FLOW MEASUREMENT TECHNIQUES

Presented by Mr. Anupam Sengupta.
Department of Mechanical Engineering.
Indian Institute of Technology, Bombay.
OVERVIEW:

• Basic/Fundamental Flow Measurement Techniques.
• Modern Flow Measurement Techniques and their capabilities.
• Need for Flow Measurement Techniques.
• Discussion on the following techniques :
  – Hot Wire Anemometry.
  – Laser Doppler Technique.
  – Particle Image Velocimetry.
  – Lorentz Force Velocimetry.
• Advantages and/or limitations if the aforementioned techniques.
• Measurement Techniques in Two Phase Flows.
• Measurement Techniques for Non Newtonian Fluids.
• Scope for future development.
FLOW MEASUREMENT TECHNIQUES

Integral Properties of Flows (Mass, Volume etc.)

a) Coriolis Technique.
b) Rotameter.
c) Orifice Meter.
d) Flow Nozzle.

Local Flow Parameters (Local Velocity etc.)

a) Hot Wire Anemometer.
b) Laser Doppler Anemometer.
c) Particle Image Velocimetry.
d) Ultrasonic Technique.
e) Magnetic Technique.
Integral Flow Property Measurement Techniques
Coriolis Flow Meters:
- Also known as Inertial Flow Meter / Mass Flow Meter.
- It measures the mass of fluid flowing and not the volume.
- Based on the principle of Vibrations: superposition of tube vibrations in flow and no-flow situations.

Rotameters:
- Variable Area Flowmeter.
- Based on Balance of Forces.
- It measures the Volume of the fluid flowing.

Orifice Meters:
- Differential Pressure Flowmeter.
- The pressure difference before and after the orifice plate is used to calculate the flow velocity.
- Based on Bernoulli’s Principle.
Local Flow Parameter Measurement Techniques:

- HOT WIRE ANEMOMETRY.
- LASER DOPPLER ANEMOMETRY.
- PHASE DOPPLER ANEMOMETRY.
- PARTICLE IMAGE ANEMOMETRY.
- MAGNETIC FLOW METERS.
- ULTRASONIC FLOW METERS.

The capabilities of the above techniques are characterised by one or more of the following:

- Measurement of flow parameters very close to any end wall.
- High Frequency Response.
- High Spatial Resolution.
- High reliability.
WHY EXPERIMENTAL STUDIES IF WE HAVE COMPUTERS?

- The physics behind any process can be understood only through first hand experience.
- Computers alone are lame: They simulate situations only based on the input parameters.
- Input parameters are decided only if we have understood the physics of the process inside out.
- Experimentation is a more lucid means of disseminating facts and knowledge. It helps in proper visualisation and thus better comprehension.
HOT WIRE ANEMOMETRY

- Most well known Thermal Anemometer
- Measures a fluid velocity by measuring the velocity dependent heat convected away by the fluid.
- Core of anemometer is an exposed hot wire. Heat lost to fluid convection is a function of the fluid velocity.
**HOT WIRE**

### CONSTANT CURRENT
- Wheatstone bridge is fed by constant electric current.
- The series resistivity of the energy source has is set large w.r.t. to the total resistivity of the bridge, in order to keep current constant at all times.
- Temperature and resistivity change of the hot wire induces an unbalance of the tension at the vertical bridge diagonal, which is manifested as flow velocity.

\[ I = \text{const.} \quad : \quad R = R(U) \]

### CONSTANT TEMPERATURE
- Maintaining constant resistance \( R \) of the probe implies that temperature is also kept constant.
- The output voltage provides measure of the heat transfer from the probe.
- This heat transfer is a measure of the fluid parameter under consideration at that time.
Physics Involved

• The Electrical Power Input is equal to the power lost to Convective Heat Transfer

\[ I^2 R_w = h \cdot A_w \left( T_w - T_f \right) \]

where \( I \) is the input current, \( R_w \) is the resistance of the wire, \( T_w \) and \( T_f \) are the temperatures of the wire and fluid respectively, \( A_w \) is the projected wire surface area, and \( h \) is the heat transfer coefficient of the wire.

