$	40	40	40	40		
Cooling Load	$\frac{\dot{Q}}{kW}$	0	0.5	1.0	1.5		
Make-Up Quantity	$\frac{m_E}{kg}$						
Time Interval	$\frac{y}{s}$						
Pressure Drop Across Packing	$\frac{\Delta p}{mm\ H_2O}$						

Specimen Calculations

The pump transfers approximately 100W to the water, and this should be added to the load imposed in the load tank.

For Test No. 3: Total cooling load

$$\begin{aligned}\text{Total cooling load} &= \text{Applied load} + \text{Pump input}\\ &= 1.0 + 0.1 \text{ kW}\\ &= \underline{\underline{1.1}} \text{ kW}\end{aligned}$$

$$\begin{aligned}\text{"Approach to Wet Bulb"} &= t_D - t_{A_W}\\ &= 23.2 - 16.4 \text{ K}\\ &= \underline{\underline{6.8}} \text{ K}\end{aligned}$$

$$\text{Specific volume at outlet (typically)} = 0.87 \text{ m}^3/\text{kg}$$

$$\begin{aligned}\dot{m}_a &= 0.0137 \surd \frac{x}{v_B}\\ &= 0.0137 \surd \frac{16}{0.87}\\ &= \underline{\underline{0.0587}} \text{ kg/s}\end{aligned}$$

$$\begin{aligned}\text{Cross sectional area of column (A)} &= 0.15 \times 0.15 \text{ m}^2\\ &= \underline{\underline{0.0225\text{m}^2}}\end{aligned}$$

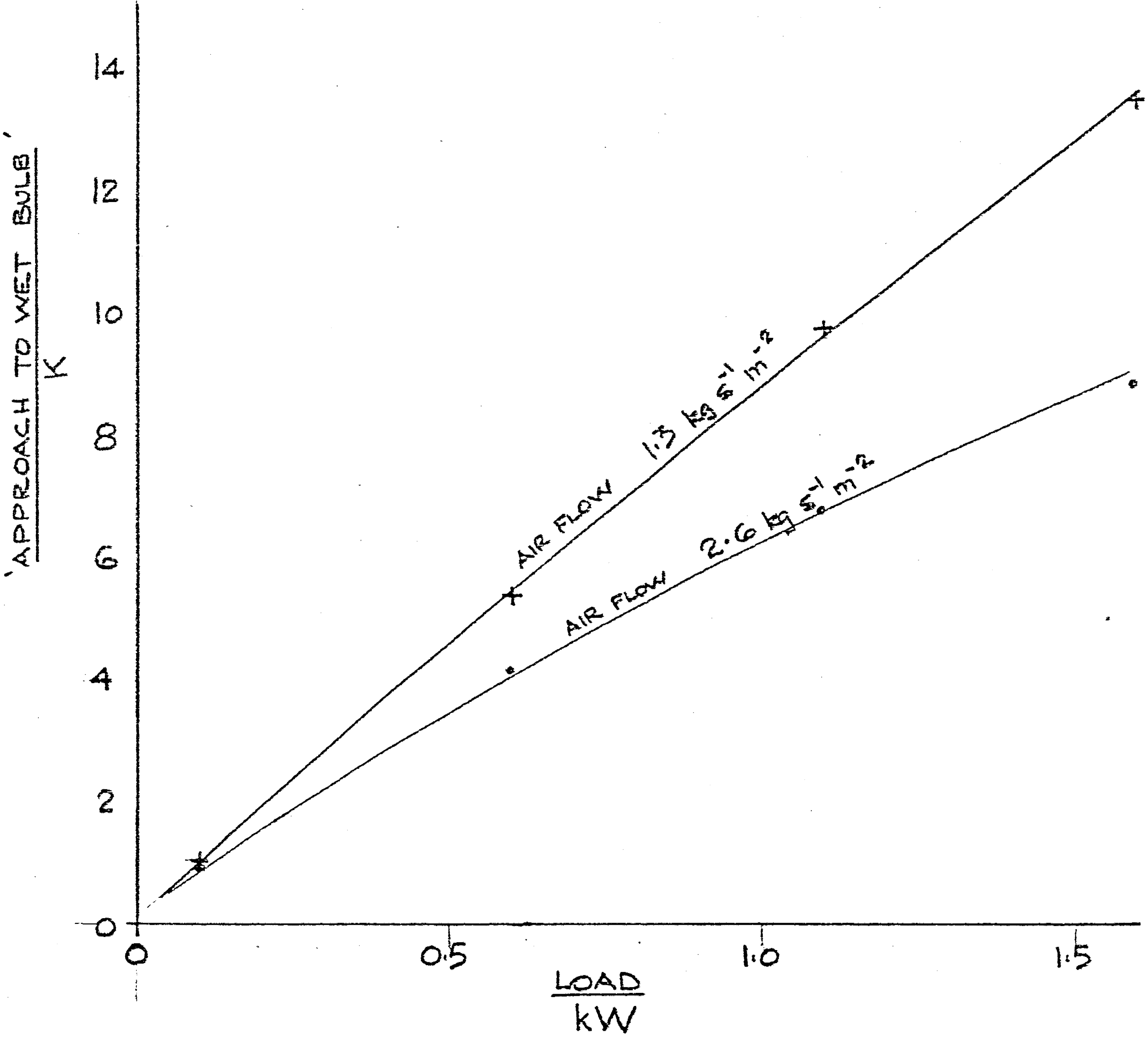
$$\begin{aligned}\text{Air mass flow per unit area} &= \frac{\dot{m}_a}{A}\\ &= \frac{0.0587}{0.0225} \text{ kg s}^{-1} \text{ m}^{-2}\\ &= \underline{\underline{2.6}} \text{ kg s}^{-1} \text{ m}^{-2}\end{aligned}$$

$$\begin{aligned}\text{Water flow rate per unit area} &= \frac{\dot{m}_w}{A}\\ &= \frac{0.04}{0.0225} \text{ kg s}^{-1} \text{ m}^{-2}\\ &= \underline{\underline{1.777}} \text{ kg s}^{-1} \text{ m}^{-2}\end{aligned}$$

Derived Results		1	2	3	4
Packing Density	m^{-1}	110	110	110	110
Air Flow per Unit Area	kg s^{-1} m^{-2}	2.6	2.6	2.6	2.6
Total Cooling Load	kW	0.1	0.6	1.1	1.6
Approach to Wet Bulb	K	1.0	4.2	6.8	8.8

RELATIONSHIP BETWEEN COOLING LOAD AND APPROACH TO WET BULB TEMPERATURE.

DATA :-		
	PACKING	B (110 m^{-1})
	WET BULB TEMPERATURE AT INLET	≏ 16°C
	WATER FLOW RATE	1·78 kg s^{-1} m^{-2}



4. Relationship between air velocity and: (i) Wet bulb approach
(ii) Packing pressure drop

The Bench Top Cooling Tower should be prepared with the selected packed column and set to stabilise at a cooling load of say 1.0 kW and, at maximum air flow and with a water flow of say 40 gm s^{-1}.

The observations as indicated on Page 32 should then be made.

Note: To measure the pressure drop across the packings it is necessary to temporarily disconnect the plastic tube from the orifice tapping point. The tube should be reconnected to the pressure tapping point just below the packing, and another tube between the right-hand tapping on the manometer and the pressure tapping point at the top of the packings.

The test should be repeated with orifice pressure drops of 10, 4 and 1.0mm H_2O, but with unchanged water flow rate and cooling loads.

Typical observations are shown on Page 32.

The test may then be repeated:

(i) At another constant load.
(ii) At another constant water flow rate.
(iii) Using another packing.

HILTON BENCH TOP COOLING TOWER

OBSERVATION SHEET

Date: Investigation: Atmospheric Pressure: 994 mbar

	TEST No.	1	2	3	4	5	6
Packing Installed		C	C	C	C		
Packing Density	m^{-1}	200	200	200	200		
Air Inlet Dry Bulb	t_1 / °C	21.75	22.0	21.9	24.2		
Air Inlet Wet Bulb	t_2 / °C	18.25	18.5	17.6	18.2		
Air Outlet Dry Bulb	t_3 / °C	22.0	23.9	25.5	32.0		
Air Outlet Wet Bulb	t_4 / °C	21.9	23.9	25.5	31.8		
Water Inlet Temperature	t_5 / °C	28.5	30.6	31.9	37.8		
Water Outlet Temperature	t_6 / °C	22.9	24.75	26.25	31.9		
Water Make-Up Temperature (Assumed same as ambient dry bulb temperature t_1)	t_7 / °C						
Orifice Differential	x / mm H_2O	18.5	10	4.5	1.0		
Water Flow Rate	$\dot{m}_w$ / gm s^{-1}	40	40	40	40		
Cooling Load	$\dot{Q}$ / kW	1.0	1.0	1.0	1.0		
Make-Up Quantity	m_E / kg						
Time Interval	y / s						
Pressure Drop Across Packing	Δp / mm H_2O	6	2.9	1.4	0.3		

Specimen Calculations

Test No. 2 (Page 32)

Inlet wet bulb temperature (t_2) = 18.5°C

Outlet water temperature (t_6) = 24.75°C

"Approach to wet bulb" = 24.75 - 18.5 K
= 6.25 K

Specific volume of air at outlet (by plotting t_{B_d} and t_{B_w} on the psychrometric chart) = $0.86 \ m^3 \ kg^{-1}$

$$\text{Air mass flow rate} = 0.0137 \sqrt{\frac{h}{v_B}}$$

$$= 0.0137 \sqrt{\frac{10}{0.86}}$$

$$= \underline{\underline{0.0467}} \ kg \ s^{-1}$$

$$\text{Air volume flow rate} = \dot{m} v_B$$

$$= 0.0467 \times 0.06 \ m^3 \ s^{-1}$$

$$\dot{V} = \underline{\underline{0.04}} \ m^3 \ s^{-1}$$

$$\text{Cross sectional area of empty tower} \quad A = 0.15 \times 0.15$$

$$= \underline{\underline{0.0225 m^2}}$$

$$\text{Air velocity} \quad \frac{\dot{V}}{A} = \frac{0.04}{0.0225}$$

$$= \underline{\underline{1.78}} m \ s^{-1}$$

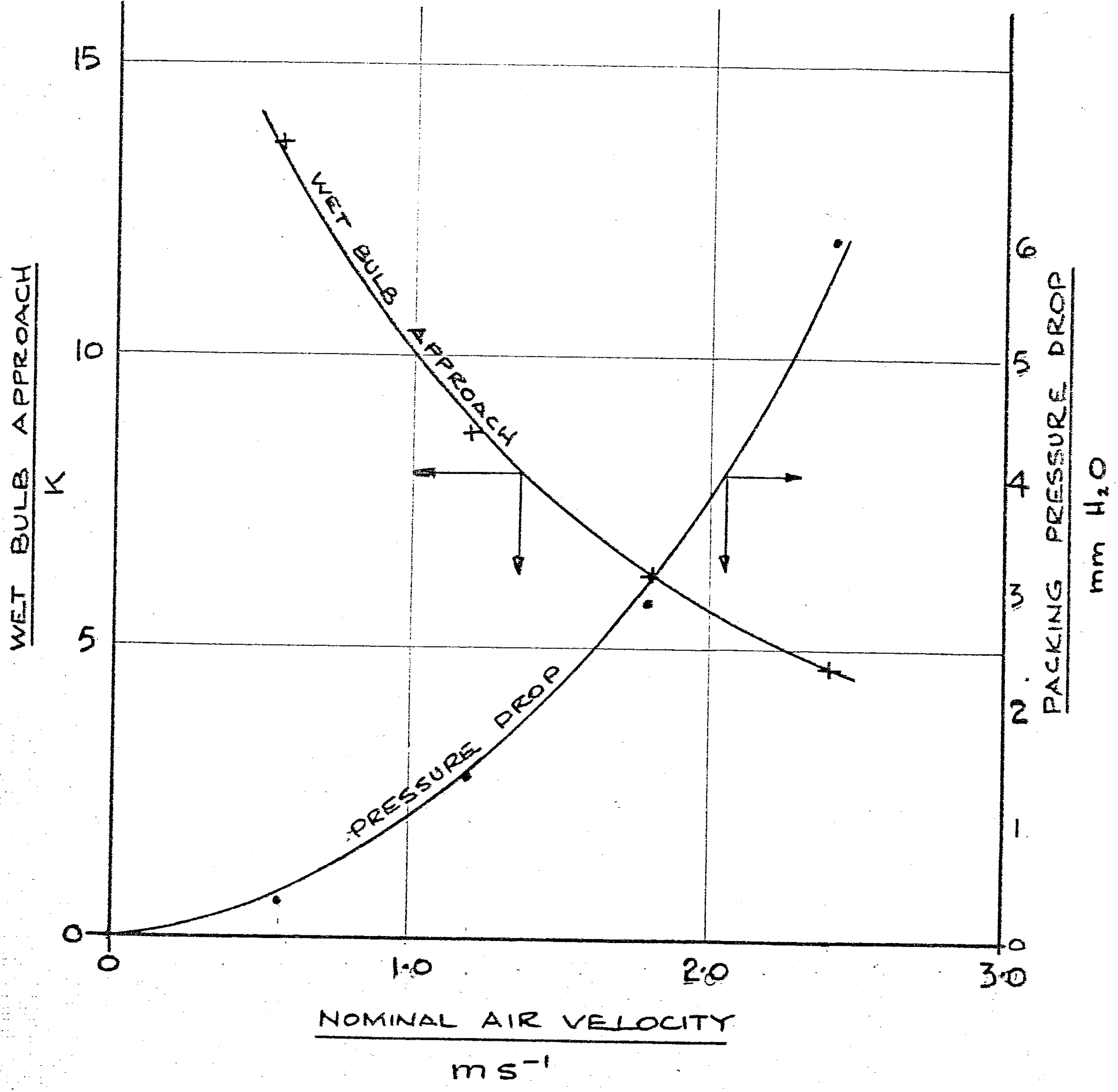
Results

		1	2	3	4
Nominal Velocity of Air	$m \ s^{-1}$	2.42	1.79	1.2	0.57
"Wet Bulb Approach"	K	4.65	6.25	8.65	13.7
Pressure Drop	mm H_2O	6	2.9	1.4	0.3

These results are shown graphically on Page 34.

