EVALUATION OF DIFFERENT VELOCITY MEASUREMENT METHOD OF TURBINE TESTING

A DISSERTATION

Submitted in partial fulfillment of the requirements for the award of the degree

of

MASTER OF TECHNOLOGY

in

ALTERNATE HYDRO ENERGY SYSTEMS

By

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JUNE, 2006

CANDIDATE'S DECLARATION

I hereby declare that the work, which is being presented in this dissertation entitled **"EVALUATION OF DIFFERENT VELOCITY MEASUREMENT METHOD OF TURBINE TESTING"**, in partial fulfillment of the requirements for the award of the degree of **MASTER OF TECHNOLOGY** in **ALTERNATE HYDRO ENERGY SYSTEMS,** submitted in Alternate Hydro Energy Centre, Indian Institute of Technology Roorkee, is an authentic record of my own work carried out from July 2005 to June 2006, under the guidance and supervision of **Shri M.K.Singhal,** Senior Scientific Officer, Alternate Hydro Energy Centre and **Dr.B.K.Gandhi, Associated Professor**, Department of Mechanical & Industrial Engineering, Indian Institute of Technology Roorkee.

I have not submitted the matter embodied in this dissertation for the award of any other degree.

Dated: June 30,2006

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CERTIFICATE

This is to certify that the above statement made by the candidate is correct to the best of our knowledge and belief.

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ACKNOWLEDGEMENT

I would like to express my sense of gratitude to my guides **Shri M.K.Singhal,** Senior Scientific Officer, Alternate Hydro Energy Centre,**Indian Institute of Technology Roorkee**, Roorkee, India and **Dr.B.K.Gandhi,** Associated Professor, Department of Mechanical & Industrial Engineering, **Indian Institute of Technology Roorkee**, for guiding me to undertake this dissertation as well as providing me all the necessary guidance and support throughout this dissertation work. I can never forget their caring words and support in the difficult times. They have displayed unique tolerance and understanding at every step of progress, without which this dissertation work would not have been in the present shape. I feel it is my privilege to have carried out the dissertation work under their valuable guidance.

I owe a great deal of appreciation to Faculty of Alternate Hydro Energy Centre for imparting knowledge during my M.Tech course.

I would also like to thank all my friends, for their help and encouragement at the hour of need. Finally I would like to mention my parents who are with me all the times to assist me with their caring and affection right from my childhood.

Date: June 2006 **(Naveen Kumar Gupta)**

ABSTRACT

The Hydropower is the outcome of utilization of energy of water using water turbines into useful mechanical power, and this (power) is converted into electricity with the help of electric generators. The amount of waterpower available depends upon the amount of water flowing through the turbine. Discharge is the volume of water per unit time flowing through any section in the system. Measuring discharge is a critical need in hydro power Plants. The flow measurement is vital parameter in estimating the relative efficiency of the plant. There are many flow measurement methods, but none gives satisfactory results.. The measurement of discharge in a hydroelectric plant can be performed with desired accuracy only when the specific requirements of the choosen methods are satisfied. It is therefore in the interest of the parties involved to select the methods to be used for an acceptance test at an early stage in the design of the plant because later provision may be expensive or even impracticable.

For the measurement of flow we either require flow meters, or may calculate the discharge by measuring velocity of flow through a known area [17,19]. A current meter is an instruments used to measure the velocity of flowing water or liquid. Current meters are being used since decades for velocity measurement in large pipe diameters apart from rivers and open channels. The principle of operation is based on the proportionality between the velocity of the water and the resulting angular velocity of the rotor. By placing a current meter at a point in a stream and counting the number of revolutions of the rotor during a measured interval of time, the velocity of water at that point is determined. The propeller current meter consists of a propeller mounted in a bearing and a shaft. The fluid to be measured is passed through the current meter, causing the propeller to spin with a rotational speed proportional to the velocity of the flowing fluid. A device to measure the speed of the propeller is employed to make the actual flow measurement

H-Horizontal Acoustic Doppler Current Profiler (H-ADCP) measures horizontal Velocity profile across a channel by its two horizontal acoustic beams. H-ADCP also measures water level by its up-looking acoustic beam. When using H-ADCP for flow monitoring, H-ADCP collects horizontal velocity profile data and water level data in real-time. Users need to select an appropriate method for discharge

calculation using the velocity and water level data. Index-velocity method and Numerical method are two independent methods for calculating discharge. These two methods are based on different approaches and are independent. A major difference between the two Methods is that Index-velocity method requires rating or calibration, while numerical method does not. Another major difference is that Index-velocity method does not require H-ADCP profiling range cover the majority of channel cross-section. Therefore it can be used not only for small streams, but also for large rivers with its width much greater than H-ADCP profiling range. Numerical method in principle requires H-ADCP profiling range to cover the majority of channel cross-section.

This Dissertation work involves Study of Two Velocity measurement method namely current meter & Acostic of Turbine Testing according to IEC-41 and the measurement of discharge using the two Instruments.

The techniques applied in such measurements are of great significance for more efficient utilization of capital and the manpower involved.

The main objectives of this Dissertation work are:

(1) To Make Comparison of Velocity measurement by two methods using the propeller current meter & Horizontal acoustic Current profiler meter (H-ADCP) in an open-channel that involves the tasks such as:

    (a) Study of current meters.

    (b) Study of Velocity measurement method (Acoustic method & ultrasonic transit time Flow meter) according to IEC 41 Standard.

    (c) Study of national & international standards for open-channel Discharge Measurement.

    (d) Proper number & locations of current meters are worked out in channel Where discharge is to be measured.

(2) Discharge calculation by Graphical method (improved scheme using Cubic Spline Interpolation, Cubic Interpolation & Power Law Extrapolation as per ISO-748.

(3) Calculating discharge using Propeller Current meter and Horizontal Acoustic Doppler Current Profile meter in open channel at same time. Based on this discharge calculation a comparative study between these two methods.

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INTRODUCTION

1.1 INTRODUCTION

Discharge is the volume of water per unit time flowing through any section in the system (volume flow rate). Measuring discharge of liquids is a critical need in many industrial Plants. Hydropower plant is one where the flow measurement is vital parameter in estimating the relative efficiency of plant. There is lots of flow measuring principles, but not all of them are satisfactory. The measurement of discharge in a hydroelectric plant can be performed with desired accuracy only when the specific requirements of the choosen methods are satisfied. It is therefore in the interest of the parties involved to select the methods to be used for an acceptance test at an early stage in the design of the plant because later provision may be expensive or even impracticable.

The hydropower comes from the conversion of energy of flowing water through the turbine into useful mechanical power, and this (power) is converted into electricity with the help of electric generators. The amount of energy captured depends upon the amount of water flowing through the turbine. Discharge being one of the main parameters in the performance testing of turbines at power plants, so accurate determination of the rate of flow or discharge is our main concern. The methods and the techniques applied in such measurements are of great significance for more efficient utilization of capital and the manpower involved.

For the measurement of flow we require flow meters, which generally, can be classified into several categories namely as mechanical, electromagnetic, ultrasonic, etc [17,19]. Current meters are being used since decades for flow measurement in large pipe diameters apart from rivers and open channels. A current meter is an instruments used to measure the velocity of flowing water or liquid. The principle of operation is based on the proportionality between the velocity of the water and the resulting angular velocity of the meter rotor. By placing a current meter at a point in a stream and counting the number of revolutions of the rotor during a measured interval of time, the velocity of water at that point is determined.

The Propeller current meter consists of a propeller mounted in a bearing and a shaft. The fluid to be measured is passed through the current meter, causing the propeller to spin with a rotational speed proportional to the velocity of the flowing fluid. A device to measure the speed of the propeller is employed to make the actual flow measurement.

The choice of the methods for measuring discharge may dictate the conduct and duration of the performance test. Some of the factors that may affect this choice are:

a) Limitations imposed by the design of the plant
b) Cost of installation and special equipment
c) Limitations imposed by plant operating conditions, for example Draining of the system, constant load or discharge operation etc.

1.2 TYPES OF FLOW

Flow is classified into open channel flow and closed conduit flow. Open channel flow condition occurs whenever the flowing stream has a free or unconstrained surface that is opened to the atmosphere. Flow in canals or vented pipelines which are not flowing full are typical examples. The presence of free water surface prevents the transmission of pressure from one end of the conveyance channel to another as in fully flowing pipelines.

In hydraulics, a pipe is any closed conduit that carries water under pressure. The filled conduit may be square, rectangular or any other shape, but is usually round. Flow occurs in a pipeline when a pressure or head difference exists between ends.

The fluid flow is classified as;

(i) Steady and Unsteady flow
(ii) Uniform and No-uniform Flows
(iii) Laminar and Turbulent flow
(iv) Compressible and incompressible flow
(v) Rotational and irrotational flow
(vi) One, two and three dimensional flows

In laminar Flow the Fluid Particles moved along well – defined paths or streamline and all the stream- lines are straight and parallel. Thus the particles move in laminas or layers gliding smoothly over the adjacent layer.

Whereas in turbulence flow, the fluid particles in a Zigzag way, the eddies formation takes place which are responsible for high-energy loss. For a pipe flow, the type of flow is determined by a non-dimensional Number VD/υ called Reynold number.

Where D is the Diameter of Pipe

V is the mean velocity of Flow in Pipe

υ is the Kinematic Viscosity of fluid

Complexity of flow is so big that its accurate measurement is one of the challenging problems facing in this field. This is because the velocity profile of the flow cannot be accurately known for a particular situation. It can be stated that the flow velocity is not constant over the entire cross-section of the flow. The difficulty of measurement is more when the flow in the conduit is partial.

1.3 VELOCITY PROFILE IN OPEN CHANNEL FLOW

Flow can be classified into open channel flow and closed conduit flow, [25]. Open channel flow conditions occurs whenever the flowing stream has a free or an unconstrained surface that is open to the atmosphere. Flows in canals or in vented pipelines which are not flowing full are typical examples. The presence of the free water surface prevents transmission of pressure from one end of the conveyance channel to another as in fully flowing pipelines. Thus, in open channels, the only force that can cause flow is the force of gravity on the fluid. As a result, with steady uniform flow under free discharge conditions, a progressive fall or decrease in the water surface elevation always occurs as the flow moves downstream.

The actual distribution of flow velocity is generally quite complex. Open channel flow is often laminar or near-laminar, with the different layers moving at different velocities. Flow velocity at the contact point with the channel boundary is low. Typically, the highest velocity flow is located in the center of the flow channel and slightly below the water surface. Fig. 2.1 shows typical velocity profile or vertical velocity distribution under open channel flow conditions.

