FAN EFFICIENCY ASSESSMENT & ENERGY CONSERVATION

by

S. K. Gupta
Holtec Consulting Private Limited, New Delhi

INTRODUCTION

Energy conservation is becoming the main thrust area in operating present day cement plants. Fans consume approximately 35% of total energy requirements in a dry process (calciner) cement plant.

Fans are one of the important equipment in the cement manufacturing process. Fans are used right from the crushing stage to the packing of cement, either for venting or for controlling actual process. Use of the fans in a cement manufacturing process can be summarised as below

Area	**Application**
Crushing	For cleaning out the dusty vent air in the bag filters
Grinding	For venting out the dusty gases/air
Pyro-Processing	For handling the exhaust gases, controlling the operational parameters and supplying cooling air
Packing	For cleaning the dusty vent air in the bag filters
Nuisance, Bag Filters	For cleaning the dusty air in the bag filter

It is important to select the most efficient fan for a particular application.

FANS

A fan is a machine for applying power to a gaseous fluid to increase its energy content. This energy enables movement or flow of the gas against various degrees of resistance. Fans, blowers, compressors, all move air but at greatly different pressures. Fan pressures range is from few mmWG to about 3,000 mmWG. The fan is basically designed as a volumetric machine which moves quantities of air or gas from one place to another. In doing so, it overcomes resistance to flow. Physically, a fan has a bladed rotor (also called impeller) and a stationary housing to collect the incoming air or gas and directs its flow. The amount of energy required depends on the volume of gas moved, the resistance against which the fan works and the machine efficiency.

The flow of air or gas is caused by the pressure differential created by the energy transmitted to the gas by the rotating impeller. If no resistance to flow exists, as in the case of a fan in free space with no inlet & outlet duct, the fan provides the gas with velocity energy only and no compression or retraction occurs. When either inlet or outlet duct is added frictional resistance is imposed and partial compression occurs on the outlet side.

The extent of the resistance imposed at the discharge governs the quantity of gas delivered by the fan. The greater volume is delivered under zero resistance or "Free delivery" conditions. As the resistance to flow is increased, the volume is decreased progressively until at infinite resistance the volumetric delivery is zero, corresponding to "blocked tight" or "static no delivery" condition.

There are four types of installation which can be used with fans.

Type A	:	Free inlet, Free outlet
Type B	:	Free inlet, Ducted outlet
Type C	:	Ducted inlet, Free outlet
Type D	:	Ducted inlet, Ducted outlet

When considering fan problems the energies imparted to the air are referred to in terms of potential and kinetic energy.

Potential Energy - The air within the duct system connected to a fan will be at a different pressure than the atmosphere outside the duct and will have a capacity, therefore, for doing work by virtue of that difference in pressure i.e. will have potential energy.

Kinetic Energy – When the air is in motion and it will have energy, therefore, by virtue of that motion, i.e. it will have kinetic energy.

Total Energy - The total energy is the algebraic sum of the potential energy and kinetic energies.

TYPES OF FAN

There are three basic types of fans :

Axial flow fans
Propeller fans
Centrifugal Fans

Axial Flow Fans : These fans comprise of impeller, or impellers with blades of aerofoil cross section rotating in a cylindrical casing. The airflow through the fans is virtually parallel to impeller shaft. The straight through airflow enables the fans to be inserted directly to straight ducting. The prominent factor influencing performance is the design of blades and their aerofoil section.

Propeller Fans : These fans in general are used where there is no duct system or too small ducting length and thus, resistance to flow is low. They are extensively used for general ventilation purpose. These fans have an impeller with two or more blades, usually of sheet steel, set an angle to the hub, the propulsive effect of blades varies according to the slope.

Centrifugal fans : These fans consists of impeller which rotates in a casing having a spirally shaped contour. Air enters the impeller in an axial direction and is discharged at the periphery, impeller rotation being towards casing outlet. The casing has an inlet on axis of wheel and the outlet at right angles to it.

As impeller rotates, the blades at its periphery throw off air centrifugally in a direction following the rotation. The amount of work done on the air is evident in the pressure development of the fans, depends primarily on angle of fans blades w.r.t. direction of rotation at the periphery of impeller. The form of blades influence the force exerted on the air and the proportion of energy imparted in the form of velocity.

