P.A. HILTON LTD.

EXPERIMENTAL

OPERATING
&
MAINTENANCE MANUAL

EXPERIMENTAL REACTION TURBINE

F840

F840M/E/2
MAR 89

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.

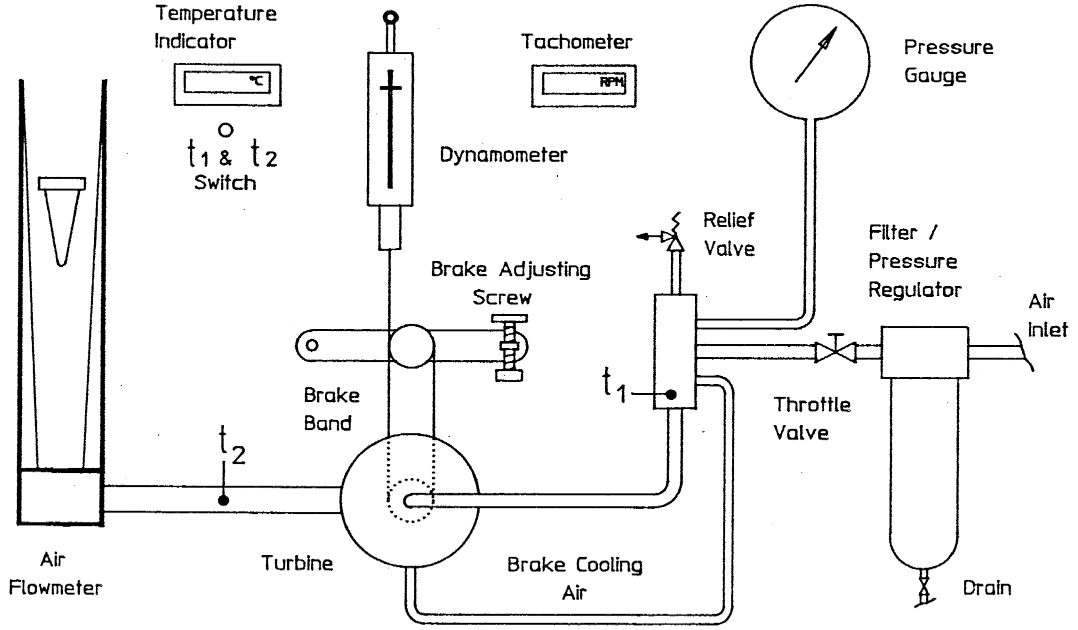
Paul A. Hilton

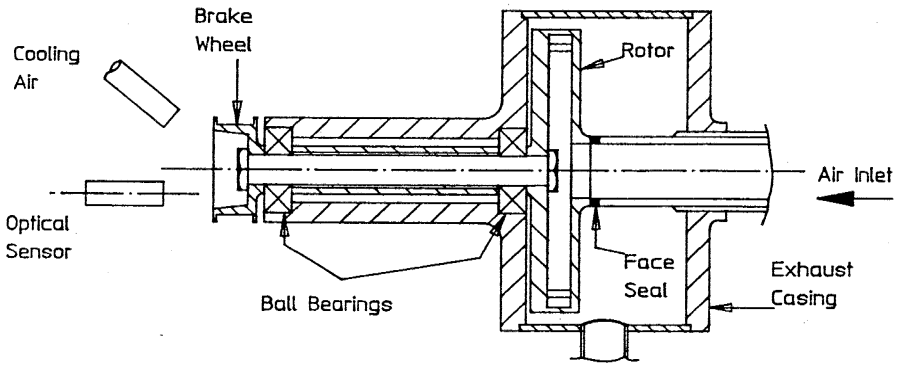
G. A. Hewett

Paul A. Hilton.

Gerald A. Hewett.

F840 EXPERIMENTAL REACTION TURBINE





SECTION THROUGH TURBINE

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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SYMBOLS AND UNITS

Symbol	Quantity	Fundamental Unit
Cp	Specific Heat Capacity at constant pressure	$J\ kg^{-1}\ K^{-1}$
F	Force	N
h	Specific Enthalpy	$kJ\ kg^{-1}$
I	Moment of Inertia	$kg\ m^2$
$\dot{m}$	Mass Flow Rate	$kg\ s^{-1}$
M	Torque	Nm
n	Rotational Speed	$Rev\ min^{-1}$
p	Pressure	$N\ m^{-2}$
P	Power	W
q	Heat Transfer per Unit Mass	$J\ kg^{-1}$
$\dot{Q}$	Heat Transfer Rate	W
r	Radius	m
s	Specific Entropy	$J\ kg^{-1}\ K^{-1}$
t	Temperature (Customary)	°C
T	Temperature (Absolute)	K
U	Velocity	$m\ s^{-1}$
w	Work per Unit Mass	$J\ kg^{-1}$
α	Angular Acceleration	s^{-2}
ω	Angular Velocity	s^{-1}
γ	Ratio Cp/Cv	-
η	Efficiency	-

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 AND/OR STATES

1	Inlet
2	Exhaust
f	Friction
S	Shaft
'	(e.g. T') denotes a state reached by an isentropic process

INTRODUCTION

Turbines are machines which develop torque and shaft power as a result of momentum changes in the fluid which flows through them.

The fluid may be a gas, vapour or liquid, but the following notes apply to turbines operating on a gas or a vapour.

For the fluid to achieve the high velocity required to provide worthwhile momentum changes, there must be a significant pressure difference between the inlet and exhaust of the turbine.

Sources of pressurised gas include previously compressed (and possibly heated) gas - as in a gas turbine, or in the turbine of a turbo-charger for an I.C. engine. Steam generated in high pressure nuclear or fossil fueled boilers is extensively used in turbine driven alternators for the electrical power industry.

There are numerous types of turbine from the elementary example used in a dental drill to the large multi-stage turbines used in generating stations which may develop as much as 1000 MW.

The turbine used in the Hilton Experimental Turbine F840 is classified as a "single stage, radial flow, reaction turbine".

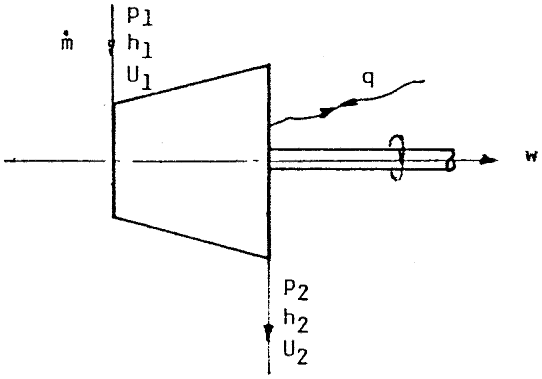
"Single stage" means that the expansion of the fluid from the turbine inlet pressure to the exhaust pressure takes place within one stator and its corresponding rotor.

"Radial flow" indicates that the fluid enters and leaves the rotor at different radii without significant axial components in its velocity.

Finally, "reaction" means that the fluid pressure drop (and consequent increase of velocity) takes place in the rotor. The fluid therefore passes through the stator at an almost constant pressure.

Velocity diagrams and calculations of the theoretical torque and power for turbines with various degrees of reaction are described in most standard thermodynamic text books and will not be described here. However, it is useful to review the turbine as a work producing machine undergoing a steady flow process, and to consider its efficiency relative to a machine without irreversibilities or heat transfers.

Application of the First Law of Thermodynamics



The diagram represents a turbine through which unit mass of fluid flows under steady flow conditions. The pressures, specific enthalpies and velocities at inlet and exhaust are p_1 h_1 U_1 and p_2 h_2 U_2 respectively. While unit mass of fluid flows, a work transfer w and a heat transfer q take place.

Applying the First Law in the form of the Steady Flow Equation,

$$q = h_2 - h_1 + \frac{U_2^2 - U_1^2}{2} + w$$

or

$$q = (h_2 + \frac{U_2^2}{2}) - (h_1 + \frac{U_1^2}{2}) + w$$

Usually the velocities in the inlet and outlet pipes are similar, and are low relative to the velocities within the turbine, so that the $\frac{U^2}{2}$ term may be neglected.

Thus

$$q = h_2 - h_1 + w$$

Practical turbines are compact machines dealing with large mass flow rates, and although there will be a heat transfer, the heat transfer per unit mass is usually small enough to be neglected.

Thus

$$w = h_1 - h_2$$

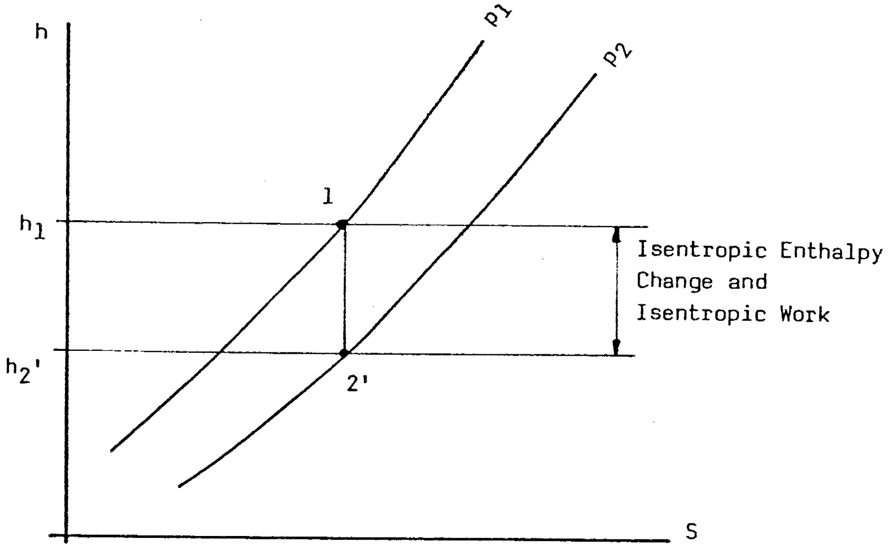
and

$P = m(h_1 - h_2)$ where P is the power developed.

