Techniques for airflow rate measurements

Environment, Air

My company is setting up an experiment to measure the airflow rate in a duct. Airflow measurement techniques are necessary especially in many industries. Some of the common airflow measuring applications include ventilation testing, air balancing, ductwork, air planes and so on. Many research and studies have been put into improving and inventing new equipments to measure air flow. This is so to enable user to get the most accurate result and at the same time using the least cost.

This report outlines the different airflow measurement techniques and devices that are available today. There are many different types and ways to measure air flow but I will concentrate on those that are more popular and commonly used. They are the Pitot-tube, Orifice plate, Venturi meter, Cup anemometer, Sphere anemometer and Hot-Wire anemometer.

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Techniques and devices for airflow rate measurements

2. 1 Pitot tube

A pitot-static tube is used in wind tunnel experiments and on airplanes to measure the air flow rate. It is also used in many industrial applications. It was invented by the French engineer Henri Pitot in the early 1700s and was later modified to its modern form in the mid 1800s by French scientist Henry Darcy. It is a slender tube that has two holes on it (Figure 1). The front hole is placed in the airstream to measure what’s called the stagnation pressure. The side hole measures the static pressure. By measuring the difference between these pressures, we are able to get the dynamic pressure that can be used to calculate the air velocity.

By Bernoulli's principle,

Stagnation pressure = static pressure + dynamic pressure

Solving that for velocity we get:

Where V: fluid velocity; pt: stagnation or total pressure; ps: static pressure; Ï🚹 : fluid density

Figure 1: Pitot-Static Tube

The incorporation of sensors to measure the air temperature, barometric pressure, and relative humidity can further increase the accuracy of the velocity and flow measurements. The Pitot tube can also measure the velocity with the use of a pressure transducer that generates an electrical signal which is proportional to the difference between the pressures generated by the total pressure and the static pressure. The volumetric flow is then calculated by measuring the average velocity of an air stream passing through a passage of a known diameter. When measuring volumetric flow, the ' passage of a known diameter' must be designed to reduce air turbulence as the air mass flows over the Pitot tube.

To obtain an estimate of the volumetric flow in the duct from a series of pitot-static tube velocity

measurements, one must integrate the velocity over the duct area.

There are many of different methods for approximating the above integral. One of the methods is to divide the duct cross-section into a number of equal area sectors, and then measure the

“ average” velocity at the center of each sectors.

For example, we can divide the cross-section of the duct in the figure below:

The velocity will be by calculating

the sum:

2. 1. 1 Advantages and Disadvantages

The advantages of using pitot-static tube is that it can be inserted in small airstream and it presents little resistance to flow. It is simple, inexpensive and suited for a variety of environmental conditions including extremely high temperatures and a wide range of pressures.

The disadvantages would be that if the flow rate is low, the difference in pressures will be too small to accurately measure with the transducer. If the air flow is high (supersonic), assumptions of Bernoulli’s equation will be violated and thus leading us to wrong measurement. Furthermore, if the tubes are clogged, the reading by the transducer will be inaccurate resulting in dire consequence in the context on airplane. Icing of the pitot tube had caused plane to crash.

2. 2 Orifice Plate

Orifice plate is used for flow rate measuring in pipe systems. An orifice plate is placed in a pipe containing a fluid flow, which constricts the smooth flow of the fluid inside the pipe. By restricting the flow, the orifice meter causes a pressure drop across the plate. By measuring the difference between the two pressures across the plate, the orifice meter determines the flow rate through the pipe.

Figure 2: Orifice Plate in a duct

Applying Bernoulli’s equation to a streamline flowing down the axis of the tube gives,

Where,

P: pressure

Ï : density of the fluid

V: Velocity of the fluid

As shown in the above diagram(Figure 2), point 1 is upstream of the orifice, and point 2 is behind the orifice. It is recommended that point 1 be positioned one pipe diameter upstream of the orifice, and point 2 be positioned one-half pipe diameter downstream of the orifice. Since the pressure at 1 will be higher than the pressure at point 2, the pressure difference will be a positive quantity.