The centrifugal fans, depending upon the form of blades are categorised as:

Straight or paddle blade fans
Forward-curve blade fans
Backward-curve blade fans

Straight or paddle blade fans: These fans are simple in construction, as flat straight radial blades are mounted on arms extending radially from central hub. The fan impeller is unshrouded and blades are fitted to the drive hub. Fans are suitable for moderate pressure and have efficiency of low order. They absorb highest power at the point of maximum volume. Fans are self cleaning type as air stream does not cling to the blades and hence suitable for handling dust laden air or gases.

Forward curve blade fans: These fans have curved blades having the concave side facing direction of rotation. The impeller of fans have shrouded blades with annular plates fitted at each end of the blades, giving mechanical strength to the impeller and reducing leakages between blades & casing. These fans are high volume flow fans as they have small radial depth of blades allowing large inlet opening. They develop highest pressure for a given impeller diameter and speed. Fans have higher efficiency than straight radial type of centrifugal fans. The rise of power absorbed towards maximum volume is even more marked as compared to straight radial blade fans. Fans have shallower blades, hence the number of blades is more to have necessary influence on air during its passage through impeller.

Backward curve blade fans: Fans have curved blades having convex side facing the direction of rotation of fans. Fan blades are radially longer than forward curve type and usually heavier, while impellers are strongly reinforced with stiffening rings & large section shafts are required. They operate at higher tip speed than other type of centrifugal fans. Fans have highest efficiency among the centrifugal fans as they have improved air flow through the blades by reducing shock and eddy losses. The air output for a given wheel diameter is less than forward curve blade fans.

The different types of fan impellers are shown in **figure 1.**

SELECTION OF FANS

Fan selection is a procedure that begins with specification of requirements and ends with the evaluation of alternative possibilities. Among number of fan which may be capable of satisfying a particular capacity pressure requirement, best selection is the one that does job most economically.

In majority of the fan applications it is not necessary to design a completely new fan for specific job requirements. The various standard designs are available in each of the various aerodynamic type of fans. Therefore, fan selection is usually a matter of selection of the best size and type from those available.

The fan pressure requirement for each capacity must be specified so that fan develops enough pressure to accelerate air or gases from the velocity at entrance to that at the exit of the system ; to overcome any difference in pressure between entrance & exit and to overcome the friction and shock losses encountered in the system. The sum of the total pressure losses through the system should include an allowance for any elements required to connect the fan to the system.

The general specifications required by the supplier, are given below:

- Type of impeller
- Size of connecting duct and layout
- Site elevation
- Service condition
- Capacity (m^3/hr) at fan inlet - maximum and nominal
- Fan pressure at each capacity - static pressure and total pressure
- Gas analysis and humidity
- Temperature – Operating and maximum (design)
- Type of dust and concentration
- Motor rating and its characteristics
- Preferred arrangement - directly coupled, directly mounted, v-belt drive
- Physical data - number of inlets, type of drive, direction of entry for inlet boxes, rotation discharge, preferred fan speed and motor position

FAN CHARACTERISTICS

Fan characteristics are inherent to the type and design of the individual fan and are common to fans of geometrically similar design. The statement of fan performance have five basic characteristics established under standardised procedures:

- Fan inlet volumetric flow rate
- Pressure differential across fan
- Fan speed
- Fan motor power
- Density of gas

The typical plot of basic characteristic and performance curve of a fan is shown in **figure 2.**

The curve illustrates the basic qualitative form of static pressure and power input curves of a given fan, when operating at fixed speed and gas density, with progressive stages of resistance to gas flow imposed.

The additional secondary characteristics values derived from the basic characteristics, useful in selection and application of fan are:

- Static efficiency
- Total efficiency
- Tip speed
- Outlet velocity
- Total pressure ratio
- Velocity pressure ratio
- Static pressure ratio

FAN LAWS

Three basic fan laws encompass all fan functions principally. Numerous corollaries laws can be formulated for specific conditions but all originates from the three basic laws:

Fan speed variations (at constant fan size, constant system and constant density)

- Volume flow α Fan speed
- Pressure α [Fan speed]^2

- Power α [Fan speed]^3

Fan size variations (for geometrically similar fans, constant system and constant density, constant tip speed)

- Volume flow α [Wheel diameter]^2
- Pressure = Constant
- Power α [Wheel diameter]^2
- Fan speed α [Wheel diameter]$^{-1}$

Gas density variations (constant fan speed, size and constant system)

- Volume flow = Constant
- Pressure α Gas density
- Power α Gas density

Note: Fan laws apply to all fans and are independent of the type and design of the fans.