Isentropic Expansion

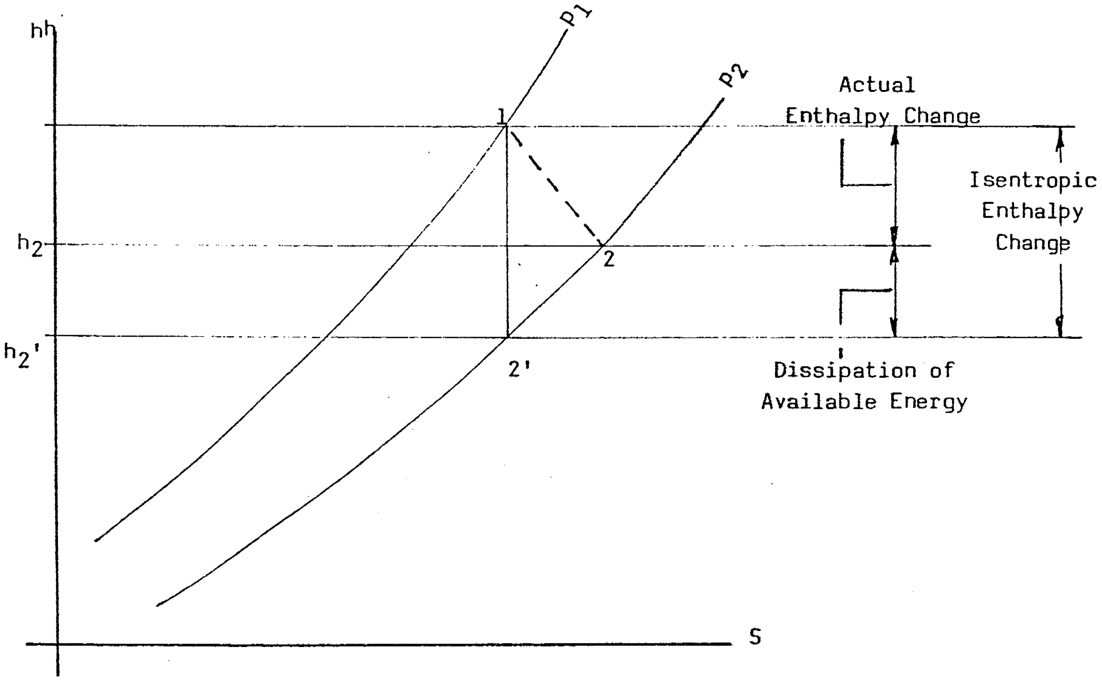
Expansion through an ideal turbine will be without heat loss or gain (i.e. adiabatic) and without dissipation of any of the available energy due to friction, throttling, etc., (i.e. reversible). A reversible and adiabatic process takes place at constant entropy (i.e. is isentropic).

If such an expansion is drawn on an enthalpy/entropy diagram, the ideal work transfer can be determined.



Isentropic Efficiency

Due to irreversibilities in a real turbine, the actual work transfer will be less than in an ideal machine and consequently the specific enthalpy at exhaust will be higher than h_2'. The end states in a real turbine will be as indicated, and the dissipation of available energy is clearly seen.



The dissipation of available energy in a turbine is mainly due to:

(i) Fluid friction in the stator.
(ii) Fluid friction in the rotor passages.
(iii) Fluid leakage through the face seal.
(iv) Friction between rotor and fluid.
(v) Kinetic energy rejected from the rotor and then dissipated by friction.

The ratio $\frac{\text{Actual Enthalpy Change}}{\text{Isentropic Enthalpy Change}}$ is called the "Isentropic Efficiency" of the turbine. Strictly, this should be called the "Internal Isentropic Efficiency" since it is based on the enthalpies of the fluid at inlet and exhaust.

Practically, the more interesting figure is the "External Isentropic Efficiency" which is

$$\frac{\text{Shaft Work}}{\text{Isentropic Enthalpy Change}}$$

This will usually be a little different than the Internal Efficiency due to the effect of heat transfer and, possibly, bearing friction.

Application of the Steady Flow Equation to the Hilton Experimental Reaction Turbine

Due to the enthalpy change across the turbine, the exhaust temperature will usually be below ambient temperatures and there will be a corresponding small heat transfer to the casing (i.e. +ve).

Since the turbine operates on air it is convenient to use a temperature-entropy diagram and to calculate the enthalpy change from

$$h_1 - h_2 = Cp(T_1 - T_2)$$

DESCRIPTION

The turbine is a single stage, radial flow reaction machine, operating on air, specially designed and manufactured by P.A. Hilton Limited for experimental and teaching purposes.

The turbine rotor is carried on a steel shaft running in oil lubricated ball bearings.

Compressed air, delivered to the rotor through a central duct provided with a face seal, passes into the rotor and then moves radially to convergent nozzles formed in the periphery. The resulting high velocity jet leaving the rotor and the momentum changes associated with the air movement produces a REACTION which drives the rotor and produces a shaft power output.

The turbine rotor is housed within a thick walled stainless steel exhaust casing and air from this passes to the atmosphere via a flow meter.

A filter regulator is provided to clean the air from the local compressed air supply* and reduce its pressure to 90 kN m^{-2} gauge before it passes to the turbine via the throttle valve.

A relief valve is fitted and set to discharge at 100 kN m^{-2} gauge to prevent the turbine from exceeding its safe speed in the event of mal-function of the pressure regulator.

By releasing five knurled nuts, the main components of the turbine can be quickly disassembled for examination.

PERFORMANCE MEASUREMENTS

Torque

A simple fabric belt brake operating on a brake wheel fitted to the turbine shaft, applies and measures the resisting torque. The power absorbed is dissipated from the surface of the brake wheel by an air jet supplied from the manifold.

Air Pressure

The air inlet pressure is measured by a pressure gauge connected to the manifold. The outlet pressure is sensibly equal to that of the atmosphere.

*If no compressed air is available, P.A. Hilton Ltd., will be pleased to forward particulars of a suitable compressor.

Air Flow

A glass, variable area flow meter in the exhaust stream indicates the air mass flow rate at a standard density. Correction factors are provided for other air densities.

Rotational Speed

An optical sensor, working in conjunction with a light source and a reflective surface on the brake wheel, senses the rotational speed of the turbine and this is displayed by a digital indicator on the panel. The display is up-dated at uniform intervals and this is convenient when determining the acceleration or retardation of the rotor.

Air Temperature

The air inlet and exhaust temperatures are sensed by K type thermocouples fitted to the manifold and exhaust casing respectively. The temperature is displayed on the panel by a digital indicator with a resolution of 0.1°C.

SPECIFICATION

General	Bench top unit housing a radial flow single stage reaction turbine operating on air. Fitted with a dynamometer and all controls and instruments for the evaluation of turbine performance and efficiency.
Detailed	
Panel	High quality G.R.P. panel on which all components are mounted.
Turbine	Single stage, radial flow reaction type - No load speed approx. 35,000 rev. min^{-1}, power - approx. 40W at 20,000 rev. min^{-1} with air at 80 kN m^{-2} gauge. Bearings - Ball races with oil lubrication.
Dynamometer	Spring balance and fabric belt operating on brake wheel - air cooled.
Filter/Regulator	To filter and pressure stabilise air supply.
Instruments	Temperature - Digital indicator with selector switch and K thermocouples to indicate inlet and exhaust temperatures. Range: -50 to 1200°C. Resolution: 0.1°C.
0 – 72 cfm	Air Flow - Glass variable area flow meter. Range 1 to 9 g s^{-1}.
	Speed - Optical sensor and 5 digit display. Range 0 to 99999 rev.min^{-1}.
	Pressure - Pressure gauge. Range -100 to +100 kN m^{-2} gauge.
Safety	Relief valve to prevent over-pressure and consequent over-speeding of turbine. Heavy guard ring surrounding turbine rotor. Electrical Safety The unit is protected from overload by a miniature circuit breaker which also operates as the On-Off switch. This appears on the front panel as an illuminated orange switch. To protect against earth leakage faults, a 30mA Residual Current Circuit Breaker (RCCB) is fitted inside the unit.
Services Required	Electrical - Either: A. 20W, 220/240 Volts, Single Phase, 50Hz (With earth/ground) or: B. 20W, 110/120 Volts, Single Phase, 60Hz (With earth/ground) Compressed Air: 400 litres free air per minute at a pressure of 300 to 1000 kN m^{-2} gauge.

USEFUL DATA

Brake Wheel:	Effective Radius (i.e. radius of wheel + half thickness of band)	- 14.5mm
Rotating Parts:	Moment of Inertia of moving parts	- 22×10^{-6} kg m^2

INSTALLATION

Remove the unit from the packing case and stand it on a bench or table close to the compressed air supply. Do not destroy any packing materials until the packing list has been checked.