RELATIONSHIP BETWEEN NOMINAL AIR VELOCITY AND (i) WET BULB APPROACH (ii) PACKING PRESSURE DROP

DATA:- INLET WET BULB TEMPERATURE 18°C
COOLING LOAD 1·1 kW
PACKING INSTALLED C (200 m^{-1})
WATER FLOW RATE 40 gm s^{-1}



5. Relationship Between Cooling Load and Cooling Range.

The Bench Top Cooling Tower should be prepared with the selected packing and set to stabilise with no load, a water flow rate of say 40 gm s^{-1} and an orifice differential of say 16mm H_2O.

Observations as indicated on Page 36 should then be made.

The cooling load should then be increased to 0.5 kW without changing the water or air flow and after stabilisation the observations repeated.

The observations should then be made at 1.0 and 1.5 kW cooling load.

The tests can then be repeated:
- (i) At other water flow rates
- (ii) At other air flow rates
- (iii) With other packings

Typical results and graphs are shown on Pages 36 and 37.

HILTON BENCH TOP COOLING TOWER

OBSERVATION SHEET

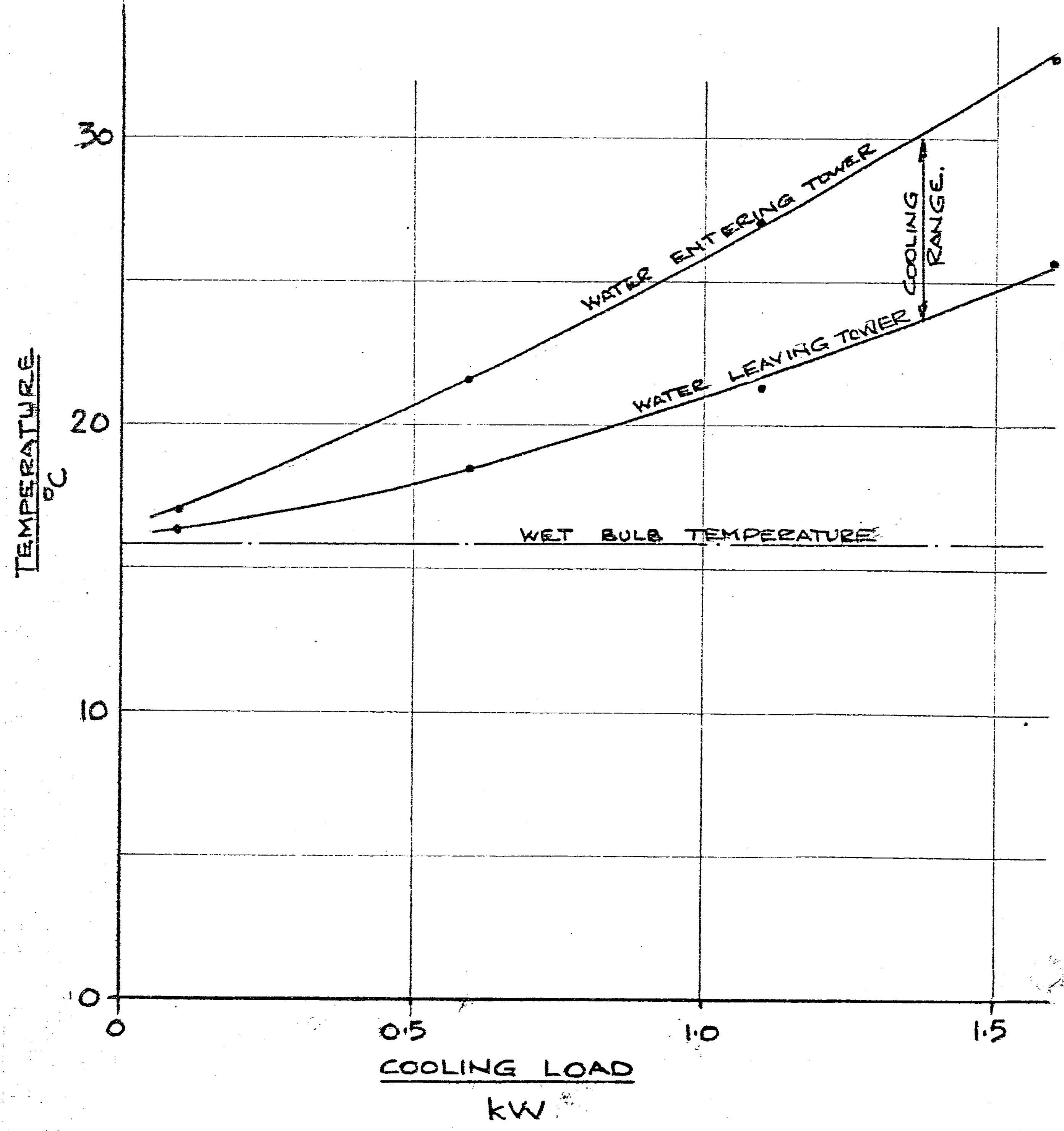
Date: Investigation: Atmospheric Pressure: 1020 mbar

TEST No.	1	2	3	4	5	6
Packing Installed	B	B	B	B		
Packing Density m^{-1}	110	110	110	110		
Air Inlet Dry Bulb $\frac{t_1}{°C}$	19	19	19.4	19.7		
Air Inlet Wet Bulb $\frac{t_2}{°C}$	15.6	15.4	15.8	16.5		
Air Outlet Dry Bulb $\frac{t_3}{°C}$	16.8	18.4	20.5	23.0		
Air Outlet Wet Bulb $\frac{t_4}{°C}$	16	18	20.4	23.0		
Water Inlet Temperature $\frac{t_5}{°C}$	17	21.6	27.2	32.7		
Water Outlet Temperature $\frac{t_6}{°C}$	16.4	18.6	21.3	23.9		
Water Make-Up Temperature (Assumed same as ambient dry bulb temperature t_1) $\frac{t_7}{°C}$						
Orifice Differential $\frac{x}{mm\ H_2O}$	16	16	16	16		
Water Flow Rate $\frac{\dot{m}_w}{gm\ s^{-1}}$	40	40	40	40		
Cooling Load $\frac{\dot{Q}}{kW}$	0	0.5	1.0	1.5		
Make-Up Quantity $\frac{m_E}{kg}$						
Time Interval $\frac{y}{s}$						
Pressure Drop Across Packing $\frac{\Delta p}{mm\ H_2O}$						

RELATIONSHIP BETWEEN COOLING LOAD AND COOLING RANGE

DATA:-

AIR FLOW RATE	≑ 0·058 kg s^{-1}
PACKING	B
WATER FLOW RATE	40 gm s^{-1}



6. Investigation of the Effect of Packing "Density" on the Performance of the Cooling Tower.

The Bench Top Cooling Tower should be prepared, started and allowed to stabilise under the following suggested conditions:

Orifice differential	16mm H_2O
Load	1.5 kW
Water flow rate	30gm s^{-1}
Column installed	A

Observations as set out on Page 39 should then be made.

Column A should then be removed and Column B substituted. After preparation and stabilisation at the same conditions as above, the observations should be repeated.

Finally, Column C should be installed and the observations repeated.

Note: Before removing and replacing a column, it may be desirable to carry out a series of tests at other loads, water flow rates and/or air flow rates.

Typical results for the given conditions are given on Page 39 and the corresponding graph is shown on Page 40.

Derived Results

Packing Density	m^{-1}	77	110	200
Wet Bulb Approach	K	7.4	5.3	4.5

Graph (Page 40)

Although only three points can be plotted, it appears that the expected trend is confirmed.

HILTON BENCH TOP COOLING TOWER

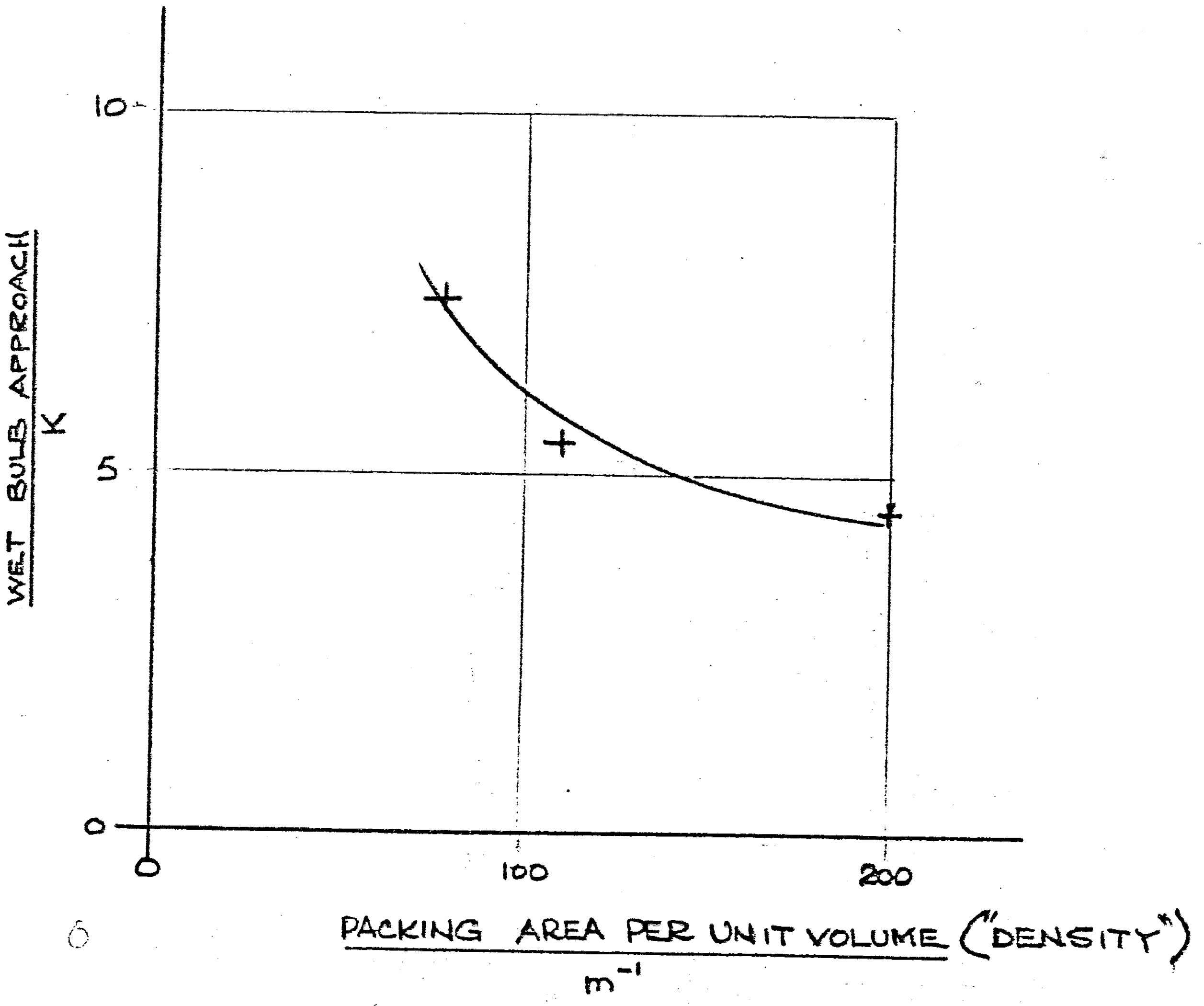
OBSERVATION SHEET

Date: Investigation: Atmospheric Pressure: 1013 mbar

	TEST No.	1	2	3	4	5	6
Packing Installed		A	B	C			
Packing Density	m^{-1}	77	110	200			
Air Inlet Dry Bulb	$\frac{t_1}{°C}$	20.5	20.6	19.8			
Air Inlet Wet Bulb	$\frac{t_2}{°C}$	17.1	17.8	16.5			
Air Outlet Dry Bulb	$\frac{t_3}{°C}$	25.0	25.0	23.5			
Air Outlet Wet Bulb	$\frac{t_4}{°C}$	24.0	24.4	23.5			
Water Inlet Temperature	$\frac{t_5}{°C}$	37.4	35.25	33.25			
Water Outlet Temperature	$\frac{t_6}{°C}$	24.5	23.1	21.0			
Water Make-Up Temperature (Assumed same as ambient dry bulb temperature t_1)	$\frac{t_7}{°C}$						
Orifice Differential	$\frac{x}{mm\ H_2O}$	16	16	16			
Water Flow Rate	$\frac{\dot{m}_w}{gm\ s^{-1}}$	30	30	30			
Cooling Load	$\frac{\dot{Q}}{kW}$	1.5	1.5	1.5			
Make-Up Quantity	$\frac{m_E}{kg}$						
Time Interval	$\frac{y}{s}$						
Pressure Drop Across Packing	$\frac{\Delta p}{mm\ H_2O}$	5.75	5.25	5.75			

RELATIONSHIP BETWEEN "WET BULB APPROACH" AND PACKING "DENSITY"

DATA.		
	COOLING LOAD	1·6 kW.
	AIR VELOCITY	2·2 m s^{-1}
	WATER FLOW	1·35 kg s^{-1} m^{-2}



7. Investigation of Locally Designed and Manufactured Packings.

P.A. Hilton Ltd., will be pleased to quote for and supply an empty column into which locally manufactured packings may be assembled.