From continuity equation, the velocities can be replaced by cross-sectional areas of the flow and the volumetric flow rate Q,

Where,

A: cross sectional area

Solving for the volumetric flow rate Q gives,

The above equation remains true with perfectly laminar, inviscid flows. As for real flows like water or air, we have to take into account of the viscosity and turbulence that are present . To account for this effect, a discharge coefficient Cd is introduced into the above equation to marginally reduce the flow rate Q,

Since the actual flow profile at point 2 downstream of the orifice is quite complicated, the following substitution introducing a flow coefficient Cf is made,

Where,

Ao: area of the orifice

As a result, the volumetric flow rate Q for real flows is given by the equation,

The flow coefficient Cf is found from experiments and is tabulated in reference books. It ranges from 0. 6 to 0. 9 for most orifices. Since it depends on the orifice and pipe diameters (as well as the Reynolds Number), one will often find Cf tabulated versus the ratio of orifice diameter to inlet diameter, sometimes defined as b,

The mass flow rate can be found by multiplying Q with the fluid density,

There are mainly 3 different types of orifice plates. They are Concentric, Segmental and Eccentric. This is to accommodate for different applications so that the meter has the optimum structure. The density and viscosity of the fluid, and the shape and width of the pipe do influence the choice of plate shape to be used.

The concentric orifice is the most common of the 3 types. In this design, the orifice is equidistant. It is generally used for clean liquid and gas flow in pipes under six inches, where Reynolds numbers range from 20, 000 to 107. We will therefore use concentric orifice for our experiment purposes. (which deals with air).

Segmental orifice is similar to concentric orifice with regard to its functioning. The circular section is concentric with the pipe while the segmental part is mounted in a horizontal pipe. This installation helps to eliminate of foreign materials on the upstream side of the orifice.

Eccentric orifice plates are designed in such a way that the edge of the orifice is reallocated towards the interior of the pipe wall. It is used in similar manner as the segmental orifice plate.

Figure 3 below shows the different types of orifice plates:

2. 2. 1 Advantages and Disadvantages

With no moving parts and a simple design, the orifice is easily machined. It is low lost and can be easily inserted into a duct or an existing pipeline with a minimum alteration to the layout. Therefore orifice plate has been a popular device for flow measurement.

The disadvantage is that it creates a rather large non-recoverable pressure due to the turbulence around the plate, leading to high energy consumption (Foust, 1981).

2. 3 Venturi meter

Most of the unrecoverable loss of pressure with an orifice is due to the sudden change in the cross sectional area. The sudden increase of area after the air passes the section of minimum area: the rapid convergence of the stream on the upstream side contributes considerably to the total loss. We are able to recover most of the pressure by leading the stream with the use of a conical length of pipe, with its smaller end of the same cross section as the jet, and gradually expanding in size along the direction of flow until the full pipe diameter is reached. An arrangement of this kind, with a conical entry is known as a venturi tube.

The Venturi effect is named after Giovanni Battista Venturi (1746-1822), an Italian physicist.

A venturi meter consists of a cylindrical length, a converging length with an included angle of 20o or more, and short parallel throat, and a diverging section with an included angle of about 6o. The internal finishes and proportions are designed in such a way to enable us to achieve the most accurate readings while ensuring minimum head losses.

Assuming that the fluid is inviscid with no losses due to viscosity, the velocity at section 1 and 2 are V 1 and V 2 respectively. The velocities are steady and uniform over areas A 1 and A 2

Applying Bernoulli’s equation to a streamline passing along the axis between the two sections (1 & 2).

Where,

V: Velocity of the fluid

P: Pressure

Ï🚹 : density of the fluid

Z: Height

Using continuity equation,

Q = A1 V 1 = A 2 V 2

When real world effects such as fluid friction and turbulence are included a correction factor, called the coefficient of discharge, Cd is introduced into the venturi equation giving

For low viscosity fluids C d = 0, 98.

2. 3. 1 Advantages and Disadvantages

The venturi tube introduces substantially lower non-recoverable pressure drops (Foust, 1981). Therefore venture tube can be used on more viscous fluid.

