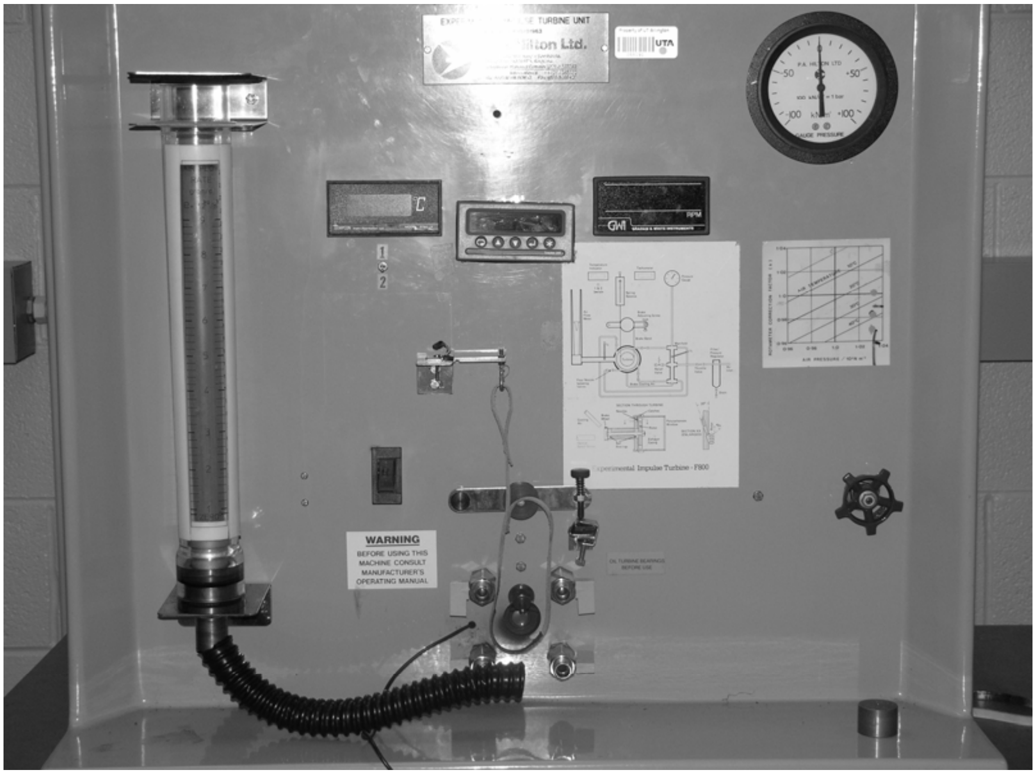
Impulse Turbine



Motivation

The purpose of this experiment is to revise the concepts of turbine cycle, its practical implementation, improve the general understanding of how to calculate work, power, efficiency and effectiveness for open boundary thermo-mechanical systems. Before coming/performing this lab, you must know the following topics

1. Static and stagnation values.
2. Basic concept of power, work and efficiency in a thermodynamic process.
3. Closed and open systems and the way efficiency is calculated in both.
4. Enthalpy, internal energy and total energy of a gaseous system.
5. Good understanding of constant entropy processes and adiabatic process, reversibility and its relation to entropy and energy of the system.
6. Types of turbines and structural and functional differences between them.
7. Various mechanisms to convert one form of energy into another and where turbine fits in the broader picture.
8. Conversion of pressure and temperature into mechanical energy in a turbine.

Introduction

Turbines are machines which develop torque and shaft power as a result of a momentum change in the fluid which flows through them. The fluid may be a gas, vapor, or liquid. For the fluid to achieve the high velocity required to provide worthwhile momentum changes, there must be significant pressure differences between the inlet and exhaust of the turbine. Sources of pressurized 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. In power generating plants, fossil or nuclear fuel is used to boil large amounts of water into steam vapor at high pressures. A turbine converts the energy of the steam into work that drives electric generators. This process provides the electricity that we use in homes and businesses.