Alternatively the packings may be removed from one of the columns supplied with the standard Bench Top Cooling Tower.

Removal of Packings

1. Remove the column from the base unit.

2. Unscrew the six mushroom headed screws which secure the three distribution troughs at the top of the column.

3. Withdraw the troughs and the packing from the column, and store carefully to prevent damage.

Design of Packings (including the water distributor)

1. An ideal packing for a cooling tower will,
   - (a) expose a large and uniform water surface to the air stream,
   - (b) offer a small but uniform resistance to the passage of air,
   - (c) be inexpensive,
   - (d) be robust, easily formed and handled,
   - (e) be durable under the conditions prevailing (e.g. from dry and well ventilated during a shut-down, to continuous soaking in warm water and possibly contaminated with airborne pollution, biological growth and excessive dissolved solids).
   - (f) be incombustible.

2. When designing and installing locally manufactured packings, the following points should be considered:
   - (a) The fan installed limits the resistance of the packing to about 10mm H_2O at a normal air velocity through the column (i.e. about 2m s^{-1}).
   - (b) "Splash" packings offer a smaller resistance than "Film" packings, but the formation of small airborne droplets of water may be troublesome.
   - (c) If a loose filling is used it must be supported on a grid (e.g. a wire mesh screen) at the lower end of the column.
   - (d) Packing materials should not break up or decompose during use (although the pump will handle a certain amount of suspended matter, the filter and water flow meter are likely to become choked).
   - (e) The water must be uniformly applied to the top layer of packing.

USE OF BENCH TOP COOLING TOWER H890 IN CONJUNCTION WITH OTHER HILTON EQUIPMENT.

Many industrial and commercial refrigeration and other plants reject heat to the atmosphere via a COOLING TOWER.

The combination of a cooling tower and refrigeration plant condenser (or cooling tower and any other process requiring cooling water) and its characteristics can easily be demonstrated as shown in the accompanying sketch.

All connections should be made with 10mm (3/8") bore plastic tubing and the length of these tubes should be kept to the minimum.

The pump selected must be capable of producing a head of 1.5m + the resistance in the cooling water circuit, at a maximum flow rate of $50 cm^3 s^{-1}$.

The following restrictions apply:

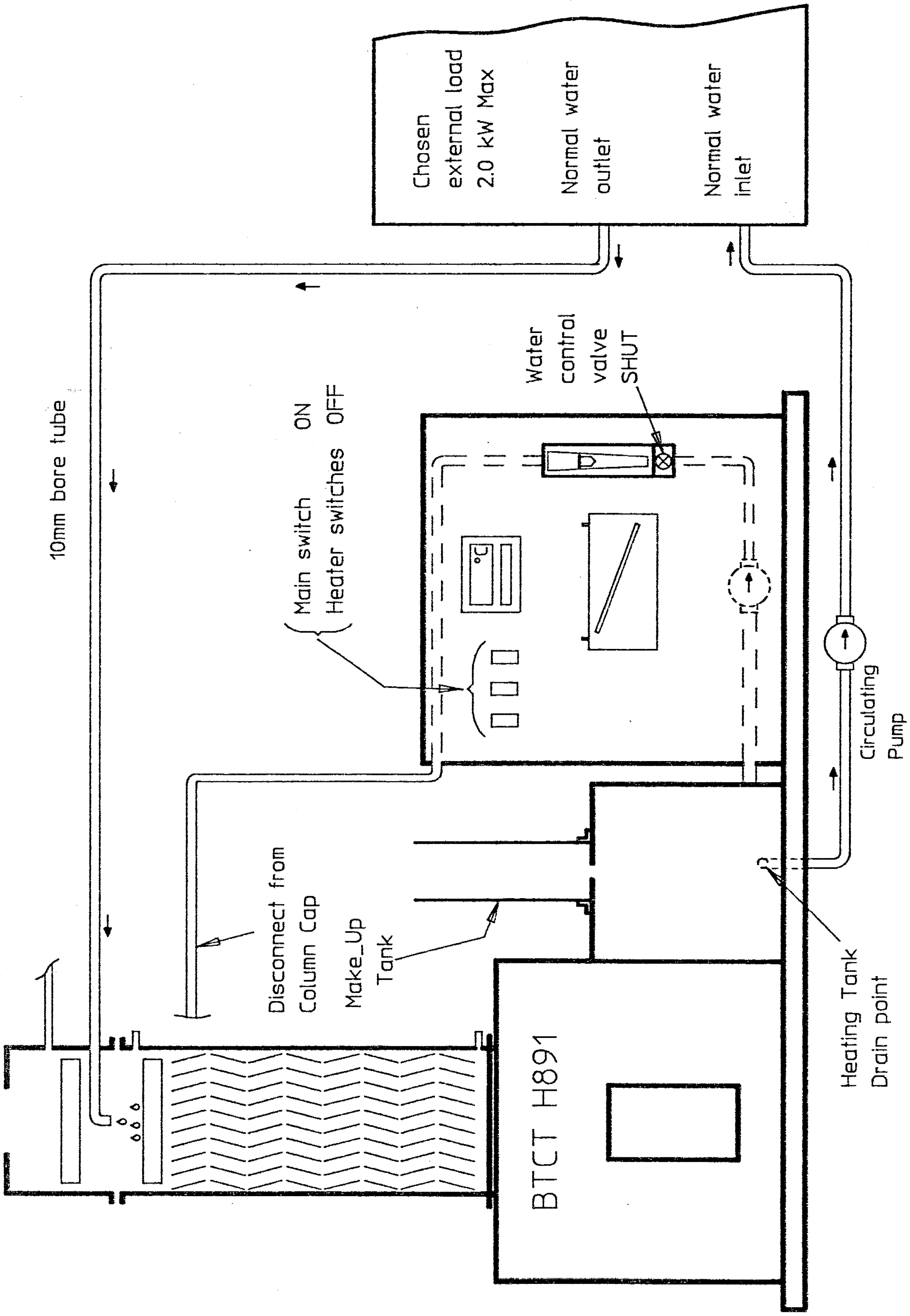
Maximum cooling load	2kW
Maximum water temperature (at tower inlet)	50°C
Maximum wet bulb temperature	23°C
Maximum water flow rate	$50 cm^3 s^{-1}$
Minimum water flow rate	$10 cm^3 s^{-1}$

The Bench Top Cooling Tower load tank heaters and circulating pump must be switched off.

The water circuit should, if possible, be filled with demineralised or distilled water.

Water make-up must be supplied to the make-up tank at a maximum rate of 2.5 litre/hour.

CONNECTIONS BETWEEN HILTON BENCH TOP COOLING TOWER & REFRIGERATION OR ANY OTHER UNIT REQUIRING COOLING WATER



HILTON BENCH TOP COOLING TOWER

OBSERVATION SHEET

Date: Investigation: Atmospheric Pressure: mbar

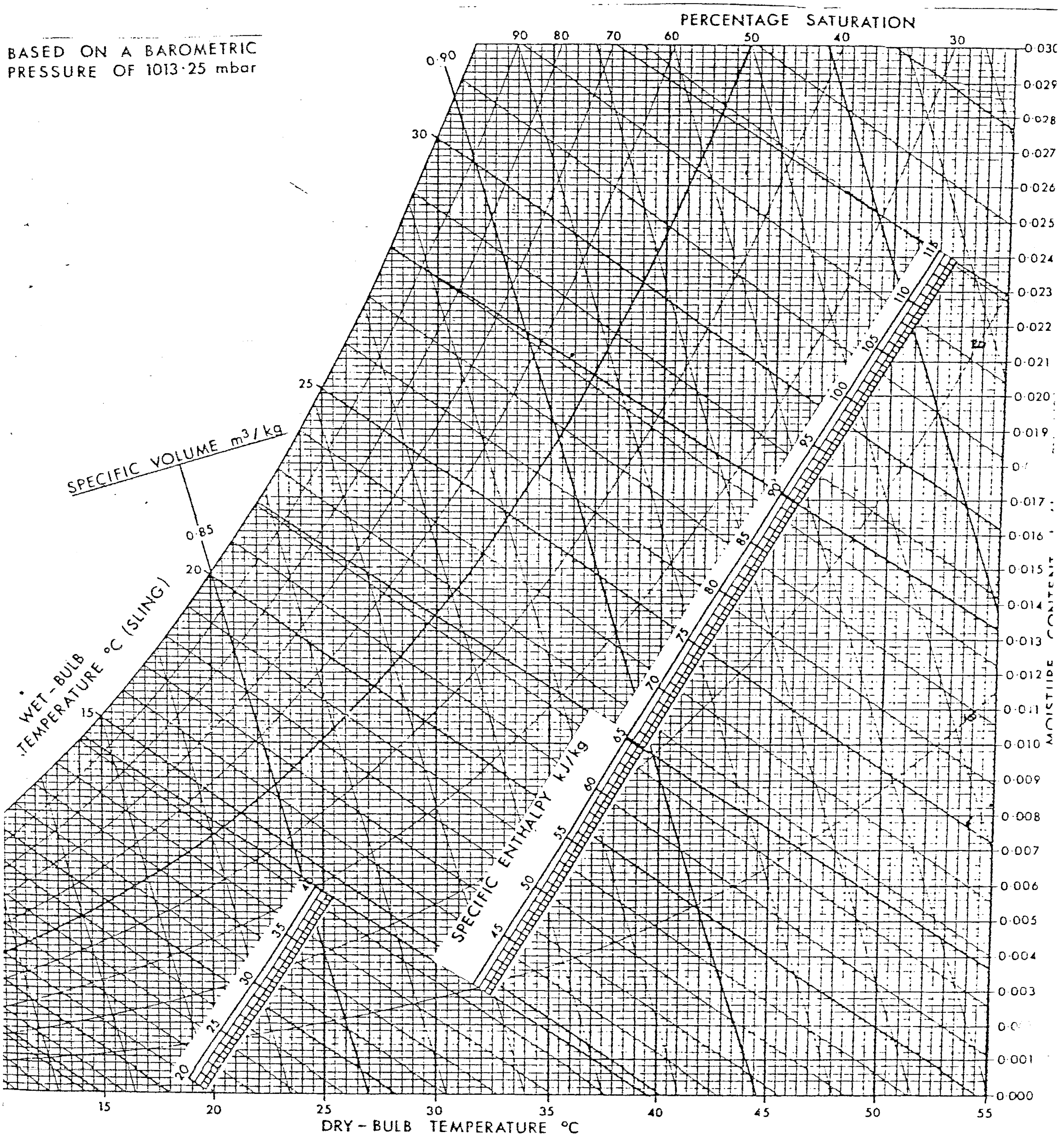
TEST No.		1	2	3	4	5	6
Packing Installed							
Packing Density	m^{-1}						
Air Inlet Dry Bulb	$\frac{t_1}{°C}$						
Air Inlet Wet Bulb	$\frac{t_2}{°C}$						
Air Outlet Dry Bulb	$\frac{t_3}{°C}$						
Air Outlet Wet Bulb	$\frac{t_4}{°C}$						
Water Inlet Temperature	$\frac{t_5}{°C}$						
Water Outlet Temperature	$\frac{t_6}{°C}$						
Water Make-Up Temperature (Assumed same as ambient dry bulb temperature t_1)	$\frac{t_7}{°C}$						
Orifice Differential	$\frac{x}{mm\ H_2O}$						
Water Flow Rate	$\frac{\dot{m}_w}{gm\ s^{-1}}$						
Cooling Load	$\frac{\dot{Q}}{kW}$						
Make-Up Quantity	$\frac{m_E}{kg}$						
Time Interval	$\frac{y}{s}$						
Pressure Drop Across Packing	$\frac{\Delta p}{mm\ H_2O}$						

IHVE

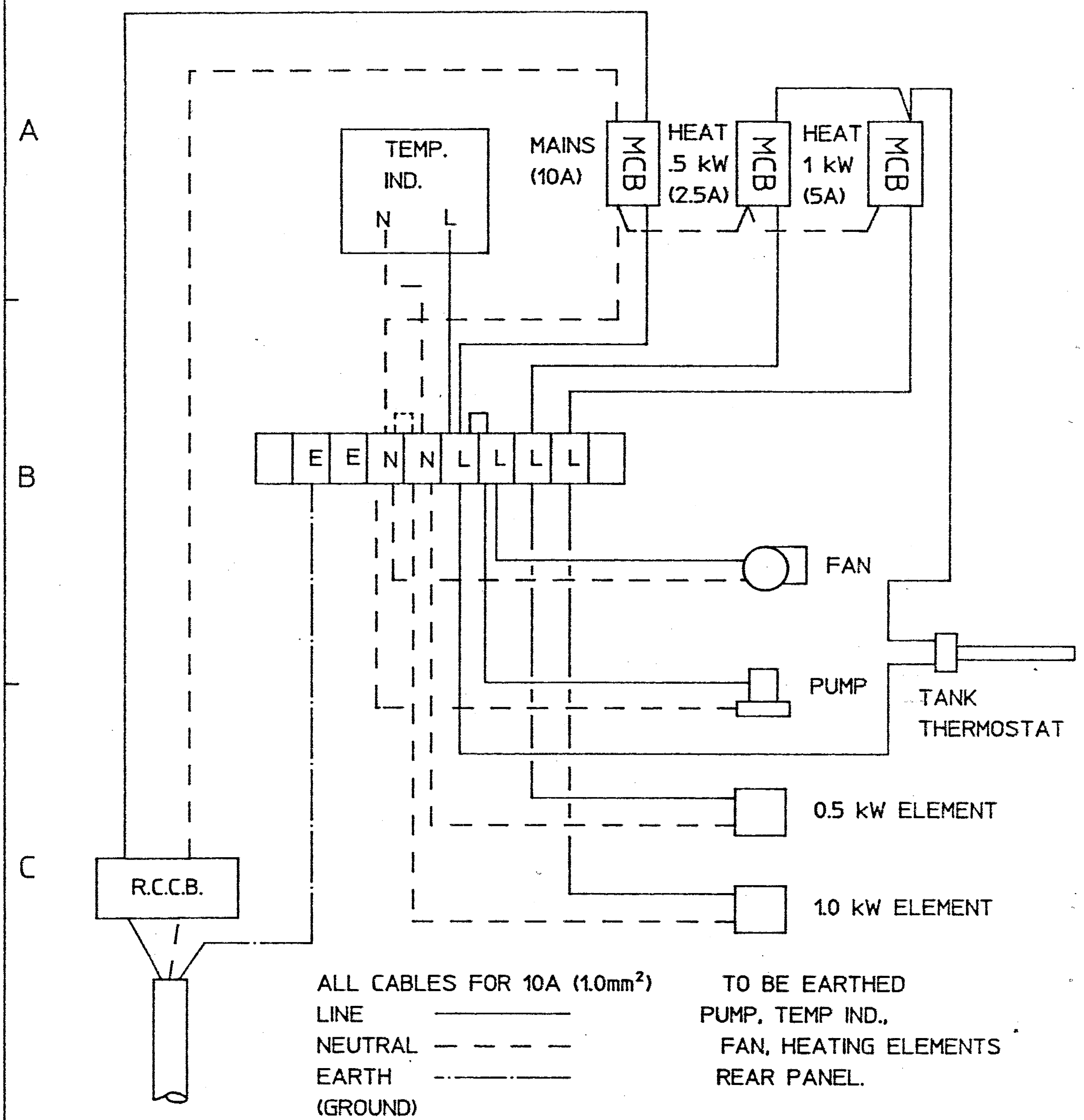
P.A. Hilton Ltd.
Horsebridge Mill, King's Somborne,
Hants SO20 6PX, England.
Tel: King's Somborne (STD 079-47) 382. Telex 477538