Examine the unit for damage in transit - if any is found, the insurers should be notified immediately.

Assembly of Flowmeter

(i) Remove the rear panel from the unit.
(ii) Undo the two screws which secure the upper flowmeter bracket and remove the bracket.
(iii) Ensure that the flowmeter tube is clean and that the float is inserted with the pointed end downward.
(iv) Fit the flowmeter over the lower brass spigot and 'O' ring seal, ensuring that the tube is kept vertical to prevent breakage - a little light oil may be used on the upper 'O' ring if necessary. The tube should be pushed down until the lower end is supported by the second 'O' ring against the lower flange of the spigot.
(v) Fit the upper flowmeter bracket and tighten the screws.

Assembly of Spring Balance

The spring balance is located between the two stainless steel washers on the front of the panel and the loop on the brake band is fitted over the hook at the lower end of the spring balance. The knurled disc at the top of the balance may be rotated to "zero" the indicator.

Electrical Connections

Inside the rear of the panel is a small transformer and a lever switch. Set the switch to the local supply voltage, 110V or 240V. Refit the rear cover.

Connect the cable which projects from the rear of the unit to the local electrical supply using a fused outlet for 2 amps. The unit must be connected to a good and reliable earth (ground).

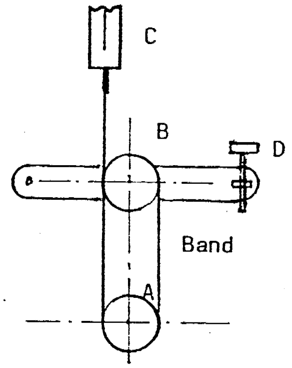
The BROWN cable should be connected to the LINE (LIVE)
BLUE " " NEUTRAL
GREEN/YELLOW " " EARTH (GROUND)

Compressed Air

The compressed air for the unit should be free from dirt, scale, water and oil, and at a reasonably steady pressure between 300 and 1000 kN m^{-2} gauge (i.e. 3 to 10 atmospheres). The air flow required is about 8 gm sec^{-1} (i.e. 400 litre min^{-1} free air).

Using the reinforced plastic hose supplied, connect the filter/regulator (located inside the right hand side of the panel) to an isolating valve in the local compressed air supply.

Preparation



(i) Ensure that the brake band is correctly fitted to the two pulleys (A and B) and the spring balance (C). The band must not be twisted. Turn the adjusting screw (D) until the belt is slack.

(ii) Ensure that the knurled nuts around the turbine housing are tight.

(iii) Introduce four drops of the oil supplied into the oil hole in the top of the shaft housing. (A small funnel is supplied to help with this.)

(iv) Switch on the electrical supply - both digital indicators should operate.

(v) Turn on the compressed air and slowly open the throttle valve until the inlet pressure is between 30 and 40 kN m^{-2} gauge. The turbine should now run up to 20,000 rev min^{-1}. If this speed is not reached, refer to Gland Adjustment on Page 10.

(vi) Adjust the brake load screw to get the "feel" of the load control and then adjust the speed to about 15,000 rev min^{-1}.

(vii) Slowly, fully open the throttle valve and check that the inlet pressure is no more than 80 kN m^{-2} gauge.

(Note: The filter regulator was adjusted to achieve this pressure before the unit left P.A. Hilton Limited's works, but final adjustment may be needed to suit the local compressed air supply.

To adjust, push down the knob on the regulator and rotate to obtain the desired pressure - then pull up the knob to lock the setting.

The unit is now ready for use.

CAUTIONS

(i) As with all high speed machines, the turbine must be treated and used with care. If there are any unusual noises or vibration, the throttle valve must be closed immediately and the cause investigated.

(ii) The maximum continuous speed of the turbine is 35,000 rev min^{-1} but it may be run up to 40,000 rev min^{-1} for short periods.

(iii) With the turbine at rest, it may be dismantled for close examination.

THE EXHAUST CASING MUST ALWAYS BE IN POSITION AND THE TURBINE FULLY ASSEMBLED WHENEVER IT IS RUNNING.

(iv) The relief valve fitted to the manifold is factory set to discharge at 100 kN m^{-2} gauge and must not be adjusted to a higher pressure.

(v) The bearings must be lubricated as instructed.

(vi) Water and oil must be drained from the filter/regulator at regular intervals. The regulator is fitted with a drain which opens automatically when the supply pressure is low and which may be opened at other times by pulling on the knurled knob on the bottom of the casing.

MAINTENANCE

Gland Adjustment

The correct adjustment of the face seal between the stator and the rotor is important.

Initial Setting

(i) Close the throttle valve.
(ii) Ensure that the 5 knurled nuts are tight.
(iii) Slacken the brake band.
(iv) Slacken the hexagonal union nut on the turbine axis where the air supply pipe enters the turbine (it should be only "finger tight").
(v) With a 3mm dia. pin, slacken the locking ring against the end face of the turbine housing.
(vi) Using another 3mm dia. pin, turn the gland adjusting screw until a very small resistance is felt when the brake pulley is rotated.
(vii) Lock the gland adjusting screw and check the turbine for freedom of rotation.

Final Setting

(i) Tighten the hexagonal union nut (finger tight only).
(ii) Run the turbine at about 20,000 rev/min without load for two or three minutes.
(iii) Ease the locking ring and adjust the gland so that maximum turbine speed is reached, but without air leakage from the gland.
(iv) Finally, tighten the locking ring and hexagonal union nut.

Note: The gland should be reset when,
(a) The turbine has been disturbed.
(b) Leakage is suspected.
(c) Rotational friction resistance seems large.

Dismantling the Turbine

(i) Disconnect the unit from the mains electrical and compressed air supplies.
(ii) Slacken the brake band.
(iii) Undo the hexagonal union nut in the sir supply to the turbine - take care not to lose the 'O' ring seal.
(iv) Remove the five knurled nuts from the front of the turbine - push down the bolt through the lower flange of the front plate.
(v) Remove the front plate.
(vi) Draw out the turbine housing complete and then separate into three components, i.e. turbine and bearing housing; exhaust casing; end plate and gland. Take care with the two 'O' ring seals.
(vii) The turbine may now be examined - it is recommended that the bearings are not disturbed unless they are to be replaced.
(viii) Reassemble in reverse order, ensuring that the three 'O' rings are in place - then adjust the gland.

Lubrication

The turbine bearings must be given four drops of the sewing machine oil provided at the beginning of each test and at hourly intervals during running. A small funnel is provided to assist with the introduction of the oil into the hole in the top of the shaft housing. The spring clip covering the oil hole should be replaced to prevent the entry of dust and grit.

After lubrication, the turbine should be run at about 30,000 rev min^{-1} for two minutes to expel surplus oil. Surplus oil will tend to collect in the exhaust casing which should be removed and wiped clean as necessary.

Tachometer

If the speed displayed by the tachometer is obviously incorrect or erratic, it is probable that either

(a) the reflective disc inside the brake wheel is dirty
or (b) the optical sensor is misaligned
or (c) the lens of the optical sensor is dirty.

To clean the reflective disc and lens,

(i) Isolate the unit from the electrical and compressed air supplies.
(ii) Slacken the brake band tensioning screw. Dismantle the turbine (see Page 10)
(iii) With a little solvent or metal polish, clean and then polish the reflective disc.
Note that the disc must show approximately equal sectors of polished and matt black surfaces to the optical sensor. If the matt black surface is damaged it may be renovated with a spirit type felt tipped pen of the type supplied.
(iv) Before replacing the turbine, the lens of the optical sensor (which may be seen through the opening in the panel behind the turbine) should be cleaned with a soft brush or a moistened, very soft cloth.
(v) Replace the turbine, carefully positioning the brake band before the union nuts are tightened.

To check alignment of sensor,

(i) Remove the rear panel.
(ii) Switch on the electrical supply but DO NOT TOUCH ANYTHING INSIDE THE PANEL.
(iii) Check that the beam of light from the sensor falls squarely onto the reflective disc and is sharply defined.
(iv) If not, ISOLATE THE UNIT FROM THE ELECTRICAL MAINS.
(v) Adjust the sensor to obtain the desired effect.
(vi) Test again, and if satisfactory replace the rear cover.

Brake

Erratic action of the brake is probably due to dirt, grease or moisture on the brake wheel or band. If this happens, the brake band should be removed and the surface of the wheel cleaned with a solvent. In extreme cases, metal polish may be used, but all traces must be removed before use. Smooth operation is helped by rubbing the contact face of the band with a soft (2B) graphite pencil.

Replacement brake bands are supplied with the unit.

Note that the brake band can be fitted without removing the turbine by passing the band between the rear face of the brake wheel and the cooling air nozzle.

The turbine should be test run on a moderate load to "bed in" the new brake band.

Residual Current Circuit Breaker

Every three months the R.C.C.B. should be checked by a competent person. To do this, remove the rear panel and check that the R.C.C.B. is in the 'ON' position. Switch the power on at the supply and at the miniature circuit breaker switch. Push the button marked 'T' on the R.C.C.B., but DO NOT TOUCH ANYTHING ELSE INSIDE THE UNIT. Check that the R.C.C.B. turns to the 'OFF' position and the neon is no longer illuminated, indicating that the unit is isolated from the R.C.C.B. onwards. If the power remains on, the R.C.C.B. is faulty and will need to be replaced by a qualified electrician.