FANS CAPACITY CONTROL

The control of capacity (volume flow rate) in fans can be obtained using three different methods:

- Damper Control
- Inlet Vane Control
- Speed Control

All of these methods of control of volume flow rate in fans can be applied to centrifugal fans.

Damper control : On fan performance curves volume flow of centrifugal fans at fixed speed & given gas density is determined by cut of system resistance line with the pressure line hence it is apparent that flow control can be done by alteration of the system resistance i.e. damper control. The closing of regulating damper increases resistance of system to the passage of air or gases resulting in the reduced volume flow. The Damper control is essentially a wasteful method (loss of power) of obtaining volume control.

Inlet Vane Control : The volume control of centrifugal fans with inlet vane control require the creation of a rotating air flow at the inlet of fan impeller in the same direction as impeller rotates itself. This rotating air flow reduces the power absorbed by the fan, during volumetric flow control, at the same time as the volumetric flow and pressure characteristics. The air entering centrifugal fan suction usually travel towards the inner edges of the blades in a radial direction. The air is made to rotate within the fan runner in the same direction as the rotation of the fan, thus pressure head which could be set up by fan rotating at the same speed would be reduced.

All method of inlet vane control therefore aims at giving controlled rotary motion within the eye of fan runner, lowering the pressure which the fan can set up for a firm volume. This reduction in pressure is accompanied by the reduction in power consumption so that the control of volume by this method results in a saving of power. In Inlet Vane Control (IVC) units are fitted in the conical section of the inlet bell-mouths, the efficiency obtained at partial loads is little higher than that obtained by using inlet dampers for the same volume flow & pressure characteristics.

Speed Control : The volume control of centrifugal fans is also achieved by varying the speed of fans. This can be accomplished by driving the fan by a variable speed drive, where the motor efficiency remains practically unchanged throughout the speed range.

In slip ring AC motors the speed is controlled by inserting resistance in the rotor circuit. In order that these may run under the lower speed conditions for long periods, the resistance must be continuously rated. The different speeds in steps are available however intermediate duties again have to be obtained by damper control.

Variable speed is also possible by the use of commutator type AC motors but owing to the high initial cost they are not commonly used.

Variable speed is also obtained by use of a variable speed gear like hydraulic coupling. By its use variations in fan speed can be obtained with constant motor speed thus eliminating use of dampers for control purpose.

It is to be noted that with DC drives the motor efficiency remains practically unchanged throughout the speed range, whereas the efficiency of hydraulic coupling and rotor controlled AC motor is a function of the speed and this efficiency is to be taken into account when considering the power input of fan.

COMPARISON OF FLOW CONTROLLING DEVICES

Damper control	• Gives quick response • Not very efficient • Volume flow regulation not very precise
Inlet Vane Control	• More efficient than the damper control • Better volume flow regulation
Speed Control	• Volume flow changes in proportion to speed • Most efficient method • Relatively expensive method

POWER DEMAND

When flow is adjusted, the power consumed by the fan in percentages, without taking into account the losses in motor and speed control equipment is shown in **figure 3.**

TESTING OF FANS

The instruments used in the cement industry for the measurement of different parameters, determination of fan flow and efficiency are listed below:

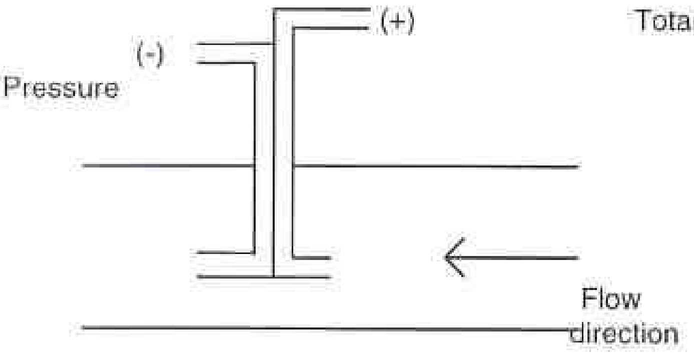
Pressure	:	Barometers Manometers Pitot tube
Temperature	:	Mercury Thermometer or Thermocouples
Density of air or gases	:	Orsat apparatus or Electronic Gas Analysers

Rotational speed	:	Revolution Meter Stroboscope
Power	:	Torsion meter Electrical Instrumentation

The various parameters measured during fans testing are Pressure, Temperature, Density of air or gases, Rotational speed and Power.