PSYCHROMETRIC CHART

BASED ON A BAROMETRIC PRESSURE OF 1013·25 mbar



1 2 3 4 Amendments



ALL CABLES FOR 10A (1.0mm²)

LINE ————————

NEUTRAL — — — —

EARTH —·——·——

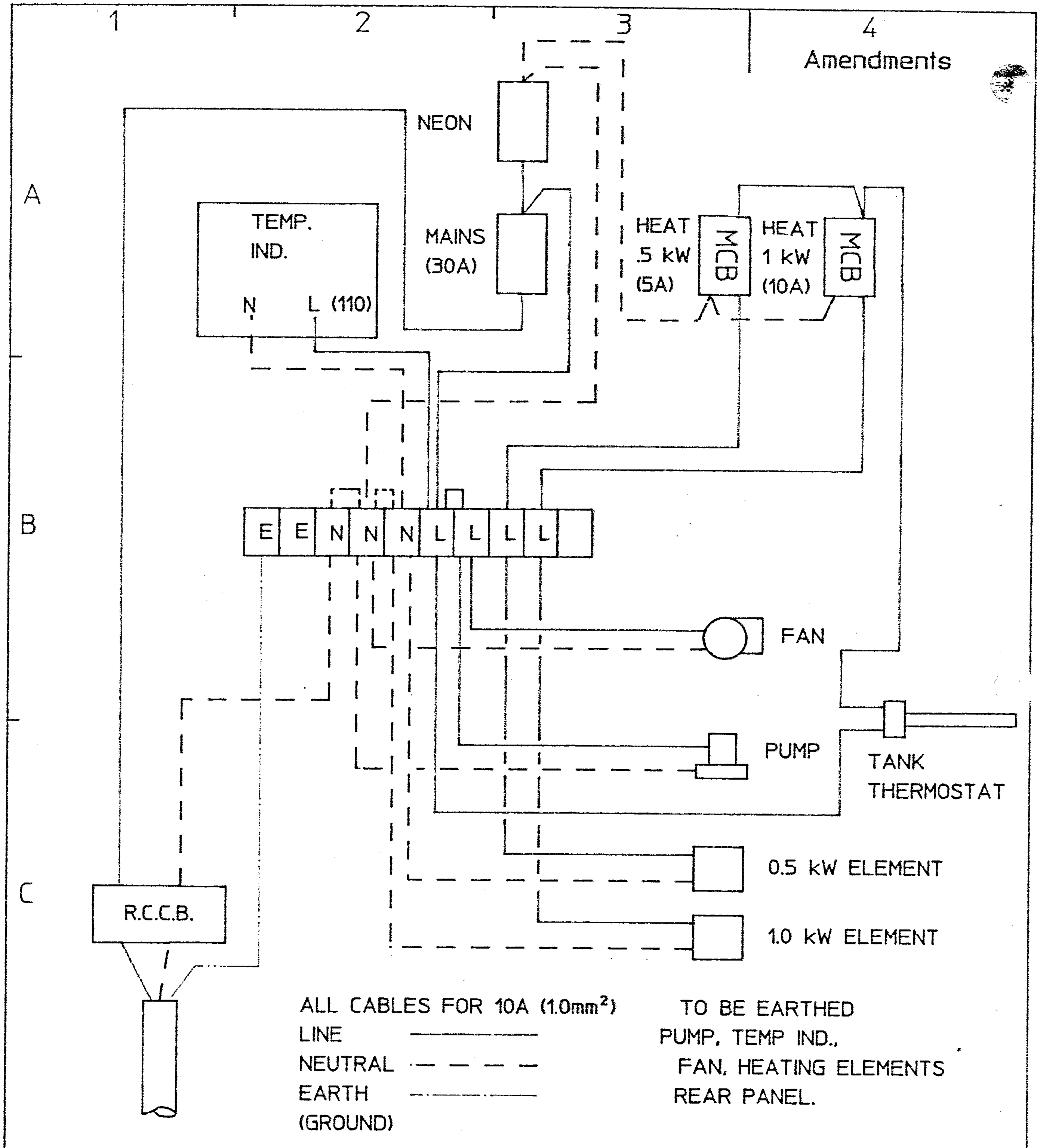
(GROUND)

TO BE EARTHED
PUMP, TEMP IND.,
FAN, HEATING ELEMENTS
REAR PANEL.

The supplier is required to deliver goods strictly according to drawing. Component inspection is the suppliers responsibility. Remove all sharp edges and burrs.

Drawn by: JB
Dimensions: ————
Limits unless otherwise stated : Fractions ± 1/64"
Decimals ± 0.25 mm
Projection: ◎ ◁
Issue: 1
TITLE: WIRING DIAGRAM H891 220/240V
Date: 29.3.88
DRG. No. 89112S
MTL: ————————
Scale. ——
FINISH: ————————
no/rig. ——

P. A. HILTON LTD . KINGS SOMBORNE HAMPSHIRE ENGLAND



ALL CABLES FOR 10A (1.0mm^2)
LINE ————————
NEUTRAL — — — —
EARTH ——·——
(GROUND)

TO BE EARTHED
PUMP, TEMP IND.,
FAN, HEATING ELEMENTS
REAR PANEL.

The supplier is required to deliver goods strictly according to drawing. Component inspection is the suppliers responsibility. Remove all sharp edges and burrs.

Limits unless otherwise stated : Fractions ± 1/64"
Decimals ± 0.25 mm

Drawn by: JB
Dimensions: ————
Projection: ◎ ◁
Issue: 1

TITLE: WIRING DIAGRAM H891 110V
MTL: ————————
FINISH: ————————

Date: 29.3.88
Scale. ——
no/rig. ——
DRG. No. 89123S

P. A. HILTON LTD . KINGS SOMBORNE HAMPSHIRE ENGLAND

REFERENCES

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P. A. HILTON LIMITED

ADDENDUM

to

Experimental, Operating and Maintenance Manual

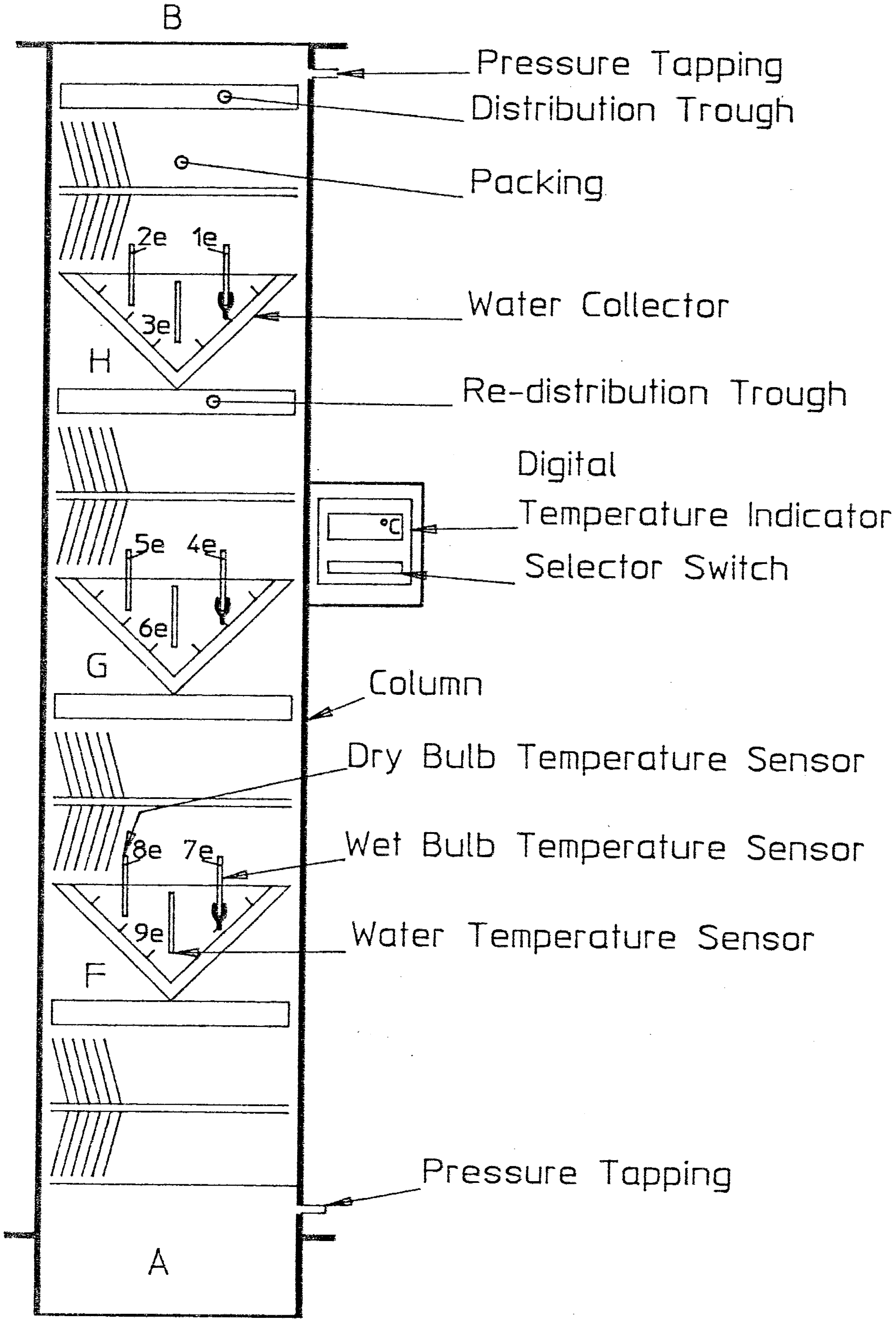
for

BENCH TOP COOLING TOWER H891

PACKING CHARACTERISTICS COLUMN

INDEX TO ADDENDUM

H891E Packing Characteristics Column



INTRODUCTION

In addition to all the facilities available with the Hilton Bench Top Cooling Tower H891, the Packing Characteristics Column allows water and air conditions to be measured at three additional stations (F, G and H) within the column.

This enables driving force diagrams to be constructed and the determination of the Characteristic Equation for the Tower.

SYMBOLS AND UNITS

The symbols used in the following pages are those normally used in mass transfer studies. It should be noted that these may differ slightly from those given on Page 2.

Symbol	Quantity	Fundamental Unit
a	Area of contact between air and water per unit volume of packing	m^{-1}
C_{p_w}	Specific heat capacity of water	$J\ kg^{-1}\ K^{-1}$
f	Correction factor from chart on Page 55	
H	Specific enthalpy of water	$J\ kg^{-1}$
h	Specific enthalpy of air	$J\ (kg\ dry\ air)^{-1}$
Δh_m	Corrected arithmetic mean enthalpy driving force	$J\ (kg\ dry\ air)^{-1}$
K	Mass transfer coefficient per unit plan area	$kg\ s^{-1}\ m^{-2}$
$\dot{m}_w$	Mass flow rate of water per unit plan area of packing	$kg\ s^{-1}\ m^{-2}$
$\dot{m}_a$	Mass flow rate of air per unit plan area of packing	$kg\ s^{-1}\ m^{-2}$
$\dot{m}_w'$	Mass flow rate of water	$kg\ s^{-1}$
$\dot{m}_a'$	Mass flow rate of air	$kg\ s^{-1}$
T	Temperature of water	°C
t	Temperature of air	°C
V	Volume occupied by packing per unit plan area	m
v_B	Specific volume of moist air leaving the top of the column	$m^3\ kg^{-1}$
x	Orifice differential pressure	mm H_2O
Z	Depth of packing	m
γ	Enthalpy difference	$J\ (kg\ dry\ air)^{-1}$

PACKING DATA: Packing Type - C

Number of Blocks - 4

Number of Decks per Block - 2

Number of Plates per Deck - 18

Total Surface Area of Packing - 2.16 m^2

Height of Packing - 4 blocks each 0.12m = 0.48m

Packing "Density" $\frac{\text{Area}}{\text{Volume}}$ - 200 m^{-1}

THEORY

It is recognised that the theoretical treatment of the processes of heat and mass transfer occurring within a cooling tower differ from one authority to another. Full details of the generally accepted procedure and symbols used is to be found in the references.