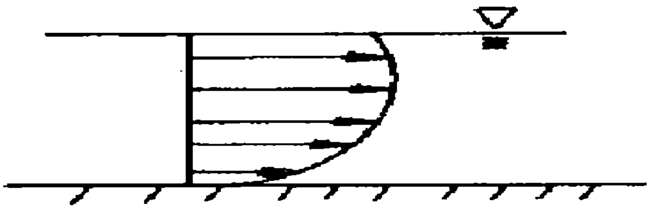


Fig.2.1 Typical Velocity Profile in Open Channel, (Source: www.usgs.com,) [25]

A general knowledge of velocity distributions is extremely important in evaluating and selecting a method of flow measurement. Sites with irregular or complicated channel geometries, such as meanders or riffle areas, can cause a decrease in measurement accuracy when using methods that rely on velocity measurements to calculate discharge.

1.4 VELOCITY MEASUREMENT METHODS

The Velocity measurement can be directly used in the discharge calculations. The Velocity measurement for IEC acceptance test shall be made by an absolute method. The important methods described in this IEC-41 standard are:

1. Current-meter method
2. Acoustic method
3. Pressure-Time method (Gibson method)
4. Tracer method (Transit time or dilution measurement)
5. Pitot tube method
6. Standardized differential pressure devices
7. Weirs
8. Volumetric Gauging
9. Thermodynamic method
10. Ultrasonic Transit time Method
11. Tracer Time Method

1.5 DISCHARGE CALCULATION FROM VELOCITY MEASUREMENT

Discharge is the quantity of a fluid flowing per second through a section of a pipe or a channel. For an incompressible flow (or liquid) flowing across the section per second. For compressible fluids, the rate of flow is usually expressed as the weight of fluid flowing across the section the rate of flow or Discharge is express the volume as the volume of fluid.

The equation based on the principle of conservation of mass is called continuity equation. according to this equation ,for a fluid flowing through the pipe at all the cross section, the quantity of fluid second is constant.

According to law of conservation of mass, rate of fluid flowing at any section is constant.

Discharge is calculated by the relation from Continuity Equation for Compressible Fluid

Discharge = density* Velocity* area

$$Q = \rho * A * V \quad [1.1]$$

Where ρ is the density of flowing fluid

A is the area of cross sectional of channel

V is the average velocity of fluid flowing

If the flowing fluid is water, discharge is calculated from relation

Q= area* average velocity

$$Q = A * V \quad [1.2]$$

This Dissertation work will be highlighting on various methods of velocity measurement of Turbine testing as mentioned in IEC-41.

1.6 REVIEW OF POSSIBLE TEST METHODS OF FLOW MEASUREMENT

The following selection criteria for the appropriate test method was established:

1. Expected accuracy
2. International test code acceptance
3. Suitability of unit geometry (test code requirement relative to actual Unit configuration)

4. Economical factors (Unit outage, test set-up cost, test cost, and test Equipment removal)
5. The safe operation of the unit.

All test methods that are recognized by the test codes were considered and the test requirements were compared to the unit configuration. These test methods are:

The Current-Meter and the Pressure Time Methods were selected for more in-depth comparison. All other test methods were eliminated from consideration because of many unacceptable conditions such as high uncertainty, unit configuration (short and multiple water passages) and very high cost of test set-up.

CHAPTER-2

CURRENT METER METHOD

2.1 WORKING PRINCIPLE

The current meter method requires a number of propeller-type current meters. These are located at specified points in a suitable cross section of an open channel or closed conduit. Simultaneous measurements of local mean velocity with the meters are integrated over the gauging section to estimate the discharge. Current meters are instruments designed as propellers with 2 or 3 blades. Fig. 2.1 shows an example of a current meter design with a two-blade propeller.

The current meter is put in the flow with the propeller axis parallel to the flow direction and the propeller peak against the flow. The rotational speed n of the propeller is a linear function of the flow velocity c in the measuring point.

$$V = k*n + b \qquad [2.1]$$

Where k and b are constants of the respective current meter and has to be determined by calibration tests.

The rotational speed of the current meter is detected by an electric contact giving a pulse frequency signal proportional to rotational speed. The flow velocity is recorded in the center of gravity of each grid element of the cross section area as shown on Fig.2.1.

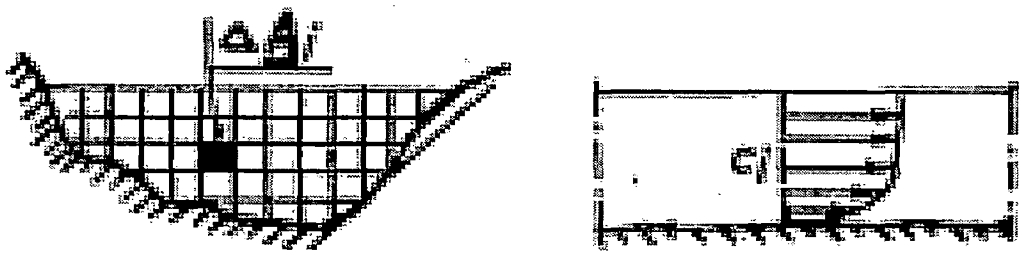


Fig 2.1 Flow cross-section

By considering an arbitrary element with area A_i where the recorded velocity is c_i, the discharge $\Delta Qi = c_i A_i$ through this element. If the flow cross section is divided in n elements, the total flow discharge is found by

$$Q_i = \sum_{i=1}^{n} c_i A_i \qquad [2.2]$$

Depending on the conditions on site the arrangement of current meter measurements may be carried out by a number of current meters installed in a kind of structure being built across the flow section. Current meter measurements may be applied in open drains, channels, rivers as well as in closed pipes. To achieve accurate results, it is however important that the flow through the cross section of the measurements is regular and as rectilinear as possible. The accuracy by current meter gauging of the discharge depends essentially on factors related to the flow, the quality of measurements, a careful reflection of the gauge point distribution and the method of discharge calculation.

2.2 TYPES OF CUREENT METER

Current meters are kind of turbine flow meters that measure the flow of water in pipes, open-channels, etc. They are velocity measuring devices that sample at a point. These flow meters are typically manufactured from austenitic stainless steel but are also available in a variety of material, including plastics. The advantages of these flow meters are listed below as:

1. Corrosion-Resistant
2. Analogs or Pulse Output
3. Wide operating range
4. Wide variety of Electronics available
5. Good Repeatability and Accuracy
6. Cheap and easily available

Each point velocity measurement by the current meter is assigned to a meaningful part of the entire cross section passing flow. The velocity-area principal is used to compute discharge from current-meter data. Total discharge is determined by summation of partial discharges.

A propeller current meter consists of a rotor or propeller mounted on a bearing and shaft. The fluid to be measured in passed through the housing, causing the propeller to spin with the rotational speed proportional to the velocity of the flowing fluid within the meter. A device to measure the speed of the rotor is employed to make the actual flow measurement.

The sensor is generally an electronic type sensor that detects the passage of each rotor blade generating a pulse. The principle of the operation is based on the proportionality between the velocity of the water and the resulting angular velocity of the meter rotor. By placing a current meter at a point in a stream and counting the number of revolutions of the rotor during the measured interval of time, the velocity of water at that point is determined. The number of revolutions of the rotor is obtained by an electrical circuit through the contact chamber. Contact points in the chamber are designed to complete an electrical circuit at selected frequency of revolutions. Contact chamber can be selected having contact points that will complete the circuit twice per revolutions, or once per revolution. The electrical impulse produces an audible click in a headphone or registers a unit on a counting device. The intervals during which meter revolutions are counted are timed with a stopwatch.

The current meter is put in the flow with the propeller axis parallel to the flow direction and the propeller peak against the flow. The rotational speed N, (Hz) of the propeller is a linear function of the flow velocity V, m/s in the measuring point;

$$V = (K) * N + B; \qquad [2.3]$$

Where;

N: It is the number of pulses counted for a given preset time, Hz

K: Hydraulic Pitch of Propeller, m

B: Characteristics of Current Meter, m/s

The K and B are constants of the respective current meter and have to be determined by calibration tests [16].

