## MEP 365

## Thermal Measurements

## Ch. 9 Pressure \& Velocity Measurements

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1-Introduction

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## 1-Introduction

Pressure $=$ Force $/$ area $=\mathrm{N} / \mathrm{m}^{2}=\mathrm{Pa}$

$$
P=\frac{F}{m^{2}}=P a
$$

As altitude increases, the pressure decreases


## Standard atmospheric pressure at sea level

$1 \mathrm{~atm}=101.32 \mathrm{kPa}$
14.696 psi
1.013 bar.
$101.32^{*} 1000=\rho g h$
$h=$
760 mm Hg
$10350.8 \mathrm{~mm} \mathrm{H}_{2} \mathrm{O}$
29.92 in Hg
407.523 in $\mathrm{H}_{2} \mathrm{O}$

1 Torr $=1 \mathrm{~mm} \mathrm{Hg}$
$=13600 * 9.81^{*}(1 / 1000)=$
$=133.4 \mathrm{~Pa}$

# Gage and absolute pressure 

$$
P_{g a g e}=P_{a b s}-P_{a t m}
$$

## Gage and absolute pressure



$$
P_{g a g e}=P_{a b s}-P_{a t m}
$$

## Hydrostatic pressure variation with depth



Fluid specific weight, $\gamma$

$$
P=P_{o}+\rho g h=P_{o}+\gamma h \quad \gamma=\rho g \quad \mathrm{Kg} /\left(\mathrm{m}^{2} . \mathrm{s}^{2}\right)
$$

# 2-Pressure Reference instruments 

McLeod Gauge
Barometer
Manometer
Deadweight tester

## McLeod Gauge

Used for sub atmospheric pressure<br>0.1 mm Hg to 1 mm Hg


(a) Sensing position

A gas of unknown pressure is trapped at known volume when the gauge is inverted


## McLeod Gauge


(a) Sensing position
$\mathrm{V}_{1}$ volume of gas initially=Constant

$$
\begin{gathered}
p_{1} V_{1}=p_{2} V_{2} \\
p_{2}=p_{1}+\gamma \\
V_{2}=y A \\
p_{1}=p_{2}-\gamma y \\
p_{1}=p_{1}\left(V_{1} / V_{2}\right)-\gamma y \\
p_{1}\left(V_{1} / V_{2}-1\right)=\gamma y \\
p_{1}=\frac{\gamma A y^{2}}{V_{1}-y A}
\end{gathered}
$$

## McLeod Gauge


(b) Indicating position

## Barometer

A device to measure the atmospheric pressure
$\mathrm{p}_{\mathrm{v}} \approx 0$

$$
p_{v}+\gamma_{m} h=p_{a t m}
$$



## Barometer

Fortin Barometer

Figure 9.4 Fortin barometer.


Manometers

Figure 9.5 U-tube manometer.

## Manometers



Figure 9.5 U-tube manometer.


$$
p_{1}-p_{2}=\left(\gamma_{m}-\gamma\right) H
$$

$\mathrm{K}=$ Sensitivity of the manometer=Output/input

$$
K=\frac{\Delta H}{\Delta p}=\frac{1}{\gamma_{m}-\gamma}
$$

Figure 9.5 U-tube manometer.

## Micro-manometers

Used for measuring a very small differential pressure down to $0.005 \mathrm{~mm} \mathrm{H}_{2} \mathrm{O}$

Micro-manometers


Used to measure small differential pressure up to $0.005 \mathrm{~mm} \mathrm{H}_{2} \mathrm{O}$
Micrometer
adjusting
screw

The reference position: The reservoir is adjusted up or down until the level of the manometer within the reservoir is the same as the set mark. Bringing the reservoir level back to the set mark (i.e. H) is a measure due to pressure difference

Figure 9.6 Micromanometer.

