INSTRUCTION MANUAL

FM3SU

CAPTURE

WATER TURBINE DEMONSTRATION UNIT

FM3SU

ISSUE 4

APRIL 2004

IMPORTANT SAFETY INFORMATION

All practical work areas and laboratories should be covered by local safety regulations which must be followed at all times. If required Armfield can supply a typical set of standard laboratory safety rules.

Your Capture unit has been designed to be safe in use, when installed, operated and maintained in accordance with the instructions in this manual. As with any piece of sophisticated equipment, dangers may exist if the equipment is misused, mishandled or badly maintained.

Electrical Safety

The equipment described in this Instruction Manual operates from a mains voltage electrical supply. It must be connected to a supply of the same frequency and voltage as marked on the equipment or the mains lead. If in doubt, consult a qualified electrician or contact Armfield.

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

The equipment is designed to be powered using the Armfield IFD interface which incorporates a Residual Current Device (RCD), alternatively called an Earth Leakage Circuit Breaker to give increased operator protection. If through misuse or accident the equipment becomes electrically dangerous, the RCD will switch off the electrical supply and reduce the severity of any electric shock received by an operator to a level which, under normal circumstances, will not cause injury to that person.

If for any reason the equipment is not powered using the Armfield IFD, a separate RCD should be fitted to ensure full operator protection.

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

Water Borne Hazards

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

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

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

Under the COSHH regulations, the following precautions must be observed:-
Any water contained within the product must not be allowed to stagnate, ie. the water must be changed regularly.

Any rust, sludge, scale or algae on which micro-organisms can feed must be removed regularly, i.e. the equipment must be cleaned regularly.

Where practicable the water should be maintained at a temperature below 20°C. If this is not practicable then the water should be disinfected if it is safe and appropriate to do so. Note that other hazards may exist in the handling of biocides used to disinfect the water.

A scheme should be prepared for preventing or controlling the risk incorporating all of the actions listed above.

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

ARMFIELD LIMITED

OPERATING INSTRUCTIONS AND EXPERIMENTS

FM3SU - CAPTURE WATER TURBINE DEMONSTRATION UNIT

INTRODUCTION

This manual describes the operation of the FM3SU Turbines Service Unit, and the three turbines which can be fitted.

The service unit consists of a water tank and a pump which provide a water supply to the turbine test unit. Each turbine is mounted on a plate which sits on top of the service unit and is fitted with a brake assembly.

Each of the turbines is fitted with electronic sensors which measure the process variables. Signals from these sensors are sent to a computer via an interface device.

The service unit is supplied with a data logging software package as standard.

DESCRIPTION

FM3SU Turbines Service Unit

All numerical references in brackets relate to the diagram on page 3.

The FM3SU Turbine Service Unit is an essential accessory designed to allow self contained operation of the three Armfield Turbines FM30, FM31 and FM32.

The unit consists of a clear acrylic reservoir (3), a circulating pump and associated pipework installed on a support plinth (1), which is bench mounted. The reservoir incorporates a drain valve (2) at the base and a flange (4) at the top, to which the appropriate turbine is attached.

Water circulation is provided by a single stage centrifugal pump (8) driven by an integral electric motor (7). The motor requires a single phase electricity supply.

The pump discharge pipe (6) incorporates a screwed connector which mates with the inlet pipe on the appropriate turbine.

The flow of water is measured using a differential pressure sensor SPW1 (9) which is connected across an orifice plate (5) at the entrance to the pump inlet pipe. The pressure sensor is connected between the tapping on the orifice plate and a tapping in the wall of the reservoir. Additional tappings are provided for the connection of the appropriate instrumentation (not supplied) to facilitate calibration of the differential pressure sensor.

The differential pressure sensor is connected to channel 1 on the IFD interface console.

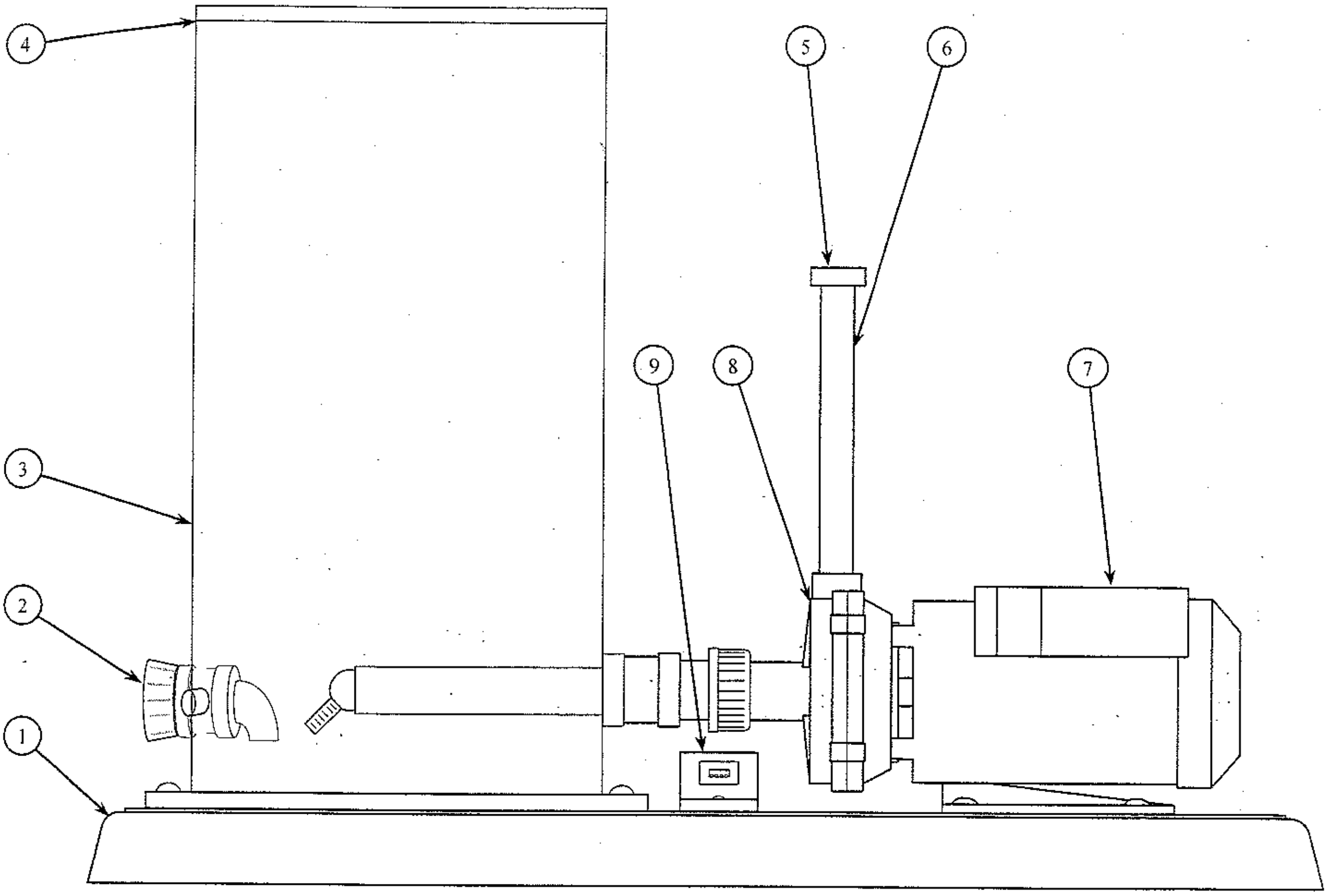


Figure 1: FM3SU Turbines Service Unit

FM30 Axial Flow Impulse Turbine

All numerical references in brackets relate to the diagram on page 5.

The Axial Flow Impulse Turbine FM30 consists of a demonstration turbine (11) mounted on a support plate (9) with appropriate controls and sensors.

The turbine rotor has 45 blades on a mean blade circle diameter of 45mm. Both the blade inlet angle and outlet angle are 40 degrees. The rotor is fitted with a stainless steel shroud ring.

The stator houses two corrosion resistant ball bearings with double shields, for lifetime lubrication, and four independently controlled nozzles. Each nozzle has an outlet diameter of 2mm and discharges at 20 degrees to the plane of rotation.

The turbine support plate (9) is designed to attach to the top flange of the reservoir on the FM3SU Turbine Service Unit and the inlet valve (7) attaches to the screwed connector on the pump discharge pipe. A filler plug (2) allows water to be added to the reservoir with the turbine installed. The nozzles in use are selected by opening/closing the appropriate selector valves (5) on the inlet manifold.

The following sensors are used to monitor the performance of the Axial Flow Impulse Turbine:

<u>Pressure sensor SPH2 connected to Channel 2 on IFD</u>

This comprises of a piezo-electric pressure sensor (6) with appropriate signal conditioning all contained in a protective case (12).

The sensor is used to measure pressure at the inlet to the turbine. An additional tapping in the inlet manifold is provided for the connection of appropriate instrumentation (not supplied) to facilitate calibration of the pressure sensor.

<u>Rotational speed sensor SSO2 connected to Channel 3 on IFD</u>

This comprises of a reflective infra-red opto switch (3) on a remote lead with appropriate signal conditioning in a protective case (10) and is used to measure the rotational speed of the turbine rotor.

The opto switch is mounted adjacent to the hub of the rotor which incorporates a reflective strip to facilitate measurement of the rotational speed. An appropriate non-contacting optical tachometer (not supplied) may be used to calibrate the rotational speed sensor.

<u>Force sensor SLR1 connected to channel 4 on IFD</u>

The load beam (4) incorporates a strain gauge which is connected to appropriate signal conditioning in a protective case (8).