Measurement of Pressure : The measurement of pressure at a point is measured on an indication such as manometer connected to measuring point by pitot static tube. The barometers are used to measure the atmospheric pressure in the test enclosure or site pressure. The barometers of direct reading mercury column type are read to the nearest 1mm of mercury. They should be calibrated and corrections applied for regional values of acceleration due to gravity 'g' and temperature. Manometers are for the measurement of the pressure difference and are normally vertical or inclined liquid column type. The pressure transducers with indicating or recording instrumentation are acceptable.

Pitot tube is located in the appropriate measurement plane in an airway with the two limbs connected to manometer or either open to atmosphere. The total pressure, static pressure and velocity pressure recorded in airway by pitot tube is as follows:



Total Pressure = Velocity/Dynamic Pressure + Static

$$Pt = Pd + Ps$$

Manometer connections to :
Pt One Manometer limb to (+)
Ps One Manometer limb to (-)
Pd Manometer limbs to both nozzles

Pitot tubes are categorised based upon their application condition such as flow condition, dust loading, ducting dimension etc. as L type and S type.

Measurement of Temperature: Temperature measurement is taken inside an airway with the sensing element being inserted directly into the air stream.

Mercury thermometer is commonly used for the temperature measurement of materials and for temperature measurement in airways thermocouples along with indicators are preferred.

The dry bulb and wet bulb temperatures in test enclosures should be measured at a point where they can record condition of air entering the test airway. The instruments should be protected against radiation from heated surfaces.The wet bulb thermometer should be located in an air stream. The sleeving should be clean, in good contact with the bulb and kept wetted with the pure water.

Determination of Density: If dry gas analysis is available then by using standard density for individual component gases, based on weighted average method the density of gases is calculated at specified pressure and temperature. The standard value of density of air (which is used when exact gas analysis is not available) are as follows:

	Kg/Nm^3	Kg/m^3 (at 100°C)
Atmospheric gases	1.293	0.95
Kiln exit gases	1.40	1.02
Auxiliary furnace exit gases	1.30	0.95
Water vapours	0.80	0.59

Measurement of Rotational Speed: The fan speed has to be measured at regular intervals throughout the period of test for each test point so as to ensure determination of average speed during each such period. No device used should significantly affect the speed of fan under test or its performance.

- The various examples of acceptable rotational speed measurement methods are :
- Digital counter measuring revolutions for a measured time interval.
- Revolution counter should be free from slip and lined over certain period per operation.
- Direct indicating mechanical or electrical tachometer
- Stroboscope
- Frequency meter

Measurement of Power Input: Power is measured by the electrical inputs measured on a calibrated meter. Power shall be determined from beam load measured on a reaction dynamometer or the torque measured on a torsion element.

Measurement of dimensions and determination of Area: The sufficient dimensional measurements shall be taken across the reference planes of airways to determine cross sectional areas in airways and other well defined regular sections.

For circular or rectangular sections mean dimension and area of the section is taken as being equal to the arithmetic mean of measured values. The alternative method of determining cross section area involves measuring the duct outer perimeter and altering for wall thickness.

Determination of volumetric flow rate: Flow is calculated from the measurement of velocity pressure & density obtained by pitot tube traverse. The local velocity is measured at number of positions across duct and mean velocity is estimated in the duct. Measurement of the cross sectional area of the duct in the traverse plane then allows to calculate flow rate.

The in-line flow meters such as venturi nozzle, orifice plate & conical inlet are primary flow meter used. Venturi nozzle is preferred device because of relatively lower pressure drop and its lower sensitivity to turbulence in the approaching air flow.

FANS TESTING AT SITE

Fans testing at site is being carried out to determine the performance of the fan under actual conditions volume flow rate, power input and total pressure rise across the fan. The disturbance in the testing of fan performance may be due to any of the following :

- Leakages in the system
- Recirculation or other fault in the system
- Inaccurate estimation of flow resistance
- Erroneous application of the standardised test data
- Bends or other system component located too close to the fan inlet
- Errors inherent in site measurement.

General Requirements for Testing

Fan and its associated equipment must be functioning properly.

- Fan must be functioning at the intended speed
- System must be functioning at stable operating conditions
- The test shall be carried out when there is no substantial variation in the system resistance.
- The test shall be carried out in manual operating condition (wherever possible)
- Precautions must be taken to prevent the changes of conditions during the test
- All testing equipment and instruments must be calibrated and information to be recorded
- The description of test set-up and test unit must be recorded.
- The test data and readings must be recorded simultaneously wherever possible.