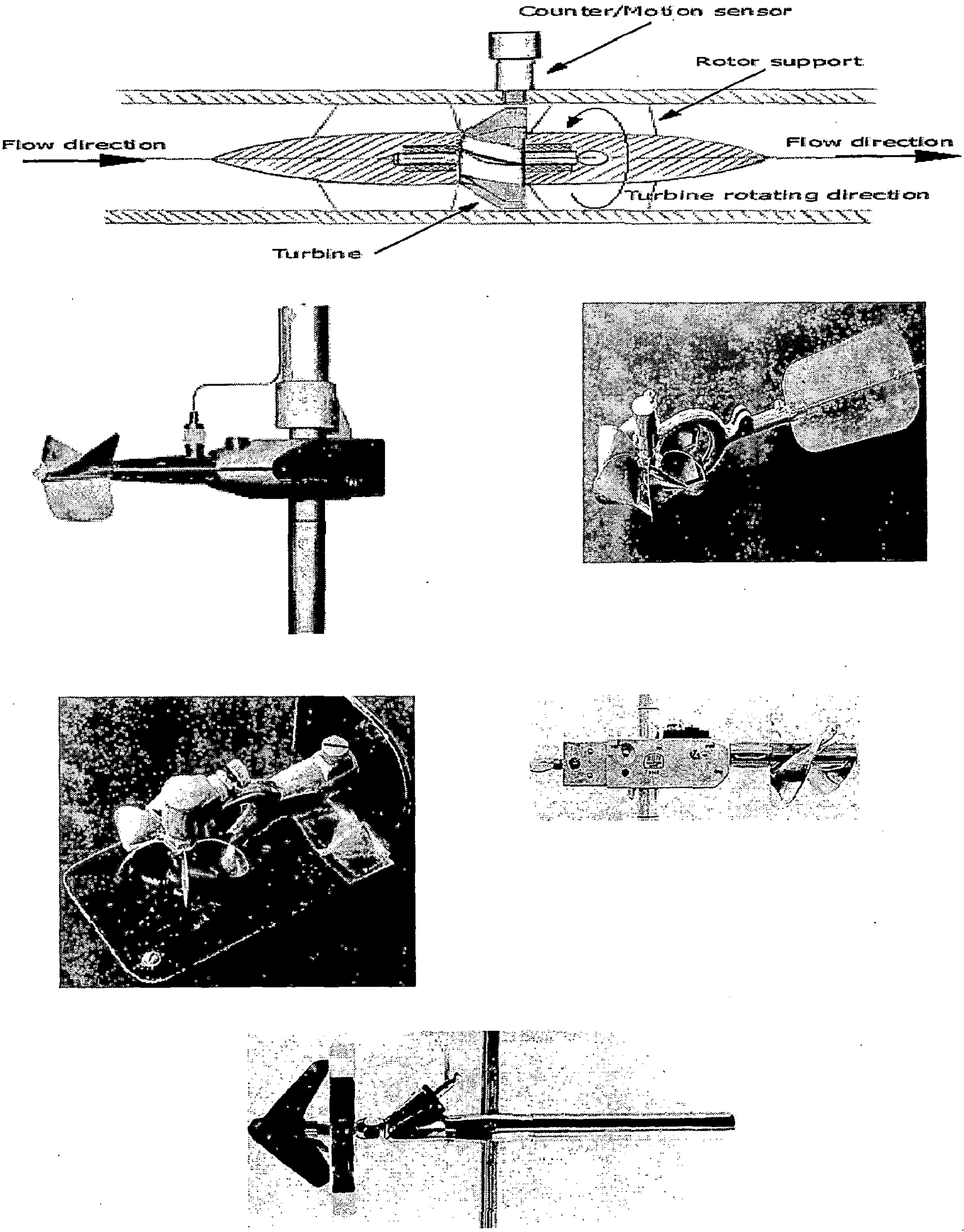


Fig: 2.2 Different types of current meters manufactured by different companies

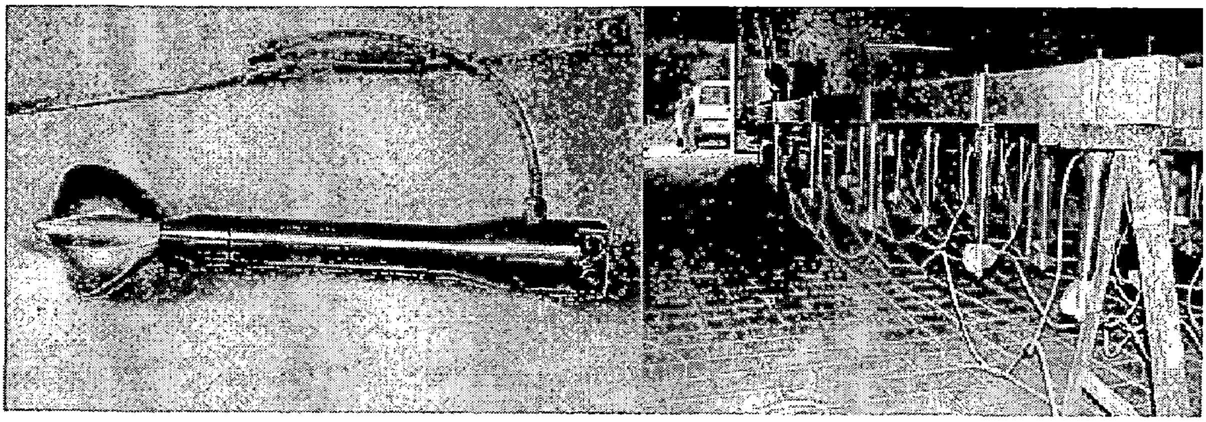


Fig 2.3: Can-Bus-Current Meter and Can-Bus-Current Meter mounted on an aluminum rod ready for installation.

2.3 GENERAL REQUIREMENTS

2.3.1 Duration of Measurement

Measurements for each current meter position shall last at least 2 min. If variations in the water velocity is present, a run shall include at least four cycles of these variations. This may have influence on the entire test programme. The duration of variations may be determined by observing the speed changes of the current meters for 10 to 15 min for at least two typical condition of operation.

2.3.2 Number of Measuring Points

The Number of current meters shall be sufficient to ensure a satisfactory determination of the velocity profile over the whole measuring section. A single point measurement is not permitted under this standard.

At least 13 measuring points shall be used in a circular penstock, one of which shall be the center point of the section. The number of measuring points per radius, Z, excluding the central point, may be determined from $4\sqrt{R} < Z < 5\sqrt{R}$, where R is the internal radius of the conduit in meters. For any given number of current meters, it is preferable to increase the number of radii than to increase the number of current meters per radius, but care must be taken to avoid excessive blockage. At least 25 measuring points shall be used in a rectangular or trapezoidal section. If the velocity distribution is likely to be non-uniform, the number of measuring points, Z, shall be determined from:

$$24\sqrt[3]{A} < Z < 36\sqrt[3]{A}$$

Where A is the area of measuring section in square meters. If the conduit or channel is divided into several sections, measurement shall be made simultaneously in all sections.

Only propeller-type current meter shall be used. The electrical impulses of propeller rotation shall be transmitted by cables to the counting and recording device in such a way that the momentary speed of the rotation of the propeller can be checked during and after the run.

Current-meter propeller shall not be less than 100mm diameter except for measurements in the peripheral zone where propellers as small as 50mm may be used. The distance from trailing edge of the propeller to the leading edge of the mounting rod shall be at least 150mm.The angle between the local velocity vector and the axis of the current meter should not exceed 5 degrees. When larger angles are unavoidable, self-compensating propellers which measure directly the axial component of the velocity shall be used, but only at angles for which they have been designed and calibrated. The response of a current meter can be affected by the axial and transverse components of the turbulence of the flow and this effect cannot be taken into account during the calibration which is carried out in still water. So propellers which are less sensitive to turbulence are used.

TABLE 2 VELOCITY AREA (CURRENT-METER) METHOD REQUIREMENTS					
ITEM	**TEST CODES REQUIREMENTS**	**IEC-41**	**PTC -18**	**ACTUAL UNIT CONFIGURATION**	**CONFOR**
1 Duration of Measurement	Measurements for each current-meter position shall be at least 2 minutes	10.2.2.1	4.42	Measurement is carried out for 2 minutes each	Yes
2 Number of measuring points	At least 25 measuring points in a rectangular or trapezoidal section. If the velocity distribution is likely to be non uniform, the number of measuring points, (Z), shall be determined from $24*(A)^{1/3} < Z < 36*(A)^{1/3}$ A = Area of measuring section in m^2	10.2.2.2		Each Intake Area = 78.1 m^2 Number of point measurement per Intake = 11x 21 = 231 Minimum Code Requirement = 103 Maximum Code Requirement = 154	Yes
3 Multiple Intake	If the conduit or channel is divided into several sections, measurements shall be made simultaneously in all sections	10.2.2.2		Three Current-meter frames, one per each Intake were used	Yes
4 Types and general requirements of Current-Meters	1. Only propeller-type 2. Electrical Impulse with counting and recording devices 3. Current-Meter shall satisfy ISO 2537 4. All meters be able to withstand water pressure 5. Current-Meter propeller shall be not less than 100 mm diameter 6. Distance from the trailing edge of the propeller to the leading edge of the mounting rod shall be at least 150 mm 7. Self Compensating propellers which measure directly the axial component of the velocity	10.4.2.1.d	4.89		Yes to each

TABLE 2 VELOCITY AREA (CURRENT-METER) METHOD REQUIREMENTS					
ITEM	**TEST CODES REQUIREMENTS**	**IEC-41**	**PTC -18**	**ACTUAL UNIT CONFIGURATION**	**CONFORMITY**
5 Calibration of Current-Meters	1. All current-meters shall be calibrated in accordance with ISO 3455 2. The current-meters shall be calibrated with the same type of mounting and mounting rods as that used during the test	10.2.2.4	4.45	Current-meters are calibrated regularly	Yes
6 Measurement in short penstocks and intake structures	ISO 3354 may be used as a guide	10.2.4.1		ISO 3354 is applied	Yes
7 Measurement in converging flow	Self Compensating propellers are best suited for this method	10.2.4.3		Self Compensating current-meters are used	Yes
8 Direct Integration method	This method is described in 7.2.2 and 7.3.2 of ISO 3354	10.2.4.4			Yes

2.4 METHODS OF DETERMINATION OF MEAN VELOCITIES IN CHANNEL

The mean velocity of the water in each vertical can be determined by any of the following methods, depending on the time available and having regard to the width and depth of the water, to the bed conditions. The following methods are used to determine mean velocities in a vertical section from the current meters:

a) Velocity Distribution Method (see 2.4.1).

b) Reduced Point Methods (see 2.4.2).

c) Other Methods (see 2.4.3).

d) Integration Method (see 2.4.4).

The above mentioned methods for the determination of mean velocity in the vertical cross-section are grouped in conformity to IS-1192 and ISO-748, depending upon the time available, width and depth of the channel, bed conditions in the measuring section and the upstream reach, rate of variation of level, degree of accuracy wanted and equipment used.

2.5 Integration Method

In this method, the current-meter is lowered and raised through the entire depth on each vertical at a uniform rate. The speed at which the meter is lowered or raised should not be more than 5 % of the mean water velocity and should not in any event exceed 0.04 m/s. Two complete cycles should be made on each vertical and if the results differ by more than 10 %, the operation (two complete cycles) should be repeated until results within this limit are obtained. This method is suitable for propeller-type current-meters and cup-type current meters and for electromagnetic current-meters, provided the vertical movement is less than 5 % of the mean velocity. The integration method gives good results if the time of measurement allowed is sufficiently long (60 s to 100 s).

2.5.1 Graphical Area- Velocity Integration Scheme

The velocities readings are taken at number of points on the vertical transect. The velocity readings recorded for each vertical are plotted against depth as shown in Fig. 2.2. The area contained by the velocity curve produced for each vertical gives the discharge for unit width or known as ***unit-width discharge*** of the corresponding section. Where necessary, velocity curves can be extrapolated to the surface and bed using power law extrapolation.