## Inclined manometer

Used to measure small pressure difference.
One of the legs of the manometer is inclined ( $10-30^{\circ}$ ) with the horizontal


19 Figure 9.7 Inclined tube manometer.


## Elementary error associated with manometers

Scale adjustment error
Zero error
Temperature error
Gravity error
Capillary
Meniscus error

## Correction for mercury specific weight as a function of temperature

$$
\begin{array}{rl}
\gamma_{H g} & =\frac{133.084}{1+0.00006 T} \quad \mathrm{~N} / \mathrm{m}^{3} \\
\gamma_{H g} & =\frac{848.707}{1+0.000101(T-32)} \mathrm{T} \text { in }{ }^{\circ} \mathrm{C} \\
\mathrm{l} / \mathrm{ft}^{3} & \mathrm{~T} \text { in }{ }^{\circ} \mathrm{F}
\end{array}
$$

Gravity correction
$e_{1}=-\left(2.637 * 10^{-3} \cos (2 \phi)+9.6 * 10^{-8} z+5 * 10^{-5}\right) \quad \mathbf{z}$ in feet
$e_{1}=-\left(2.637 * 10^{-3} \cos (2 \phi)+2.9 * 10^{-8} z+5 * 10^{-5}\right) \quad \mathbf{z}$ in meter
$\phi$ is the altitude in degrees

Capillary error can be reduced if a bore of diameter of 6 mm or greater is used.

General manometer uncertainty can be as low as 0.02-0.2\%

## Example 9.3

Inclined manometer, $\theta=30^{\circ}$ is used to measure air pressure, nominal pressure $=100 \mathrm{~N} / \mathrm{m}^{2}$, $\mathrm{u}_{\theta}=1 \mathrm{deg}$. , $\gamma_{\mathrm{m}}=9770 \pm 0.5 \%$ manometer resolution 1 mm . manometer zero error $=$ interpolation error. Estimate uncertainty in pressure

$$
\Delta p=p_{1}-p_{2}=L\left(\gamma_{m}-\gamma\right) \sin (\theta)
$$

For $\Delta p=100 \mathrm{~N} / \mathrm{m}^{2}$

$$
L=\frac{\Delta p}{\left(\gamma_{m}-\gamma\right) \sin (\theta)}=21 \mathrm{~mm}
$$

$$
u_{\Delta p}=\left[\left(\frac{\partial \Delta p}{\partial \gamma} u_{\gamma}\right)^{2}+\left(\frac{\partial \Delta p}{\partial L} u_{L}\right)^{2}+\left(\frac{\partial \Delta p}{\partial \theta} u_{\theta}\right)^{2}\right]^{1 / 2}
$$

$$
\begin{gathered}
u_{\Delta p}=\left[\left(\frac{\partial \Delta p}{\partial \gamma_{m}} u_{\gamma_{m}}\right)^{2}+\left(\frac{\partial \Delta p}{\partial L} u_{L}\right)^{2}+\left(\frac{\partial \Delta p}{\partial \theta} u_{\theta}\right)^{2}\right]^{1 / 2} \\
u_{\gamma_{m}}=9770 * 0.5 / 100=49 \mathrm{~N} / \mathrm{m}^{3} \quad u_{L}=\sqrt{u_{o}^{2}+u_{c}^{2}}=\sqrt{0.5^{2}+0.5^{2}}=0.7 \mathrm{~mm} \\
u_{\theta}=1^{\circ}=0.0175 \mathrm{rad} \\
T_{1}=\frac{\partial \Delta P}{\partial \gamma_{m}} u_{\gamma_{m}}=L \sin (\theta) * u_{\gamma_{m}}=0.51 \quad T_{2}=\frac{\partial \Delta P}{\partial L} u_{L}=\left(\gamma_{m}-\gamma\right) \sin (\theta) * u_{L}=3.42 \\
T_{3}=\frac{\partial \Delta P}{\partial \theta} u_{\theta}=\left(\gamma_{m}-\gamma\right) L \cos (\theta) * u_{\theta}=(21 / 1000) * \cos (30) * 0.0175=3.1
\end{gathered}
$$

$$
u_{\Delta p}=\sqrt{0.51^{2}+3.42^{2}+3.1^{2}}=4.6 \mathrm{~N} / \mathrm{m}^{2}
$$