Location of Flow Measurement Plane : The location for flow measurement plane must be located in any suitable straight length preferably on the inlet side of the fan, where the air flow conditions are substantially axial, symmetrical and free from swirl.

The part of the duct in which the flow measurement plane is located is termed as 'Test Length'. It must have a length equal to not less than twice of the equivalent diameter of the duct.

Test Length at Inlet side of the fan : The test length is on the inlet side of the air, its down stream end must be a distance from the fan inlet equal to at least 0.75 times of the diameter of the duct.

Test Length at outlet side of the fan : The test length is on the outlet side of the fan, the upstream end of the 'test length' must be at a distance from the fan outlet atleast three times of the equivalent diameter of the duct.

Location of Flow Measurement within the test length : The flow measurement plane must be located within the test length at a distance from the down stream end of the test length equal to atleast 0.75 times of the diameter of the duct and at a distance from upstream end at least 1.25 times the equivalent diameter of the duct.

The location of measurement planes for site testing are shown in **figure 4.**

The traverse point at measurement planes for circular and rectangle ducts for site testing are given in **Annexure I.**

FAN EFFICIENCY ASSESSMENT

The step by step approach for fan efficiency assessment can be categorised in following sections :

- Measurement of fan process parameters
- Determination of fan inlet air or gases density
- Measurement of fan inlet dynamic pressure and static pressure
- Measurement of fan inlet velocity
- Determination of fan inlet flow
- Calculations of fan efficiency

Measurement of the fan process parameters involves the measurement of parameters - fan inlet velocity/dynamic pressure, fan inlet static pressure, temperature of air, fan inlet air analysis and moisture, ducting area at fan inlet, fan outlet static pressure, power input to motor and losses, fan speed and inlet damper position.

Determination of fan inlet air or gases density involves analysis (dry or wet basis) of air by Orsat apparatus or gas analysers. The components analysed are Carbon dioxide, Oxygen, Nitrogen, Carbon monoxide and moisture. The density of dry gases at pressure 10,333 mmWG and temperature $0^{\circ}C$ is calculated from the volumetric percentage of its components given by the following formula:

Density of dry gases D_{or} $= 0.01 \times (1.965 \times CO_2 + 1.429 \times O_2 + 1.250 \times CO + 1.251 \times N_2)$

The density of wet air or gases D_o depends on the amount of water vapour W_o (Kg water vapour / Kg dry gases) it contains.

$D_o = (1 + W_o) / (1/D_{or} + W_o / 0.80)$ In Kg/Nm^3

If the volumetric gas analysis is not available then the standard value of density as mentioned earlier are considered.

The density of the air or gases D_T at temperature T $^{\circ}C$ and pressure P mmWG is calculated as follows :

$D_t = D_o \times (273 / (273+T)) \times ((Ps + B) / 10333)$ in Kg/m^3

where B is the barometric pressure and Ps is the static pressure of the air.

Depending on pitot tube traversing, number of readings for velocity/dynamic pressure and static pressure are recorded at fan inlet. The root mean square average of all the readings of dynamic pressure is considered for the calculation purpose in order to minimise the variation in readings during pitot tube traversing.

Further Fan inlet velocity V is determined by root mean square average velocity/dynamic pressure, density of air/gases and the pitot tube constant as:

$V = \text{pitot constant} \times ((2 \times 9.81 \times \text{Average dynamic pressure}) / D_T)^{1/2}$ m/sec

Fan inlet volumetric flow rate Q is determined by multiplying the fan inlet velocity with the cross sectional area of the ducting at the flow measurement point.

Fan efficiency N_T is the ratio of the Air power P_A and the shaft power P thus :

N_T = P_A / P Where,

Air power P_A = $2.725 \times 10^{-3} \times Q \times$ Fan total pressure $\times K_p$

Shaft power P = Input power to motor - Losses in motor

Fan total pressure = Static pressure at fan outlet - Static pressure at fan inlet

K_p = Compressibility coefficient = $((R^{(Y-1)/Y} - 1) \times Y) / ((R - 1) \times (Y - 1))$

$Y = C_p / C_v$ and $R = B / (B + P)$

Motor input power = 1.732 x Voltage x Current x power factor

Motor losses are = Fixed losses + Copper losses + Stray load losses etc.

ENERGY SAVING POTENTIAL IN CEMENT INDUSTRY

An energy saving potential estimation in Indian cement industry was carried out based upon the questionnaire survey and fan efficiency measurement study conducted at two specified cement plants:

- The data received from the 33 cement plants through questionnaire survey was analysed to estimate energy saving potentials for different fans which works out to be 5.13 KWH/tonne of clinker.
- Based on the fan efficiency measurements energy saving potentials in 2 identified cement plants was estimated to be 2.68 KWH/tonne of clinker.