The values of unit-width discharges (**v.** d) are then plotted for each vertical cross-section and joined to form a continuous curve. The area enclosed between this curve and the line representing the water surface gives the total discharge through the section. In the case of velocity measurements by the integration or reduced point methods, the unit-width discharge at each vertical is obtained directly as the product of the mean velocity v and the corresponding depth, d. When velocity measurements are not carried out on the same verticals on which the depth measurements are made, the v curve shall be plotted across the width of the stream and the value of v corresponding to the verticals where depth measurements are made shall be taken for plotting the v d curve.

$$Q \equiv \int q_i db \text{ or } Q \equiv \sum \overline{v}_i d_i \Delta B \tag{2.3}$$

Where, Q is the total discharge in the open-channel, m^3/s

$\overline{v}_i$ is the average velocity in i^{th} segment of vertical, m^2/s

d_i is the depth of segment of the i^{th} cross-section in vertical, m

ΔB is the incremental width along the channel, m

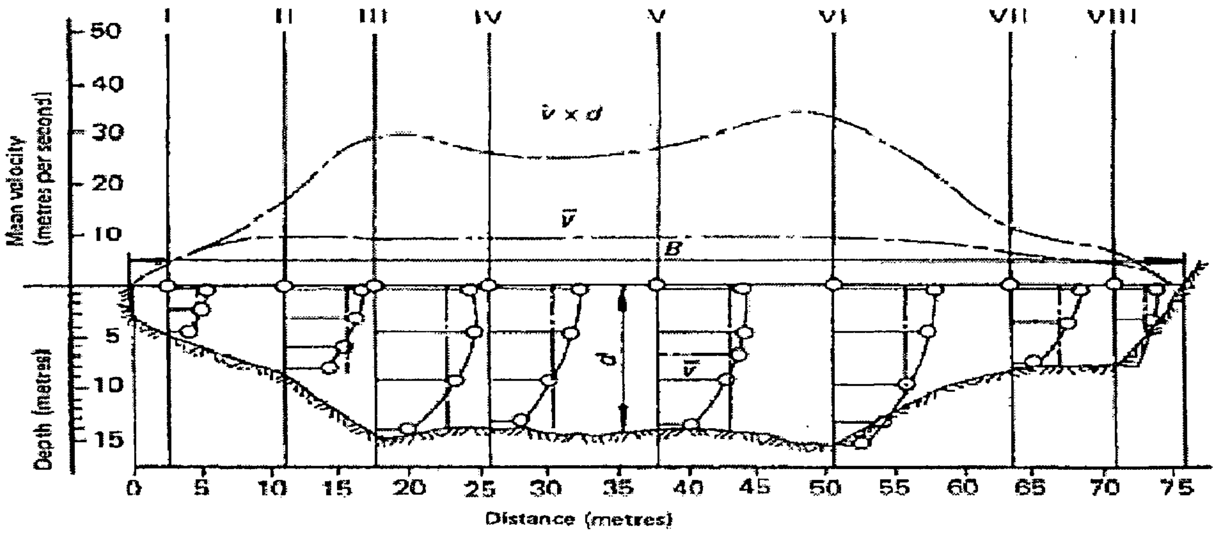


Fig. 2.4: - Computation of Discharge from Current-Meter Measurements (Depth Velocity Integration method), [Source: ISO: 748 [18], IS-1192, [19]]

Stream flow or discharge, is defined as the volume rate of flow of water over a given period of time [17]. In other words it can also be described, as the product of mean channel velocity and the cross-sectional area of the section. Discharge is usually measured in cubic meters per second. When using the propeller current meter, the observations of the width, depth, and the velocity are taken at intervals in the different cross-sections of the channel. In order to measure the mean velocity of flow in a channel, any of the schemes presented in section (2.4) can be used.

The velocity-area principle [18] is used to compute discharge/flow-rate from current-meter data. In this method, the channel is divided into finite number of sub-sections. The partial discharge in each sub-section is computed by multiplication of mean velocity of flow to the area of cross-section.

A partial discharge is the product of an average point or vertical line velocity and its meaningfully associated partial area, expressed as:

$$q_n = \overline{V}_n a_n \tag{2.4}$$

Total discharge is determined by summation of partial discharges in the cross-sections and is described as:

$$Q = \sum_{1}^{n} (\overline{V}_n a_n) \tag{2.5}$$

Represents the computation, where Q is the total discharge, a_n is the individual subsection area, and the V_n is the corresponding mean velocity of the flow normal to the subsection. The cross-sections are defined by depths at verticals 1, 2… n, where n is the number of verticals in the channel. At each vertical the velocities are sampled by current meter to obtain the mean velocity for each sub-section.

2.5.2 Cubic Spline Interpolating Scheme

In this approach, a set of cubic spline functions [11, 12] is used for velocity distribution approximation. Spline functions are partial polynomial functions that are connected in measuring points and have the same second derivative in this point. The algorithm using a set of cubic spline functions is very stable for unlimited number of measuring points and for any distance distribution of measuring points throughout the cross-section (unlike other polynomials of higher power, e.g. Newton's interpolation polynomial for non-equidistant spacing etc.). Here, the same procedure is carried out for average velocity measurement, described in section (2.7.1.1), but instead of higher degree polynomial function, the data is interpolated in the interpolating range and extrapolation can be done to find the surface velocity of the channel if the current meter is not placed very close to surface. This method of cubic spline interpolation is considered to be most commonly used for finding the velocity distribution in the vertical transect and horizontal velocity profile along the width of the channel [9, 11].

2.5.3 Power Law Extrapolation Scheme

When the turbulent flow condition exists, the velocity curve can be extrapolated from the last measuring point to the bed or wall by calculating $\mathbf{v_x}$ from the equation [18, 19];

$$v_x = v_a \left(\frac{x}{a}\right)^{\frac{1}{m}} \qquad [2.6]$$

Where;

$\mathbf{v_x}$ is the open point velocity in the extrapolated zone at a distance x from the bed or wall.

$\mathbf{v_a}$ is the velocity at the last measuring point at a distance a, from the bed or wall. The mean velocity $\overline{\mathbf{v_x}}$ between the bottom (or a vertical side) of the channel and the nearest point of measurement can be calculated directly from the equation [18, 19]:

$$\overline{V}x = \frac{m \quad * v_a}{m+1} \qquad [2.7]$$

Generally m lies between 5 and 7 but it may vary over a wider range depending on the hydraulic resistance. The value m=5 applies to coarse beds or walls while m=10 is Characteristic of smooth beds or walls.

2.6 UNCERTAINTY OF MEASUREMENT

The accuracy in a discharge measurement made by current-meter gauging depends essentially on factors related to the flow, the quality of measurement and method of discharge calculation. With good measuring techniques and flow conditions, the estimated uncertainties/9/ should be about:

- In closed conduits ± 1% to ± 1.5 %
- In open channels with rectangular section ± 1.2% to ± 2 %
- In open channels with trapezoidal section ± 1.4 to ± 2.3 %

ULTRASONIC METHOD

3.1 PRINCIPLE OF VELOCITY MEASUREMENT

The velocity of sound propagation in a flowing medium is increased by the flow velocity if the sound travels in the flow direction. Consequently, the transit time of an ultrasonic pulse is decreased when traveling with and increased when traveling against the flow, respectively.

The Ultrasonic method of discharge measurement is based on the fact that the propagation velocity of an acoustic wave (generally ultrasonic) and the flow velocity are summed vector ally. It follows that an acoustic pulse send upstream travels at a lower absolute speed than an acoustic pulse send downstream. By measuring the times of the traverse of the pulses sent in the two directions, the average axial velocity of the fluid crossing the path of the pulse is determined. Experience has shown that such measurement must be done repeatedly to establish an average and to minimize the random error.

An ultrasonic discharge measurement system includes transducers installed in the measurement section; electronic equipment is required to operate the transducers, make the measurements, process the measured data, and display or record the results. It also includes a verification program to ensure that the equipment and program are functioning properly.

There are several basic ultrasonic flow meter applications in use, including the transit time flow meter, the Doppler shift flow meter, and the correlation flow meter. Doppler shift ultrasonic flow meters send out a signal, and capture the Doppler shift of the signal reflected by particles in the flow. In this method, the ultrasonic signals reflected back to the receiver from particles in the flow are shifted slightly in frequency, which is proportional to the particle velocity. The correlation flow meter uses a device to perturb the flow and then attempts to correlate the disturbed travel time signal to the average velocity in the flow.

In the transit time flow meter technique, an ultrasonic pulse is launched from a first transducer and the elapsed time required for the pulse to arrive at a second transducer placed upstream or downstream from the transmitter is measured. In most cases, the transmitter and the receiver then change roles and the pulse is sent in the opposite direction. The difference between the upstream and downstream propagation time, Δt, can be directly related to an integrated mean fluid velocity as will be seen in a later section.

Even though several methods of acoustic discharge measurement exists, but not all have demonstrated that they are capable of achieving the accuracy required for field performance tests. Currently not included are devices based on the measurement of the refraction of an acoustic beam by fluid velocity (correlation flow meter) and Doppler shift flow meters. The only acceptable methods are based on the measurement of the transit time of an acoustic pulse along the chordal paths.

3.2 ULTRASONIC TRANSIT TIME FLOWMETER

A pair (or pairs) of transducers, each having its own transmitter and receiver, are placed on the pipe wall, one (set) on the upstream and the other (set) on the downstream. The time for acoustic waves to travel from the upstream transducer to the downstream transducer t_d is shorter than the time it requires for the same waves to travel from the downstream to the upstream t_u. The larger the difference, the higher the flow velocity.

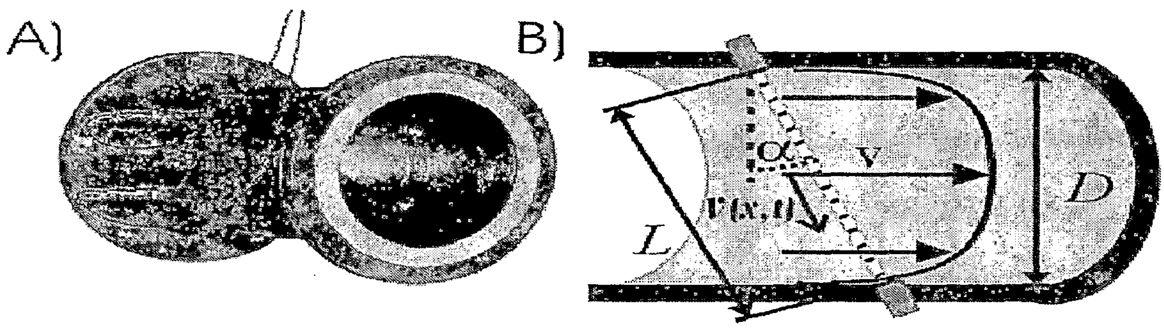


Fig 3.1 – (A) Ultrasonic flow meter with two parallel paths. (B) Schematic View of a sound path and flow profile.