However it has limited range ability. It must be used only on installations where the flow rate is well known and varies less than 3 to 1. It is rather expensive and should be flow calibrated to provide accuracy into the range of +/- 1. 00%, Units are big and weigh more than comparable head devices and thus making it difficult to install and inspect.

2. 4 Anemometer

An anemometer, also known as wind vane is a device for measuring the air flow rate in a contained flow such as duct or unconfined flow. The term is derived from the Greek word anemos, meaning wind. In around 1450, the Italian art architect Leon Battista Alberti invented the first mechanical anemometer which consisted of a disk placed perpendicular to the wind. To determine the velocity, an anemometer detects change in some physical property of the fluid or the effect of the fluid on a mechanical device inserted into the flow. They are probably best used mounted on light, preferably streamlined, supports and inserted into the airstream from one side.

2. 4. 1 Cup anemometer

This device consists of three or four hemispherical cups mounted at the ends of horizontal spokes which rotates about a low-friction vertical shaft. An electrical device is used to record the revolutions of the cups and measures the air flow rate. (Figure below)

As the anemometer is placed inside the flow stream, the concave surfaces of the cups have higher wind resistance than their convex counterparts and thus producing an unbalanced moment with respect to the center axis. This forces the cups to rotate (see schematic). Under steady flow condition, the rotational speed of the anemometer is directly related to the wind speed, that is: V= rw.

There are number of fundamental physical parameters and characteristics of an anemometer that affects the cup anemometer performance. They are:

rotor arm length

cup area

rotor inertia

drag coefficient on convex face of cup

drag coefficient on concave face of cup

static, dynamic and parabolic mechanical friction coefficients for temperature range

sensitivity characteristic to out-of-plane attack

linearised calibration curve.

A “ well designed” cup anemometer should have the following characteristics as shown in the Figure 4 below:

Let us examine a cup anemometer rotating at speed w in a free wind speed U:

The instantaneous aerodynamic torque on the rotor, MA, is given by:

where A: frontal area of the anemometer

r: the air density

Cdv : drag coefficients for the concave faces of cup

Cdx drag coefficients for the convex faces of cup

In the steady state, there is perfect torque balance (MA= 0), and the equation reduces to:

defining l and µ as the speed and drag ratios respectively:

allows further re-expression in a quadratic form:

Typical values of Cdv and Cdx are 1. 4 and 0. 4 respectively, giving a value of µ of 3. 5. The above

equation predicts that the consequential speed ratio l will be 0. 303, meaning the rotor will rotate at about one third of the wind speed. Note that this solution also proves the theoretically linear sensitivity of the cup anemometer to wind speed. It also shows that the speed ratio is dependent on the drag characteristics of the cup and not the size. Furthermore, the rotational speed is inversely proportional to rotor radius.

2. 4. 2 Advantages and disadvantages

The advantages of the cups are their reliability and ruggedness. The disadvantages are the relatively high threshold velocity (the minimum wind velocity needed to start the cups to turn). It is mainly used to only measure the horizontal component of the wind.

Another problem with cup anemometry is the different response time for increasing and decreasing wind velocities due to its moment of inertia. This results in an overestimation of wind speed under turbulent wind conditions as present in nature, the so-called over-speeding. Additionally, the rotation of the anemometer causes a wear of bearing and leads to a recalibrations with time.

2. 5 Sphere anemometer

Many research and studies have gone into the improving of such a device (Cup anemometer). For example, the sphere anemometer. It was developed at the University of Oldenburg.

This sphere anemometer, as shown in figure 4 below, is able to measure the air flow rate as well as simultaneous detection of the air flow direction. It eliminates the problem of wear of bearing as encountered in cup anemometer.

Figure 5:

The sphere anemometer uses the relationship between the point force F acting on the tip of a

rod and its resulting deflection s.

(1)

Where

l: the length of the rod

E: the elasticity modulus

Ja: the second moment of area.