## Dead weight tester

Use the fact that $P=F / A$
Used for calibration of pressure sensors 70$70^{*} 10^{7} \mathrm{~N} / \mathrm{m}^{2}$

Uncertainty 0.05 to $0.01 \%$ reading

$$
P=\frac{F}{A}+\sum \text { errors }
$$

## Dead weight tester



## Dead weight tester



## Errors associated with deadweight tester

1-Air buoyancy
2-Variation in local gravity
3-Unceratinty in mass of pistons and weights
4-Shear effect (piston with cylinder movement)
5-Thermal expansion of piston area
6 -Elastic deformation of piston

## Simple correction for errors

$$
p=p_{i}\left(1+e_{1}+e_{2}\right)
$$

$P_{i}$ indicated pressure
$e_{1}$ error due to gravity variation
$\mathrm{e}_{2}$ buoyancy error $\gamma_{\text {air }} / \gamma_{\text {mass }}$
For Jeddah Location
$\mathrm{z}=17 \mathrm{~m}$
$\phi=21.7 \mathrm{~N}$

$$
e_{2}=-\gamma_{\text {air }} / \gamma_{\text {mass }}
$$

$e_{1}=-\left(2.637 * 10^{-3} \cos (2 \phi)+2.9 * 10^{-8} z+5 * 10^{-5}\right) \quad z$ in meter
$e_{1}=-\left(2.637 * 10^{-3} \cos (2 \phi)+9.6 * 10^{-8} z+5 * 10^{-5}\right) \quad z$ in feet

## Example 9.4

$\mathrm{p}_{\mathrm{i}}=100.00 \mathrm{psi}, \phi=34^{\circ}, \mathrm{z}=841$ feet, $\gamma_{\mathrm{air}}=0.076 \mathrm{lb} / \mathrm{tt}^{3}$, $\gamma_{\text {mass }}=496 \mathrm{lb} / \mathrm{tt}^{3}$. Correct the indicated pressure

$$
e_{2}=-\gamma_{\mathrm{air}} / \gamma_{\mathrm{mass}}=-0.076 / 496=-0.000154
$$

$$
e_{1}=-\left(2.637 * 10^{-3} \cos (2 \phi)+9.6 * 10^{-8} z+5 * 10^{-5}\right)
$$

$$
e_{1}=-0.001119
$$

$\mathrm{p}=100.00^{*}(1-0.000154-0.001119)=99.87 \mathrm{lb} / \mathrm{in}^{2}$

## 3- Pressure transducers

Bourdon tube
Bellows
Diaphragms
Capsule

## 3-Pressure Transducers



LVDT-Linear Variable Differential Transducer

## 3-Pressure Transducers



Bellows


Capsule


Diaphragm

Bourdon tube

## Bourdon tube



Bourdon tube

## Bourdon tube



## Bourdon tube


p


Sector

## Bellows



As $p_{1}-p_{2}$ increases the displacement increases

Use secondary element to translate the motion into a an relectrical signal

## Converting the linear movement into electrical signal



Potentiometer pressure Transducer

## Voltage divider circuit-Excluding meter loading error



Figure 6.9 Voltage divider circuit.

$$
E_{A B}=E_{i} \frac{R_{x}}{R_{T}}
$$

## Potentiometer circuit with loading error

$$
\begin{aligned}
& I=\frac{E_{i}}{\left(R_{2}+R_{e q}\right)} \\
& I=\frac{E_{i}}{\left[R_{2}+\frac{R_{1} R_{m}}{R_{1}+R_{m}}\right]} \\
& E_{o}=I * R_{e q} \\
& \frac{E_{o}}{E_{i}}=\frac{\frac{R_{1} R_{m}}{R_{1}+R_{m}}}{\left[R_{2}+\frac{R_{1} R_{m}}{R_{1}+R_{m}}\right]}
\end{aligned}
$$