The force sensor is used to measure the force applied to the brake on the hub of the turbine rotor.

Speed of the turbine is controlled by adjusting the tension in the brake belt by adjusting the tension screw (1).

The force sensor can be calibrated by removing it from the support bracket, clamping it in a suitable fixture and attaching a dead load (not supplied).

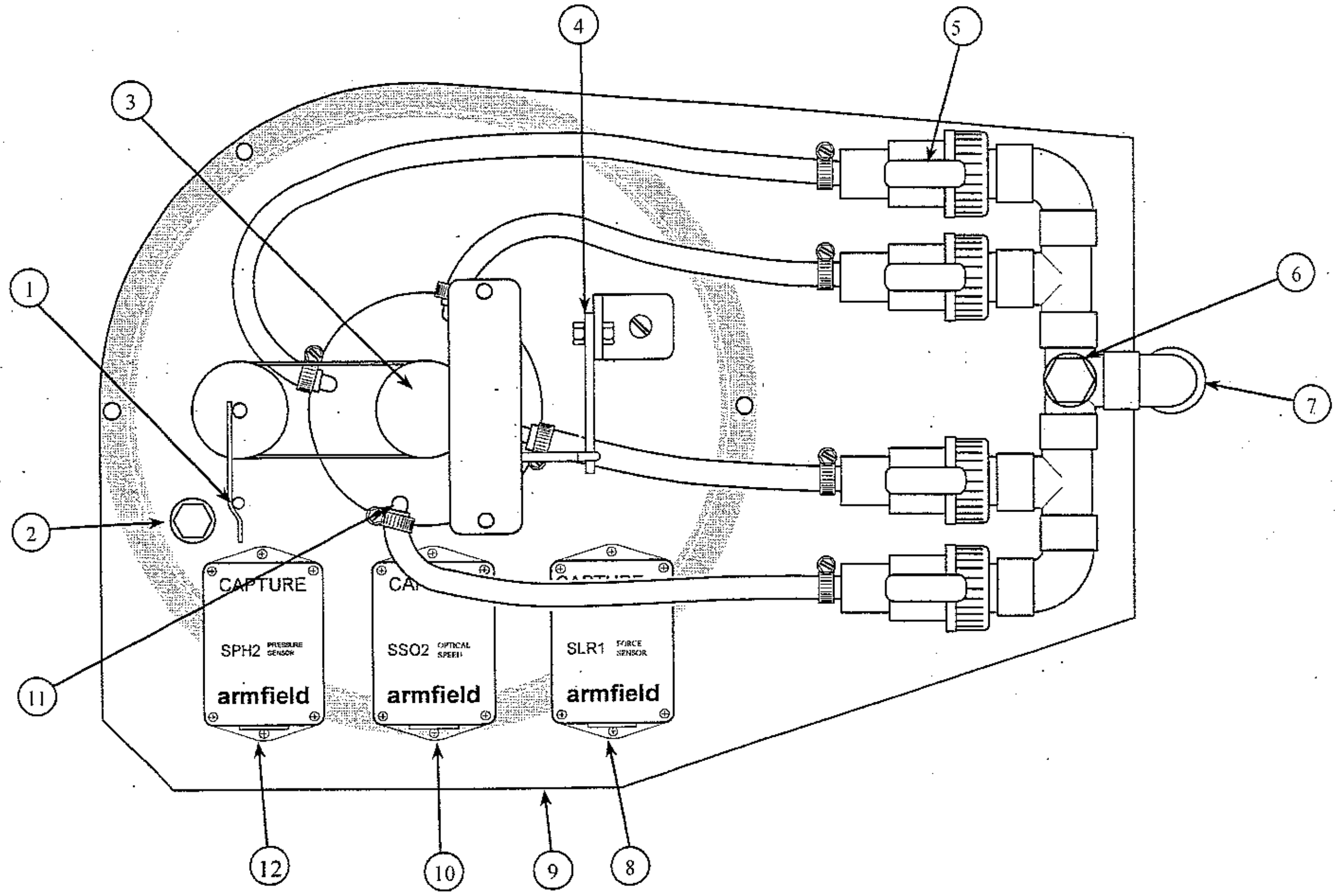


Figure 2: FM30 Axial Flow Impulse Turbine

FM31 Radial Flow Reaction Turbine

All numerical references in brackets relate to the diagram on page 7.

The Radial Flow Reaction Turbine FM31 consists of a demonstration turbine (2) mounted on a support plate with appropriate controls and sensors.

The turbine rotor has an external diameter of 45mm. Water enters the rotor through an adjustable PTFE/graphite face seal and is discharged tangentially through two passages, each having an area of approximately 8 square mm.

The rotor is mounted on a stainless steel shaft running in corrosion resistant bearings with double shields to provide lifetime lubrication.

The turbine support plate is designed to attach to the top flange of the reservoir on the FM3SU Turbine Service Unit and the inlet valve (7) attaches to the screwed connector on the pump discharge pipe. A filler plug (5) allows water to be added to the reservoir with the turbine installed.

The following sensors are used to monitor the performance of the Radial Flow Reaction Turbine:

Pressure sensor SPH2 connected to Channel 2 on IFD

This comprises of a piezo-electric pressure sensor (6) with appropriate signal conditioning all contained in a protective case (11).

The sensor is used to measure pressure at the inlet to the turbine. An additional tapping in the inlet manifold is provided for the connection of appropriate instrumentation (not supplied) to facilitate calibration of the pressure sensor.

Rotational speed sensor SSO2 connected to Channel 3 on IFD

This comprises of a reflective infra-red opto switch (3) on a remote lead with appropriate signal conditioning in a protective case (10) and is used to measure the rotational speed of the turbine rotor.

The opto switch is mounted adjacent to the hub of the rotor which incorporates a reflective strip to facilitate measurement of the rotational speed. An appropriate non-contacting optical tachometer (not supplied) may be used to calibrate the rotational speed sensor.

Force sensor SLR1 connected to channel 4 on IFD

The load beam (4) incorporates a strain gauge which is connected to appropriate signal conditioning in a protective case (9).

The force sensor is used to measure the force applied to the brake on the hub of the turbine rotor.

Speed of the turbine is controlled by adjusting the tension in the brake belt (12) by adjusting the tension screw (1).

The force sensor can be calibrated by removing it from the support bracket, clamping it in a suitable fixture and attaching a dead load (not supplied).

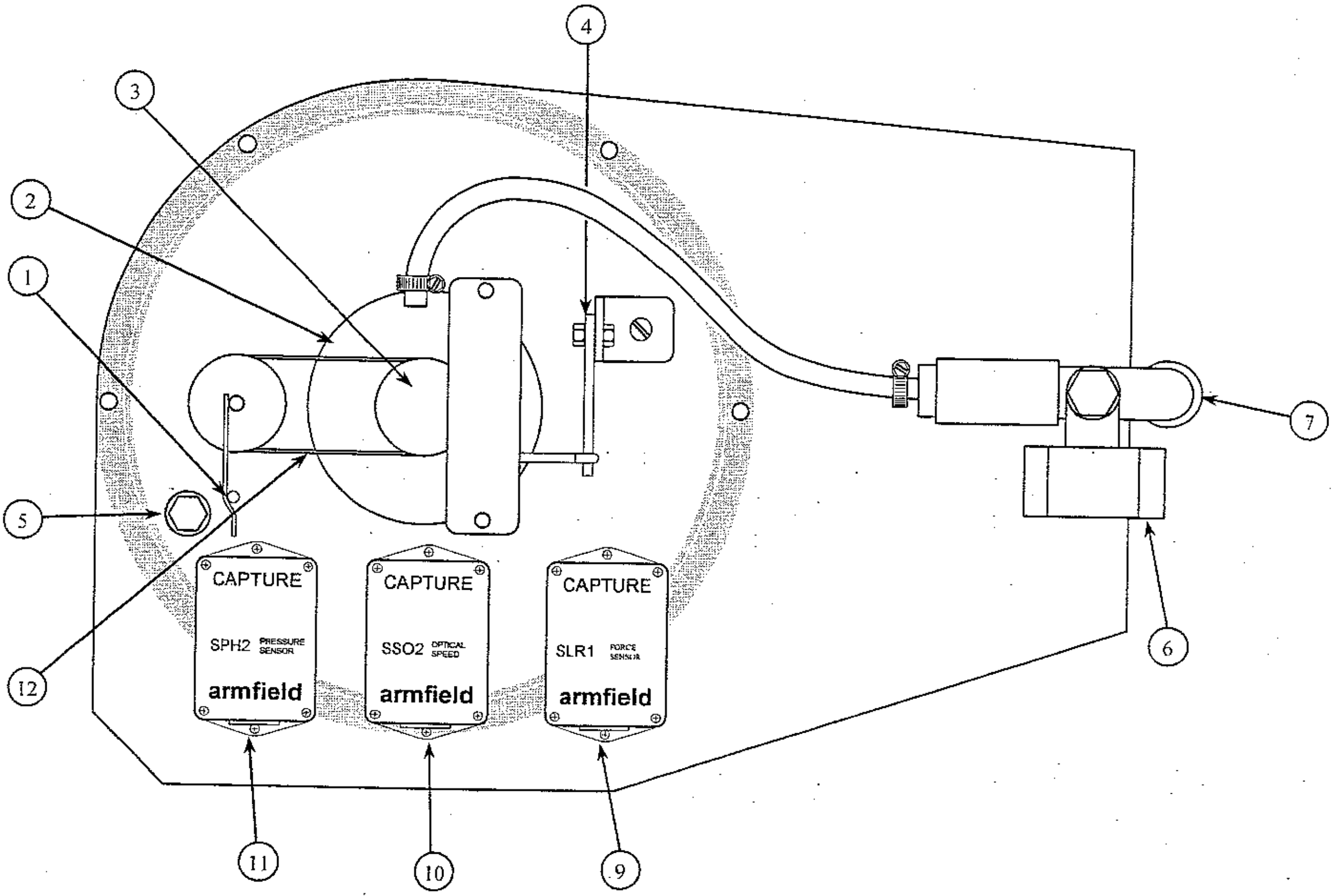


Figure 3: FM31 Radial Flow Reaction Turbine

FM32 Pelton Turbine

All numerical references in brackets relate to the diagram on page 9.