It can thus be concluded that there is huge potential of reducing cost of cement manufacturing by improving the performance of the process fans. Requirements for such improvement can be established by conducting a detailed analysis of the fan performance under actual running conditions.

CIRCULAR SECTIONS

For circular sections measurement shall be made along at least three diameters symmetrically disposed unless restricted access makes this impossible in which case two diameter at 90° may be used. The position of the points using the log linear rule are given below for 6, 8 and 10 points per diameter :

Number of measuring positions	Distance of measuring position from inside wall of airway	Minimum ratio of duct diameter to	
		Anemometer diameter	Pitot tube diameter
6 per diameter	0.032D, 0.135D, 0.321D, 0.679D, 0.865D, 0.968D	24	32
8 per diameter	0.021D, 0.117D, 0.184D, 0.345D, 0.655D, 0.816D, 0.883D, 0.979D	36	48
10 per diameter	0.019D, 0.077D, 0.153D, 0.217D, 0.361D, 0.639D, 0.783D, 0.847D, 0.923D, 0.981D	40	54

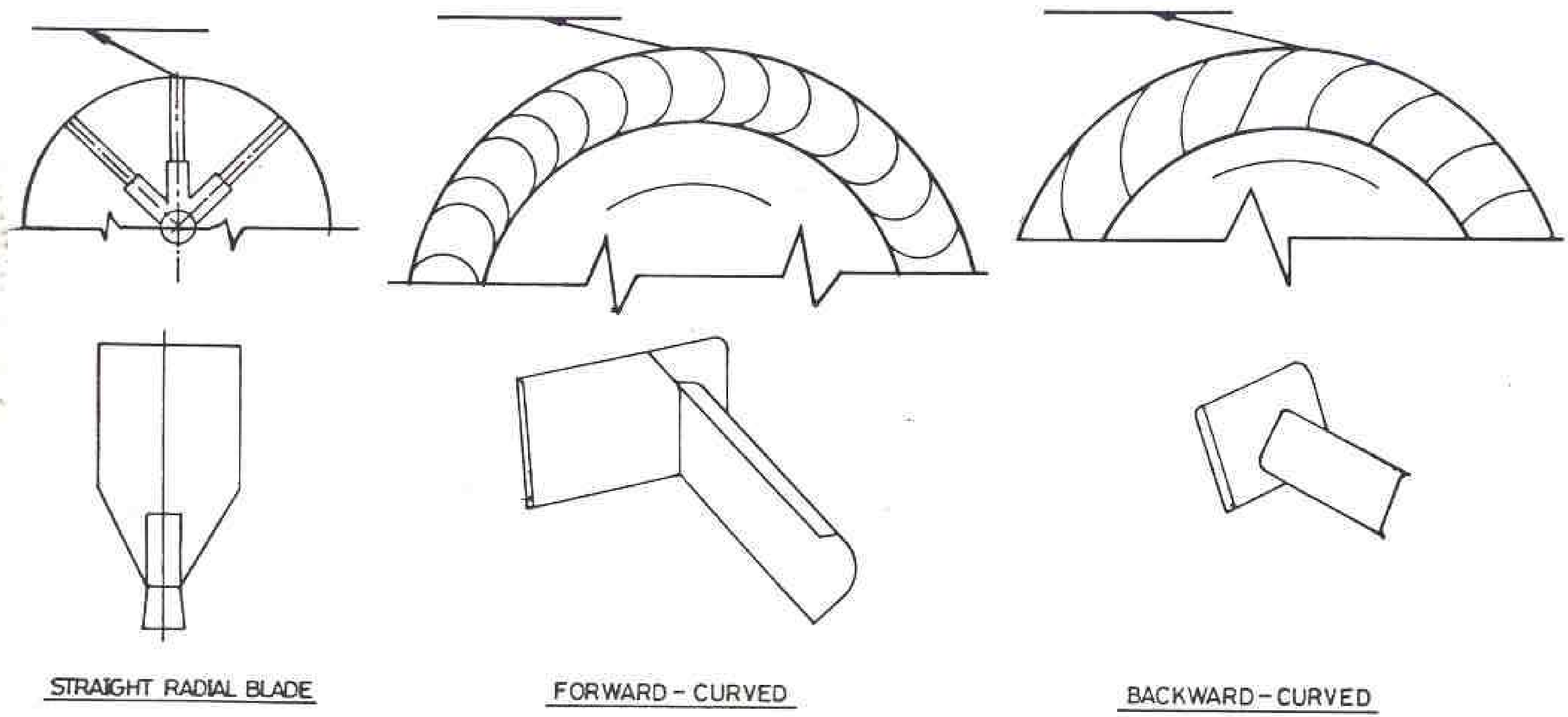
D is the inside dimension of the duct along the line on which the traverse is made