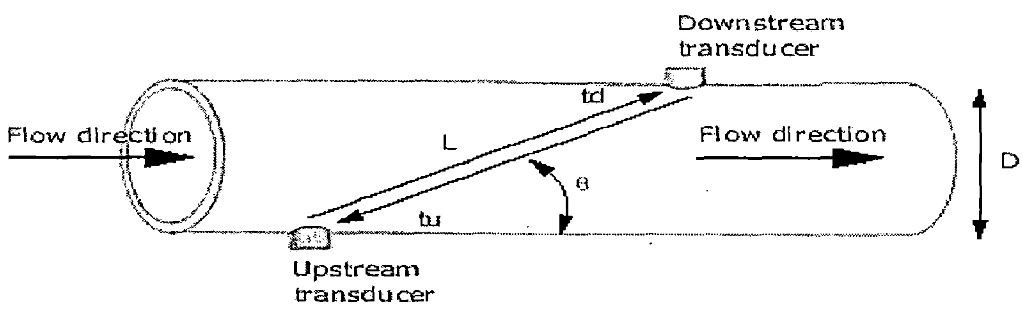


Fig 3.2 Typical Geometry for an Ultrasonic Flow Meter Angled to the Flow

t_d and t_u can be expressed in the following forms:

$$\begin{cases} t_d = \dfrac{L}{c + V\cos\theta} \\ t_u = \dfrac{L}{c - V\cos\theta} \end{cases} \quad [3.1]$$

Where c is the speed of sound in the fluid, V is the flow velocity, L is the distance between the transducers and θ is the angle between the flow direction and the line formed by the transducers. The difference of t_d and t_u is

$$\begin{aligned} \Delta t = t_u - t_d &= \frac{L}{c - V\cos\theta} - \frac{L}{c + V\cos\theta} \\ &= L\frac{2V\cos\theta}{c^2 - V^2\cos^2\theta} \\ &= \frac{2VL\cos\theta}{c^2 - V^2\cos^2\theta} \\ &= \frac{\dfrac{2VX}{c^2}}{1 - \left(\dfrac{V}{c}\right)^2\cos^2\theta} \end{aligned} \quad [3.2]$$

Where X is the projected length of the path along the pipe direction ($X = L\cos\theta$)

To simplify, we assume that the flow velocity V is much smaller than the speed of sound c, that is,

$$V \ll c \Rightarrow \left(\frac{V}{c}\right)^2 \approx 0 \ll 1 \quad [3.3]$$

We then have

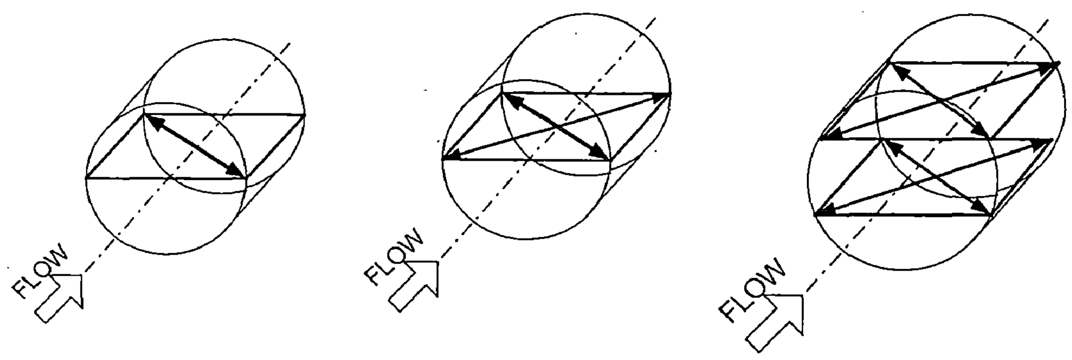
$$\Delta t \approx \frac{2VX}{c^2}$$

or,

$$V = \frac{c^2 \Delta t}{2X} \quad [3.4]$$

3.2.1 Multipath Method of Measurement

A single chord measurement, shown in figure 3.1 is not accurate, since it is measurement of flow velocity along a single plane of flow, where the flow velocity is not uniform through out the channel. More than single measurement is required to establish an average or mean and to minimize the precision error. The fluid velocity is determined by suitable integration of the individual velocity measurements. The generally used interpolation method is Gauss-Jacobi integration method.



(a) **(b)** **(c)**

Figure 3.3: - (a) Single path (1 plane) (b) Two paths crossed (1 plane) (c) Four paths crossed (2 planes)

In circular cross-sections, if the velocity distribution were fully axi-symmetric, the average velocity measured along a single path located in an axial plane could be assumed proportional to mean flow velocity in the conduit. In practice, it is necessary to take into account the actual velocity distribution by installing several pairs of transducers at opposite ends of a number of paths located in the measurement planes at an angle φ to the longitudinal axis of the conduit and distributed symmetrically about the axis as shown in figure 3 .3 (four paths).

In rectangular cross section, the measurement of the average velocity $\bar{v}$, conducted simultaneously or consecutively for a well-chosen number of parallel paths, will permit a linear integration of discharge over the whole section. In circular section the integration is done using numerical analysis methods; similar methods may also be used in rectangular sections. A systematic uncertainty, depending upon Reynolds number, conduit size and the shape and size of the transducer mount (projecting or recessed) is introduced by the local distortion of the velocity profile along the acoustic path compared to that which would exist if the transducer mount were not present.

3.2.2 Methods of Timing

There are two main methods of transit time measurements with some variations. The first consists in measuring directly the transit time in each direction between the two transducers. A variant of this method measures additionally the time difference in reception of signals transmitted simultaneously upstream and downstream.

In the second, the so-called "sling-around method", the frequency with which signals are transmitted is determined by the transit time, since each signal arriving at the receiver triggers off a new pulse at the opposite transmitter in the same direction, and difference in the frequency of both series of pulses is measured.

Both methods have their advantages and disadvantages and their choice depends on the size of the conduit, the magnitude of the velocity to be measured and the precision and cost of the timing device available on the market. The time delays in the electronic circuitry and cables and the times for acoustic pulse to traverse any non-water parts of the acoustic path, such as acoustically transparent material in the face of the transducer holder, shall be determined and taken into account.

3.3 DISCHARGE MEASUREMENTS AND CALCULATIONS

To make a velocity measurement along a given path, the transmitter and the receiver are arranged in such a way that the signals are transmitted upstream and downstream at any angle φ relative to the axis of the conduit Angles from 45° to 75° have shown to be satisfactory for the ultrasonic discharge measurement methods. The positioning of the transducers in case of circular conduit is shown in the fig.4.3. If there are no transverse flow components in the conduit and if the time delays are taken into account, the transit time of an acoustic pulse is given by:

$$t = \frac{L}{c + \varepsilon \overline{v}_a \cos \varphi} \qquad [3.6]$$

Where:

L is the distance in the fluid between the transducers faces

c is the sonic speed in the fluid at the operating conditions φ is the angle between the axis and the conduit and the acoustic path

$\overline{v_a}$ is the axial flow velocity averaged over distance L

ε =1 for signals traveling upstream

ε = -1 for signals traveling downstream

Since the transducers are generally used as trans-receivers, the difference in travel time may be with same pair of transducers. Thus the mean axial velocity crossing the path is given by:

$$\overline{v_a} = \frac{L}{2\cos\varphi}\left[\frac{1}{t_d} - \frac{1}{t_u}\right] = \frac{L}{2\cos\varphi}\left[f_d - f_u\right] \qquad [3.7]$$

Where t_d and t_u are the transit times of an acoustic pulse traveling downstream and upstream respectively. If there are transverse flow components, then

$$t = \frac{L}{c + \varepsilon\left(\overline{v_a}\cos\varphi + Y\overline{v_t}\sin\varphi\right)} \qquad [3.8]$$

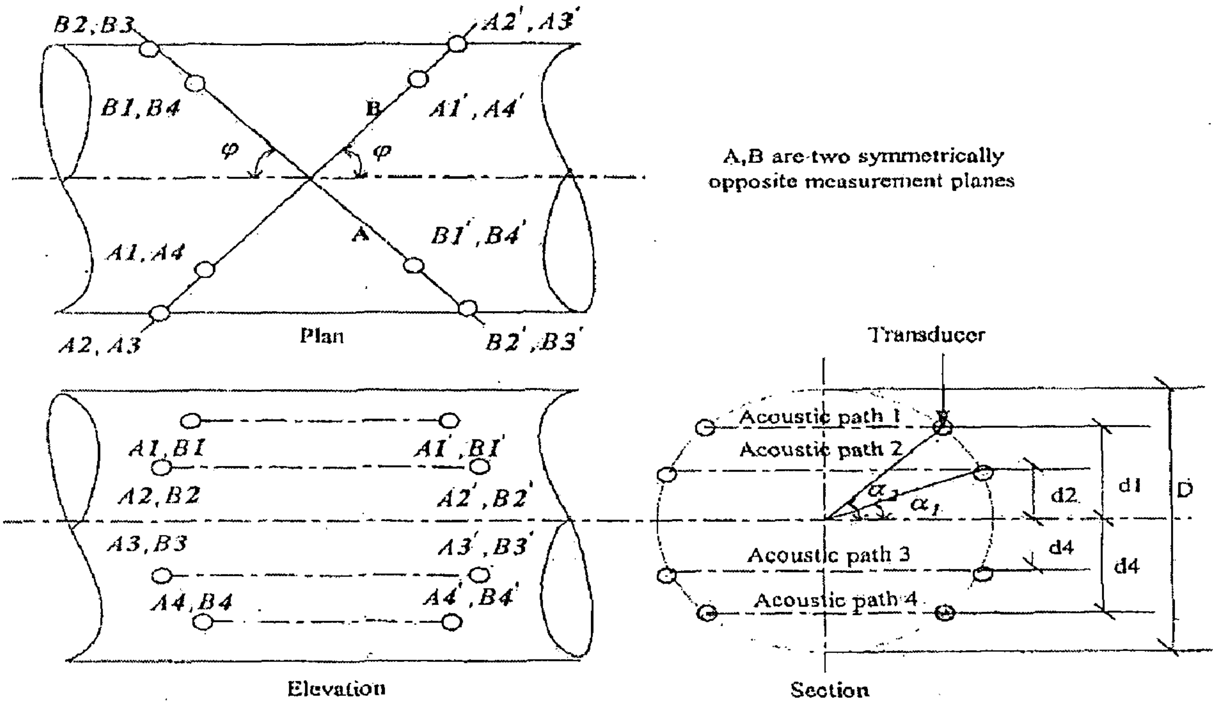


Fig 3.4: - Ultrasonic Acoustic methods – Typical Arrangement of Transducers in Circuit Conduit

Where: $\overline{v_t}$ is the distance of the flow velocity (having the component $\overline{v_t} \sin \varphi$ parallel to the acoustic path) averaged over the distance L.