The Pelton Turbine FM32 consists of a demonstration turbine mounted on a support plate (13) with appropriate controls and sensors.

The rotor (9) carries 10 divided buckets on a pitch circle diameter of 70mm. The rotor is mounted on a horizontal stainless steel shaft carried in corrosion resistant ball bearings with double shields to provide lifetime lubrication.

The spear valve (3) has a nozzle of 4.5mm diameter, fitted with an adjustable valve stem to vary the jet diameter with minimum friction loss. This allows the flow rate to be varied with a constant exit jet velocity.

A robust clear acrylic casing (4) houses the rotor and spear valve.

The turbine support plate (13) is designed to attach to the top flange of the reservoir on the FM3SU Turbine Service Unit and the throttle valve (V1) attaches to the screwed connector on the pump discharge pipe. A filler plug allows water to be added to the reservoir with the turbine installed.

The following sensors are used to monitor the performance of the Pelton Turbine:

Pressure sensor SPH2 connected to Channel 2 on IFD

This comprises of a piezo-electric pressure sensor (2) with appropriate signal conditioning all contained in a protective case (7).

The sensor is used to measure pressure at the inlet to the spear valve. An additional tapping in the inlet manifold is provided for the connection of appropriate instrumentation (not supplied) to facilitate calibration of the pressure sensor.

Rotational speed sensor SSO2 connected to Channel 3 on IFD

This comprises of a reflective infra-red opto switch (10) on a remote lead with appropriate signal conditioning in a protective case (6) and is used to measure the rotational speed of the turbine rotor.

The opto switch is mounted adjacent to the hub of the rotor which incorporates a reflective strip to facilitate measurement of the rotational speed. An appropriate non-contacting optical tachometer (not supplied) may be used to calibrate the rotational speed sensor.

Force sensor SLR1 connected to channel 4 on IFD

The load beam (8) incorporates a strain gauge which is connected to appropriate signal conditioning in a protective case (5).

The force sensor is used to measure the force applied to the brake on the hub of the turbine rotor.

Speed of the turbine is controlled by adjusting the tension in the brake belt by adjusting the tension screw (12).

The force sensor can be calibrated by removing it from the support bracket, clamping it in a suitable fixture and attaching a dead load (not supplied).

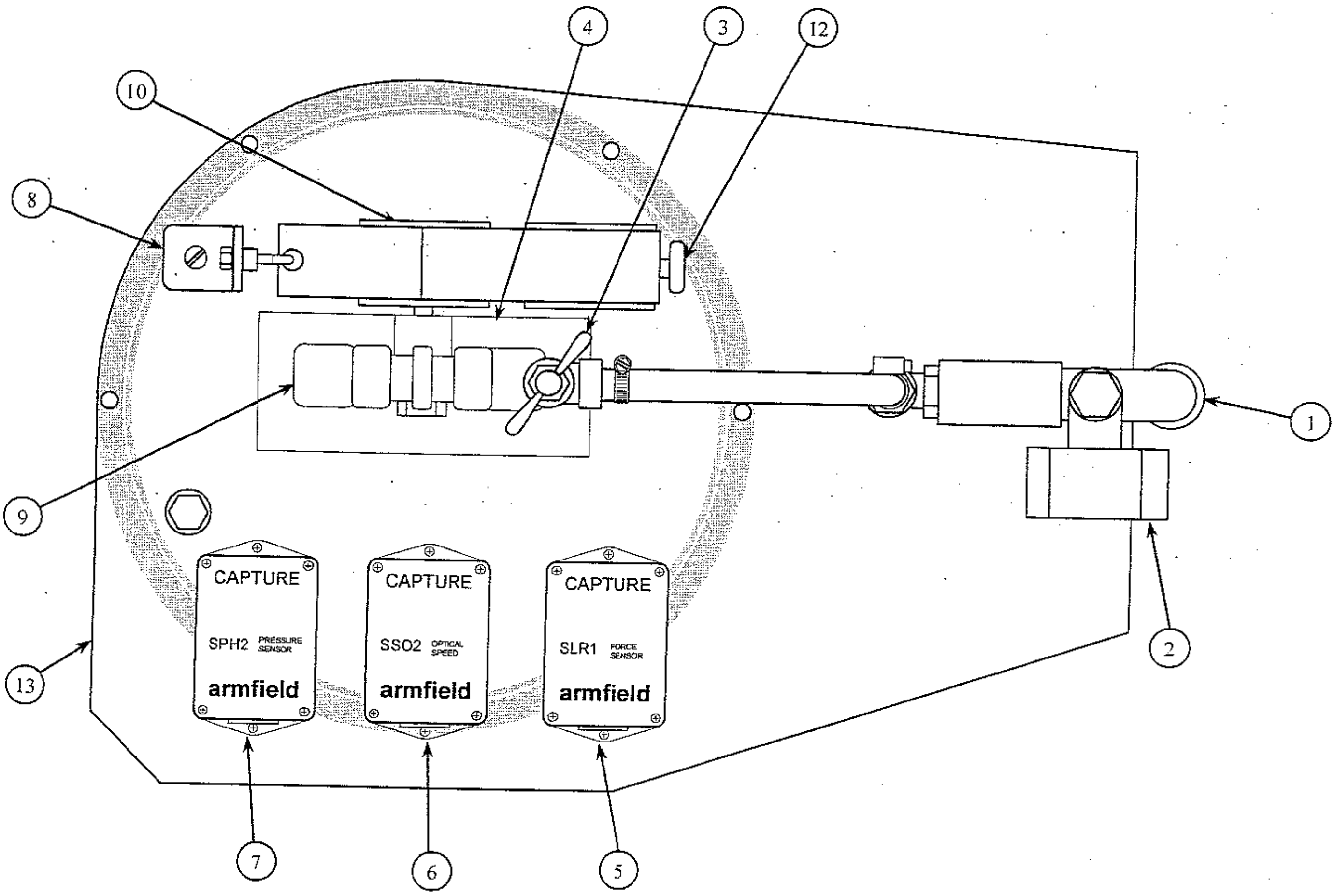


Figure 4: FM32 Pelton Turbine

OPERATION

All numerical references in brackets relate to the diagram on page 3.

Place the Turbine Service Unit FM3SU in a suitable location adjacent to a compatible microcomputer.

Check that the Differential Pressure Sensor SPW1 (9) is connected to the two tappings at the front of the reservoir. P1 LOW on SPW1 must be connected to the tapping on the orifice plate and HIGH P2 must be connected to the tapping in the wall of the reservoir.

The flexible tubing connecting differential pressure sensor SPW1 to the orifice plate should be primed with water using the priming syringe supplied. Fill the syringe with clean water. Disconnect each flexible tube from the tapping on the reservoir. Insert the syringe and back-fill the flexible tube with water. When all air bubbles have been expelled re-connect the tubing to the reservoir.

Ensure the drain valve (2) at the base of the reservoir is fully closed. Fill the reservoir (3) with clean water until the level is approximately 100mm below the top.

If air has entered the flexible tubing connecting the pressure sensor SPW1, it may be possible to squeeze the tubing and expel the bubbles via the reservoir. If air remains in the tubing after this, disconnect the tubing and use the priming syringe to completely back fill the tubing again, then reconnect the tubing to the reservoir.

Place the required turbine (FM30, FM31 or FM32) on top of the reservoir, ensuring that the O-ring seal is located in the recess in the top flange of the reservoir. Loosely attach the pipe connector from the service unit to the turbine, then fasten the base plate of the turbine to the top flange of the reservoir by tightening the thumb screws. Finally tighten the pipe connector.

Place the interface console IFD alongside the microcomputer.

Connect the mains supply lead from an appropriate electrical supply to the MAINS INPUT socket on IFD ensuring that the electrical supply is compatible with the console (indicated on the rear of the console).

If using a -A version of the FM3SU, connect the mains lead from the motor on the turbine service unit to one of the mains outlets on the IFD. Switch on IFD. Check that water circulates through the turbine. Turn off the pump.

If using a -B version of the FM3SU connect the mains lead from the turbine service unit to a separate mains supply ensuring that the electrical supply is compatible with the service unit. Before using the turbine service unit check the operation of RCD as described in the safety section at the front of this instruction manual. Switch on the RCD then operate the rocker switch. Check that water circulates through the turbine. Turn off the pump.

Connect each of the sensor conditioning boxes to the appropriate SENSOR SOCKETS on the front of IFD, using the numbered connecting leads, as follows:-

Channel 1 to sensor SPW1	on the Turbine Service Unit (FM3SU)
Channel 2 to sensor SPH2	on the base plate of the appropriate Turbine
Channel 3 to sensor SSO2	on the base plate of the appropriate Turbine
Channel 4 to sensor SLR1	on the base plate of the appropriate Turbine

Brake Belt Removal And Refitting

In order for the turbine and brake system to operate correctly the brake belt must be lightly tensioned between the turbine pulley and slave pulley.

If the belt has stretched it will need replacing as follows:

Remove any tension in the brake belt (7) by unscrewing the tensioning screw (2). When the tension has been removed unclip the belt from the tension sensor (8).