• The wire resistance \( R_w \) is also a function of temperature according to :

\[ R_w = R_{Ref} \left[ \frac{1}{1 + \alpha \left( T_w - T_{Ref} \right)} \right] \]

where \( \alpha \) is the thermal coefficient of resistance and \( R_{Ref} \) is the resistance at the reference temperature \( T_{Ref} \).

• The heat transfer coefficient \( h \) is a function of fluid velocity \( v_f \) according to King's law :

\[ h = a + b \cdot v_f^c \]

where \( a, b, \) and \( c \) are coefficients obtained from calibration .

• Combining the above three equations allows us to eliminate the heat transfer coefficient \( h \),

\[ v_f = \left[ \frac{I^2 R_{Ref} \left[ 1 + \alpha \left( T_w - T_{Ref} \right) \right]}{A_w \left( T_w - T_f \right)} - a \right] / b \]

\[ \left. \right]^{1/c} \]
• For a hot-wire anemometer powered by an adjustable current to maintain a constant temperature, $Tw$ and $Rw$ are constants. The fluid velocity is a function of input current and flow temperature:

$$a + b \cdot v_f^2 = \frac{I^2R_w}{A_w(T_w - T_f)}$$

$$= f(I, T_f)$$

Since the temperature of the flow $T_f$ can be measured, fluid velocity is reduced to a function of input current only.

• For a hot-wire anemometer powered by a constant current $I$, the velocity of flow is a function of the temperatures of the wire and the fluid:

$$a + b \cdot v_f^2 = \frac{I^2R_{Ref}[1 + \alpha(T_w - T_{Ref})]}{A_w(T_w - T_f)}$$

$$= g(T_w, T_f)$$

If the flow temperature is measured independently, the fluid velocity can be reduced to a function of wire temperature $Tw$ alone. In turn, the wire temperature is related to the measured wire resistance $Rw$. Therefore, the fluid velocity can be related to the wire resistance.
Advantages and Limitations

- The constant-temperature anemometers are more widely used than constant-current anemometers due to their reduced sensitivity to flow variations.
- High frequency response, > 10 kHz (up to 400 kHz).
- Small size of the probe reduces the probe blockage in comparison to similar measuring.
- Its primary disadvantage is fragility and can be used only in clean gas flows.
- Needs to be recalibrated frequently due to dust accumulation.
- Most of the present-day hot-wire anemometers have a limitation at high frequencies: namely that the tail of the power spectrum of the anemometer output signal has a spurious rise with frequency. This rise, which is proportional to the square of frequency, is of great concern when one deals with small-scale measurements in high-Reynolds-number flows.
Most flow measuring instruments measure physical quantities which are functions of the flow velocity.

Direct measuring of the local flow velocity often does not take place.

Measuring quantities by which flow velocity is determined, often are functions of the properties of state of the fluid medium, which have to be known.

They have to be taken into account in the calibration of the measuring method.

During the measurements, fluctuations of the state parameters of the fluid medium occur, which have to be known in order to determine unequivocal velocity values with hot-wire anemometers.

Afore-mentioned difficulties led to development of LDV.
Laser Doppler Velocimeter (LDV) is a technique for measuring the direction and speed of fluids “directly”. In its simplest form, LDV crosses two beams of collimated, monochromatic laser light in the flow of the fluid being measured. Typically, a Helium-Neon (HeNe) or Argon ion laser with a power of 10 mW to 20 W is used.

Thus the fluid is the target and the reflected radiation is collected.

Change in wavelength of the reflected radiation is a function of the targeted object’s relative velocity (Doppler effect).

Velocity of the object is obtained by measuring the change in wavelength of the reflected laser light, done by forming an interference fringe pattern (i.e. superimpose the original and reflected signals).
INTERFERENCE

• LDVs use two equal-intensity laser beams (split from a single beam) that intersect across the target area at a known angle $\theta$.