The following expressions are relevant to the determination of the packing characteristics of a Cooling Tower:

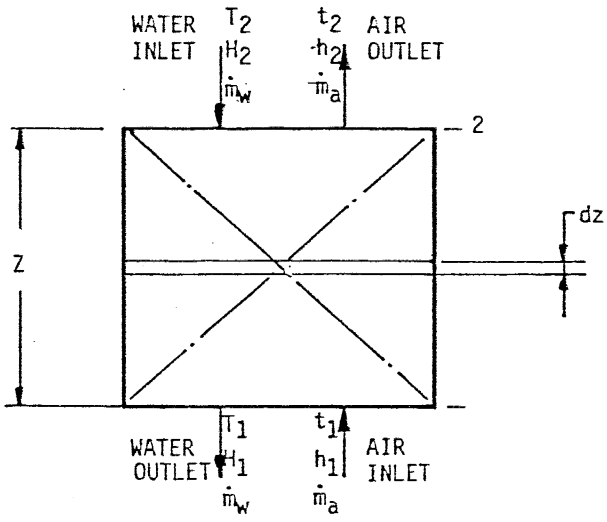


FIG. 2

FIG.2 Schematic representation of the air and water streams entering and leaving a block of packing.

It may be shown that, for a finite element of the tower (dZ), the energy balances of the water and air streams in the tower are related to the mass transfer by the following equation:

$$C_{p_w} \dot{m}_w \, dT = Ka \, dV \, (\Delta h) \qquad \text{I}$$

where Δh is the difference in specific enthalpy between the saturated boundary layer and the bulk air.

The boundary layer temperature is considered to be equal to the water temperature T and the small change in the mass of water is neglected.

From Equation I:

$$\frac{Ka \, dV}{\dot{m}_w} = \frac{C_{p_w} \, dT}{\Delta h} \qquad \text{II}$$

Integrating:

$$\frac{Ka \, V}{\dot{m}_w} = C_{p_w} \int_{T_1}^{T_2} \frac{dT}{\Delta h} \qquad \text{III}$$

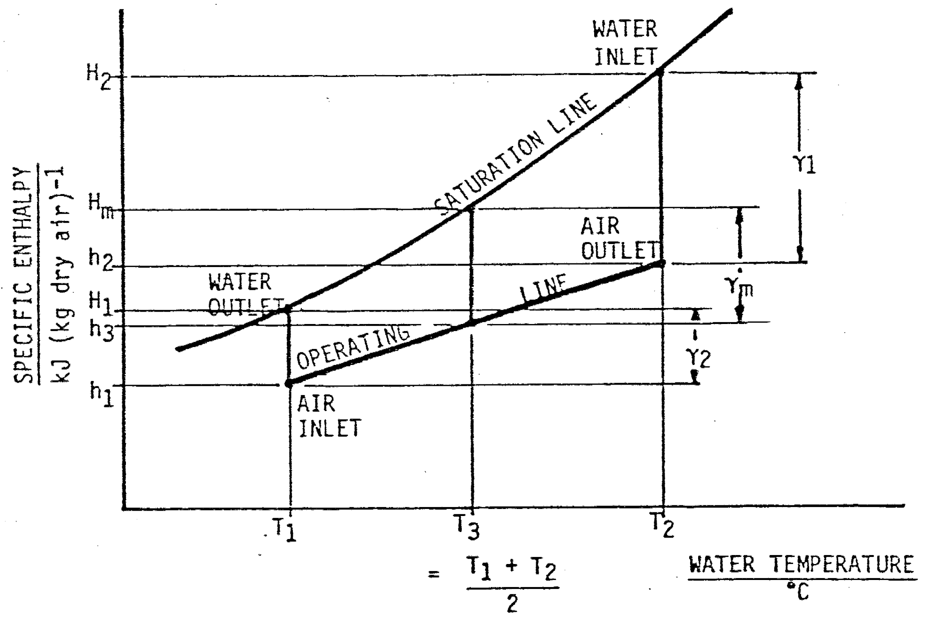
One numerical solution to the integral expression Equation III is:

$$\frac{Ka \, V}{\dot{m}_w} = \frac{C_{p_w} (T_2 - T_1)}{\Delta h_m} \qquad \text{IV}$$

where Δh_m is the corrected arithmetic mean of the water inlet and outlet enthalpies. Δh_m is generally known as the enthalpy mean driving force.

Assuming the water boundary layer is saturated and at the same temperature as the water, a driving force diagram can be constructed as shown in Figure 3.

Key: $T_3 = \frac{T_1 + T_2}{2}$



DRIVING FORCE DIAGRAM FIG.3

The five temperature measuring points evenly distributed throughout the height of the Hilton Packing Characteristics Column allow the construction of the driving force diagram (See Schematic Diagram, Page 51).

In determining the packing characteristic the method of Carey and Williamson (Page 56) is used. This depends upon the application of a correction factor, f, to the observed value of $H_m - h_3$ (at the arithmetic mean of T_1 and T_2) to obtain the mean driving force. The Carey and Williamson correction factor chart is shown on Page 55, where

$$\Upsilon_1 = H_2 - h_2$$

$$\Upsilon_2 = H_1 - h_1$$

$$\Upsilon_m = H_m - h_3$$

$$\Delta h_m = f\Upsilon_m$$

The value of Δh_m is inserted into Equation IV to yield a value for $\frac{Ka\ V}{\dot{m}_w}$ since both T_2, T_1 and the mean specific heat of water, C_{p_w} are known.

The characteristic equation of the cooling tower is obtained by plotting values of $\frac{Ka\ V}{\dot{m}_w}$ versus the ratio of water to air flow rates $\frac{\dot{m}_w}{\dot{m}_a}$.

The plot fits the equation $$\frac{Ka\ V}{\dot{m}_w} = \lambda \left[\frac{\dot{m}_w}{\dot{m}_a} \right]^n$$

where λ and n are constants for a particular packing.

By logarithmically plotting $\frac{Ka\ V}{\dot{m}_w}$ against $\frac{\dot{m}_w}{\dot{m}_a}$, the value of λ and n may be determined.

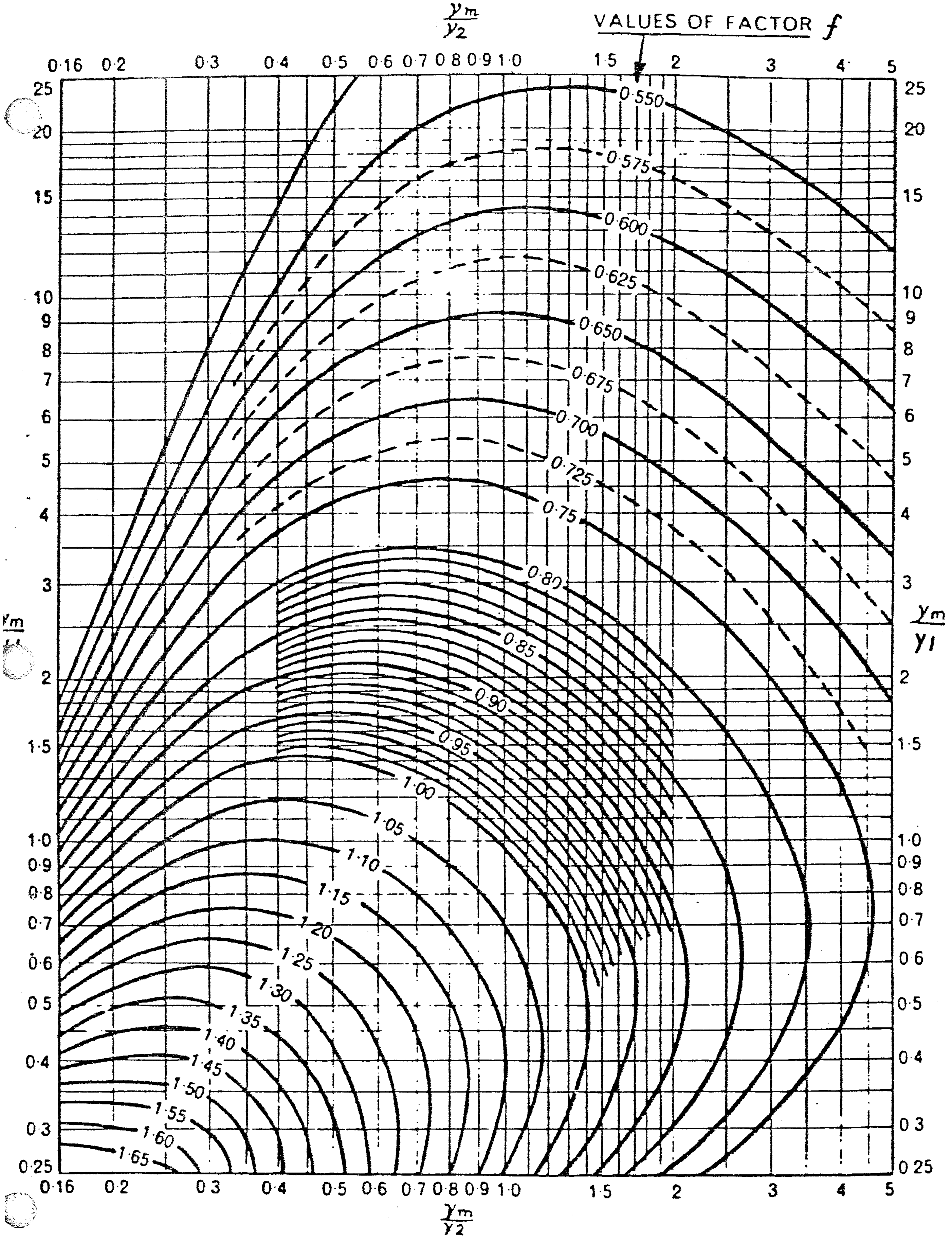


Chart for determination of mean driving force.

(By Carey & Williamson, based upon a chart prepared by W. L. Stevens).

By superimposing the characteristic equation upon the cooling water tower demand curves given in Ref. 9, the performance of a cooling tower fitted with this packing can be predicted for a wider range of conditions.

PREPARATION FOR A TEST

(i) Read page 8, substituting the Packing Characteristics Column for the packed column (A, B or C) in paragraph 4 on page 8.

(If desired, a small quantity, say 5 to 10 cm^3, of photographic wetting agent may be added to the distilled water poured into the base unit. This will reduce the time taken for the packings to become thoroughly wetted.)

(ii) Draw about 200mm of thermocouple lead from the sleeving attached to the water pipe. If there is any difficulty, remove the panel at the rear of the instrument panel and free the lead.

(iii) Fit the extension reinforced plastic hose between the connection on the cap water distributor and the end of the existing hose.

(iv) Plug the Temperature Indicator cable into a 240V A.C. socket provided.

(v) Switch on the fan, pump and temperature indicator - set the water flow rate to its maximum and leave the unit to run until the packings are thoroughly wetted.

CALIBRATION OF SENSORS

Temperatures in the base unit and cap are observed on the digital meter on the instrument panel while those in the Packing Characteristics Column are from a digital temperature indicator mounted on the side of the column. It is therefore necessary to check the calibration of the two temperature indicators as follows.

(i) Prepare the unit as indicated above.

(ii) Close the water flow control valve.

(iii) Switch on the mains. (The pump will run, but no water will flow through the column.)

(iv) Fully open the damper on the fan.

(v) Allow the unit to run for about 20 minutes in a room where the temperature is steady so that all the air sensors reach the same temperature.

(vi) Observe and note,
  (a) The dry bulb temperatures t_1 and t_3 indicated by the digital indicator on the instrument panel.
  (b) The dry bulb temperatures t_{2e}, t_{5e} and t_{8e} indicated by the digital indicator mounted on the side of the Packing Characteristics Column.

(vii) Having compared the mean of t_1 and t_3 with the mean of t_{2e}, t_{5e} and t_{8e}, the instrument discrepancy will become apparent and the necessary correction may be applied to readings observed on one or the other instrument.

REMOVAL OF WET AND DRY BULB SENSORS

The Wet and dry bulb sensors and their hoods are bent and must be removed carefully to avoid damage:

1. Remove the cap from the cable conduit at the back of the column and release sufficient thermocouple cable to allow withdrawal of the sensor.

2. Hold the end of the sensor to prevent rotation, then unscrew the black hexagonal gland nut to free the sensor.

3. Still holding the sensor, unscrew and withdraw the black hexagonal gland body.

4. Carefully withdraw the sensor, rotating it through 90° so that the wick clears the ports in the sensor hood.

When replacing the sensor, it is helpful if the wick is moistened and again, the sensor must be rotated to clear the ports in the hood.

EXPERIMENTAL PROCEDURE

Object
To determine the Characteristic Equation of the Hilton Bench Top Cooling Tower.

Apparatus
The Hilton Bench Top Cooling Tower fitted with the Packing Characteristics Column.

Preparation
Study the apparatus and identify all controls, instruments and the water and air paths.

Read the instructions given in Page 57.

Run the unit until all packings are wetted.

Procedure and Observations
(i) Fully open the fan inlet damper and set the water flow to its maximum.

(ii) Switch the water heaters to give a heat input of 1.0 or 1.5kW.

(iii) Allow temperatures to stabilise.

(iv) Observe:
  (a) Orifice differential pressure.
  (b) Water flow rate.
  (c) All temperatures (corrected as detailed on Page 57).

(v) Repeat the observations at a number of lower water flow rates down to about 10 gm s^{-1}, always allowing conditions to stabilise and making any temperature corrections necessary.