Undo and remove the top bolt from rotation sensor bracket (5) and extract the centre bolt from the slave pulley (1) then remove the slave pulley from its bracket. The belt should now be easily extracted from the system.

Reverse the above procedure for refitting the new belt. The stretched belt can usually be re-stapled with the length of the loop adjusted accordingly.

It should be noted that over tightening the slave pulley centre bolt will cause the brake belt to operate incorrectly, therefore, the slave pulley should be able to be freely rotated when there is no tension in the brake belt. If the results seem to fluctuate unduly, it is advised to apply a thin layer of graphite on the turbine pulley (4) by means of a soft leaded pencil.

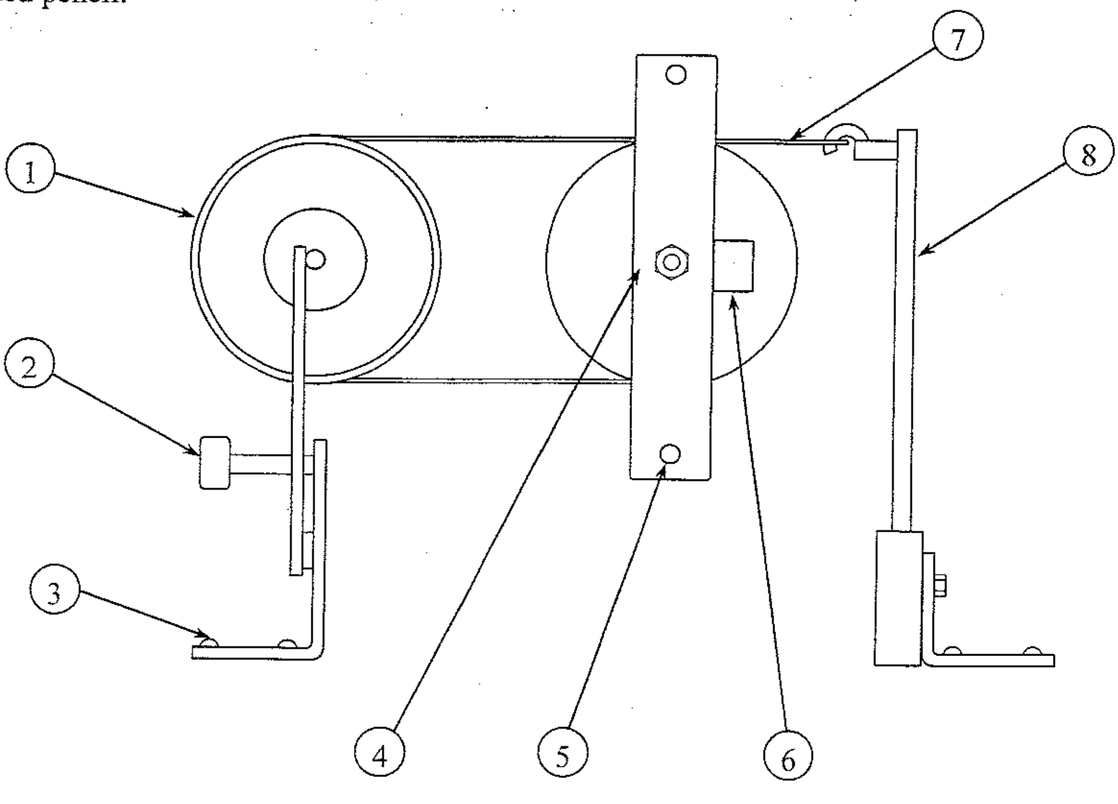


Figure 5: Brake Assembly

The equipment is ready for use with the Armfield Capture software.

NOTE: The apparatus is classified as Education and Training Equipment under the Electromagnetic Compatibility (Amendment) Regulations 1994. Use of the apparatus outside the classroom, laboratory or similar such place invalidates conformity with the protection requirements of the Electromagnetic Compatibility Directive (89/336/EEC) and could lead to prosecution.

NOMENCLATURE

The variables obtained from the sensors on the equipment are:

Symbol	Term	Units
dP_o	Orifice differential pressure	N/m^2 (Newtons per square metre) displayed as kPa (kilopascals) (1 Pa = 1 N/m^2)
P_1	Turbine inlet pressure	N/m^2
n	Turbine rotational speed	Hz (Hertz)
F_b	Brake force	N (Newtons)

Constants used in the calculations:

Symbol	Term	Units
d	Orifice Diameter	m (metres)
g	Gravitational acceleration	m/s^2(metres per second per second)
C_d	Coefficient of discharge	Dimensionless number
r	Pulley radius	m (metres)
Rho_w	Density of water	kg/m^3(kilograms per cubic metre)

Calculated variables:

Symbol	Term	Units
Q_v	Volume flow rate	m^3/s (cubic metres per second)
H_i	Input head to turbine	m (metres)
P_h	Hydraulic power at inlet to turbine	W (Watts)
T	Torque	Nm (Newton metres)
P_b	Brake Power	W (Watts)
E_t	Turbine efficiency	Percentage

Formulae Used:

$$Q_v = \frac{C_d \times \pi \times d^2 \times \sqrt{2 \times Rho_w \times dP_o}}{4 \times Rho_w}$$

$$H_i = \frac{P_1}{Rho_w \times g}$$

$$P_h = Rho_w \times g \times H_i \times Q_v$$

$$T = F_b \times r$$

$$P_b = 2 \times \pi \times n \times T$$

$$E_t = \frac{P_b}{P_h} \times 100$$

INDEX TO EXERCISES

Warning

Each of the practical exercises described in the help file requires the equipment to be set up and in working condition according to the instructions given in the Installation Guide.

The final test of readiness is made using the diagram screen, where the effect on the measured variables of changing the various physical settings can be seen numerically on screen. For example, adjusting the throttle valve (V1) by hand will also cause changes in fluid flow and head. Check that the changes in these settings give trends in the measured variables, as displayed in the boxes on screen, which you would intuitively expect. If no change in measured power, flow or head occurs whatever changes you make to the valve position, then clearly something is wrongly set up and you need to establish what the problem is by working through the installation procedures again.

Instructional Objectives

The objects of the practical work exercises described in the help screens, are to understand the operating characteristics of the turbines.

Figures 6, 7 and 8 show the rotor and nozzle arrangements for the axial flow impulse turbine (FM30), the radial flow reaction turbine (FM31) and the Pelton turbine (FM32).

In an impulse turbine (figure 6) the kinetic energy of a jet leaving a high pressure stationary nozzle is converted on impact with the turbine blades to rotational mechanical energy. As the water exiting the jet is at atmospheric pressure, the force exerted on the rotor is entirely due to changes in the direction of the flow of water. The impulse turbine is therefore associated with considerable changes of kinetic energy but little change in pressure energy.

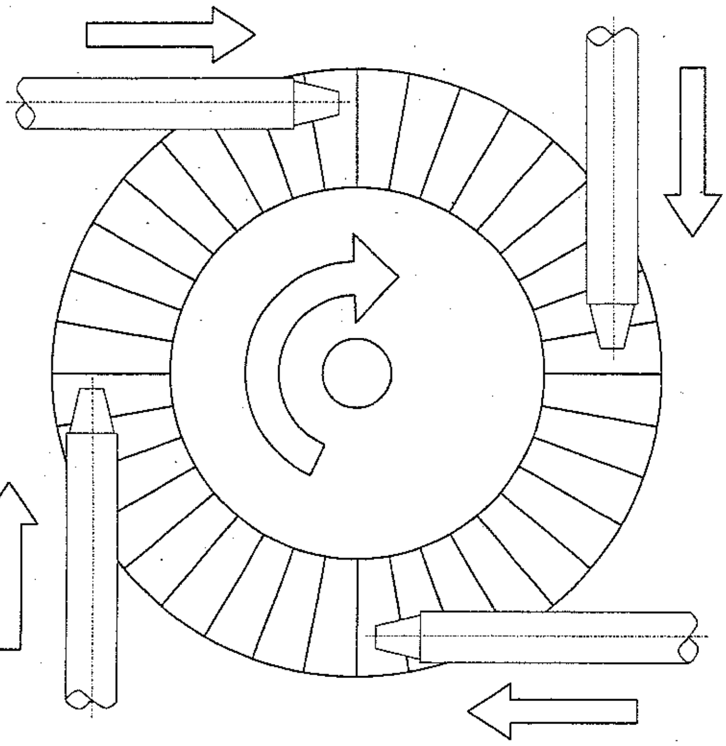


Figure 6: Rotor and nozzle arrangement on impulse turbine

In the case of the FM30 four independently controlled nozzles are installed around the rotor.

In a reaction turbine (figure 7) the water is subject to a pressure drop as it flows through the rotor. The reaction turbine is therefore associated with considerable changes in pressure energy but little change in kinetic energy and is sometimes called a pressure turbine. In the case of the FM31 water enters the rotor via a face seal and is discharged tangentially through two nozzles at the periphery of the rotor. The nozzles therefore move with the rotor.