NOTES ON OPERATION

Tachometer

The tachometer counts the number of revolutions made by the turbine in successive equal intervals of about 0.9s. After converting this to revolutions per minute the instrument gives a 5 digit display which is up-dated at these intervals. Note - the actual interval may be calculated from the time taken for say 20 "up-dates".

Minor changes of air pressure or temperature, or of frictional effects will cause the last two or possibly three digits of the display to vary.

It is recommended that generally the last two digits of the display are ignored and replaced by 00. (It should be appreciated that a change of 100 rev min^{-1} at a speed of 40,000 rev min^{-1} is a speed change of only 0.25%.)

Air Flow Measurement

The air mass flow rate is obtained by reading the scale on the glass tube against the upper face of the float. The scale value is correct for an air density of 1.2 kg m^{-3}. For other densities, the observed value should be multiplied by the Rotameter Correction Factor (k) obtained from the graph attached to the face of the panel.

Temperature Measurement

The switch below the temperature indicator enables the air temperature in the inlet pipe (t_1), or in the exhaust pipe (t_2) to be selected. The switch is biased towards the t_2 position since this varies with the change of load. In tests where temperatures are important, time must be allowed for temperatures to stabilise.

EXPERIMENTAL CAPABILITIES

1. Investigation of torque/speed and power/speed characteristics of a single stage reaction turbine.

2. Application of the First Law of Thermodynamics to a simple open system undergoing a steady flow process.

3. Determination of the isentropic efficiency of a turbine.

4. Construction of retardation curve and from this the determination of the effect of resistances due to mechanical and fluid friction.

NOTE

(i) Due to manufacturing tolerances, etc., the performance of individual turbines may differ slightly from those given in the following pages.

(ii) Before running any test the user must be aware of the cautions on Page 9 and must understand the use of the controls.

1. Investigation of torque/speed and power/speed characteristics of a single stage reaction turbine.

Procedure

(i) Prepare the turbine as described on Page 9.

(ii) Adjust the throttle valve until the inlet air pressure is the desired value - say 60 kN m^{-2} gauge (this pressure must then be constant throughout the test).

(iii) Unscrew the brake adjusting screw until the turbine runs close to its maximum speed but NOT exceeding 40,000 rev min^{-1}.

(iv) When conditions are stable, note the speed, spring balance reading and air flow rate.

(v) Rotate the brake adjusting screw until the turbine runs at about 85% of the initial speed, and when stable repeat observations.

(vi) Repeat in similar decrements of speed until the turbine finally stalls.

(vii) The test may now be repeated at other constant turbine inlet pressures.

Typical results for an inlet pressure of 60 kN m^{-2} gauge are shown.

Calculations - Using Test No. 4

Torque

$$(M) = \text{Force} \times \text{radius}$$
$$= 0.75 \times 0.0145 \text{ Nm}$$
$$M = \underline{0.0109} \text{ Nm}$$

Shaft Power

$$(P_s) = \text{Torque} \times \text{angular velocity}$$
$$= 0.0109 \times \frac{2\pi}{60} \times 16800 \text{ Watts}$$
$$P_s = \underline{19.2} \text{ Watts}$$

Derived Results - (Inlet pressure 60 kN m^{-2} g)

Test No.		1	2	3	4	5	6	7	8
Speed	$\frac{n}{10^3 \text{ Rev min}^{-1}}$	36	29	23	16.8	11	6.4	0	
Torque	$\frac{M}{10^{-3} \text{ Nm}}$	3.62	5.8	8.0	10.9	13.0	14.5	17.4	
Shaft Power	$\frac{P_s}{\text{Watts}}$	13.6	17.6	19.2	19.2	15.0	9.7	0	

These results are shown graphically on Page 15, together with results obtained with inlet pressures of 40 and 20 kN m^{-2} gauge.

OBSERVATION SHEET

HILTON EXPERIMENTAL REACTION TURBINE F840

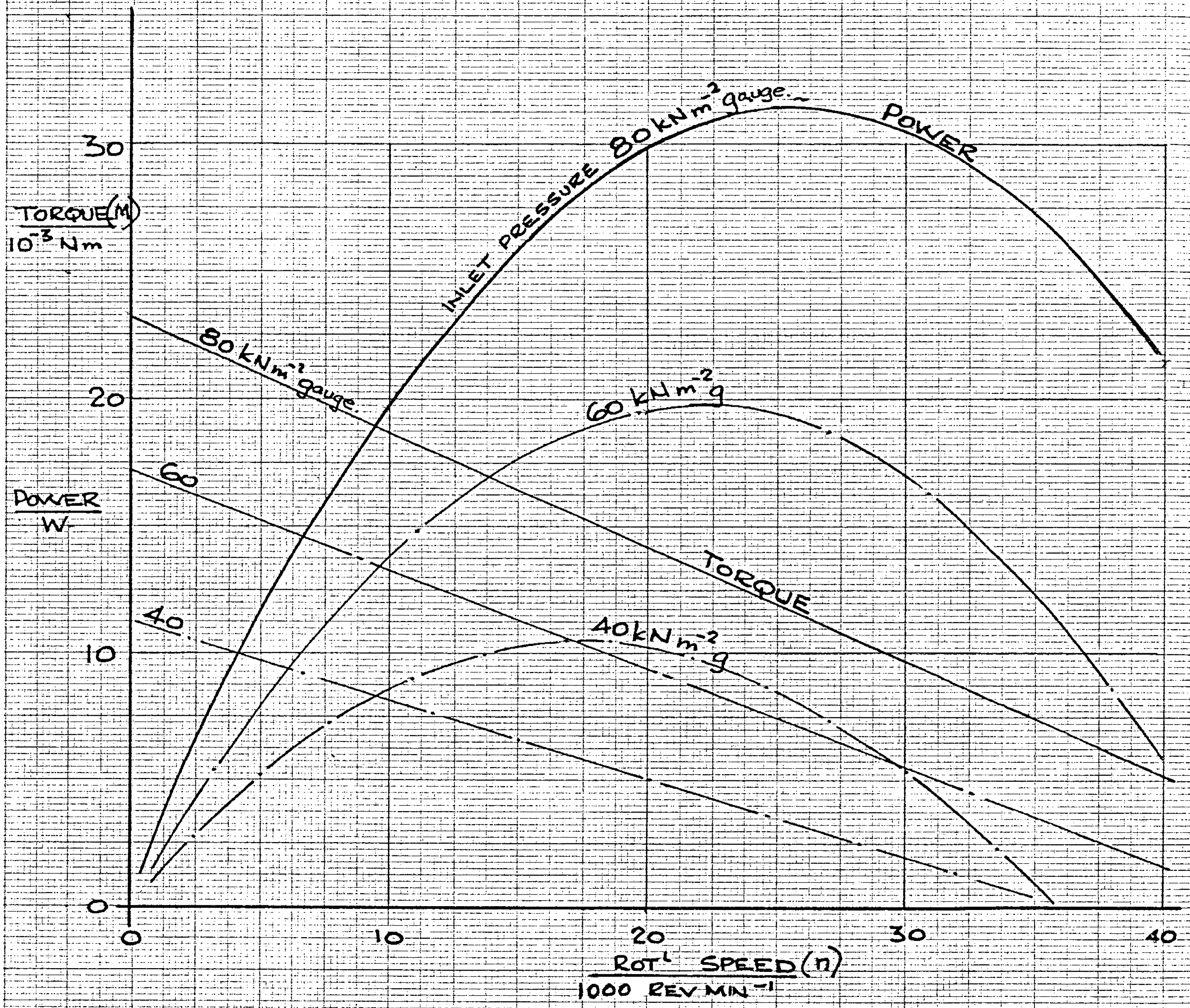
Type of Test: T/n and P/n

Date:

Atmospheric Pressure: 770 mm Hg

Ambient Temperature: 20°C

TEST No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Inlet Pressure $\frac{p_1}{\text{kN m}^{-2}\text{ g}}$	60	60	60	60	60	60	60											
Inlet Temperature $\frac{t_1}{^{\circ}\text{C}}$																		
Exhaust Temperature $\frac{t_2}{^{\circ}\text{C}}$																		
Rotational Speed $\frac{n}{10^3\text{ rev min}^{-1}}$	36	29	23	16.8	11	6.4	0											
Brake Band Force $\frac{F}{N}$	0.25	0.4	0.55	0.75	0.9	1.0	1.2											
Air Flow Rate (corrected) $\frac{\dot{m}}{\text{g s}^{-1}}$	5.5	5.5	5.5	5.5	5.5	5.5	5.5											



TORQUE v SPEED and POWER v SPEED CHARACTERISTICS

Comments

Both curves are characteristic of a reaction turbine.

The torque is derived from the product of the tangential force due to the momentum change of the air as it flows through the rotor, and the radius at which it acts. The tangential force is the product of the mass flow rate and the change in the tangential component of the air velocity across the rotor. Since both the mass flow rate and radius are constant, it follows that the torque is proportional to the change of tangential component and this decreases as speed increases. (Refer to velocity diagram in references.)

Superimposed on this is the effect of fluid friction which increases with speed and reduces the torque transmitted to the shaft.