There are numerous types of turbines. These vary from the elementary example used in a dentist drill to the large, multi-stage turbines used in the generating stations, developing as much as 1000 MW. The turbine used for the experiment, the Hilton Experimental Turbine F800, is classified as a "*simple, single stage, axial flow, impulse turbine*". "*Simple*" indicates an elementary turbine without complications such as velocity compounding. "*Single stage*" means the expansion of the fluid from the turbine inlet pressure to the exhaust pressure takes place within one stator and its corresponding rotor. "*Axial flow*" indicates that the fluid enters and leaves the rotor at the same radius and without significant radial components in the velocity. Finally, "*Impulse*" means that the fluid pressure drop (and consequent increase of velocity) takes place in the stator - i.e. in the nozzles. The fluid therefore passes through the rotor at an almost constant pressure, having only the velocity changed. It is useful to consider the turbine as a work producing machine undergoing a steady flow process, and to analyze its efficiency relative to a machine without irreversibilities or heat transfer.

Theory: Application of the first law of thermodynamics

A turbine through which unit mass of fluid flows under steady flow conditions is shown in Figure 1. The pressures, specific enthalpies and velocities at inlet and exhaust are p_1, h_1, v_1 and p_2, h_2, v_2 respectively. While unit mass of fluid flows, a specific work transfer, w, and a specific heat transfer, q, take place. Applying the first law in the form of the steady flow equation:

$$q = h_2 - h_1 + \frac{v_2^2 - v_1^2}{2} + w \tag{1}$$

$$q = (h_2 + \frac{v_2^2}{2}) - (h_1 + \frac{v_1^2}{2}) + w \tag{2}$$

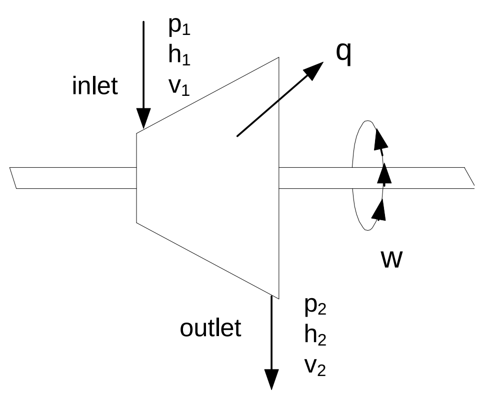


Figure 1, First Law applied to a turbine

Usually the velocities in the inlet and outlet pipes are similar, and are low relative to the velocities within the turbine, so that the $v^2/2$ terms may be neglected. Thus:

$$q = h_2 - h_1 + w \tag{3}$$

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. Therefore

$$w = (h_1 - h_2) \tag{4}$$

Isentropic Expansion

Expansion through an ideal turbine will be without heat loss or gain (adiabatic) and without dissipation of any of the available energy due to friction, throttling, etc. (reversible). A reversible and adiabatic process takes place at constant entropy (isentropic). If such an expansion is drawn on an enthalpy/entropy diagram, the ideal work transfer can be determined (Figure 2).

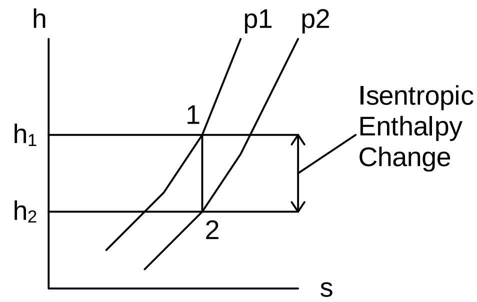


***Figure 2**, Isentropic Expansion through a turbine*

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 along with the dissipation of available energy are presented in Figure 3.