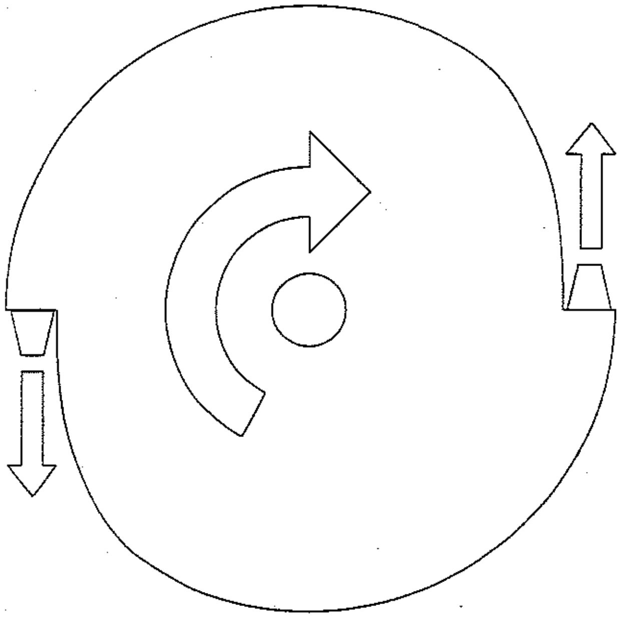


Figure 7: Rotor and nozzle arrangement on reaction turbine

The Pelton turbine (figure 8) is the most visually obvious example of an impulse machine. A spear valve directs a jet of water at a series of buckets which are mounted on the periphery of a rotor. As the water exiting the spear valve is at atmospheric pressure, the force exerted on the rotor is entirely due to changes in the direction of the flow of water. The Pelton turbine is therefore associated with considerable changes of kinetic energy but little change in pressure energy. The spear valve allows the jet diameter to be varied which allows the water flow rate to be varied with a constant jet velocity. Large turbines may include more than one spear valve around the periphery of the rotor. In the case of the FM32 a single spear valve is installed.

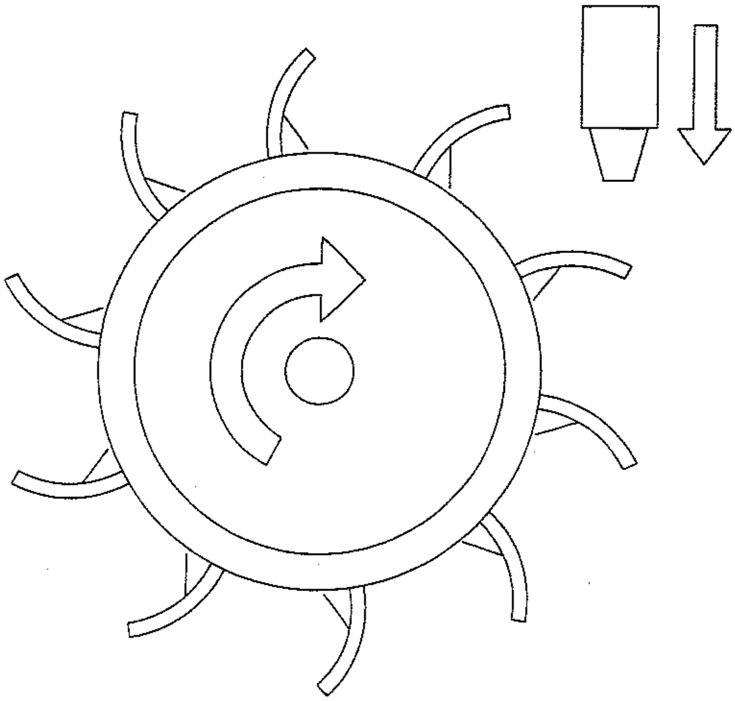


Figure 8: Rotor and nozzle arrangement on Pelton turbine

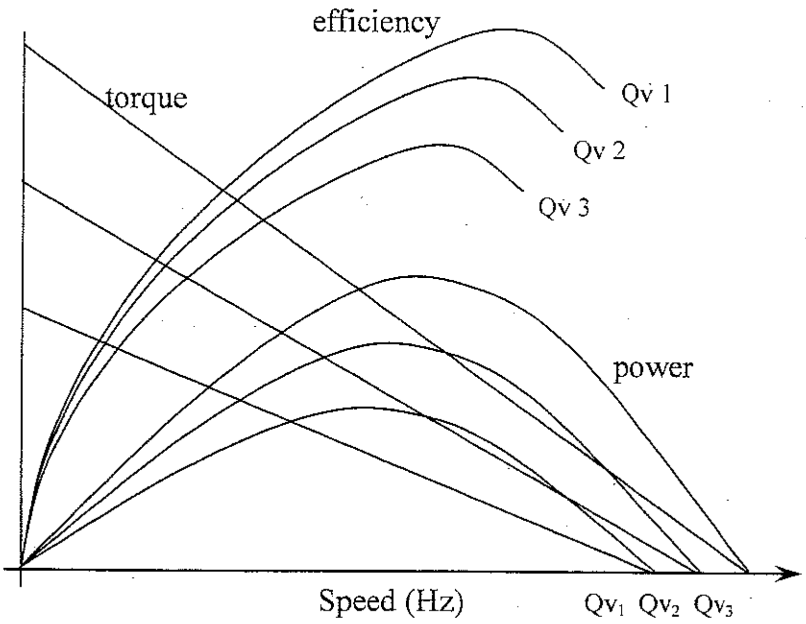


Figure 9: Example characteristics of a turbine at different flow rates

The operating characteristics of a turbine are often conveniently shown by plotting torque T, brake power P_b, and turbine efficiency E_t against turbine rotational speed n for a series of volume flow rates Q_v, as shown in figure 9. It is important to note that the efficiency reaches a maximum and then falls, whilst the torque falls constantly and linearly. In most cases a turbine is used to drive a generator in the production of electricity. The speed of the generator is fixed to produce a given frequency of electricity. The optimum conditions for operation occur when the maximum turbine efficiency coincides with the rotational speed of the generator. As the load on the generator increases then the flow of water to the turbine must increase to maintain the required operating speed.

This Armfield 'Capture' unit is designed to allow students to determine the operating characteristics of either an Axial Flow Turbine (FM30), a Radial Flow Reaction Turbine (FM31), or a Pelton Turbine (FM32), rapidly and meaningfully, using 'on-line' data acquisition and analysis. Test results may be displayed in tabular and graphical forms, and it is a simple matter to repeat or add to the data to cover areas of the turbine performance of particular interest.

At the conclusion of the work, students are asked a series of questions on an interactive basis, to ensure that a true understanding of turbine characteristics has been gained.

Energy Transfer in a Turbine

Turbines are classified in two general categories: impulse and reaction. In both types the fluid passes through a runner having blades. The momentum of the fluid in the tangential direction is changed and so a tangential force on the runner is produced. The runner therefore rotates and performs useful work, while the fluid leaves it with reduced energy. The important feature of the impulse machine is that there is no change in static pressure across the runner. In the reaction machine the static pressure decreases as the fluid passes through the runner.

For any turbine the energy held by the fluid is initially in the form of pressure, ie. a high level reservoir in a hydro-electric scheme.

The impulse turbine has one or more fixed nozzles , in each of which this pressure is converted to the kinetic energy of an unconfined jet. The jets of fluid then impinge on the moving blades of the runner where they lose practically all their kinetic energy.

In a reaction machine the changes from pressure to kinetic energy takes place gradually as the fluid moves through the runner, and for this gradual change of pressure to be possible the runner must be completely enclosed and the passages in it entirely full of the working fluid.

The general relationship between the various forms of energy, based on the 1st Law of Thermodynamics applied to a unit mass of fluid flowing through a 'control volume' (such as the turbine itself), is expressed as:-

$$-W_s = d\left(v^2/2\right) + g.dz + \int vol.dp + F \qquad (1)$$

where:-

$-W_s$ is the work performed by the fluid on the turbine.

$d(v^2/2)$ is the change in kinetic energy of the fluid

$g.dz$ is the change in potential energy of the fluid

$\int vol.dp$ is the change in pressure energy, where 'vol' is the volume per unit mass of the fluid. For an incompressible fluid of constant density Rho, this term is equal to $\int dp / Rho$ or $(p_1 - p_2)/Rho$ where p_2 refers to the turbine discharge outlet andp_1 to the turbine inlet.

F is the frictional energy loss as heat to the surroundings or in heating the fluid itself as it travels from inlet to outlet.

The first three terms of the right hand side represent the useful work W_a ie.

$$W_a = \left(\left(v_1^2 - v_2^2\right)/2\right) + g\left(z_1 - z_2\right) + \left(\left(p_1 - p_2\right)/Rho\right) \qquad (2)$$

where subscript 2 refers to the turbine outlet and subscript 1 to the inlet.

The term W_a represents the actual work produced in changing the energy stages of a unit mass of the fluid. This may alternatively be presented as the total dynamic head H of the turbine, by converting the units from work per unit mass to head expressed as a length:-

$$H = \left(\left(v_1^2 - v_2^2\right)/2g\right) + \left(z_1 - z_2\right) + \left(\left(p_1 - p_2\right)/Rho.g\right) \qquad (3)$$

It can be assumed for the purposes of the following practical experiments that the fluid is incompressible (i.e. Rho is constant).

Practical Exercise No 1 - Using Engineering Units

Objective

To ensure users fully understand the conversion of measured units of quantity to those of the variables necessary to calculate turbine performance.

Theoretical Background

The basic terms used to define, and therefore measure, turbine performance in relation to rotational speed include:

i) volume flow rate,
ii) head,
iii) torque, power output and efficiencies.

Each of these is considered in turn.

Volume Flow Rate Q_v

The volume flow rate of fluid through the turbine is the volume passing through the system per unit time. In SI units, this is expressed in cubic metres per second (m^3/s).

The Armfield FM3SU unit employs an orifice plate in the pump inlet pipeline to measure Q_v, according to the conventional relationship between the measured pressure drop dP_o across the orifice and the flow rate:-

$$Q_v = \frac{C_d \times Pi \times d^2 \times \sqrt{2 \times Rho \times dP_o}}{4 \times Rho} \qquad (4)$$

Where C_d is the orifice discharge coefficient.