(vi) Partly close the air intake damper and repeat the foregoing at manometer readings of say 6 and 2 mm H_2O.

An example of a typical Observation Sheet is given on Page 61.

CALCULATIONS

An example of a Calculation Sheet is shown on Page 65.

1. Using a Psychrometric Chart, determine the specific enthalpy of the moist air at stations A, F, G, H and B. Also determine the specific volume of the moist air at station B.

2. Draw the saturation curve for air (as shown in Figure 3) using the following temperature/enthalpy data (or alternatively, from the saturation line on the Psychrometric Chart):

Air Temperature °C	Enthalpy of Saturated Air/kJ(kg dry air)$^{-1}$
0	9.6
5	18.8
10	29.5
15	42.2
20	57.9
25	76.8
30	101.0
35	130.0
40	168.0
45	216.0
50	277.0

3. On the Driving Force Diagram plot, Page 64, the water temperature T/Air enthalpy (h) points for stations A, F, G. H and B.

4. Draw a straight line through
   (i) A and B, i.e. for four blocks of packing total height 0.48m
   (ii) A and H, " three " " " " 0.36m
   (iii) A and G, " two " " " " 0.24m
   (iv) A and F, " one " " " " 0.12m

   (These are the operating lines.)

5. Using the Driving Force Diagram, determine γ_1, γ_2 and γ_m (see Fig.3, Page 55) for each packing height.

6. Using the Carey and Williamson Chart provided, Page 56, determine the correction factor for each packing height.

7. Determine the enthalpy mean driving force Δh_m for each packing height.

8. Calculate $\frac{C_p\ (T_1 - T_2)}{\Delta h_m}$ (which is equal to $\frac{Ka\ V}{\dot{m}_w}$) for each packing height.
   ($C_p = 4.18\ \text{kJ kg}^{-1}\ \text{K}^{-1}$)

9. Calculate $\frac{\dot{m}_w}{\dot{m}_a}$ (which is equal to $\frac{\dot{m}_w'}{\dot{m}_a'}$).

10. Logarithmically, plot $\frac{Ka\ V}{\dot{m}_w}$ against $\frac{\dot{m}_w}{\dot{m}_a}$ for each packing height.

11. Draw the best straight line through the points for each packing height and estimate the equations in the form

$$\frac{Ka\ V}{\dot{m}_w} = \lambda\left[\frac{\dot{m}_w}{\dot{m}_a}\right]^n$$

which then become the Characteristic Equations of the Packing Characteristics Column.

SPECIMEN CALCULATIONS

A set of observations obtained from the Hilton Bench Top Cooling Tower fitted with the Packing Characteristics Column is shown on Page 61.

Although not essential, it is interesting to draw wet bulb, dry bulb and water temperatures against positions in the column, as shown on Page 62.

(i) From the corrected wet and dry bulb temperatures the air state points for stations A, F. G, H and B were plotted on the psychrometric chart, and the specific enthalpies obtained, see Page 63.

(ii) From the specific enthalpies of saturated air, Page 59, the saturation curve was drawn.

(iii) State points A, F, G, H and B were plotted and the Driving Force Diagram(s) and operating lines were constructed, see Page 64.

(iv) For each height of packing, the values of γ_1, γ_2 and γ_m were determined.

(v) The correction factor (f) was determined from Page 56, and the values of Δh_m calculated.

(vi) Values of $\frac{C_p\ (T_1 - T_2)}{\Delta h_m}$ $\left(= \frac{Ka\ V}{\dot{m}_w}\right)$ and of $\frac{\dot{m}_w}{\dot{m}_w}$ were calculated (see page 65).

(vii) $\frac{Ka\ V}{\dot{m}_w}$ and $\frac{\dot{m}_w}{\dot{m}_a}$ were plotted logarithmically for this and other tests, Page 66, and the Characteristic Equations obtained.

Note For clarity, only points for the whole column (A to B, i.e. 8 decks of packing) and the lower half of the column (A to G, i.e. 4 decks of packing) have been plotted.

The Characteristic Equations were found to be

$$\frac{Ka\ V}{\dot{m}_w} = 1.7\left[\frac{\dot{m}_w}{\dot{m}_a}\right]^{-0.57} \quad \text{for the whole column}$$

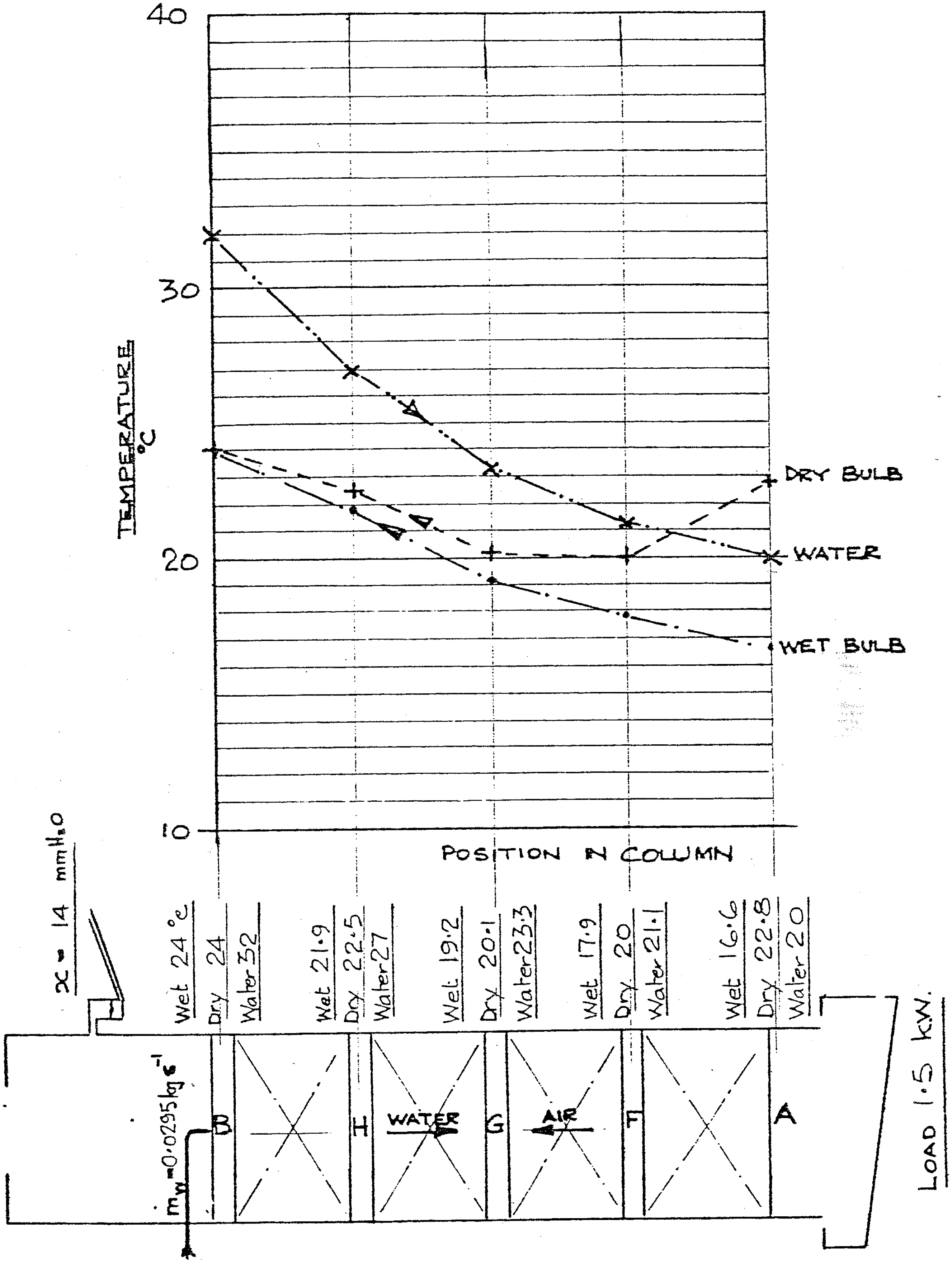
$$\text{and} \quad \frac{Ka\ V}{\dot{m}_w} = 0.75\left[\frac{\dot{m}_w}{\dot{m}_a}\right]^{-0.57} \quad \text{for the lower half column.}$$

BENCH TOP COOLING TOWER
WITH PACKING CHARACTERISTICS COLUMN

OBSERVATION SHEET

Date: Atmospheric pressure: mbar

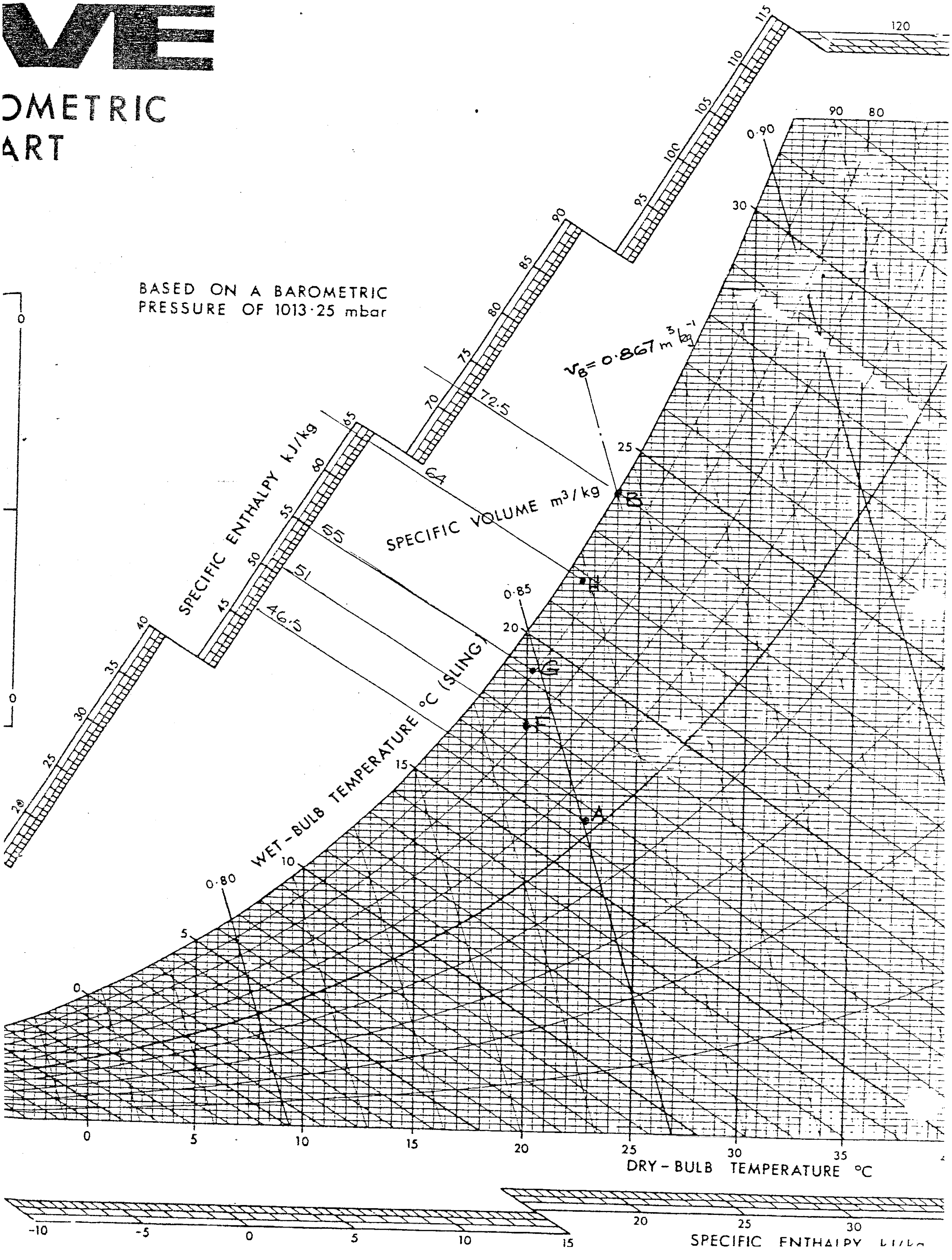
Test No.		1	2	3	4	5
Water flow rate	$\frac{\dot{m}_w}{g\ s^{-1}}$	29.5				
Orifice differential	$\frac{x}{mm\ H_2O}$	14.0				
Heater setting	$\frac{\dot{Q}}{kW}$	1.5				
Station B (Top)						
Air wet bulb temperature	°C	24.0				
Air dry bulb temperature	°C	24.0				
Water temperature	°C	32.0				
Station H						
1 Air wet bulb temperature	°C	21.9	)			
2 Air dry bulb temperature	°C	22.5	)			
3 Water temperature	°C	27.0	)			
Station G			)			
4 Air wet bulb temperature	°C	19.2	)			
5 Air dry bulb temperature	°C	20.1	) Corrected temperatures, see Page 57			
6 Water temperature	°C	23.3	)			
Station F			)			
7 Air wet bulb temperature	°C	17.9	)			
8 Air dry bulb temperature	°C	20.0	)			
9 Water temperature	°C	21.1	)			
Station A (Bottom)						
Air wet bulb temperature	°C	16.6				
Air dry bulb temperature	°C	22.8				
Water temperature	°C	20.0				