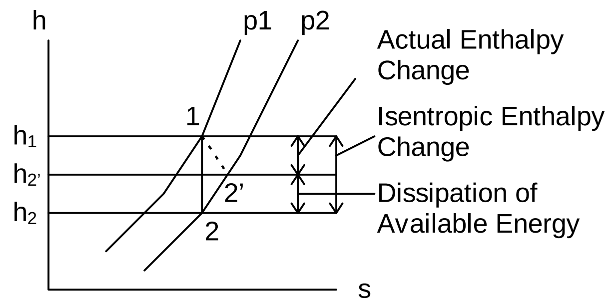


***Figure 3**, Actual expansion through a turbine*

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

1) Fluid friction in the stator (e.g. nozzles).
2) Fluid friction in the rotor passage (e.g. between blades).
3) Fluid leakage over blade tips or through seals.
4) Friction between rotor and fluid.
5) "Churning" of the fluid by blades.
6) Kinetic energy rejected from the rotor and then dissipated by friction.

The ratio of *Actual Enthalpy Change* to the *Isentropic Enthalpy Change* is called "***Internal Isentropic Efficiency***", η_{isen}, of the turbine. 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 Impulse 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. Since the turbine operates on air, it is convenient to use a temperature-entropy diagram and to calculate the enthalpy change from

$$(h_2 - h_1) = C_p(T_2 - T_1) \tag{5}$$

The "***Turbine efficiency***," η_{turb}, is given as the ratio of the actual work provided by the turbine at the shaft to the isentropic work

$$\eta_{turb} = \frac{W_{shaft}}{W_{isen}} \tag{6}$$

yielding the isentropic efficiency

$$\eta_{isen} = \frac{h_{2'} - h_1}{h_2 - h_1} \tag{7}$$

Apparatus

The experimental impulse turbine is shown in Figure 4. The turbine is a single stage, axial flow, impulse machine specially designed and manufactured by P. A. Hilton Limited for experimental and teaching purposes. The turbine rotor is carried by a steel shaft which runs in oil lubricated ball bearings housed in an extension to the nozzle plate. The rotor is machined from solid brass and has 45 blades of symmetrical shape with tip angles of approximately 40°. A stainless steel shroud ring is shrunk on to the blades to minimize tip leakage and to increase strength. The nozzle plate carries four equally spaced convergent nozzles which discharge at 20° to the plane of rotation into the blades. A removable thick walled stainless steel sleeve is attached to the nozzle plate with quick release catches, and forms a combined guard and exhaust casing for the turbine. The end of this casing is closed by a polycarbonate window which allows observation of the rotor when in operation.

The turbine is mounted centrally in the lower front of a high quality GRP panel for bench top use. All the controls and instruments are grouped conveniently around the turbine and the unit may be operated from one position. Each nozzle is provided with its own isolating valve so that the number of nozzles in operation may be varied. Compressed air from the local supply passes through a filter/regulator which reduces the pressure to approximately 65 kN/m^2 gauge. This air flows through a throttle valve to a manifold, and from this, to each of the four nozzle isolating valves. After expansion in the turbine, the air flows through the exhaust casing to the atmosphere via an air flow meter. A relief valve fitted to the manifold is set to discharge at 100 kN/m^2 gauge to prevent the turbine from exceeding its safe speed in the event of a malfunction of the pressure regulator.