Y is the factor equal to +1 or -1 depending upon the direction of transverse component of the flow parallel to the acoustic path and depending upon the orientation of the acoustic path. i.e, for a transverse flow component: Y = ±1 for an acoustic plane A and Y= ∓ 1 for an acoustic path in plane B.

The average axial velocity crossing a path may be taken as:

$$\overline{v_a} = -Y\overline{v_t} \tan \varphi + \frac{L}{2 \cos \varphi}\left(\frac{1}{t_d} - \frac{1}{t_u}\right) \qquad [3.9]$$

Due to symmetrical disposition of the acoustic planes with respect to centerline, the error due to transverse flow components (-Y $\overline{v_t} \tan \varphi$) is cancelled.

If certain mathematical conditions such as the continuity and differentiability are met by the velocity distribution, the discharge Q can be obtained from the general equation:

$$Q = k\frac{D}{2}\sum_{1}^{n} W_i \overline{v_{ai}} L_{wi} \sin \varphi \qquad [3.10]$$

With L_{wi} sin φ = D sin α_i for circular sections and L_{wi} sin φ = B for rectangular sections,

where:

L_{wi} is the distance from the conduit wall to conduit wall along the path i

D is the dimension of the conduit parallel to the two acoustic planes

B is the dimension of the conduit perpendicular to D for rectangular sections

W_i are the weighting coefficients depending on the number of paths and the integration techniques used

$\overline{v_{ai}}$ is the axial flow velocity averaged along the path i as calculated from the integration technique used

n is the number of acoustic paths in one plane

k is a correction coefficient which accounts for the error introduced by the integration technique chosen and shape of the conduit

α_i defines angular location of the end of path i relative to D

3.4 IMPROVEMENT OF INTEGRATION METHOD FOR CIRCULAR SECTION

Discharge through the conduit is determined from integration of individual path readings, resulting in an equation which sums up the weighted path readings. Usually, the integration for a multi-path acoustic flow meter is performed according to IEC 41.

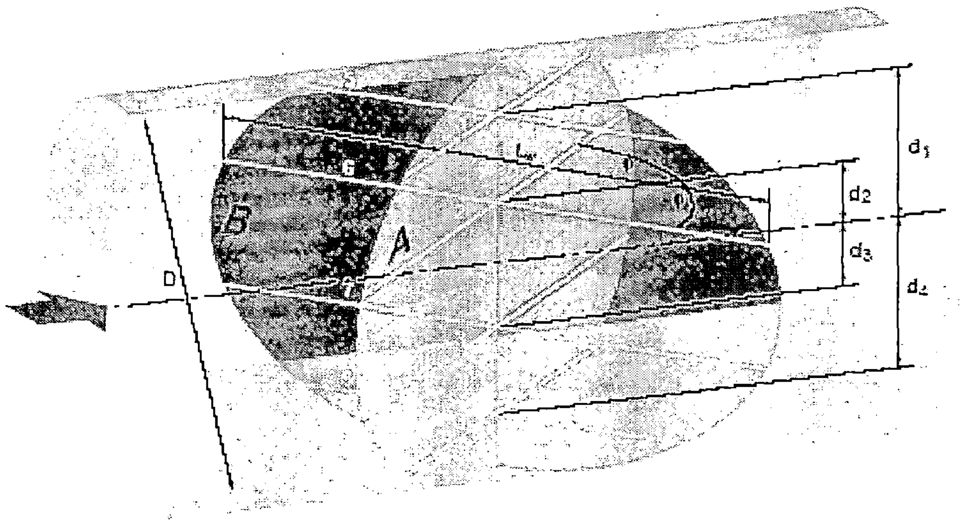


Fig. 3.5: - Horizontally mounted eight path flow meter

The two quadrature integration formulae used are

$$Q = k\frac{D}{2}\sum_{i=1}^{n} W_i \bar{v}_{ai} L_{wi} \sin\varphi \qquad [3.11]$$

For rectangular and circular sections and

$$Q = \frac{D^2}{2}\sum_{i=1}^{n} W_i' \bar{v}_{ai} \text{ with } W_i' = W_i \sin\alpha_i \qquad [3.12]$$

For truly circular sections with the paths positioned exactly at the specified locations, where α_i, defines the angular location of the path i. With the distances d_i of the acoustic paths to the centerline Eq. (3.11) can also be written as

$$Q = \frac{D}{2}\sum_{i=1}^{n} W_i \bar{v}_{ai} \sqrt{D^2 - 4d_i^2} \qquad [3.13]$$

One of the limitations of the integration methods described in IEC 41 is the fixed weighting of the paths and thus the need for a very accurate positioning of the transducers in relation to the distances d_i. It has been shown (Grego [2] and, more recently, Sugishita et al. [3]) that such a misalignment of the acoustic paths in conjunction with fixed weights can lead to relative errors of several thousands. This limitation can be overcome by calculating the weights individually from the surveying data with [22].

$$W_1 = \frac{g_1 D^2(d_3 + d_4 - d_2) - g_2 d_2 d_3 d_4}{(1 - 4d_1^2/D^2)^\kappa (d_1 - d_2)(d_1 + d_3)(d_1 + d_4)}$$
$$W_2 = \frac{g_1 D^2(d_3 + d_4 - d_1) - g_2 d_1 d_3 d_4}{(1 - 4d_2^2/D^2)^\kappa (d_2 - d_1)(d_2 + d_3)(d_2 + d_4)}$$
$$W_3 = \frac{g_1 D^2(d_1 + d_2 - d_4) - g_2 d_1 d_2 d_4}{(1 - 4d_3^2/D^2)^\kappa (d_3 - d_4)(d_1 + d_3)(d_2 + d_3)}$$
$$W_4 = \frac{g_1 D^2(d_1 + d_2 - d_3) - g_2 d_1 d_2 d_3}{(1 - 4d_4^2/D^2)^\kappa (d_4 - d_3)(d_1 + d_4)(d_2 + d_4)}$$

[3.14]

For a 4-path acoustic plane. With the constants k, g_1 and g_2 and the distances d_i listed in Table 4.1, the weights of the Gauss-Jacobi method from IEC 41 (sometimes also called Tschebyscheff method) are matched exactly. Numerical simulations have shown that path misalignments up to 2% do not affect the accuracy of the acoustic discharge measurement if Eq. (3.13) is used together with the quadrature integration Eq. (3.12) and the measured distances d_i. Another source of errors when using the Gauss-Jacobi-Method is the integration error for fully developed turbulent profiles in circular sections, the most important flow regime for the ADM.

Depending on the Reynolds number and the wall roughness, specified by the relative sand roughness k_s/D, the flow varies from hydraulically smooth to completely rough with a transition region in between. Our calculations were conducted within the hydraulic smooth flow regime, in which the velocity distribution is a function of the Reynolds number only and the completely rough flow regime depending only on the wall roughness. By simulating the acoustic discharge measurement with logarithmic laws for both velocity distributions, errors up to 0.25% were computed.

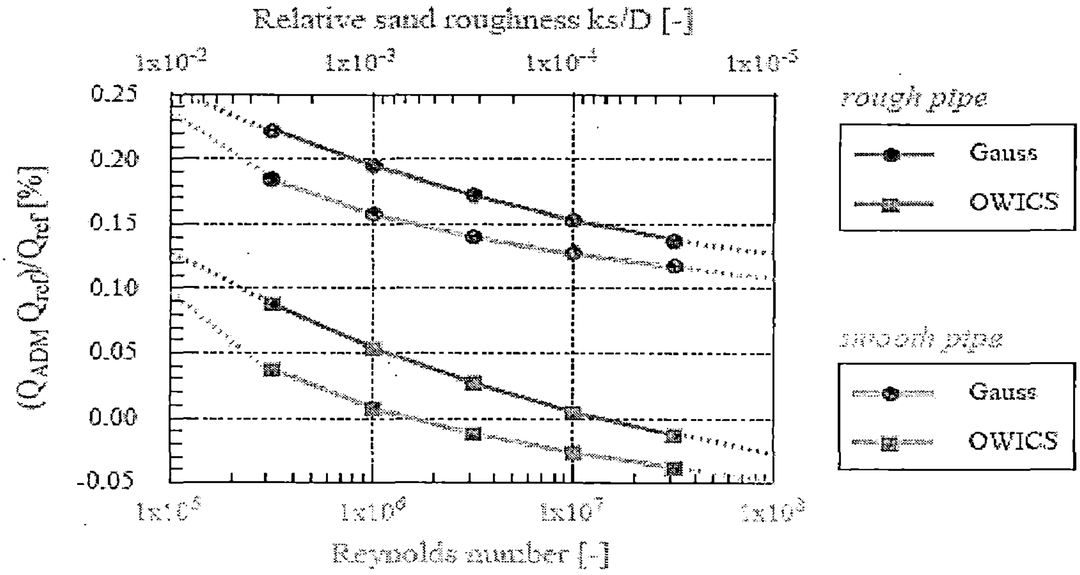


Fig. 3.6: - Integration error of ADM for fully developed turbulent velocity profiles

To avoid these errors an optimized integration method called OWICS (Optimal Weighted Integration for Circular Sections) with a slightly different weighting of the acoustic paths was developed. According to Fig. 3.5 the integration errors with the OWICS method are reduced by approximately 0.15% over the full range of Reynolds numbers and relative sand roughness, ks/D. The new integration method is mathematically comparable to the Gauss-Jacobi method, therefore the weights are also calculated with Eq. (3.10) and the coefficients listed in Table 3.1

Table 3. 1: - Constants and weights for the quadrature integration methods

	Gauss-Jacobi IEC41		OWICS	
K	0.5		0.6	
g1	0.0981748		0.0900812	
g2	1.5707963		1.5133647	
k	1		1	
	paths 1 und 4	*paths 2 und 3*	*paths 1 und 4*	*paths 2 und 3*
$d_i/(D/2)$	0.809017	0.309017	0.809017	0.309017
W_i	0.369317	0.597667	0.365222	0.598640

3.6 UNCERTAINTY OF MEASUREMENT

Both random and symmetric uncertainties have to be taken into account. The sources of uncertainty have been identified and are categorized as instrument uncertainty and the systematic uncertainty. The overall uncertainty in most cases is estimated to be less than $\pm$ 0.5%

Following are sources of uncertainty are:

-Measurement of path lengths L and L_{w}.