In case of the sphere anemometer, with a sphere radius r much bigger than the radius of the rod rR, the force can be assumed to act only on the tip. The second moment of area is then given by

(2)

Together with the force acting on the sphere

(3)

where cd: the drag coefficient of the sphere

A: the cross section of the sphere

Î¡: the density of air

V: the wind velocity

Equation 1 becomes

(4)

Therefore the deflection of the rod is proportional to the drag coefficient cd and the wind velocity squared. For a calibration it is necessary to know how the drag coefficient cd changes with wind velocities. Table 1 below shows the drag coefficient of a sphere plotted against the Reynolds number (Re) (cf [1]). It can be seen that for Reynolds numbers in the range from about 800 to 200000 the change in drag coefficient cd is negligible.

For a sphere with a radius r = 40mm this range in Re corresponds to a range in wind velocities

from 0. 17m/s to 38m/s using

where v = 1. 51 x 10-5 m2/s is the kinematic viscosity of air. Within this velocity range the

deflection s of the rod is directly proportional to the wind velocity squared. With this direct

relation it is easy to calibrate the sphere anemometer over a wide range of wind velocities.

Table 1:

2. 6 Hot wire anemometer

Thermal anemometry is the most common method used to measure instantaneous fluid velocity. The technique depends on the convective heat loss to the surrounding fluid from an electrically heated sensing element or probe. If only the fluid velocity varies, then the heat loss can be interpreted as a measure of that variable.

Working Principle

It’s principle application is the measurement of rapid fluctuations, particularly the study of turbulent flow; in this field it is the only instrument with sufficiently rapid response, and the associated electronic equipment lends itself readily to signal processing needed to record directly such properties of a turbulence as r. m. s values, correlation functions, and spectral distributions.

Governing equation

Consider a thin heated wire mounted to supports and exposed to a velocity U

Where,

W: power generated by Joule heating (W= I2Rw)

Q: heat transferred to surrounding

Qi: CwTw= thermal energy stored in wire

Cw: heat capacity of wire

Tw: wire temperature

The wire is heated electrically and placed in the flow stream. The energy balance of the heated wire at equilibrium is (equation 1):

Where,

I: an electric current

Rw: the wire resistance

h: the heat transfer coefficient

A: the heat transfer area

Tw: the wire temperature

Tf: the fluid temperature

D: wire diameter

Kf: heat conductivity of fluid

Nu: dimensionless heat transfer

In the forced convection regime (0. 02 Reynolds number: Re= (where r is the air density and U is the velocity and μ is the air dynamic viscosity).(equation 2)

Where

Substituted Eq(2) into Eq(1),

There are two types of hot-wire anemometer used in practice but I will touch on Constant Temperature Anemometer which is more commonly used.

For a case of Constant Temperature Anemometer

Where

And

The voltage is a measured of velocity U.

2. 6. 1 Advantages and disadvantages

It has good frequency response as it can measure up to several hundred kHz possible. It is able to measure a wide range of velocity. It is small in size and has rapid response.-

Thermal anemometry enjoys its popularity because the technique involves the use of very small probes that offer very high spatial resolution. The basic principles of the technique are relatively straightforward and the probes are difficult to damage if reasonable care is taken.

However, deposition of impurities in flow on sensor can alter the calibration characteristics and reduce frequency response. Probe may or burnt out easily if not carefully taken care of. It is unable to fully map velocity fields that depend on space coordinates and simultaneously on time. Furthermore, it cannot work well in hostile environment like combustion. The wire diameter needs to be very small – of the order of 0. 02mm or less.

Conclusion

In this report, I have touched on the different techniques and different devices for the measurement of airflow. There are many different devices in the market but many use similar techniques with abit of new inventions or add ons here and there. Different airflow measuring devices utilize different technologies and thus, one needs to fully understand the characteristics, techniques and its pros and cons before selecting the optimal one for use.

In summary, an ideal device to measure air flow rate should have the following characteristics

good signal sensitivity. It should be able to detect output for small changes in velocity.

High Frequency Response: to accurately follow transients without any time lag

Wide velocity range

Create minimal flow disturbance

Good Spatial Resolution

Inexpensive

High Accuracy

User friendly