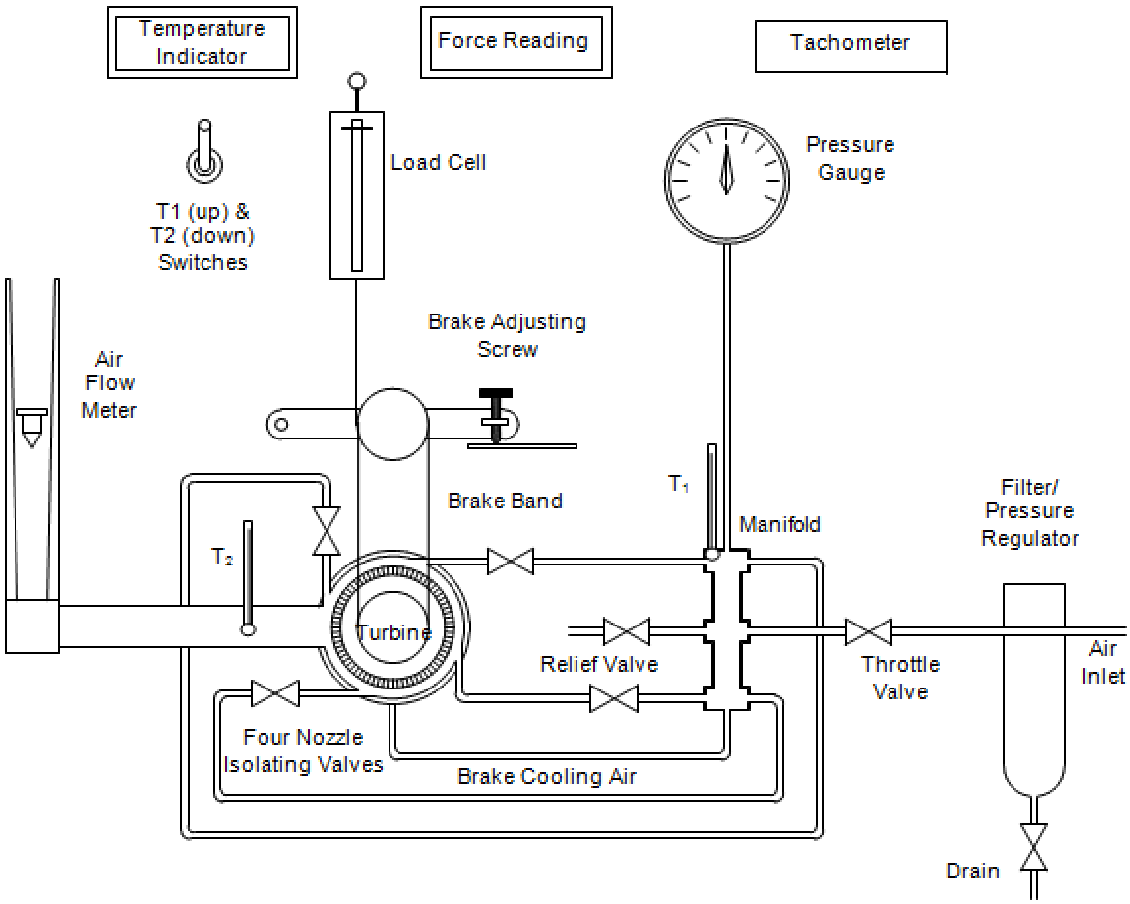


***Figure 4**, Schematic of the P.A. Hilton Experimental Turbine*

Caution!
Never run the turbine higher than 35,000 RPM!

Rotor:

Blade Circle Diameter 45 mm

Blade Inlet Angle 40 °

Blade Outlet Angle 40 °

Blade Height 4.25 mm

Brake Wheel: Effective Radius 14.5 mm

Rotating Parts: Moment of Inertia of moving parts 30×10^{-6} kg·m^2

Note: Assume air to be an ideal gas

Objective

To determine and characterize the performance of the Hilton Experimental Turbine F800.

Requirements

Experiment 1

Calculate the torque and shaft power for each point on Tables 1 & 2. Produce two graphs; 1) Torque versus RPM and 2) Power verses RPM. Each graph should contain data for all four pressures used. Given that the power curves developed are second order, determine a relationship between peak power available and input pressure.

Note, in order to calculate the torque you need to find out the force exerted into the turbine by tightening the screw and multiply by the effective radius of the brake wheel. However, to determine the force you must calibrate the force sensor. Loosen the brake band and use the provided weights to obtain a no load plus at least four (4) additional measurements by placing the weights and their combinations at the end of the cantilever beam of the sensor. Create a table/graph of the measured value on the digital readout as function of the weight at the end. Using statics analysis theory, identify the curve fit to be used and find the calibration equation. In your report you must show the analysis followed and discuss the curve fit/calibration equation selected and why. You can measure the weights at the scales in the lab.