The combination of the above effects produces the characteristic shape of the torque/speed curve.

Since the shaft power is the product of torque (M) and speed (ω), it is obvious that power will be zero when $M = 0$ and when $\omega = 0$ and will rise to a peak value between these speeds.

Students should note that a turbine passes the same amount of air at any speed (this is in contrast to a positive displacement expander in which air flow increases with speed). Because of this, it is obvious that the efficiency of a turbine reaches a maximum at the same speed as the power reaches a maximum. By inspection, this is seen to be at about half the no load speed.

2. Application of the First Law of Thermodynamics to a simple open system undergoing a steady flow process.

Procedure

(i) Prepare the turbine as described on Page 9.

(ii) Set the throttle valve to give an inlet pressure of 80 kN m^{-2} gauge.

(iii) Adjust the brake load so that the turbine develops its maximum power (refer to M/n graph in previous experiment), usually about 24,000 rev min^{-1}.

(iv) Hold the inlet pressure and speed steady until the inlet and exhaust air temperatures are quite steady.

(v) Observe and record all instruments and the brake band force.

The test may be repeated at other conditions.

Typical Observations

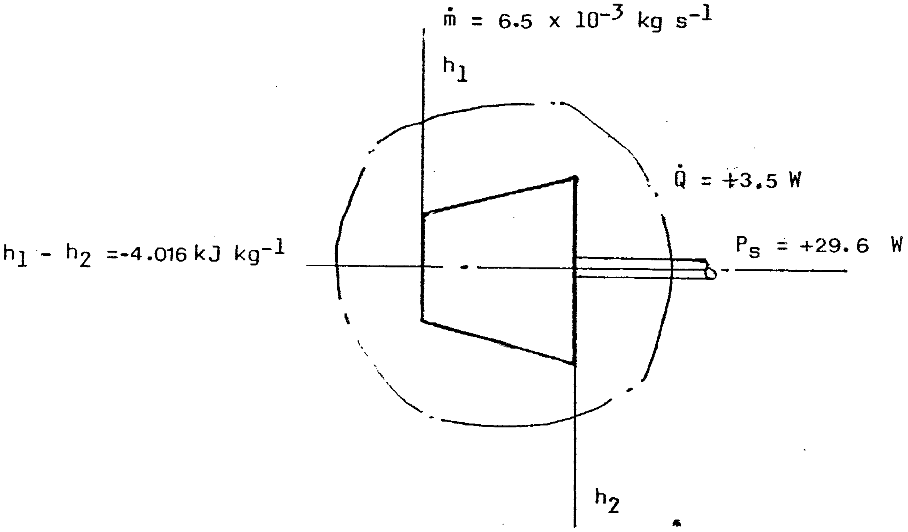
Ambient temperature		21°C
Inlet pressure	(p_i)	80 kN m^{-2} gauge
Inlet temperature	(t_1)	20.7°C
Exhaust temperature	(t_2)	16.7°C
Rotational speed	(n)	25,000 rev min^{-1}
Brake band force	(F)	0.78 N
Air flow rate (corrected)	$(\dot{m})$	6.5 g s^{-1}

Shaft Power

$$\begin{aligned} (P_s) &= M\omega \\ &= Fr\omega \\ &= 0.78 \times 0.0145 \times \frac{2\pi}{60} \times 25000 \text{ Watts} \\ P_s &= \underline{\underline{29.6}} \text{ Watts} \end{aligned}$$

Assuming that Cp for air at the mean temperature $(\frac{20.7 + 16.7}{2}\ {}^\circ C)$ is 1.004 kJ kg^{-1} K^{-1},

$$\begin{aligned} \text{Change of specific enthalpy } (h_2 - h_1) &= Cp(t_2 - t_1) \\ &= 1.004(16.7 - 20.7) \text{ kJ kg}^{-1} \\ &= \underline{\underline{-4.016}} \text{ kJ kg}^{-1} \end{aligned}$$



Applying the 1st Law in the form of the steady flow equation,

$$\begin{aligned} \dot{Q} &= \dot{m}(h_2 - h_1) + P_s \\ &= 6.5 \times 10^{-3} \times (-4.016 \times 10^3) + 29.6 \text{ W} \\ &= -26.1 + 29.6 \\ \dot{Q} &= \underline{\underline{+3.5}} \text{ W} \end{aligned}$$

Comments

This result shows that during the passage of the air through the turbine, work was transferred to the surroundings at the rate of 29.6 Watts; the enthalpy of the air fell by 26.1 Watts and heat was transferred from the surroundings to the system at the rate of 3.5 Watts.

This result is reasonable since the exhaust casing which has a relatively large area compared with the turbine contained air at a temperature below that of the surroundings. The direction and magnitude of the heat transfer is therefore as expected.

3. Determination of the isentropic efficiency of a turbine.

Procedure

(i) Prepare the turbine as described on Page 9.

(ii) Adjust the throttle and brake load so that the turbine runs at about 50% of no load speed with the desired inlet pressure, say 60 kN m^{-2} gauge.

(iii) Hold conditions steady until the inlet and exhaust temperatures have stabilised.

(iv) Record all observations.

The test may be repeated at other conditions.

Typical Observations

Ambient temperature		22°C
Atmospheric pressure	(p_a)	765 mm Hg
Inlet pressure	(p_i)	80 kN m^{-2} gauge
Inlet temperature	(t_1)	22°C
Exhaust temperature	(t_2)	18°C
Rotational speed	(n)	24,000 rev min^{-1}
Brake band force	(F)	0.8 N
Air flow rate (corrected)	($\dot{m}$)	6.5 gm s^{-1}

Calculations

Shaft Power

$$(P_s) = M\omega$$
$$= Fr\omega$$
$$= 0.8 \times 0.0145 \times \frac{2\pi}{60} \times 24000 \text{ Watts}$$
$$P_s = \underline{\underline{29.15}} \text{ Watts}$$

Absolute Temperature at Inlet

$$T_1 = 22 + 273 \text{ K}$$
$$= \underline{\underline{295}} \text{ K}$$

Atmospheric Pressure

$$= \frac{755}{750} \times 100 \text{ kN m}^{-2}$$
$$= \underline{\underline{100.6}} \text{ kN m}^{-2}$$

Absolute Pressure at Inlet

$$p_1 = 100.6 + 80 \text{ kN m}^{-2}$$
$$= \underline{\underline{180.6}} \text{ kN m}^{-2}$$

Absolute Pressure at Exhaust (neglecting resistance of pipe and flowmeter)

$$p_2 = 100.6 \text{ kN m}^{-2}$$

Turbine Pressure Ratio

$$r_p = \frac{p_1}{p_2}$$
$$= \frac{180.6}{100.6}$$
$$= \underline{\underline{1.795}}$$

Exhaust Temperature after Isentropic Expansion

$$\begin{aligned} T_2' &= T_1/r_p^{\frac{\gamma - 1}{\gamma}} \\ T_2' &= 295/1.795^{\frac{1.4 - 1}{1.4}} \\ T_2' &= \underline{\underline{249.5}}\text{ K} \end{aligned}$$

Isentropic Enthalpy Change Rate

$$\begin{aligned} \dot{\Delta H} &= \dot{m}\, C_p(T_1 - T_2') \\ &= 6.5 \times 10^{-3} \times 1.004 \times 10^3(295 - 249.5)\text{ W} \\ &= \underline{\underline{297}}\text{ Watts} \end{aligned}$$

External Isentropic Efficiency

$$\begin{aligned} \eta_s &= \frac{\text{Actual Power}}{\text{Isentropic Enthalpy Change Rate}} \\ &= \frac{29.15}{297} \\ &= \underline{\underline{9.8\%}} \end{aligned}$$

Notes: (i) The isentropic power could be calculated from $\dot{m}\, C_p\, T_1(1 - 1/r_p^{\frac{\gamma - 1}{\gamma}})$

(ii) The temperature after isentropic expansion could be read directly from the T-s diagram, page 22.