-Measurement of acoustic path length angles φ.

-Measurement of path Spacing d and conformity with the position prescribed.

-Measurement of D.

-Time measurement and time resolution.

-Non-water path time estimation.

-Internal computational precision.

-Uncertainty due to flow distortion around the transducers.

-Existence of tranverse flow components.

-Flow profile distortions

-Spatial variations of speed of sound.

-Spatial variations of flow velocity along the conduit.

-Variation of flow velocity, speed of sound and discharge with time.

Figure 3.6 shows three placements that can be used for the two transducers. All are identified as single measuring path because the sonic beam follows a single path, and in all three the two transducers are connected by cable to a converter that can output a 4-20 mA DC signal. The selection of one configuration over another is dictated by several factors associated with the installation, including pipe size, space available for mounting the transducers, condition of the inside pipe walls, type of lining, and nature of the flowing liquid.

There are three methods of mounting the two transducers, Z, V, and W. The choice is dictated by installation factors such as size and condition of the pipeline.

The Z configuration places the transducers on opposite sides of the pipe, one downstream of the other. Generally, the distance downstream is ~D/2, where D = pipe diameter. The converter uses specific data on piping parameters to compute the optimum distance. The Z method is recommended for use only in adverse conditions

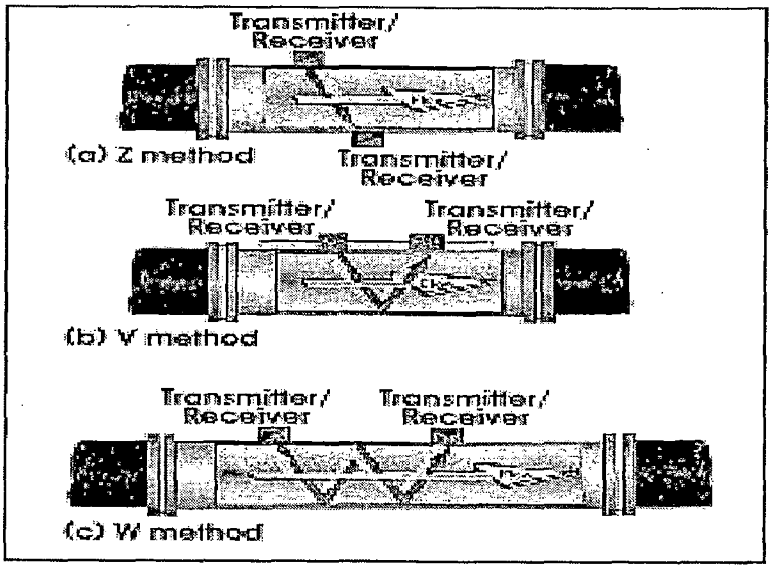


Fig. 3.7: - Single-path measurements with the transit-time flow meter

such as where space is limited, the fluid has high turbidity (e.g., sewage), there is a mortar lining, and when the pipe is old and a thick scale has built up on the inside wall that tends to weaken the received signals. It is not recommended for smaller pipes, where its measuring accuracy tends to degrade.

In most installations, the V method is recommended, with the two transducers on the same side of the pipe about a pipe diameter apart. The rail attachment that can be clamped on the pipe facilitates sliding the transducers horizontally along the pipe and positioning them the calculated distance apart.

The W method should be considered on pipe 1½ in. down to ½ in. dia. Its main limitation is a possible deterioration in accuracy due to buildup of scale or deposits on the pipe wall-note that the sonic signal must bounce off the wall three times. Turbidity of the liquid also could be harmful since the signal has a longer distance to travel.

3.7 Effect of Turbulence on Ultrasonic Transit time flow measurement

The dominant source of fluctuations in flow reading for an ultrasonic flow meter are the turbulent fluctuations of the flow. This leads to fluctuations of the measured volumes. For a typical meter configuration the standard deviation when repeatedly metering the 'meter volume' $_3 D$ is about 3% of the volume. For larger volumes, which are of more practical relevance, the standard deviation decreases with the square root of the volume divided by the cube of the meter size.

The ultrasonic measurement technique has advanced to a level of accuracy where the turbulence of the measured media is the main source of fluctuations in the measured flow value. For any flow meters the accuracy, range, repeatability etc. of the device are important parameters to determine if the meter is appropriate for a given application. This contribution focuses only on the repeatability of flow measurements with ultrasonic transit time meters. Theoretical considerations show how turbulence affects the meter reading, how the statistical properties of the turbulent flow determines the statistical properties of the fluctuations of the meter reading. turbulence is in fact the mayor source of fluctuations in the measurement signal. Especially electronic noise can be neglected in comparison to turbulence induced noise. Because there is always a trade off between response time and repeatability our findings have Implications for applications where a high repeatability and a fast response time is needed, for example in leak detection applications.

ACOUSTIC (DOPPLER) METHOD

4.1. WORKING PRINCIPLE OF HORIZONTAL ACOUSTIC DOPPLER CURRENT PROFILE METER

Horizontal Acoustic Doppler Current Profiler (H-ADCP) is an acoustic Doppler instrument for real-time flow monitoring in rivers, streams, and open channels. H-ADCP measures velocity horizontal profile across a channel by its two horizontal acoustic beams (Figure 4.1). H-ADCP also measures water level by its up-looking acoustic beam.

Horizontal Acoustic Doppler Current Profiler (H-ADCP) for flow monitoring, collects velocity horizontal profile data and water level data in real-time. Users need to select an appropriate method for discharge calculation using the velocity and water level data. Index-velocity method and Numerical method are two independent methods for calculating discharge. A major difference between the two Methods is that Index-velocity method requires rating or calibration, while numerical method does not. Another major difference is that Index-velocity method does not require H-ADCP profiling range cover the majority of channel cross-section. Therefore it can be used not only for small streams, but also for large rivers with its width much greater than H-ADCP profiling range. Numerical method in principle requires H-ADCP profiling range cover the majority of channel cross-section.

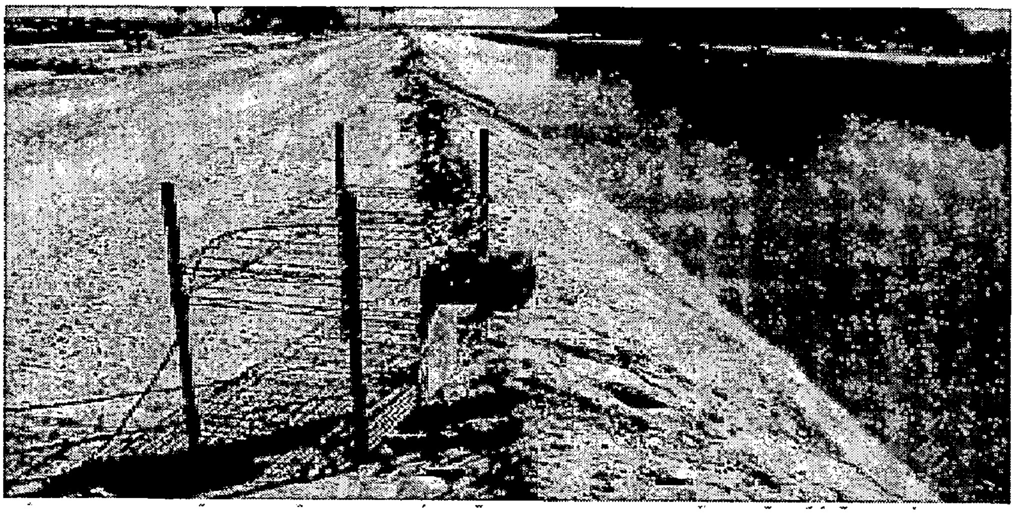


Fig. 4.1: - H-ADCP at the Canal site

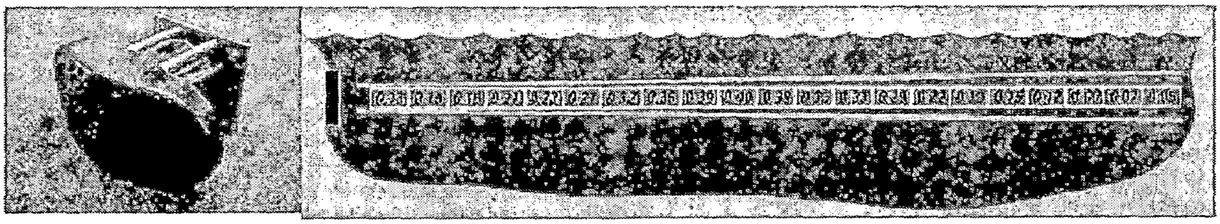


Fig 4.2: - A H-ADCP and Velocity Profiling. Numbers are velocities at cells.

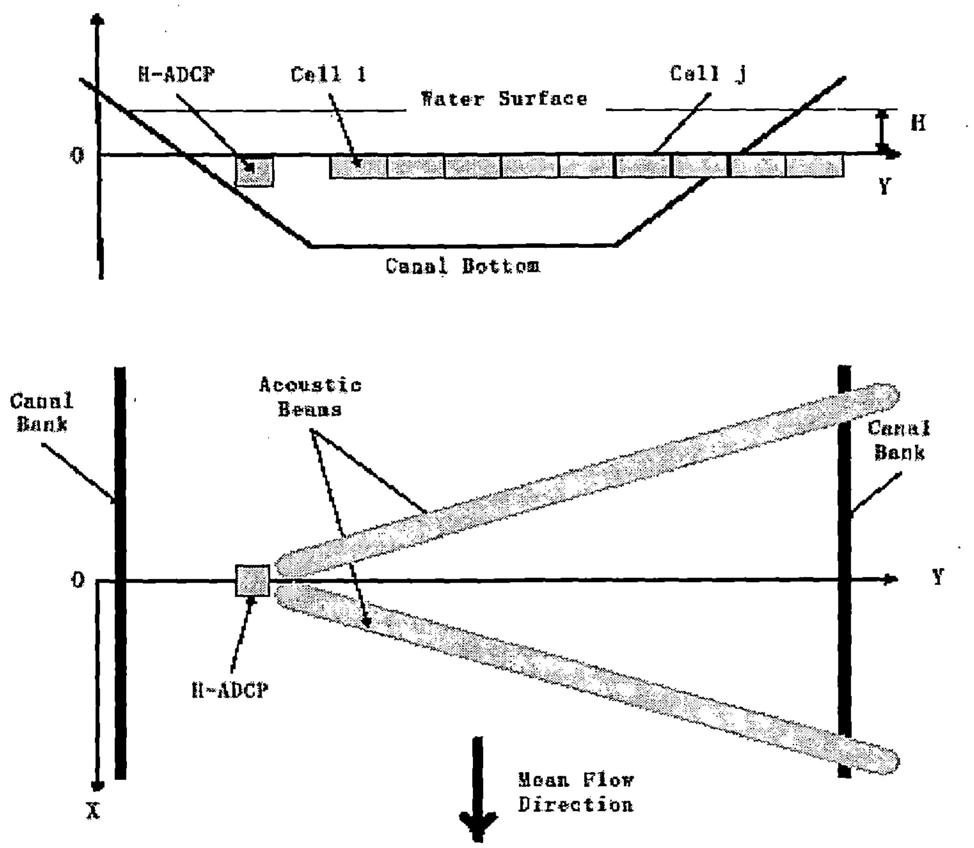


Fig 4.3: - Sketch for Channel Master ADCP Set up (not to Scale)