(This applies when the orifice diameter d is no more than 50% of the pipe diameter.)

The appropriate constants needed to use this equation for deducing discharge Q_v from dP_o are given in the Nomenclature section of the software help.

Head H

The term 'head' refers to the elevation of a free surface of water above or below a reference datum. In the case of a turbine we are interested in the head of the water entering the rotor, which of course has a direct effect on the characteristics of the unit.

Terms specifically applied to the analysis of turbines and generating systems are illustrated graphically in figure 10, and are briefly defined below.

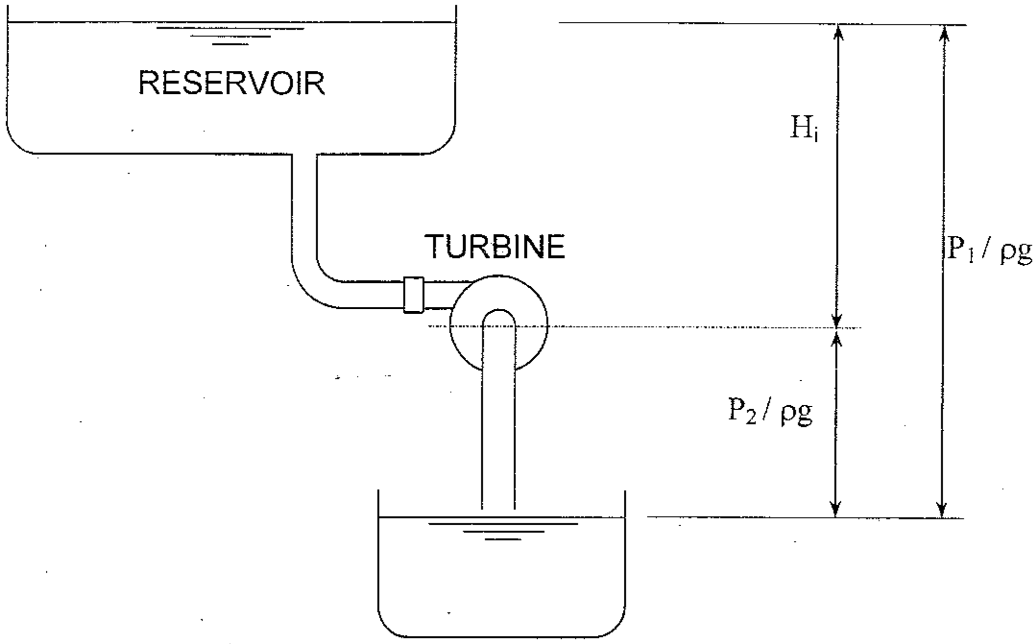


Figure 10: Definitions of Head across a turbine

1) Manometric suction head H_{m1} is the gauge reading (metres) measured at the inlet nozzle of the turbine, referenced to the rotor centreline datum.

2) Manometric discharge head H_{m2} is the gauge reading (metres) measured at the discharge nozzle of the turbine, referenced to the rotor centreline.

3) Input head to the turbine (H_i) is the head used by the turbine in performing work. For the turbine shown in Fig 3, H_i is given by:

$$H_i = [H_{m1} - H_{m2}] \tag{5}$$

Equation (3) relates precisely to Equation (5) for a control volume enclosing the turbine outlet and inlet, as H_{m1} and H_{m2} are the measured pressures equal to

$z_1 + (p_1/Rho.g)$ and $z_2 + (p_2/Rho.g)$ respectively .

The Armfield instrumentation is such that the inlet pressure is measured in relation to atmospheric pressure (P_1). As the outlet of the turbine is at atmospheric pressure, it can be assumed that the reading given by P_1 is the pressure difference across the turbine.

Therefore, (H_{m1} - H_{m2}) is actually measured as a differential pressure P_1 (Pascals), but converted in subsequent calculations to p_1/Rho.g metres (see 'Formulae Used' in this Help File).

Power Output and Efficiencies

The brake power P_b produced by the turbine in creating a torque T on the brake at rotor speed n is given by Equation (6):

$P_b = 2 \,.\, Pi \,.\, n \,.\, T$ [Nm/s = Watts] (6)

The torque itself is given by the equation:

$T = Fb \,.\, r$ [Nm]

where F_b is the brake force reading on the Capture sensor and r is the pulley radius.

However, the fluid friction 'losses' in the turbine itself, represented as F in Equation (1), require a hydraulic efficiency E_h to be defined as:-

$$E_h = \frac{\text{Power absorbed by the rotor } (P_r)}{\text{'Useful' fluid power supplied } (P_h)} \times 100\%$$

Further, the mechanical losses in the bearings etc require a mechanical efficiency E_m to be defined as

$$E_m = \frac{\text{Power supplied by the rotor } (P_m)}{\text{Power absorbed by the rotor } (P_r)} \times 100\%$$

The Armfield turbine units do not include the direct measurement of mechanical power Pm, but instead measures brake force applied to the rotor via pulleys. A further efficiency is therefore required, expressing the friction losses in the pulley assembly E_b:-

$$E_b = \frac{\text{Power absorbed by the brake } (P_b)}{\text{Power supplied by the rotor } (P_m)} \times 100\%$$

The overall turbine efficiency E_t is thus:-

$$E_t = \frac{\text{Power absorbed by the brake } (P_b)}{\text{'Useful' fluid power supplied } (P_h)} \times 100\%$$

$$= \frac{2 \times Pi \times n \times T}{Rho_w \times g \times H_i \times Q_v} \times 100 \qquad (7)$$

(Rho.g.H.Q being the standard calculation for fluid power)

It will be seen that

$$E_t = E_h \,.\, E_m \,.\, E_b \qquad (8)$$

Equipment Set-Up

As described in the help. The View the diagram screen to display the measured variables on-line in the appropriate boxes on the turbine schematic diagram.

Procedure

Close valve V1 then start the pump (pump motor started under minimum load). Open inlet valve V1, then, if using the FM32, open the spear valve, or, if using the FM30, open all four nozzle valves. Allow the water to circulate until all air bubbles have dispersed. View the diagram and note the value of the volume flow indicated at the bottom of the screen. Gradually close valve until the volume flow is approximately half of the maximum reading.

Place a load on the turbine by tightening the thumbscrew on the second pulley to a desired level. The speed of the turbine should slow and the reading for the brake tension belt will increase.

When the indicated readings of the 4 measured variables are reasonably constant, click 'GO' to take a sample. It is only necessary to take one set of results for this exercise. Now view the table, and you will see the results of your test sample laid out as one row of a table. Write down on a piece of paper the values of the measured variables your sample took, as follows:

Differential pressure across orifice dP_o	[kPa]
Turbine inlet pressure P_1	[kPa]
Rotational speed of turbine	[Hz]
Brake force on turbine F_b	[N]

From your own classroom notes, or using the appropriate theory and equations in the Theory section, you can calculate the various turbine performance variables for yourself and compare your calculated figures with those computed in this software and displayed as 'Calculated Variables' in the row of tabulated results from your sample. In your own calculation, you will have to use the values of the various physical constants listed in the Nomenclature.

Variable to be calculated	Your calculated result	Armfield software result
Volume flow rate Q_v [m^3/s]		
Input head H_i [m]		
Hydraulic input power P_h [W]		
Torque [N/m]		
Brake power P_b[W]		
Turbine efficiency E_t[%]		

Practical Exercise No 2 - Turbine Characteristics

Objective

To obtain the characteristic curves for a turbine operating at a range of fluid flow rates.

Theoretical Background

The best way to describe the operating characteristics of a turbine is through the use of characteristic curves. (figure 11). This figure shows the interrelation of Torque T, Brake Power P_b, turbine efficiency E_t, and turbine rotational speed n, for a given turbine running at constant fluid flow rate.

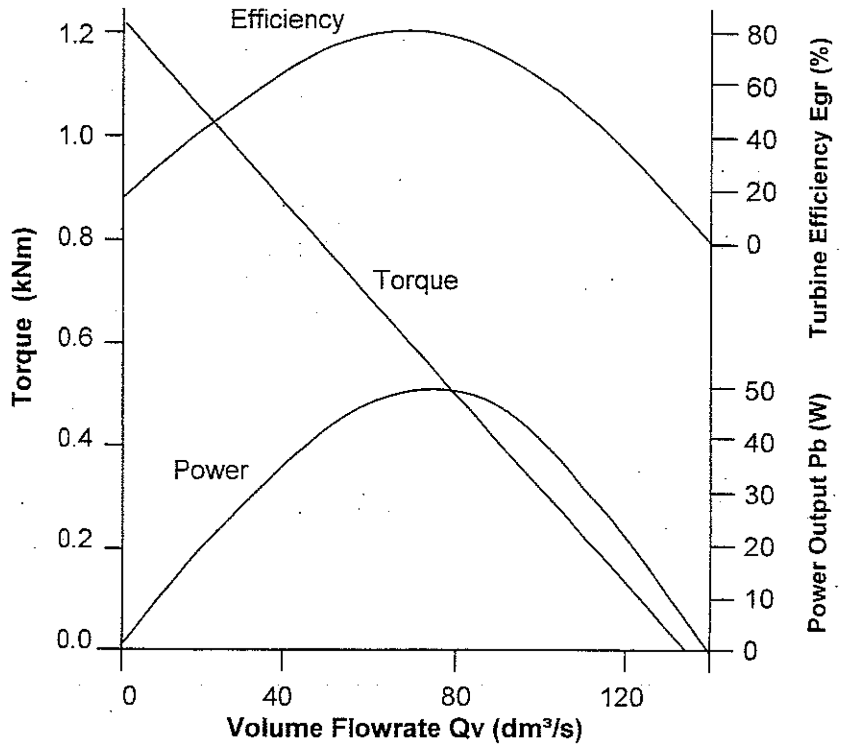


Figure 11: Characteristic curves for a turbine

The P_b - n curve of figure 11 shows the relation between power output and turbine rotational speed. The E_t - n curve relates turbine efficiency to speed. For a turbine having the characteristics of figure 11, maximum efficiency would occur at a speed of 65 Hz, and a power output of 58 Watts.