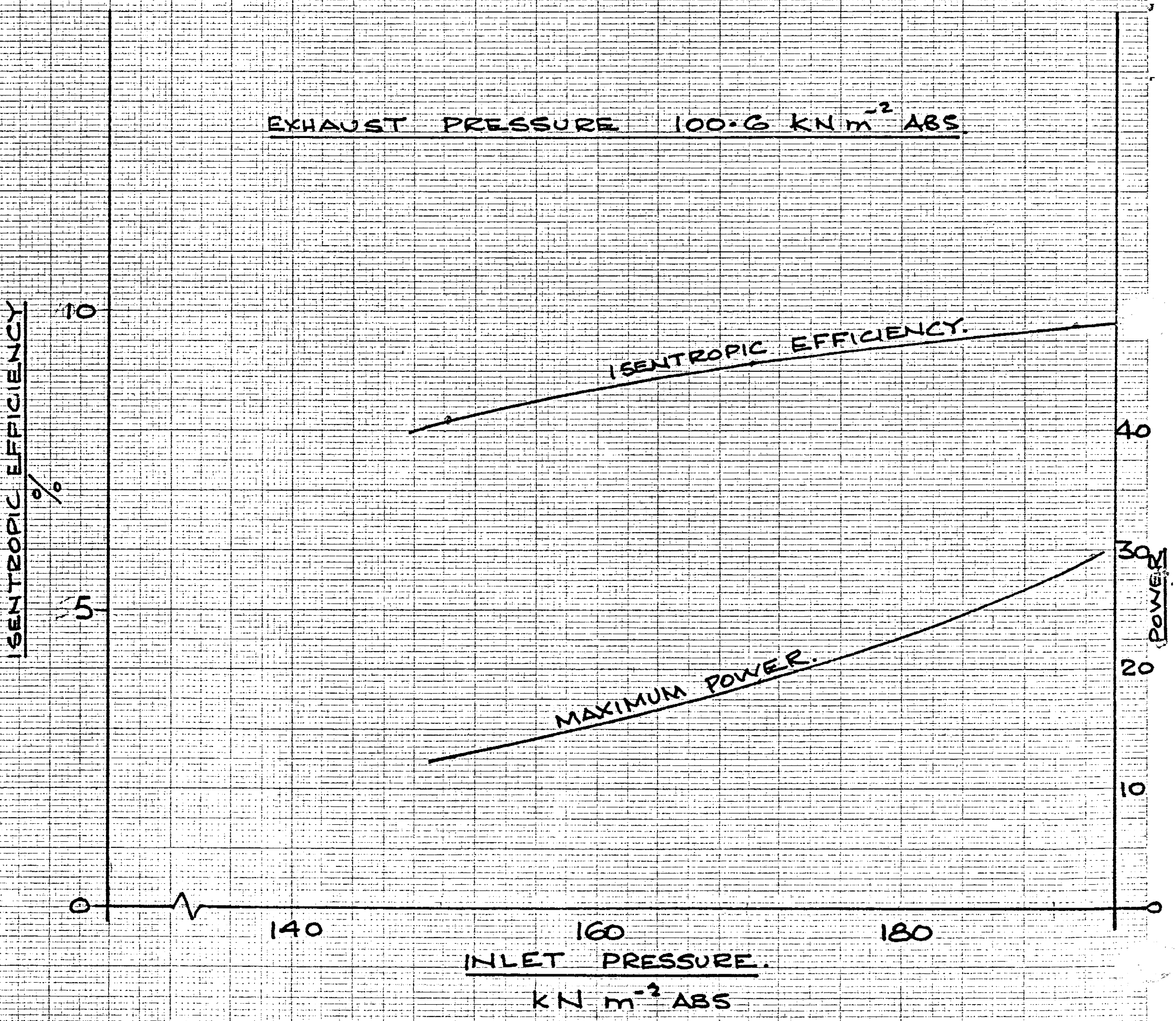
The actual end states may be plotted on a T-s diagram as shown on page 22.

It will be noted that there is a discrepancy between the external work (= 47.37 Watts) and $\dot{m}\, C_p(T_1 - T_2)$ (= 36.9W). This is due to the heat transfer to the air between inlet and exhaust.

Comments

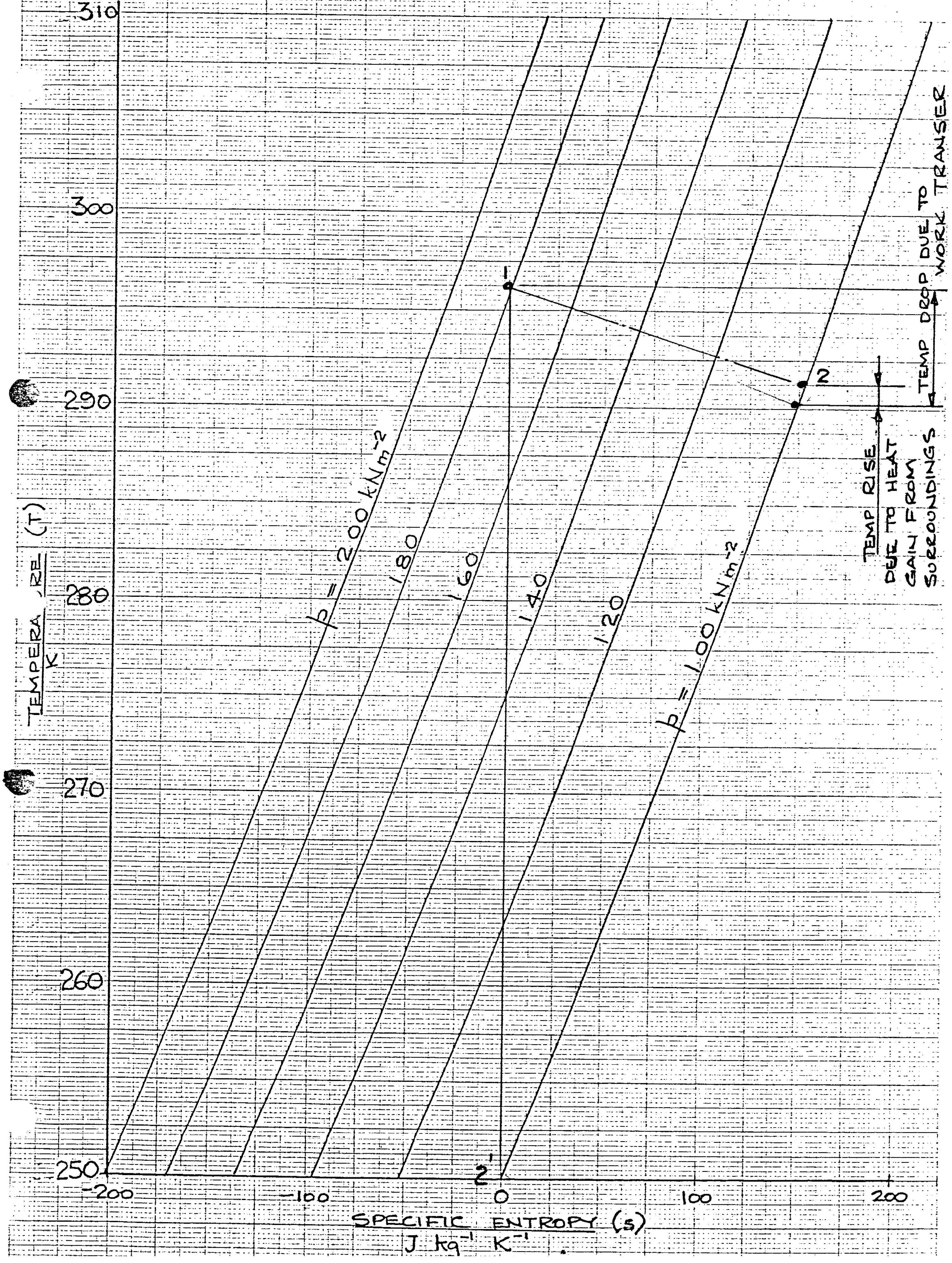
An isentropic efficiency of 9.8% is as expected for a small turbine.

The factors which contribute to the dissipation of available energy are given on page 24.



EFFECT OF INLET PRESSURE ON POWER OUTPUT AND ON TURBINE ISENTROPIC EFFICIENCY.

$\left(\begin{array}{l} C_p = 1005\ \mathrm{J\,kg^{-1}K^{-1}}\ \text{CONSTANT} \\ R = 287{\cdot}1\ \mathrm{J\,kg^{-1}K^{-1}}\ \text{"} \end{array}\right)$



4. Construction of retardation curve and from this the determination of the effect of resistances due to mechanical and fluid friction.

Procedure

(i) Prepare the turbine as described on Page 9.

(ii) Slacken and then remove the brake band from the brake wheel.

(iii) With a stopwatch determine the intervals at which the tachometer display is updated (this is normally 0.9 second intervals).

(iv) Run the turbine up to about 37,000 rev min^{-1} and then quickly close the throttle valve.

(v) As the turbine speed falls, observe and note alternate tachometer displays (i.e. the speed at 1.8 second intervals).

(vi) The observations should be repeated.

Typical Observations

Time	/sec	0	1.8	3.6	5.4	7.2	9.0	10.8
Speed	$n/10^3$ rev.min^{-1}	36.0	32.0	27.6	24.0	20.2	17.5	15.3
Time	/sec	12.6	14.4	16.2	18.0	19.8	21.6	23.4
Speed	$n/10^3$ rev.min^{-1}	13.5	12.0	10.6	9.4	8.3	7.6	7.0

These results are plotted on page 25.

Derived Results

By drawing tangents to the speed/time curve, the retardation of the turbine due to the various frictional effects at any speed, can be closely estimated.

For the tangent shown, the angular retardation at 14,000 rev min^{-1} is

$$\alpha = \frac{\Delta\omega}{\Delta t}$$

$$= \frac{6000}{6.12} \times \frac{2\pi}{60} \text{ rad s}^{-2}$$

$$\alpha = \underline{\underline{102.6}} \text{ rad s}^{-2}$$

The moment of Inertia of the rotating parts (I) is 22×10^{-6} kg m^2. Thus, the frictional torque at 14,000 rev min^{-1}

$$M_f = I\alpha$$

$$= 22 \times 10^{-6} \times 102.6 \text{ Nm}$$

$$M_f = \underline{\underline{2.26 \times 10^{-3}}} \text{ Nm}$$

and the power dissipated by these frictional effects at this speed

$$P_f = M_f\omega$$

$$= 2.26 \times 10^{-3} \times \frac{14000}{60} \times 2\pi \text{ W}$$

$$= \underline{\underline{3.3}} \text{ W}$$

Results obtained for other speeds are:

Speed $n/10^3$ rev min^{-1}	30	22	14	10	8		
Angular Retardation α/rad s^{-2}	250	186	102.6	82	63 .		
Frictional Torque $M_f/10^{-3}$ Nm	5.5	4.09	2.26	1.8	1.4		
Power Dissipated P_f/W	17.2	9.42	3.3	1.9	1.17		

These results are plotted on page 26.