• If laser light has a wavelength $\lambda$, we find the spacing $\delta$ of the interference fringes where the combined laser light intensity is zero.

• When the targeted area is within a flowfield, entrained particles passing through the fringes produce a burst of reflected light whose flicker frequency depends on fringe spacing and particle velocity normal to fringes:

$$\nu_h = f_D \cdot \delta = \frac{f_D \cdot \lambda}{2 \sin \left(\frac{\theta}{2}\right)}$$

• Note that there are no negative terms in the above formula. Thus direction of the particle motion cannot be determined by this formula. Furthermore, the measured velocity of the particle is the velocity component normal to the fringe pattern, not the actual velocity.
Two Phase Flows:

- Two-phase turbulent flow are of considerable engineering importance in a wide range of applications such as rocket motors, ramjet combustion, jet cutting and in jet blast nozzles.
- Improving the performance of two-phase flow devices requires a knowledge of the instantaneous velocities of gaseous and solid phases.
- Velocity measurements in two-phase flow fields are complicated by particle-probe interactions and blockage of transmitted and scattered light by the dispersed phase.

Clinical Measurements:

- Multi dimensional use in medicine.
- Most widely used in flow of blood in the vascular system, Microcirculatory blood flow in tissue transplants and changes in blood flow under administration of various medicines etc.
Advantages and Limitations

- Non Contact Flow Measurement Technique.
- Direct way of measuring local velocity in all three spatial coordinates.
- Very high frequency response.
- Ideal for real time flow measurement.
- Sufficient transparency is required between the laser source, the target surface, and the photodetector (receiver).
- Accuracy is highly dependent on alignment of emitted and reflected beams.
- For some applications, for e.g. investigations in extended flow fields, the indicated errors can is significant, appropriate steps have to be taken to ensure an optimal beam intersection point.
- Expensive; (fortunately) prices have dropped as commercial lasers have matured.
Lorentz Force Velocimetry

- Used for Electrically Conducting Fluids.
- Based on exposing the fluid to magnetic field and measuring the drag force acting upon the magnetic field lines crossing the melt flow.
- Measurements can be done in two ways:
  a. The force is determined through the angular velocity of a rotary magnet system
  b. The force on a fixed magnet system is measured directly.
- The measured signal is a linear function of the flow velocity for both the cases.
- The velocity is measured by formulating a “Scaling Law”. It relates force on a localized distribution of magnetized material to the velocity of an electrically conducting fluid.
LFV BASICS
• Non Contact Technique.
• Suitable for high temperature applications.
• A number of additional parameters can be evaluated.
• Has very relevant utilities in the high end practical experimentations.
• Has a number of industrial applications: Metallurgy, semiconductor crystal growth, Glass manufacturing etc.
PARTICLE IMAGE VELOCIMETRY

- Non-intrusive, full field optical measuring technique for fluid motion velocity.
- The fluid of interest is seeded with tracer particles illuminated by a sheet of bright light.
- The positions of these particles at different times are recorded on a camera.
- Then, by measuring the particle displacements, the motion of the fluid can be ascertained.
- PIV is used to obtain and has been applied to a diverse range of flows including water dynamics, aerodynamics, air-conditioning systems, acoustics, blood circulation and boundary layer turbulence.
• PIV is usually a planar laser light sheet technique.
• Light sheet is pulsed twice, and images of fine particles lying in the light sheet are recorded on a video camera or a photograph.
• Displacement of the particle images is measured in the plane of the image and used to determine the displacement of the particles in the flow.
• The most frequent technique used is by dividing the image plane into small interrogation spots and subsequent cross correlating the images from the two time exposures.
• The spatial displacement that produces the maximum cross-correlation statistically approximates the average displacement of the particles in the interrogation cell.
• Velocity associated with each interrogation spot is the displacement divided by the time between the laser pulses.
Typical PIV apparatus consists of

- a camera (normally a digital camera)
- a high power laser (double-pulsed Nd-YAG laser or copper vapour laser)
- an optical arrangement to convert the laser output light to a light sheet (normally using a cylindrical lens)
- and the fluid/gas under investigation