Manufacturers provide information on the performance of their turbines in the form of characteristic curves, such as those shown in figure 12.

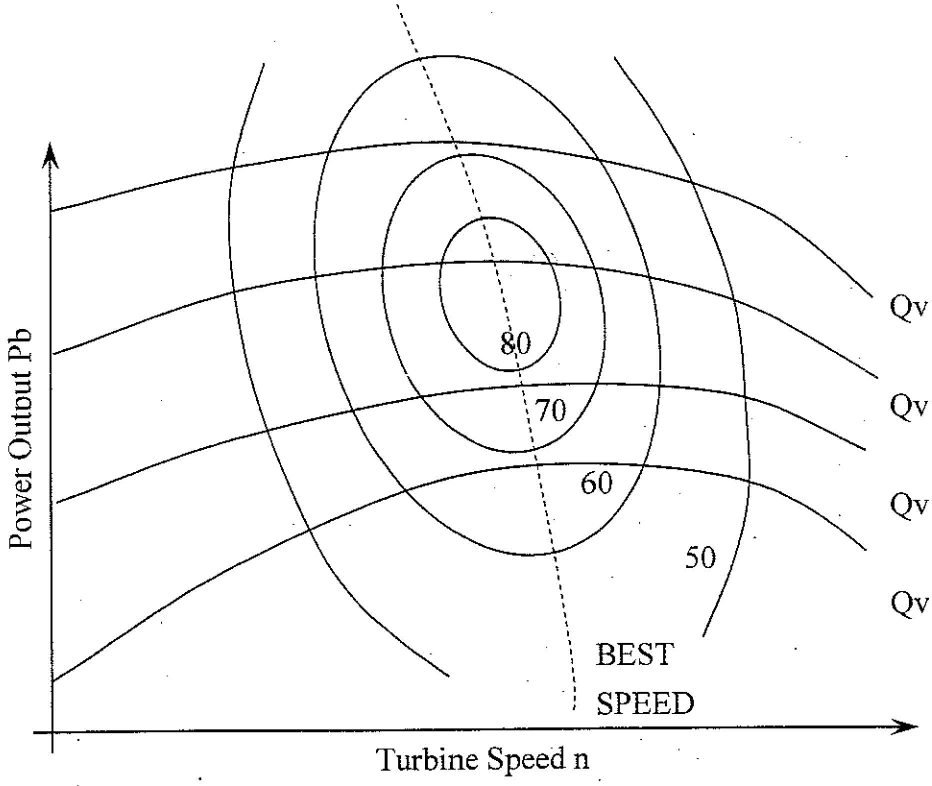


Figure 12: Typical graph showing turbine operating characteristics at different flows.

A chart of this type makes it possible to determine at what speed, and at what gate opening (volume flow rate), the turbine should be run to develop a given power output, and yet have the best possible efficiency. The best speed line is obtained by drawing a line through the major axes of the iso-efficiency curves.

Equipment Set-Up

Exactly the same as that for Practical Exercise No 1.

If using the FM30 Impulse Turbine, all four nozzle valves should remain open for the duration.

If using the FM32 Pelton Turbine, the spear valve should be opened fully and left open. Select 'chart'. Close spear valve then open until full flow on channel 1.

All control of volume flow rate will be performed by the throttle valve V1 on the relevant unit.

Procedure

i) Close turbine throttle valve then start the pump (pump motor started under minimum load). Open valve fully and allow the water to circulate until all air bubbles have dispersed. Tighten up the tensioning screw on the second pulley wheel until the turbine is almost stalled (rotor just turning).

ii) View the diagram and note the value of the pulley brake force. Decide on suitable increments in force to give adequate sample points (typically 15 points between zero and maximum flow).

iii) Slacken off the tensioning screw so no force is being applied to the turbine, i.e. $F_b \approx 0$. When the measured readings as indicated in the boxes on the schematic diagram are sufficiently steady, click 'GO' to take a sample. This represents the first point on the characteristic curve.

iv) Tighten the screw, to give the first increment in force for the brake. When readings are steady enough, click 'GO' to take a sample.

v) Repeat step iv) above for a gradually increasing set of F_b values, i.e. increasing values of torque. The final sample point will correspond to the turbine stalling.

vi) The recorded set of data may now be examined in the various software screens or downloaded into a spreadsheet. Be sure to save the data before taking new readings.

vii) Now increase or decrease the volume flow rate to a new setting by changing the throttle valve position, and repeat the taking of samples for gradually increasing values of torque, as in iii) above. Repeating this step will produce a series of result sets for comparison.

Practical Exercise No 3 - FM30 - Comparison of Nozzle and Throttle Valve

Objective

To show the difference in performance between throttle control and nozzle control of turbine speed.

Theoretical Background

Figure 13 shows the form taken by the curve relating hydraulic efficiency and the ratio of rotor bucket to jet speed.

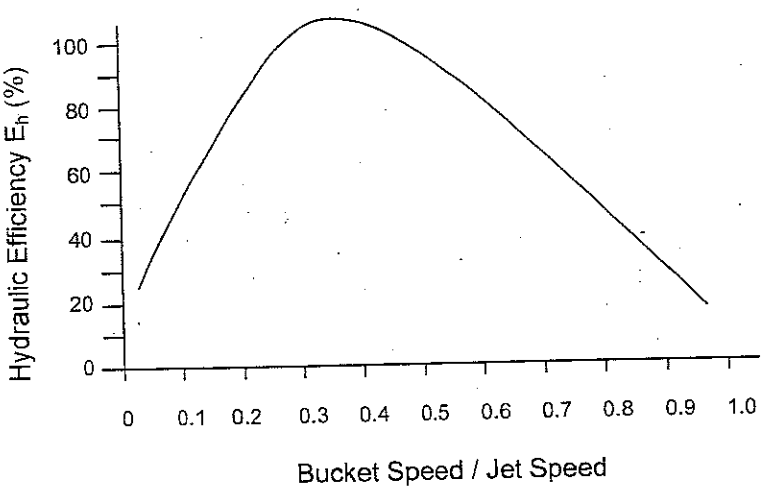


Figure 13: Hydraulic efficiency versus bucket/jet speed ratio.

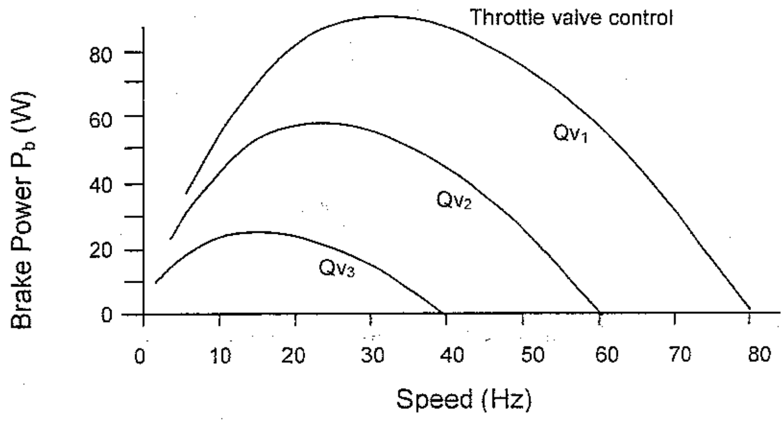
The graph shows how the curve rises to a relatively sharp peak, and hence for a high hydraulic efficiency it is essential for the ratio of bucket to jet speed to remain close to the theoretical value of one half (the velocity of the jet being twice that of the bucket).

The rotational speed (and hence the bucket speed) of the rotor is required to remain constant in a generating installation in order to produce power at the correct frequency. It then follows that for the hydraulic efficiency to remain high, the jet speed must also remain the same. This is so even when the power demand falls off and the volume flow rate passing through the turbine is therefore reduced (or vice-versa).

With a standard throttle valve, the area of the outlet jet remains the same as the flow rate changes. This causes a change in the jet velocity (Q_v/A).

With the Impulse turbine there are four jets. Power production is lowered by turning off one or more of the jets. The resulting slight rise in pressure can be removed by a throttle valve, meaning the remaining jets are still ejecting water at the same velocity, but a lower flow is passing through the turbine.

The following graphs demonstrate the different characteristics obtained:



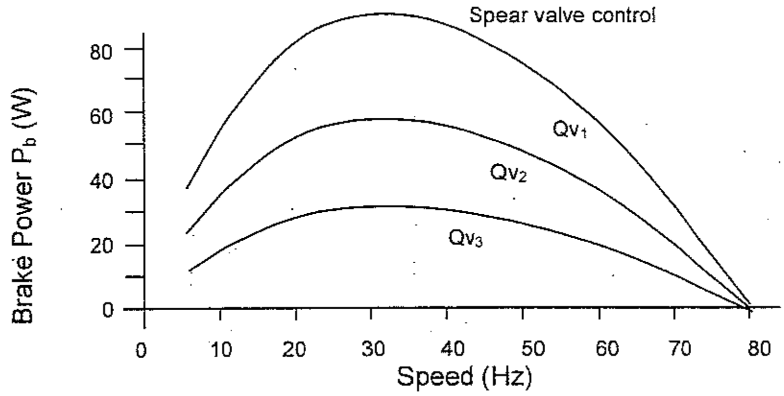


Figure 14: Typical brake power - speed curves for throttle and nozzle control.