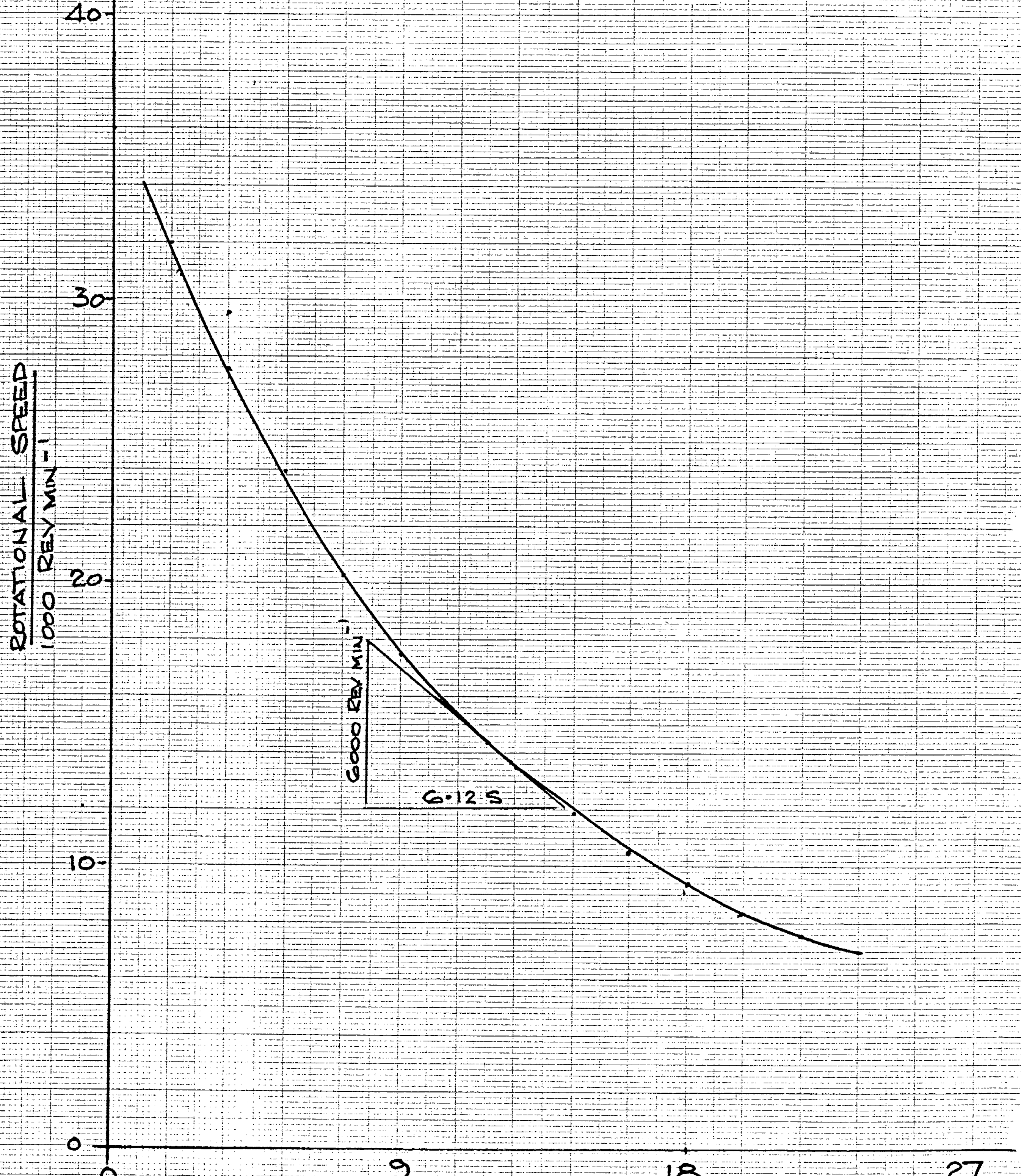
Comments

It is apparent that the frictional torque increases rapidly with speed.

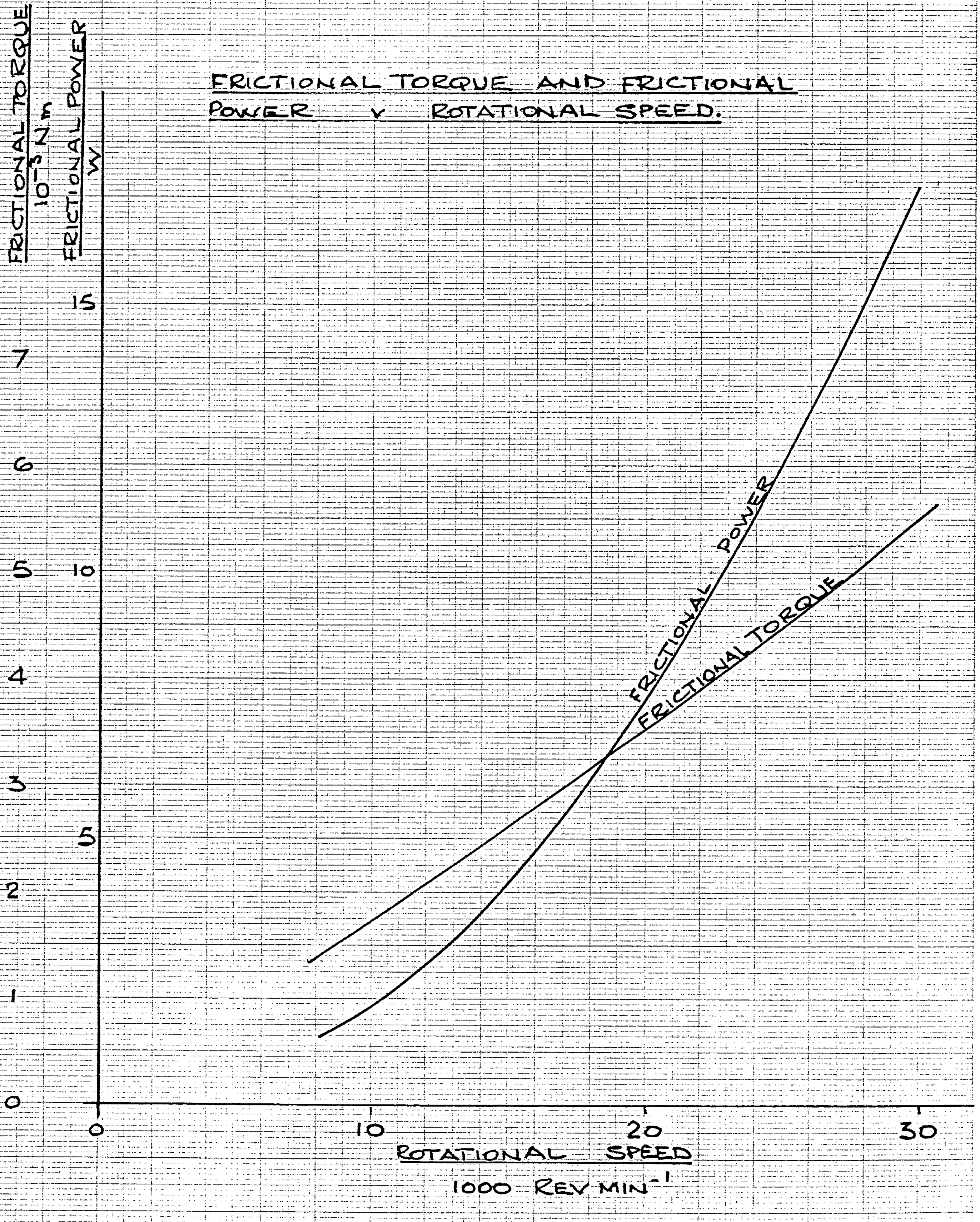
It is not possible to separate the various frictional effects, but they will include:

<u>Bearings</u> - due to rolling, cage, shield and viscous resistances.
<u>Rotor</u> - due to viscous resistances between the turbine and the air.

The results show that at high speeds these frictional effects have a serious effect on the output of a turbine.



40
30
20
10
0
ROTATIONAL SPEED
1000 REV MIN⁻¹
6000 REV MIN⁻¹
6·12 S
0
9
18
27
TIME
S



FRICTIONAL TORQUE AND FRICTIONAL POWER v ROTATIONAL SPEED.