## Potentiometer circuit with loading error

$\frac{E_{o}}{E_{i}}=\frac{1}{1+\left(R_{2} / R_{1}\right)\left(R_{1} / R_{m}+1\right)}$

In order to reduce the loading effect make $R_{m}$ as large as possible

Diaphragm pressure transducer

## Diaphragm pressure transducer

Diaphragm deforms due to pressure difference acting at both sides


Diaphragm can be used for either static or dynamic pressure measurements


Corrugated diaphragm

Use stain gauge to covert diaphragm movement into electrical signal

## Strain Gage

Strain gages are the most popular electrical elements used in force or pressure measurements. The strain gage measures pressure indirectly by measuring the deflection it produces in a calibrated primary sensor. The resistance strain gage is a resistive element, which changes in length, hence resistance, as the force applied to the base on which it is mounted causes stretching or compression


## Strain gage



Bonded strain gage

Use stain gauge to covert diaphragm movement into electrical signal

Quarter-bridge strain gauge circuit


## Use of strain gauges for pressure measurements



(b) Bridge-strain gauge circuit for pressure diaphragms.

## LVDT: Linear Variable Differential Transformer

Another means to convert the mechanical movement of a primary pressure transducer into electrical signal

Can be used to convert bellows or diaphragm linear movements
 into electrical signal

## LVDT: Linear Variable Differential Transformer

A rod drives
the slidirg core

$\Delta V=K \Delta x$
where,
$\Delta V=$ output voltage
$K=$ coristant for device
$\Delta x=$ core displacement


# LVDT: Linear Variable Differential Transformer 

AC Voltage is supplied to the primary coil. The amplitude output from the secondary coils is proportional to the core movement.


## LVDT: Linear Variable Differential Transformer

AC Voltage is supplied to the primary coil. The amplitude output from the secondary coils is proportional to the core movement.


For short core displacement the voltage output from the secondary coil is proportional to the displacement $x$


Core displacement, $x$

For additional information about LVDT see Ch. 12 in your book or search the internet

## LVDT: Linear Variable Differential Transformer



## Capacitance pressure transducer



Figure 9.13 Capacitance pressure transducer. In this schematic, the diaphragm is conductive and its deflection exaggerated.

## Capacitance pressure transducer



Figure 9.14 Capacitance pressure transducer.

## Capacitance pressure transducer

## The capacitance changes with $t$ and area A

$$
C=c \varepsilon A / t
$$

C=capacitance in Farad
$\varepsilon=$ permittivity ( $=8.85 \mathrm{E}-12 \mathrm{~F} / \mathrm{m}$ )
A is the overlapping area of the two plates

C=dielectric constant ( $\mathrm{C}=1$ for air, c=80 for water)


Figure 9.14 Capacitance pressure transducer.
$t$ is the distance between the two plates
Sensitivity

$$
K=\frac{\partial C}{\partial t}=-\frac{c \varepsilon A}{t^{2}}
$$

The measured voltage will be proportional with the separation distance t

$$
E_{o}=E_{i} \frac{C_{1}}{C}
$$

## Piezoelectric crystal elements



A piezoelectric disk generates a voltage when deformed

## Piezoelectric crystal elements

Generally used for transient (dynamic pressure measurement)
Under compression, tension or shear the crystal will deform and develop a surface charge q which is proportional to force acting

The relation between the charge develop and the pressure is given by

$$
q=K_{q} p A \quad \mathrm{~K}_{\mathrm{q}} \text { is the sensitivity coefficient }
$$

voltage develop across the electrode $E_{o}=q / C$
Using

$$
C=c \varepsilon A / t
$$

Gives

$$
E_{o}=K_{q} p t / c \varepsilon=K_{E} p t
$$

For Quartz, the most common material used $\mathrm{K}_{\mathrm{q}}=2.2 \mathrm{E}-9$

## Piezoelectric crystal elements

The charged produced due to deformation is a measure of pressure



Figure 9.15 Piezoelectric pressure transducer.