Experiment 2

Calculate the turbine efficiency and isentropic efficiency for each point at 35 kN/m^2 and produce the corresponding plot of both on the same graph (Efficiency versus RPM).

Uncertainty Analysis

One set of readings at high (> 20K) rpm or medium (7.5K to 12.5K) rpm (ask GTA which set to analyze)

Caution!

Do not allow the turbine to run higher than 35,000 RPM!

Procedure for Experiments

1) Read and record the room temperature and atmospheric pressure (the barometer and thermometer are located in the diagonally opposite corner of the room, ask the GTAs if you are having trouble locating it).
2) Switch on the electrical supply
3) Ensure that the brake band is correctly fitted to the pulleys
4) Ensure that the exhaust casing is in position and locked
5) Ensure that the nozzle valves are all open

6) Close the throttle valve on the front of the operating panel
7) Open the air pressure supply valve located behind the apparatus on the bench top
8) Open the throttle valve and adjust the brake screw until the turbine runs up to 20,000 RPM
9) Shut off the throttle valve
10) Ask the instructor to calibrate the load cell

Caution!
Do not allow the turbine to run higher than 35,000 RPM!

Experiment 1

1) Adjust the throttle valve to the required inlet pressure as indicated in Table 1
2) Unscrew the brake adjusting screw until the turbine runs up to a maximum speed of approximately 30,000 RPM. **Do not allow the turbine to run higher than 35,000 RPM**. If the rotational speed of the turbine rises too much, pulling up on the brake band adjusting screw will rapidly decrease the speed of the turbine.
3) Calculate an interval based on the maximum speed to give 7 readings (including the maximum reading of approximately 30,000 RPM and the minimum reading of zero RPM)
4) Wait for conditions to stabilize
5) Record the force reading and actual speed
6) Adjust the brake screw until the speed has been decreased by the value (interval) found in step 2
7) Repeat process of readings and decreasing until turbine reaches zero RPM
8) Repeat for other inlet pressures as described in Table 1

Experiment 2

1) Adjust throttle valve to the required inlet pressure as indicated on Table 2
2) Follow steps as in Experiment 1, but use Table 2 and additionally record the inlet and outlet temperatures as well as the mass flow rate at each speed.

Nomenclature

C = specific heat

H = specific enthalpy

q = specific heat transfer

p = pressure

s = specific entropy

T = temperature

v = velocity

w = specific work

W = work

η = efficiency

Subscripts

1 = inlet

2 = outlet, ideal

2' = outlet, actual

Isen = isentropic

p = constant pressure

shaft = turbine shaft

turb = turbine

References

1) Daughtry, R. L., Franzini, J. B., and Finnemore, T. J., *Fluid Mechanics with Engineering Applications*, 8th edition, McGraw Hill, New York, 1985.

2) Van Wylen, G. J. and Sonntag, R. E., *Fundamentals of Classical Thermodynamics*, 3rd edition, John Wiley and Sons, New York, 1985.

Table 1, Experiment data sheet 1

Inlet Pressure (kN/m^2)	30	30	30	30	30	30	30
Rotational Speed (RPM)							
Brake Band Strain Reading							
Brake Band Force (N)							

Inlet Pressure (kN/m^2)	25	25	25	25	25	25	25
Rotational Speed (RPM)							
Brake Band Strain Reading							
Brake Band Force (N)							

Inlet Pressure (kN/m^2)	15	15	15	15	15	15	15
Rotational Speed (RPM)							
Brake Band Strain Reading							
Brake Band Force (N)							

Room Temperature

Atmospheric Pressure

Student Names:

Date:

Instructor's Initials

Table 2, Experiment data sheet 2

Inlet Pressure (kN/m^2)	35	35	35	35	35	35	35
Rotational Speed (RPM)							
Brake Band Strain Reading							
Brake Band Force (N)							
Inlet Temperature (Units?)							
Exhaust Temperature (Units?)							
Air Flow (g/s)							

Room Temperature

Atmospheric Pressure

Student Names:

Date:

Instructor's Initials