OBSERVATION SHEET

HILTON EXPERIMENTAL REACTION TURBINE F840

Type of Test:

Date:

Atmospheric Pressure:

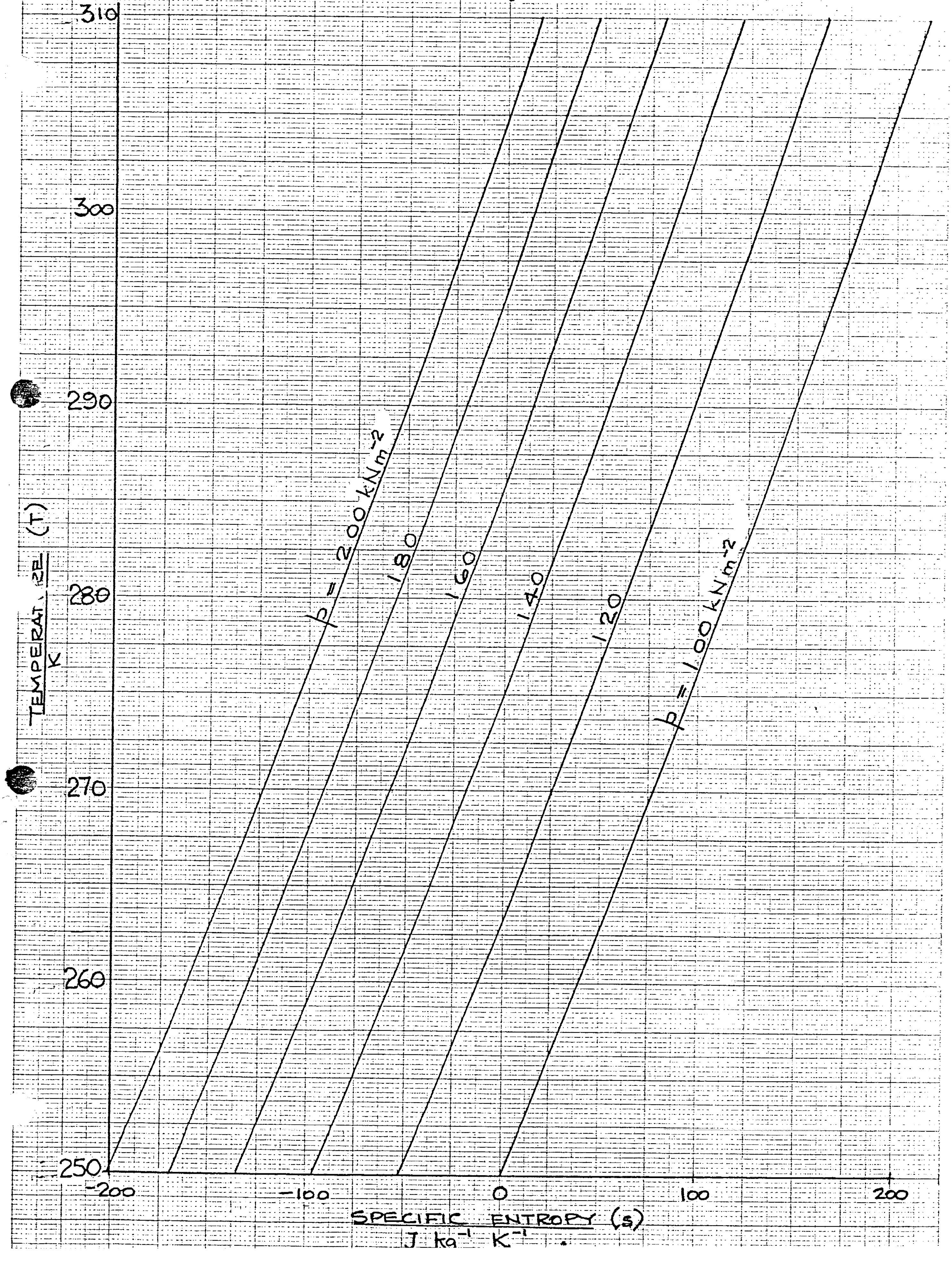
Ambient Temperature:

TEST No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Inlet Pressure $\frac{p_1}{\text{kN m}^{-2}\text{ g}}$																		
Inlet Temperature $\frac{t_1}{^\circ\text{C}}$																		
Exhaust Temperature $\frac{t_2}{^\circ\text{C}}$																		
Rotational Speed $\frac{n}{10^3\text{ rev min}^{-1}}$																		
Brake Band Force $\frac{F}{\text{N}}$																		
Air Flow Rate (corrected) $\frac{\dot{m}}{\text{g s}^{-1}}$																		

TEMPERATURE ENTROPY DIAGRAM FOR AIR

(C_p = 1005 J kg^{-1} K^{-1} CONSTANT

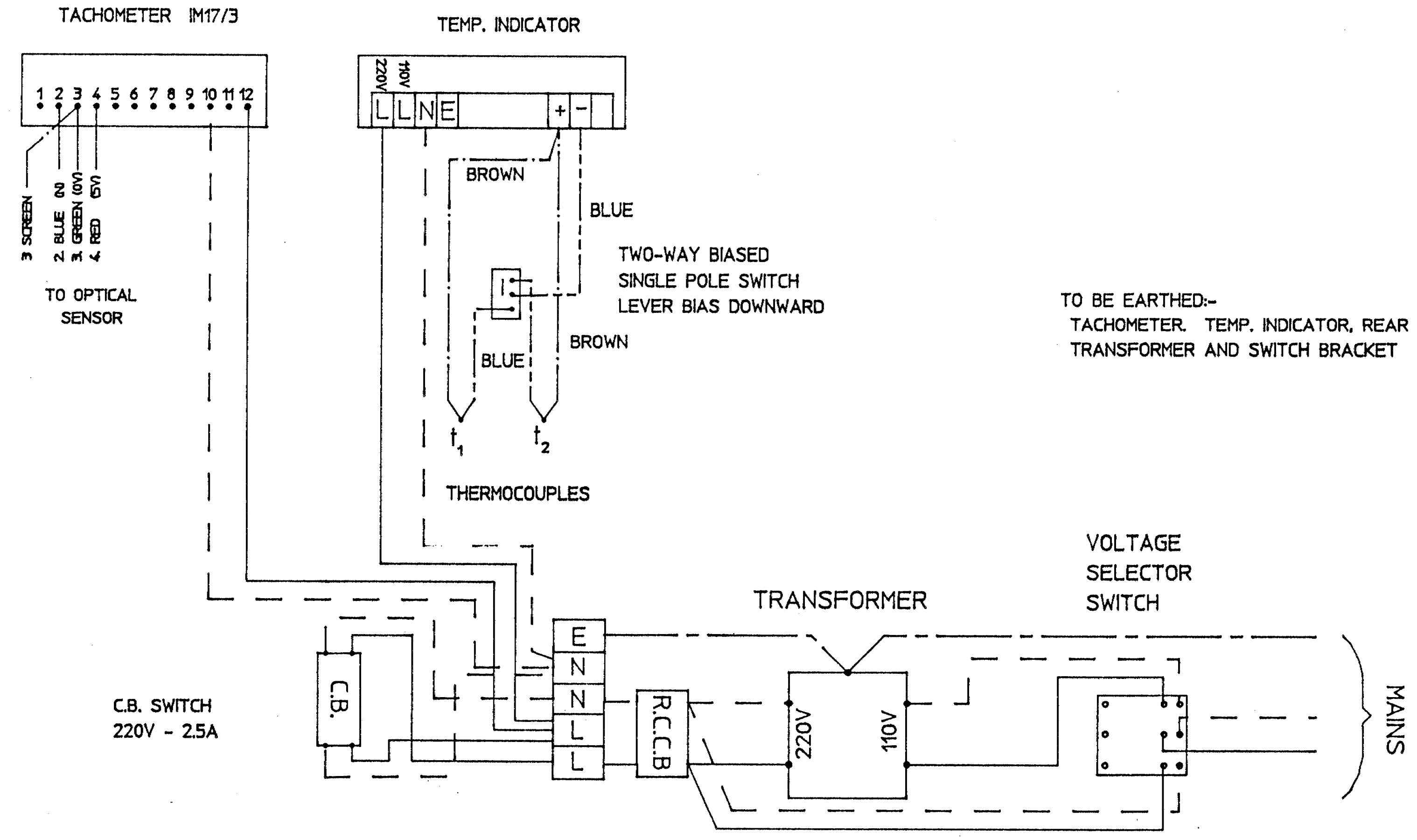
R = 287·1 J kg^{-1} K^{-1} ")



5

Amendments

2 TRANSFORMER AND
SWITCH ADDED
REDRAWN ON A3
DRG No. NOW
84023M
23.7.88 JB



TO BE EARTHED:-
TACHOMETER. TEMP. INDICATOR, REAR PANEL
TRANSFORMER AND SWITCH BRACKET

EXCEPT FOR THERMOCOUPLES
AND 3 CORE CABLE, ALL
CABLES 0.5mm

LINE ———— RED
NEUTRAL— — — BLACK
EARTH ——— – – GREEN/YELLOW

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	Checked
	Dimensions: mm	by:
Limits unless otherwise stated : Fractions ± 1/64" Decimals ± 0.25 mm	Projection: ◎ ◁	
	Issue: 2	
TITLE: F840 WIRING DAIGRAM 220V/110V	Date: 23.7.88	DRG. No.
TO BE USED ON UNIT	Scale. ——	84023M
SERIAL No. F840/_ _ _ _ _ ONLY	no/rig. 1	
P. A. HILTON LTD . KINGS SOMBORNE HAMPSHIRE ENGL		

REFERENCES

Author	Title	Publisher
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G.F.C. Rogers and Y.R. Mayhew	Engineering Thermodynamics Work and Heat Transfer	Longmans