Cross section in a piezoelectric crystal pressure sensor

## pressure measurement in moving fluid



Figure 9.17 Streamline flow over a bluff body.

Streamlines A and B
flow can not be perpendicular to stream line

## pressure measurement in moving fluid

## Bernoulli's principle

$p_{1}+\rho U_{1}^{2} / 2=p_{2}+\rho U_{2}^{2} / 2-$

Figure 9.17 Streamline flow over a bluff body.
$\mathrm{U}_{2}=0.0$ Stagnation point

$$
p_{1}+\rho U_{1}^{2} / 2=p_{2}=p_{t}
$$

The term $\quad \rho U_{1}^{2} / 2 \quad$ is called dynamic pressure

## pressure measurement in moving fluid



Figure 9.17 Streamline flow over a bluff body.
pressure at location 1,3 , and 4 is called static pressure. It is the pressure sensed by fluid particle as it moves with same velocity as local flow
since $U_{4}>U_{3}$ due to mass conservation. $p_{3}>p_{4}$

## Total pressure measurement


(a) Impact cylinder
(b) Pitot tube
(c) Kiel probe

Figure 9.18 Total pressure measurement devices. (a) Impact cylinder. (b) Pitot tube. (c) Kiel probe.

$$
p_{t}=p_{s}+\rho U^{2} / 2
$$

## Static pressure measurement


pressure measurement should not disturb the flow

## Static pressure measurement

## Improved Prandtl static tube

flow must be smooth around the probe
frontal area of


## Static pressure measurement




Figure 9.20 Improved Prandtl tube for static pressure. (a) Design. (b) Relative static error along tube length.

## Fluid velocity measurements

$\qquad$

## U

$$
\begin{gathered}
p_{t}=p_{x}+\frac{1}{2} \rho U_{x}^{2} \\
p_{v}=p_{t}-p_{x}=\frac{1}{2} \rho U_{x}^{2} \\
U_{x}=\sqrt{\frac{2\left(p_{t}-p_{x}\right)}{\rho}}
\end{gathered}
$$

## Fluid velocity measurements



## Fluid velocity measurements



## Fluid velocity measurements

$$
p_{v}=p_{t}-p_{x}=\frac{1}{2} \rho U_{x}^{2}
$$

Pitot tube
manometer

## Pitot tube

## correction for viscous flow i.e. $\operatorname{Re}_{\mathrm{r}}<500$

$$
\begin{gathered}
\mathrm{Re}_{r}=\frac{U r}{v} \quad r \text { the probe radius } \\
p_{v}=C_{v} p_{i}
\end{gathered}
$$

$p_{i}$ is the indicated pressure and $C_{v}$ is the correction factor given by

$$
C_{v}=1+\left(4 / \operatorname{Re}_{r}\right)
$$

## High velocity flow

Compressibility effect

Stagnation temperature

$$
\frac{U^{2}}{2}=C_{p}\left(T_{t}-T_{x}\right)
$$

assuming isentropic process

$$
\frac{T_{x}}{T_{t}}=\left(\frac{p_{x}}{p_{t}}\right)^{(k-1) / k}
$$

Define Mach number M as

$$
M=\frac{U}{a}
$$

$$
a=\sqrt{k R T_{x}}
$$

$$
p_{v}=p_{t}-p_{x}=\frac{1}{2} \rho U_{x}^{2}\left[1+M^{2} / 4+(2-k) M^{4} / 24+\ldots\right]
$$

$$
\begin{aligned}
& \text { Correction due to Mach number } \\
& p_{v}=p_{t}-p_{x}=\frac{1}{2} \rho U_{x}^{2} \\
& p_{r v}=p_{t}-p_{x}=\frac{1}{2} \rho U_{x}^{2}\left[1+M^{2} / 4+(2-k) M^{4} / 24+\ldots . .\right] \text { Equation } 9.41 \\
& (3 \text { terms) }
\end{aligned}
$$