Equipment Set-Up

Exactly the same as that for Practical Exercise No 1.

Begin the experiment with all four nozzle valves open.

Procedure

i) Close turbine throttle valve then start the pump (pump motor started under minimum load). Open valve fully and allow the water to circulate until all air bubbles have dispersed. Tighten up the tensioning screw on the second pulley wheel until the force stops the turbine.

ii) View the diagram and note the value of the pulley brake. Decide on suitable increments in force to give adequate sample points (typically 15 points between zero and maximum flow). Note the value of the inlet pressure as this will be used for all result sets.

iii) Slacken off the tensioning screw so no force is being applied to the turbine, ie. $F_b \approx 0$. When the measured readings as indicated in the boxes on the schematic diagram are sufficiently steady, click 'GO'. This represents the first point on the characteristic curve.

iv) Tighten the screw, to give the first increment in force for the brake. When readings are steady enough, click 'GO'.

v) Repeat step iv) above for a gradually increasing set of F_b values, i.e. increasing values of torque. The final sample point will correspond to the turbine stalling. Save the results.

vi) Now close one of the nozzle valves. The pressure at the inlet will increase. Bring it back to the original level (as previously noted) using the throttle valve. Repeat the taking of samples for gradually increasing values of torque, as in iii) above.

vii) Continue until results have been obtained for turbine with 4, 3, 2 and 1 jets operational.

viii) The recorded sets of data may now be examined and assessed in the various software screens or downloaded into a spreadsheet. Be sure to save the data each time before taking new readings.

Note: Additional comparisons may be made with the turbine operating under throttle control only by taking four new sets of results with all four nozzles fully open. Each result set should correspond to a volume flow rate obtained in the previous experiment, giving a direct comparison (similar to that shown in figure 14).

Practical Exercise No 4 - FM32 - Comparison of Throttle and Spear Valve

Objective

To show the difference in performance between throttle control and spear valve control of turbine speed.

Theoretical Background

Fig 10 shows the form taken by the curve relating hydraulic efficiency and the ratio of rotor bucket to jet speed.

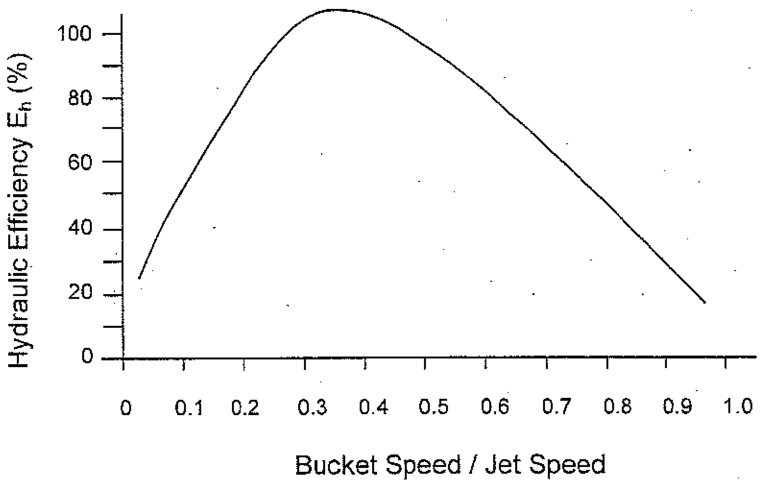


Figure 14: Hydraulic efficiency versus bucket/jet speed ratio

The graph shows how the curve rises to a relatively sharp peak, and hence for a high hydraulic efficiency it is essential for the ratio of bucket to jet speed to remain close to the theoretical value of one half (the velocity of the jet being twice that of the bucket).

The rotational speed (and hence the bucket speed) of the rotor is required to remain constant in a generating installation in order to produce power at the correct frequency. It then follows that for the hydraulic efficiency to remain high, the jet speed must also remain the same. This is so even when the power demand falls off and the flow rate passing through the turbine is therefore reduced (or vice-versa).

With a standard throttle valve, the area of the outlet jet remains the same as the volume flow rate changes. This causes a change in the jet velocity (Q_v/A).

With the Pelton turbine a spear valve is usually used for control. Power production is lowered by moving the spear further into the nozzle. This decreases the volume flow rate (ie. the volume of liquid passing through the turbine), but due to the smaller area of the jet impacting on the bucket its speed remains the same (Fig 11).

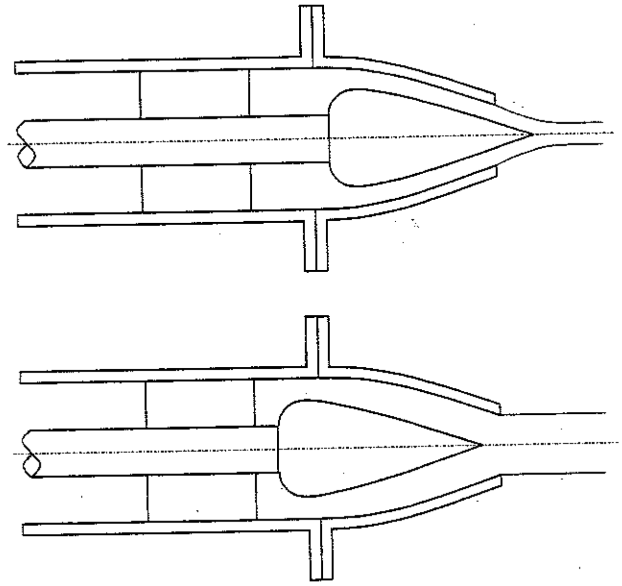


Figure 16: Spear valve operation.

The following graphs demonstrate the different characteristics obtained:

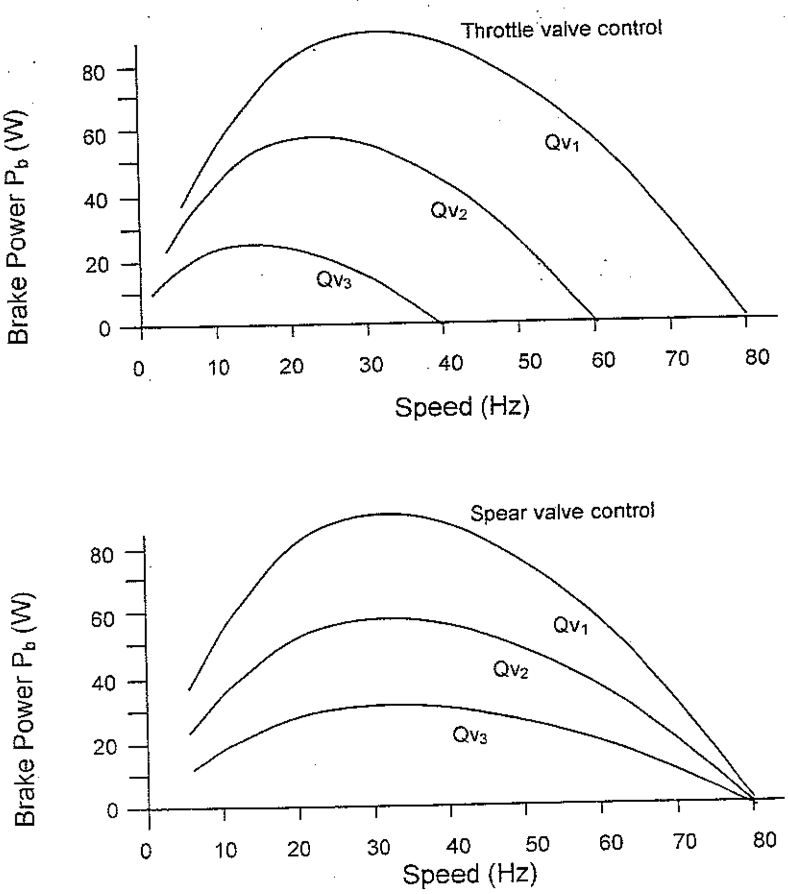


Figure 17: Typical brake power - speed curves for throttle and nozzle control

Equipment Set-Up

Exactly the same as that for Practical Exercise No 1.

The throttle valve will remain fully open during the experiment.

Procedure

i) Close turbine throttle valve then start the pump (pump motor started under minimum load). Open throttle and select 'charts' - open spear valve until full flow and allow the water to circulate until all air bubbles have dispersed. Tighten up the tensioning screw on the second pulley wheel until the force stops the turbine.

ii) View the diagram and note the value of the brake force. Decide on suitable increments in force to give adequate sample points (typically 15 points between zero and maximum flow).

iii) Slacken off the tensioning screw so no force is being applied to the turbine, i.e. $F_b \approx 0$. When the measured readings as indicated in the boxes on the schematic diagram are sufficiently steady, click 'GO'. This represents the first point on the characteristic curve.

iv) Tighten the screw, to give the first increment in brake force for the brake. When readings are steady enough, click 'GO'.

v) Repeat step iv) above for a gradually increasing set of F_b values, ie. increasing values of torque. The final sample point will correspond to the turbine stalling. Save the results.

vi) Now partially close the spear valve. Repeat the taking of samples for gradually increasing values of torque, as in iii) above.

vii) Continue until several result sets have been obtained.

viii) The recorded sets of data may now be examined and assessed in the various software screens or downloaded into a spreadsheet. Be sure to save the data each time before taking new readings.

Note: Additional comparisons may be made with the turbine operating under throttle control. Each result set should correspond to a volume flow rate obtained in the previous experiment, giving a direct comparison (as displayed in Fig 17 of the theory section).