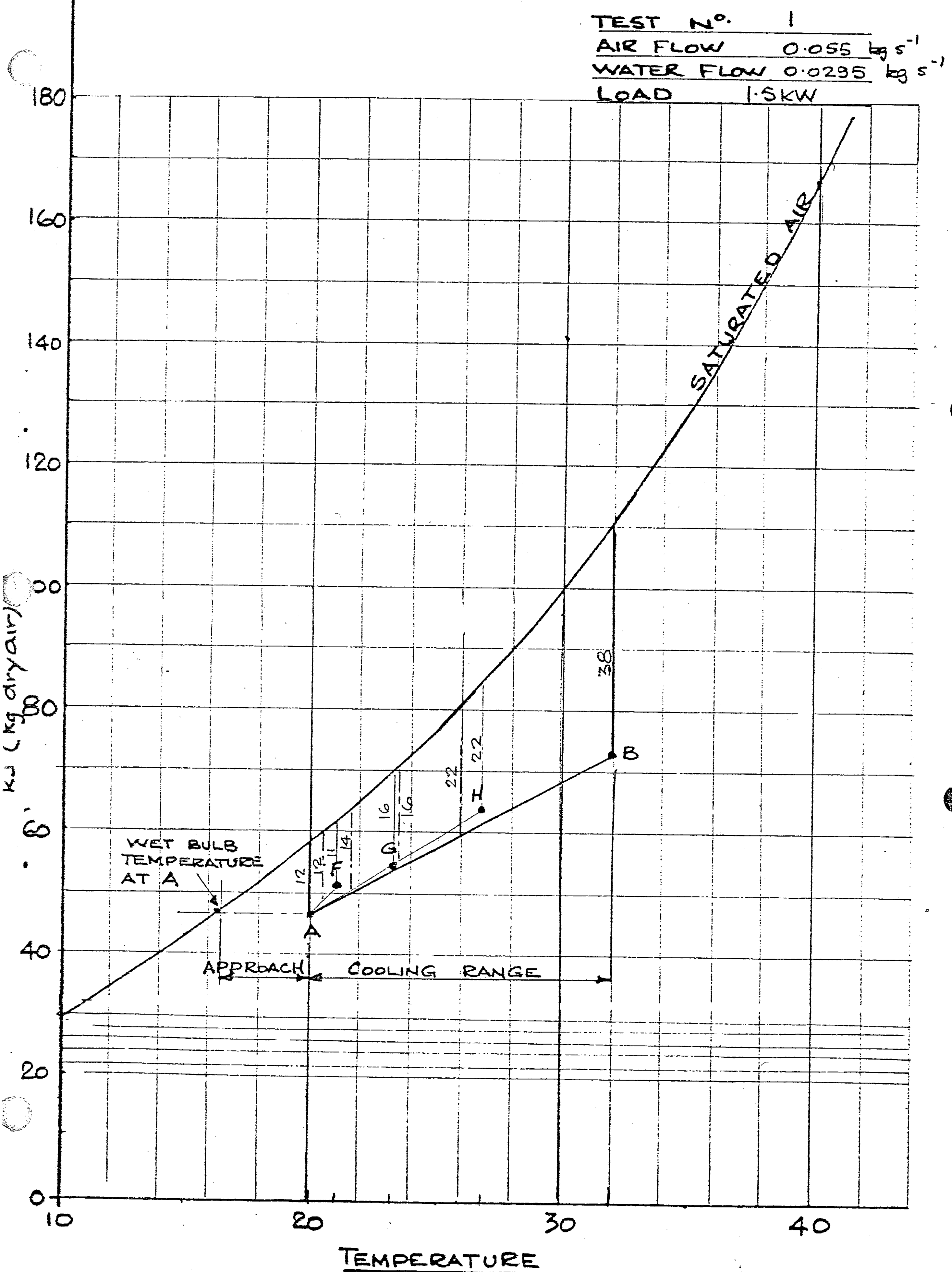
TEMPERATURE DISTRIBUTION IN PACKING CHARACTERISTICS COLUMN.

OMETRIC
ART

BASED ON A BAROMETRIC PRESSURE OF 1013·25 mbar



DRIVING FORCE DIAGRAM



PACKING CHARACTERISTICS COLUMN

CALCULATION SHEET

Test No. 1 Date:

Station	Air Temperature $\frac{t}{^\circ C}$		Water Temperature $\frac{T}{^\circ C}$	Air Enthalpy $\frac{h}{kJ(kg\ dry\ air)^{-1}}$
	Dry Bulb	Wet Bulb		
B	24	24	32	72.5
H	21.9	22.5	27	64
G	19.2	20.1	23.3	55
F	17.9	20	21.1	51
A	16.6	22.8	20	46.5

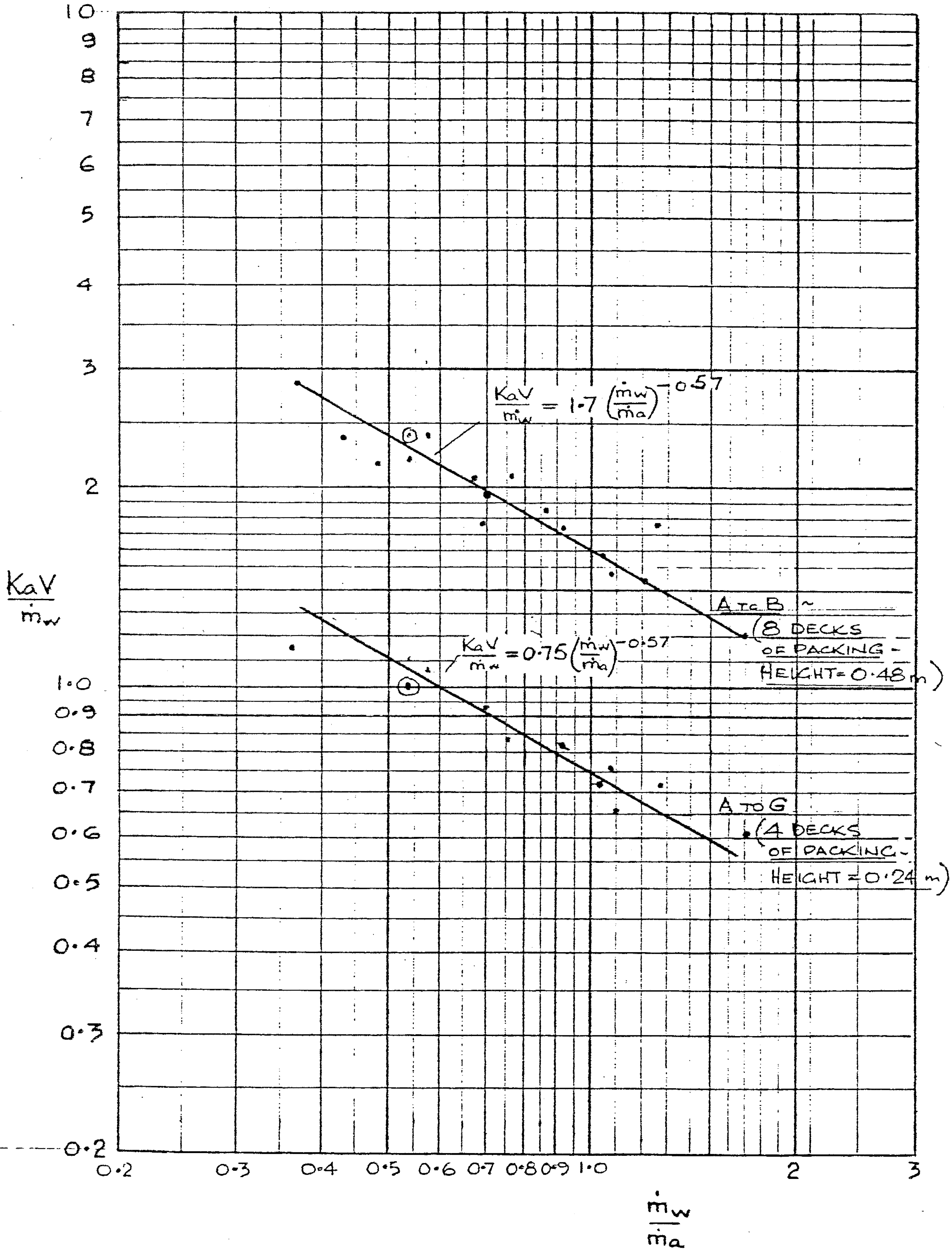
$\dot{m}_w' = 0.0295\ kg\ s^{-1}$

$v_B = 0.867\ m^3\ kg^{-1}$

$\dot{m}_a' = 0.0137 \sqrt{\frac{x}{v_B}}\ kg\ s^{-1}$

$\dot{m}_a = 0.055\ kg\ s^{-1}$

Sections/No. of Decks	A to F/2	A to G/4	A to H/6	A to B/8
T_1	20	20	20	20
T_2	21.1	23.3	27	32
$T_3 = \frac{T_1 + T_2}{2}$	20.55	21.65	23.5	26
$\gamma_1 = H_2 - h_2$	11	16	22	38
$\gamma_2 = H_1 - h_1$	12	12	12	12
$\gamma_m = H_m - h_3$	12	14	16	22
$\frac{\gamma_m}{\gamma_1}$	0.92	0.875	0.73	0.58
$\frac{\gamma_m}{\gamma_2}$	1	1.17	1.16	1.83
f (from Fig.4)	1.01	0.99	1.01	0.95
$\Delta h_m = f\ \gamma_m$	12	13.8	16.2	20.9
$\frac{Ka\ V}{\dot{m}_w} = \frac{Cp\ (T_2 - T_1)}{\Delta h_m}$	0.383	1.0	1.8	2.4
$\frac{\dot{m}_w}{\dot{m}_a} = \frac{\dot{m}_w'}{\dot{m}_a'}$	0.53	0.53	0.53	0.53



PACKING CHARACTERISTICS

BENCH TOP COOLING TOWER WITH PACKING CHARACTERISTICS COLUMN

OBSERVATION SHEET

Date:

Atmospheric pressure: mbar

Test No.		1	2	3	4	5
Water flow rate	$\frac{\dot{m}_w}{g\ s^{-1}}$					
Orifice differential	$\frac{x}{mm\ H_2O}$					
Heater setting	$\frac{\dot{Q}}{kW}$					
Station B (Top)						
Air wet bulb temperature	°C					
Air dry bulb temperature	°C					
Water temperature	°C					
Station H						
1 Air wet bulb temperature	°C					
2 Air dry bulb temperature	°C					
3 Water temperature	°C					
Station G						
4 Air wet bulb temperature	°C					
5 Air dry bulb temperature	°C					
6 Water temperature	°C					
Station F						
7 Air wet bulb temperature	°C					
8 Air dry bulb temperature	°C					
9 Water temperature	°C					
Station A (Bottom)						
Air wet bulb temperature	°C					
Air dry bulb temperature	°C					
Water temperature	°C					

PACKING CHARACTERISTICS COLUMN

CALCULATION SHEET

Test No. 1

Date:

Station	Air Temperature $\frac{t}{^{\circ}C}$		Water Temperature $\frac{T}{^{\circ}C}$	Air Enthalpy $\frac{h}{kJ(kg\ dry\ air)^{-1}}$
	Dry Bulb	Wet Bulb		
B				
H				
G				
F				
A				