## Thermal Anemometry

Anemo=wind
Anemometer=measurement of wind force and velocity

The heat transfer from an object at $T_{s}$ subjected to a fluid at $\mathrm{T}_{\infty}$ is given by

$$
Q=h A\left(T_{s}-T_{\infty}\right)
$$

as the fluid velocity increases, the heat transfer increases. Therefore the heat can be related to the velocity

$$
Q=I^{2} R=A+B U^{n}
$$

King's Law
$A, B$ and $n$ are constants

## Thermal Anemometry

The basic idea of thermal anemometry is to subject a metallic temperature sensor to the flow, and relates the resistance to the temperature, and relates the heat transfer to the fluid velocity.

Relation between resistance and temperature

$$
R_{s}=R_{o}\left[1+\alpha\left(T_{s}-T_{o}\right)\right]
$$

If the resistance is kept constant. The current must be changed with velocity. The relation between heat and velocity is

$$
Q=I^{2} R=A+B U^{n}
$$

## Thermal Anemometry



Figure 9.26 Schematic of a hot-wire probe.

## Thermal Anemometry

Hotwire anemometer shapes
Handheld hotwire anemometer


## Thermal Anemometry



## hot-wire

tungsten or platinum wire, $L=1$ to $4 \mathrm{~mm}, \mathrm{~d}=1.5$ to $15 \mu \mathrm{~m}$. It can be used in non-conducting media

## hot-film

a thin $2 \mu \mathrm{~m}$ platinum or gold film deposited on glass and covered with high thermal conductivity coating. The coating is to electrically insulated the film and for mechanical protection. It can be used in either conducting or non conducting media

## Thermal Anemometry

$\longrightarrow$ constant current
Modes of operation
$\longrightarrow$ constant resistance

## constant current

The resistance as well as the sensor temperature change while the current is fixed. Bridge voltage is a measure of velocity

## constant resistance

Most common for velocity measurements. Resistance and temperature is kept constant. The circuit has a closed loop to adjust the voltage and therefore the current to bring the resistance to set point value.
applied voltage

$$
E^{2}=C+D U^{n} \quad \begin{aligned}
& \text { using an } \\
& \text { electronic } \\
& \text { linearizer }
\end{aligned} \quad E_{1}=K U
$$

## Thermal Anemometry

## Constant current mode

Potentiometer or EVM


Thermal anemometry showing constant current mode

## Thermal Anemometry

Constant resistance mode


The resistance is kept constant i.e. the temperature is kept constant. The applied voltage changes

Thermal anemometry showing constant resistance mode. The
^) voltage $E$ is proportional to velocity

$$
E^{2}=C+D U^{n}
$$

## Doppler effect

## Sound wave

static sound source


$$
c=\frac{\lambda}{T}=\lambda f
$$

$\mathrm{f}=$ Frequency
$=1 / \mathrm{T}$ in Hz

## Ultrasonic \& Doppler effect velocity measurements

Frequency of sound for a source moving toward and a way from a receiver

Doppler effect


## Ultrasonic velocity measurements

Doppler effect
(Doppler shift)


The difference between the sent and received frequency is related to object velocity

$$
C=\lambda f \quad \mathrm{C}=\text { speed of sound, } \lambda=\text { wavelength, } \mathrm{f}=\text { frequency }
$$

## Doppler effect

## Source is moving towards the receiver

## Receiver or observer



D

$$
L_{R}=D-V_{s} T
$$

$$
D=\frac{c}{f}
$$

$$
L_{R}=\frac{c}{f}-\frac{V_{s}}{f}=\left(\frac{1}{f}\right)\left(c-V_{s}\right)
$$