RECTANGULAR SECTION

A number of straight traverse lines are selected parallel to the smaller side of the rectangle and on each of them number of measuring points are located. There shall be a minimum of five traverse lines and five measuring points per traverse line. The following table specifies the positions of the measuring points for 5, 6, and 7 traverse line or measuring points per traverse line.

Number of measuring positions	Proportional Distance of measuring position from inside wall of airway	Minimum ratio of short side to:	
		Anemometer diameter	Pitot tube diameter
5	0.074, 0.228, 0.500, 0.712, 0.926	10	25
6	0.061, 0.235, 0.437, 0.563, 0.765, 0.939	12	25
7	0.053, 0.203, 0.366, 0.500, 0.634, 0.797, 0.947	14	25

FIGURE-1



DIFFERENT TYPES OF FAN IMPELLERS

Figure - 2

TYPICAL FAN CHARACTERISTIC CURVE

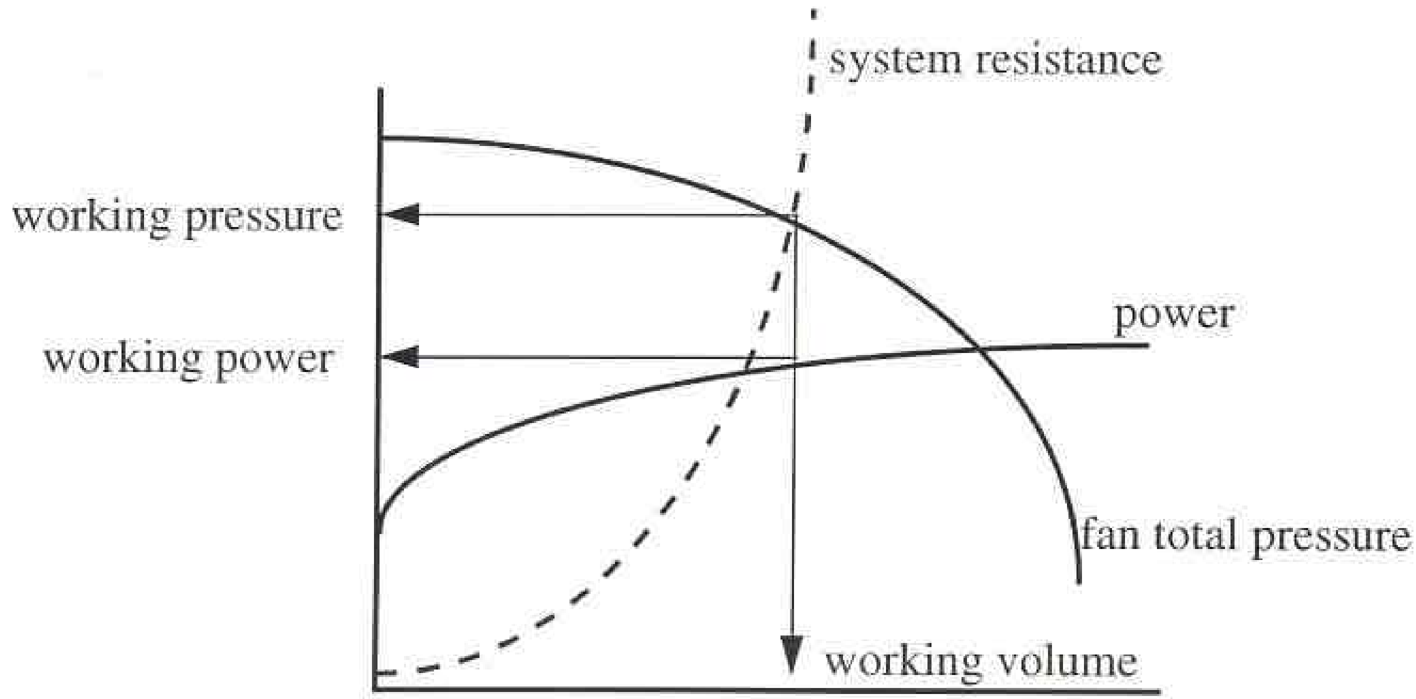
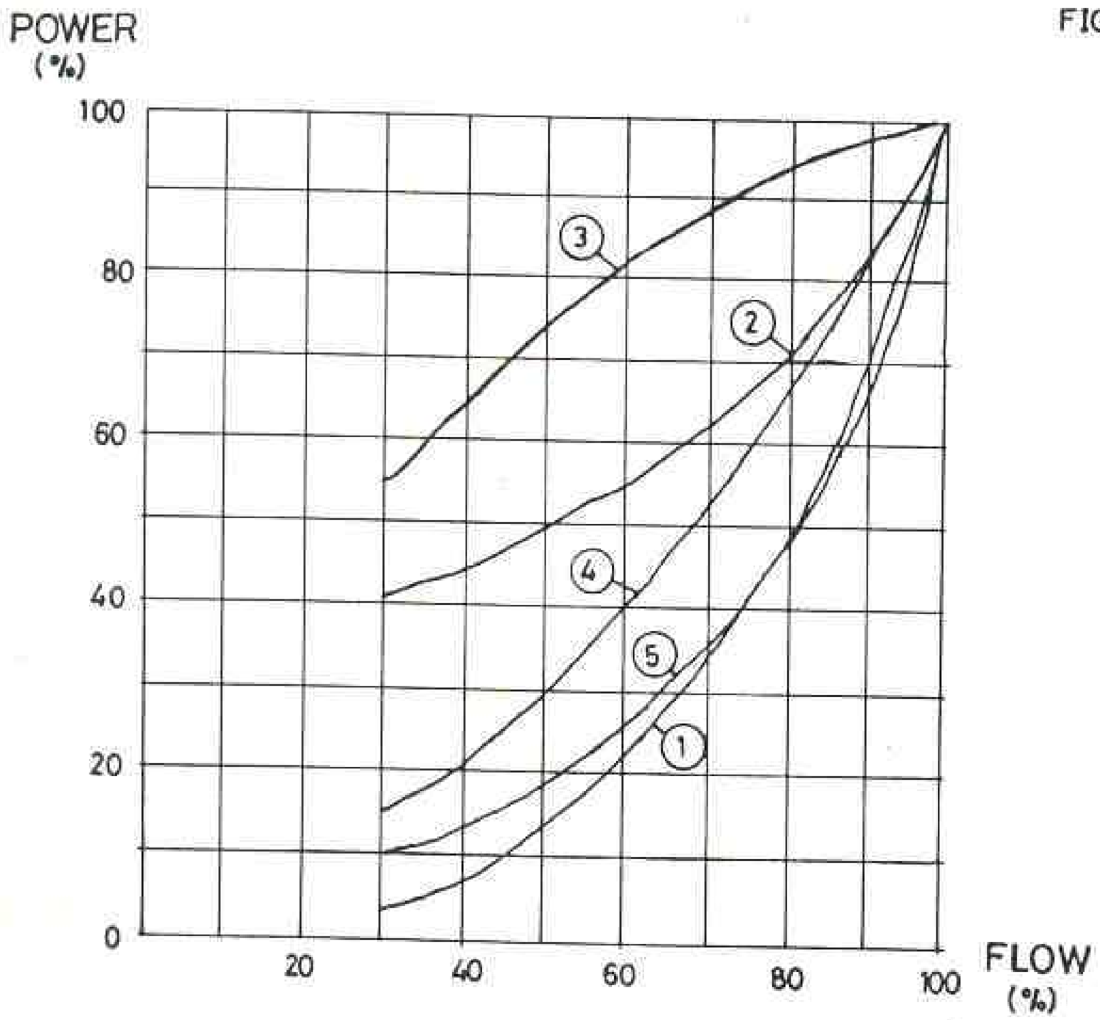


FIGURE-3



COMPARISON OF POWER REQUIREMENT WITH DIFFERENT FLOW CONTROL METHODS

1 SPEED CONTROLLED ELECTRICAL DRIVE SYSTEM
2 GUIDE VANE ADJUSTMENT
3 DAMPER ADJUSTMENT
4 HYDRAULIC/EDDY CURRENT COUPLING OR LRC
5 FAN BLADE PITCH ADJUSTMENT

Figure -4

LOCATION OF MEASUREMENT PLANES FOR SITE TESTING