A fibre optic cable connects the laser to the cylindrical lens setup. The laser acts as a photographic flash for the digital camera. The particles in the fluid scatter the light. This scattered light is detected by the camera. To measure the velocity at least two exposures are needed. They can be recorded on one or several frames. The frames are split in a large number of interrogation areas called tiles. Displacement vector for each tile is calculated with help of signal processing (auto-correlation/cross-correlation). This is converted to a velocity using the time between image exposures.
PIV Applications

- Aerodynamics
- Hydrodynamics
- Internal Combustion Engines
- Reactive Flows
- Mixing Flows
- Spray Formation
- Flows in Pumping and Rotating Machinery
- Flows in Devices for Life Sciences and Biomedical Work
- Quantifying the deformation and motion of solid materials or tissues that have embedded markers or are in some other way visually heterogeneous
Advantages and Limitations

- Nonintrusive.
- Negligible distortion of the fluid flow.
- Avoids the need for intrusive flow measurement probes.
- Capable of measuring an entire two-dimensional cross section (geometry) of the flow field simultaneously.
- Allows the generation of large numbers of image pairs which, are analysed in real or later time. Thus a near continuous information may be gained.
- High degree of accuracy, since each vector is the statistical average for many particles within a particular tile. Accurate down to 10% of one pixel on the image plane.

- The particles will, due to their higher density, not exactly follow the motion of the fluid (gas/liquid).
- PIV in general will not be able to measure components along the z-axis (towards to/away from the camera).
- The size of the recordable flow field is limited by the size of the tracer particles.
- The resulting velocity field is a spatially averaged representation of the actual velocity field. Accuracy of spatial derivatives of the velocity field, vorticity, and spatial correlation functions (derived from PIV velocity fields) are affected.
FLOW-RATE MEASUREMENT IN TWO-PHASE FLOWS

In-Stream Sensors with Electrical Output
a) Conductivity Devices
b) Impedance Void Meters
c) Hot-Film Anemometers
d) Radio Frequency Probes
e) Optical Probes

In-Stream Sensors with Mechanical Output
a) Wall Scoop
b) Isokinetic Sampling Probe
c) Wall Shear and Momentum Measuring Device.

Out-of-Stream Measuring Devices
a) X-Ray, Gamma Ray Methods
b) Beta ray Methods
c) Neutron Methods
Measurements in Non-Newtonian Fluids

- Flow Measurements are primarily Optics based e.g. LDV.
- This calls for fluid to be transparent...however most of the Non-Newtonian Fluids are opaque.
- Hot Wire/Wall Anemometry is also used; disadvantages being sample fouling due to thermal degradation and mechanical failure due to high viscosity.
- PIV is an important method as impurities in the sample serve as tracers.
Flow Measurement: Current and Future Developments

- Currently Flow Measurement Techniques are primarily non intrusive.
- They can directly measure local velocity fields.
- Characterized by high spatial and temporal resolution and frequency response.
- In phase flows, most techniques are average based thus increasing uncertainty.
- Nuclear Magnetic Resonance (NMR) and Pulsed Neutron Activation (PNA) offer direct measurement of individual phase fractions and velocities,
- Currently both are technically difficult and expensive to achieve.
- Cost effectiveness is the key to technology feasibility.
SUMMARY

• Looked into basic/primitive flow measurement means.
• Genesis of modern flow measurement techniques: their capabilities, advantages, and limitations.
• Measurement Techniques in multiphase and non-Newtonian flows.
• Current scenario and future scope.
Acknowledgement

- Prof. Franz Durst for his untiring support and help to make this presentation a successful one.
- Prof. Heiner Ryssel for the timely updates that he has kept providing us.
- Prof. Chacko Jacob for helping me with the various logistic related queries and activities.
- Prof. A.W. Date of I.I.T. Bombay for his constant encouragement during the course of my preparation.
- And am truly thankful to University of Erlangen-Nürnberg and the I.I.Ts for the wonderful event.