Divide by c

$$
\begin{aligned}
\frac{L_{R}}{c} & =\left(\frac{1}{f}\right)\left(1-\frac{V_{s}}{c}\right)=\frac{1}{f_{R}} \\
f_{R} & =\frac{f}{1-\frac{V_{s}}{c}}
\end{aligned}
$$



Relation between speed, period and frequency of a wave
Source
D
$\longleftarrow \mathrm{V}_{\mathrm{S}}$

$$
c=\frac{\lambda}{T}=\lambda f
$$

c=speed of sound
$\approx 340 \mathrm{~m} / \mathrm{s}$

## Doppler effect

Source is moving away from the receiver


## Doppler effect General case

$$
f_{o}=\frac{c \pm V_{o}}{c \bar{\mp} V_{s}} f_{s}
$$

$+V_{0}$ when the observer is moving towards the source $-\mathrm{V}_{0}$ when the observer is moving away from the source
$-V_{s}$ when the source is moving towards the object
$+\mathrm{V}_{\mathrm{s}}$ when the source is moving away from the object
$C$ is the speed of sound
$f_{\mathrm{o}}$ is the observer frequency
$f_{\mathrm{s}}$ is the source frequency

# Ultrasonic \& Doppler effect velocity measurements 

Two ideas

Time transient (To be seen later in Ch. 10)

Doppler effect (Explained in Ch. 9)

## Doppler Anemometry

Basic idea: The frequency of light or sound emitted from a source that is traveling toward or a way from the observer is shifted from its original value by an amount proportional to its speed (Doppler 1853)

Small particles are suspended in the fluid are used to generate Doppler effect. Either acoustic waves or light waves are used. If laser beam is used then it is called Laser Doppler Anemometer (LDA)

For an observer watching frequency

$$
f_{s}=f_{i} \pm f_{D}
$$

## where

$f_{s}$ is the scattered light as seen by the observer
$f_{i}$ is the frequency of the incident beam (in the order of $10^{14} \mathrm{~Hz}$ )
$f_{D}$ is the Doppler shift (in the order $10^{3}-10^{7} \mathrm{~Hz}$ )

## Doppler Anemometry



## Laser Doppler Anemometry

Dual laser beam mode to overcome the difficulties in detecting the Doppler shift


Figure 9.27 Laser Doppler anemometer. Shown in the dual-beam mode of operation.

## Doppler Anemometry

Relation between velocity, Doppler shift and wavelength

$$
U=\frac{\lambda}{2 \sin (\theta / 2)} f_{D}
$$

where
$\lambda$ is the wavelength of the beam
$f_{D}$ is the Doppler shift
$\theta$ lines scattering angle, see the figure
speed of light $c$ and relation with wavelength $\lambda$ and frequency $v$

$$
c=\lambda f=3 * 10^{8} \mathrm{~m} / \mathrm{s}
$$

## Doppler Anemometry

## Example 9.11

Doppler laser anemometer $\lambda=632.8 \mathrm{~nm} . \theta=11^{\circ}, f_{D}=1.41$ MHz . Estimate the velocity U

$$
U=\frac{\lambda}{2 \sin (\theta / 2)} f_{D}
$$

$$
U=\frac{632.8 * 10^{-9}}{2 \sin (11 / 2)} 1.41 * 10^{6}=4.655 \mathrm{~m} / \mathrm{s}
$$

## Particle Image Velocimetry (PIV)

In this method the full field 2D velocity is measured.
The technique is based on tracking the displacement of particles

The image of particles that are suspended in the flow is captured by a camera at predefined frequencies

The images are recorded and the traveled distances by the particles are calculated. the velocity is found using

$$
U=\frac{\Delta x_{i}}{\Delta t_{i}}
$$

## PIV Particle Image Velocimetry

2D laser sheet flashes on the particles and at the same time a camera takes images.

The travel distance can be found from the comparison of the two images.

## Particle Image Velocimetry