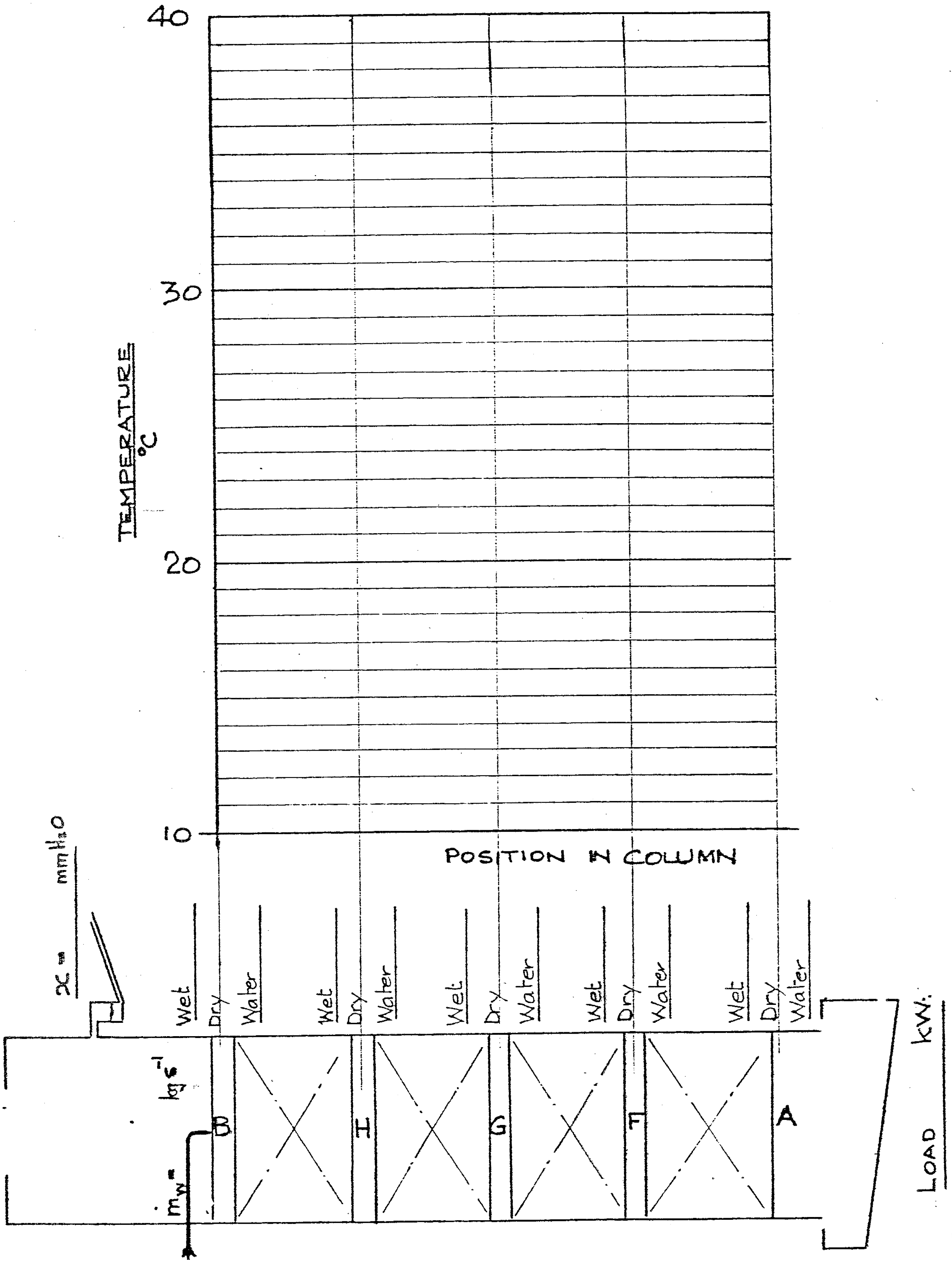
$\dot{m}_w' =$ kg s^{-1}

$v_B =$ $m^3\ kg^{-1}$

$\dot{m}_a' = 0.0137 \sqrt{\frac{x}{v_B}}$ kg s^{-1}

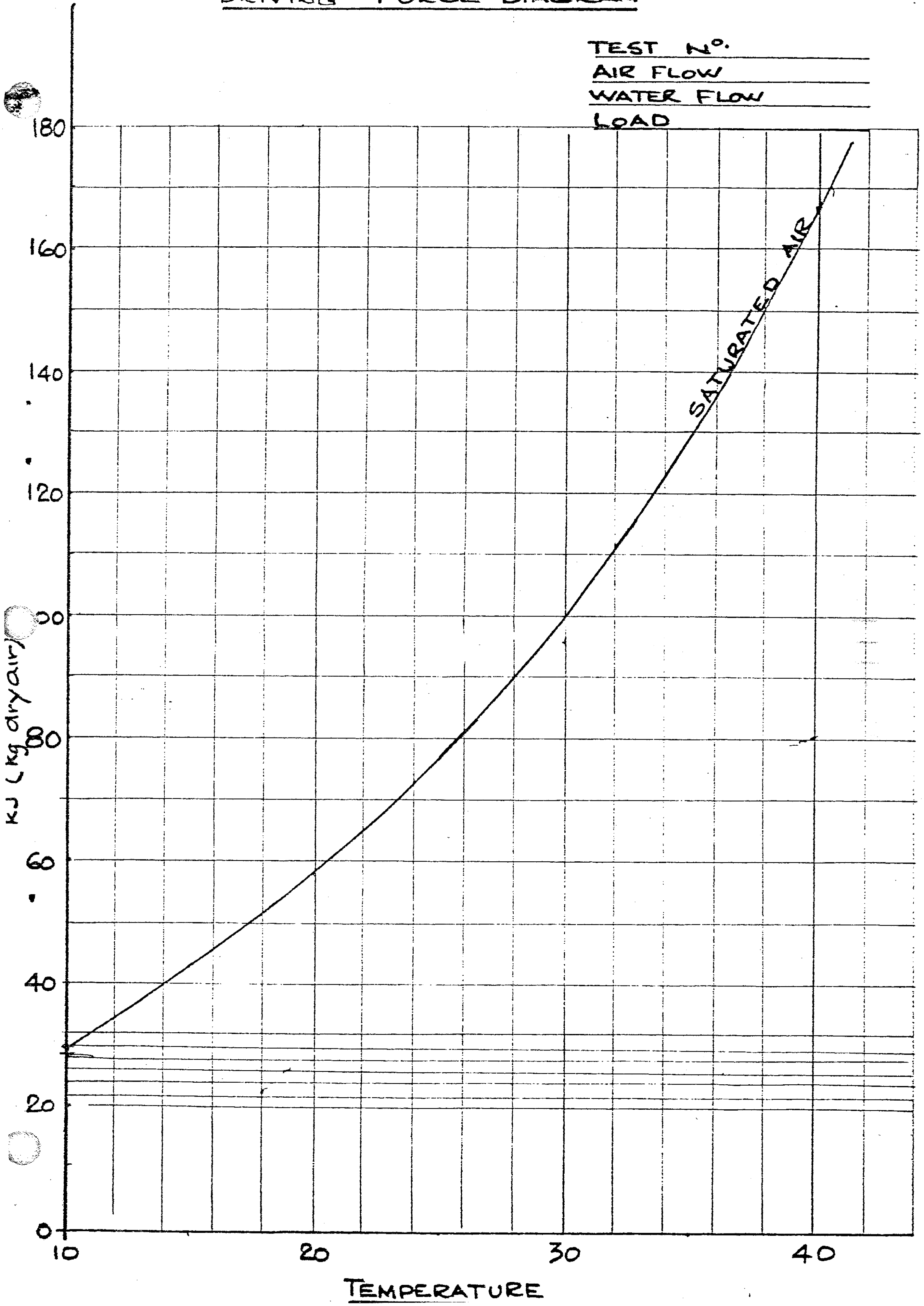
$\dot{m}_a =$ kg s^{-1}

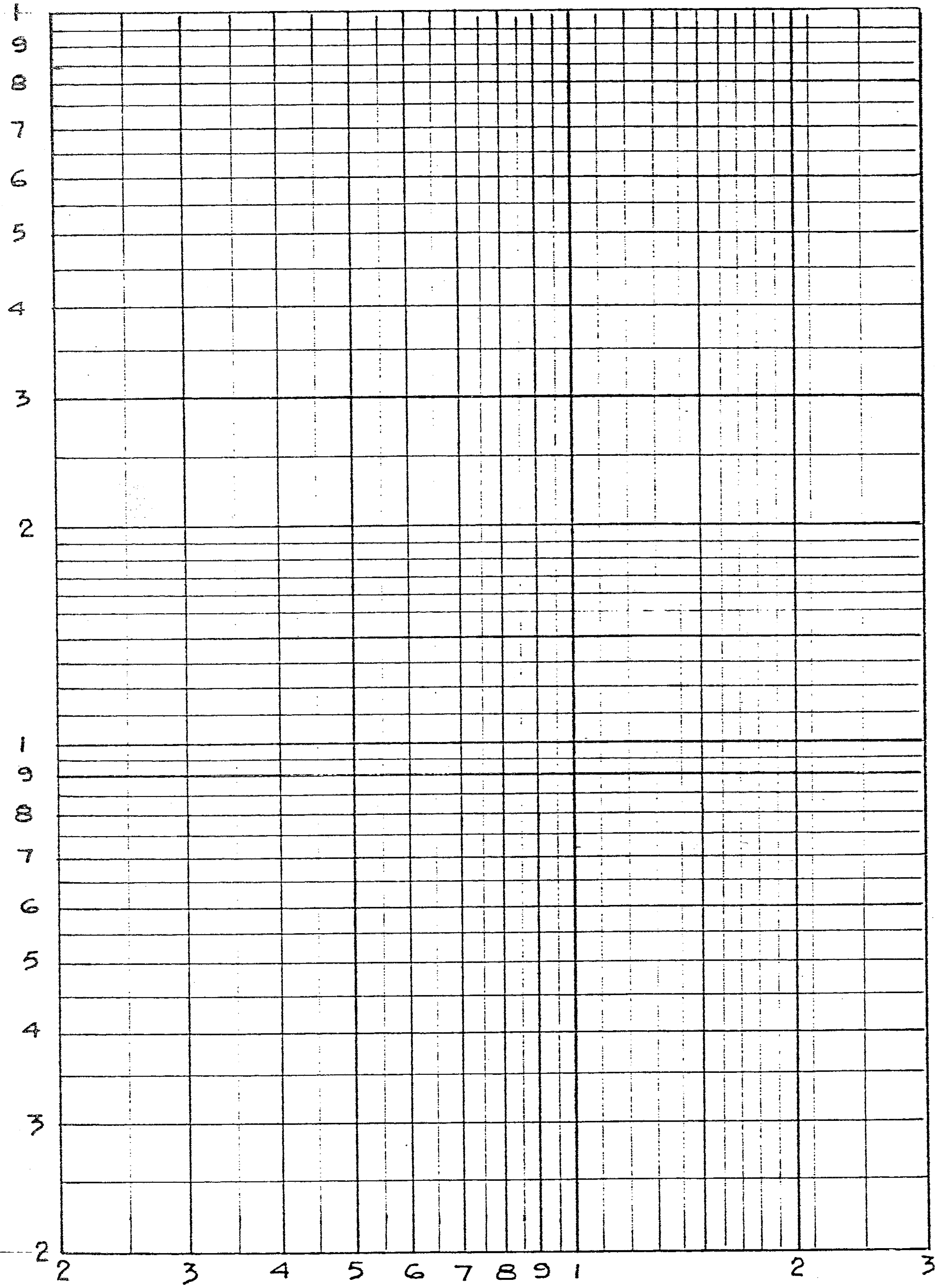
Sections/No. of Decks	A to F/2	A to G/4	A to H/6	A to B/8
T_1 T_2 $T_3 = \frac{T_1 + T_2}{2}$				
$\gamma_1 = H_2 - h_2$ $\gamma_2 = H_1 - h_1$ $\gamma_m = H_m - h_3$				
$\frac{\gamma_m}{\gamma_1}$ $\frac{\gamma_m}{\gamma_2}$ f (from Fig.4)				
$\Delta h_m = f\ \gamma_m$ $\frac{Ka\ V}{\dot{m}_w} = \frac{Cp\ (T_2 - T_1)}{\Delta h_m}$				
$\frac{\dot{m}_w}{\dot{m}_a} = \frac{\dot{m}_w'}{\dot{m}_a'}$				


40
30
20
10
TEMPERATURE
°C
POSITION IN COLUMN
x = mmH2O
mw = kg s-1
Wet
Dry
Water
Wet
Dry
Water
Wet
Dry
Water
Wet
Dry
Water
Wet
Dry
Water
B
H
G
F
A
LOAD kW

DRIVING FORCE DIAGRAM

TEST No.
AIR FLOW
WATER FLOW
LOAD




1
9
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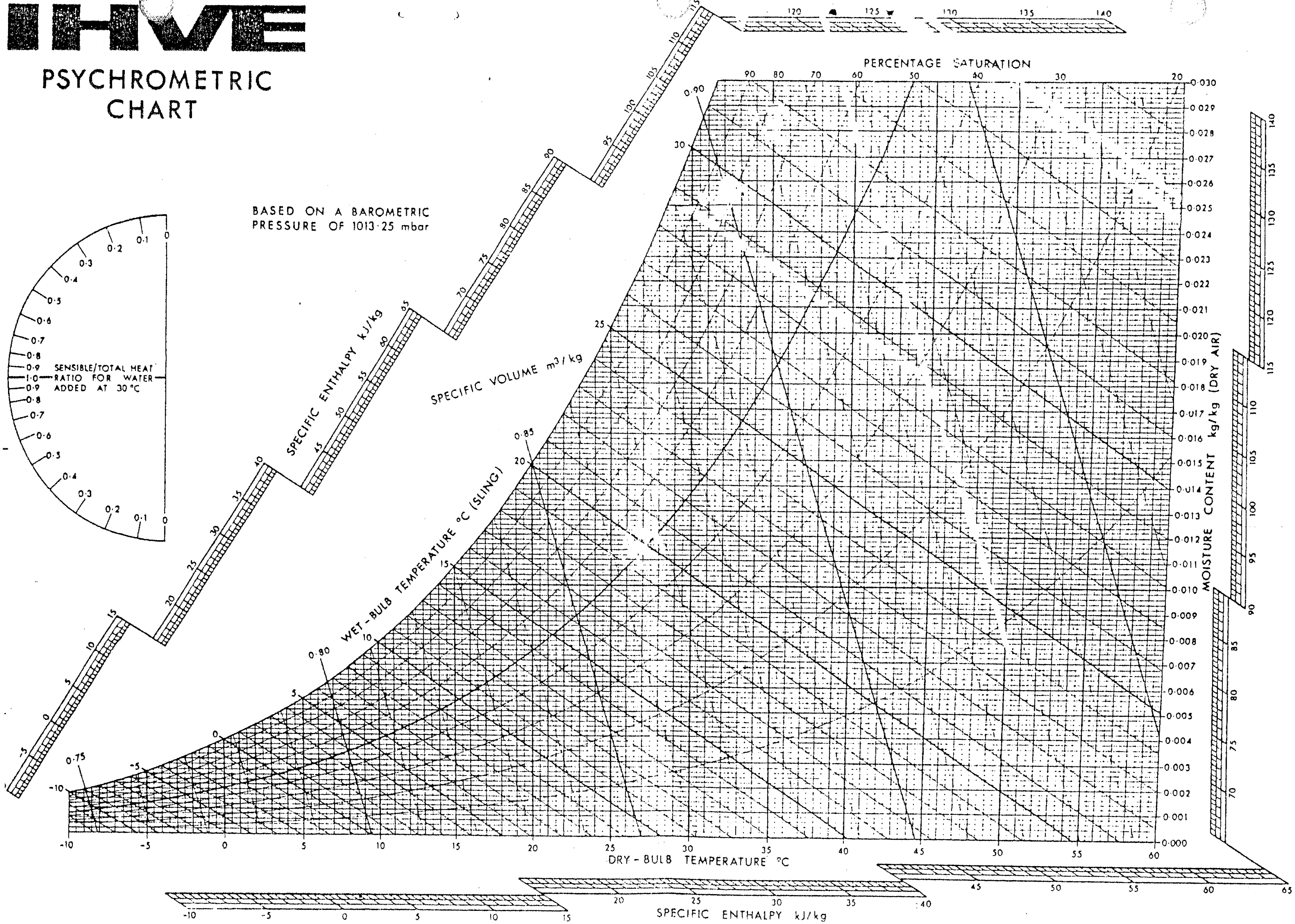
IHVE

PSYCHROMETRIC CHART



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