4.2. DISCHARGE CALCULATION METHODS FOR REAL-TIME FLOW MONITORING

4.2.1 Index-Velocity Method

Index-velocity method was developed and used by United States Geological Survey (USGS) for Discharge (flow rate) Monitoring or recording at stream flow gauging stations where flow conditions may make the use of conventional "Stage discharge Rating" method Practical or Impossible. These flow conditions include flow reversals, backwater effects, hysterstetis effect (different Discharge relation for Rising and Falling Stages), and Channel – Roughness Changes (Morlock et.al.2002). It has-been used by USGS for over 20 years (e.g., Morlock et. al. 2002; Rantz, 1982a and 1982b).

The principle of Index-velocity method is to establish a rating or regression Equation (or rating Curve) for the relationship between the channel mean velocity and Index-velocity. Water level may be also a parameter for the rating. The Index-velocity is an average velocity measured at a local area in the channel cross-section. The mostly used Index-velocity is a horizontal line velocity measured by an acoustic velocity meter such as an H-ADCP. Index-velocity method can be used for a channel with its width much greater than the H-ADCP profiling range.

Discharge is calculated by:

$$Q = AV \qquad [4.1]$$

Where: V = channel mean velocity, A = wetted area in channel cross-section. The wetted

Area is a function of cross-section geometry and water level.

For a given site, it is a function of water level only (the so-called stage-area rating):

$$A = f(H) \qquad [4.2]$$

Where: H = water surface level referring to a local datum. The wetted area usually is Presented as a table or cover for a site.

A general form of Index-velocity rating (that is, the mean velocity V as a function of the

Index-velocity and stage) is as follows:

$$V = f(V_I,\ H) \qquad [4.3]$$

Where: V_I = Index-velocity, f=velocity regression or rating equation.

In most case channel mean velocity is a function of Index-velocity only:

$$V = f(V_I) \qquad [4.4]$$

The development of an Index-velocity rating involves two steps. The first step is to collect data for discharge and Index-velocity. While a H-ADCP samples velocities (Index velocities), discharge measurements are conducted concurrently using a traditional velocity meter method or the moving boat ADCP method. The channel means velocities are calculated from the measured discharge Q and wetted area A. The wetted area is calculated from the stage-area rating. The field data collection needs to be conducted at a range of discharge.

The second step is to create a relationship between the channel mean velocity and Index velocity by regression analysis of field data. The regression procedure involves (1) the selection of an appropriate analytic regression equation, and (2) the determination of

Coefficients in the regression equation by the least-square method. The analytic regression equation should be selected to be the best fit to the field data. It also needs to comply with the hydraulics at the site.

A number of analytic regression equations may be used for index-velocity rating (Table 1). The most common one is linear. But it can also be non-linear or compound that may consist of two or more regression equations (represented by two or more discrete curves).

Table 4.1: - Analytic regression equations for Index-velocity rating developer

Equation Name	Expression
Linear (one parameter)	$V = b_1 + b_2 V_I$
Second-order polynomial	$V = b_1 + b_2 V_I + b_3 V_I^2$
Power law	$V = b_1 V_I^{b_2}$
Compound linear	$V = b_1 + b_2 V_I \quad V_I \leq V_c$ $V = b_3 + b_4 V_I \quad V_I \geq V_c$
Two parameter linear	$V = b_1 + (b_2 + b_3 H) V_I$

Note: b_1, $b2$, $b3$, $b4$ are regression coefficients.

The regression analysis can be performed using commercially available software.

Table 4.2: - Shows three such software and their features.

Name of Regression Analysis Software	**Main Features**
Excel By Microsoft Corporation	Liner regression only. Non-linear rating forms may be used When transformed into linear function.
IVR-Creator By Hydro Acoustic Soft	Linear and nonlinear regression analysis. IVR-Creator is Specially designed for creating Index-velocity ratings. It

Corporation	accepts Field data for channel cross-section geometry, discharge, water Level (stage), and Index-velocity, and fits the data with five Built-in analytic regression equations shown in Table 1.
NLREG By Sherrod, NLREG Developer	Linear and nonlinear regression analysis. NLREG can handle Linear, polynomial, exponential, logistic, periodic, and general Nonlinear functions.

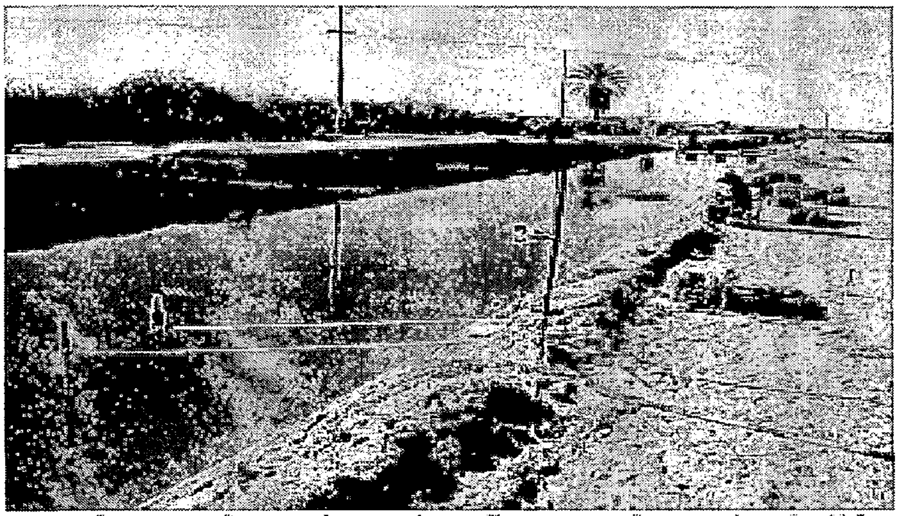


Fig 4.4: - Set-up of H-ADCP and moving-float ADCP at the canal site

4.2.2 Numerical Method

A Numerical method for discharge calculation using H-ADCP data was developed by Wang and Huang (2005). The method employs power law for open channel velocity vertical profile to obtain velocity distribution in the wetted area in channel cross-sect ion. Discharge is then calculated by integration of the velocity distribution. In principle, the numerical method does not require calibration. Below is a summary of the numerical method. Details on the method can be found in Wang and Huang (2005).

An H-ADCP is mounted on a bank at an elevation Z_{adcp} (measured at the surface of the Vertical transducer, Z=0 is a local datum). X-Y is the H-ADCP instrument coordinate. The H-ADCP is mounted with its orientation perpendicular to the channel mean flow direction. That is, X is parallel to the mean flow direction and Y is pointing to the cross-section direction. The effective velocity profiling range of H-ADCP should cover the majority of the channel cross-section.

Let be the velocity component perpendicular to the channel cross-section. Discharge Q can be calculated from the following:

$$Q = \iint_s V(y,z)\, dxdy \qquad [4.5]$$

Where s is the wetted area of the cross-section.

Assume the velocity distribution follows a power law:

$$V(y,z) = \alpha(y)\cdot(z - z_b)^{\beta} \qquad [4.6]$$

Where z_b is the channel bottom elevation, $\alpha(y)$ is the velocity distribution coefficient as a function of y, β is an empirical constant. β depends on channel roughness and flow Regime. β=1/6 is suggested by Chen (1991) for open channel flows. α (y) can be resolved from Eq. (4.6):

$$\alpha(y) = \frac{V(y, z_{adcp})}{(z_{adcp} - z_b)^{\beta}} \qquad [4.7]$$

Where $V(y, Z_{adcp})$ is the velocity measured by H-ADCP at cell located (y, Z_{adcp}).

A Numerical scheme was developed to implement the above flow calculation model. The Channel cross-section is first divided into a grid with square or rectangular elements. The Width of an element is usually one tenth of the maximum depth at the channel. Velocity at each element is calculated from Eq. (4.6). Finally, a Gaussian numerical integration is Applied to Eq. (4.5) to calculate discharge. A Windows-based software named Q-Monitor (Written in C++) was developed by Hydro Acoustic Soft Corp. to implement the discharge Calculation model with the numerical scheme. Q-Monitor can be used to set up H-ADCP, Acquire and display data, and calculate discharge in real-time.

4.3 UNCERTAINTY ANALYSIS OF ACOUSTIC METHOD

Ultrasonic flow meter is based on the measurement of the transit time of an acoustic pulse against the flow and in direction of the flow. To determine the mean flow velocity or the flow rate the absolute time of each pulse and the difference time between two opposite pulses of the same acoustic path are required. The most difficult problem is to reach a sufficient time resolution because the difference transit time can reach small values (dependent on the diameter of the section and the flow velocity). The acoustic discharge measurement method (ADM) is based on the superposition of the propagation velocity of a transmitted acoustic pulse (fig 4.5) with the flow velocity. To determine the mean velocity of the flow, the transit times t_u and t_d of an upstream and a downstream signal are needed.

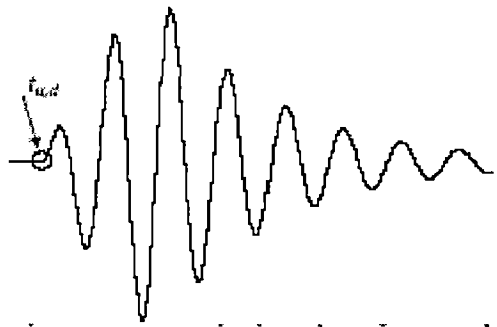


Fig 4.5: - A typical received acoustic signal where $t_{u,d}$ denotes the transit time

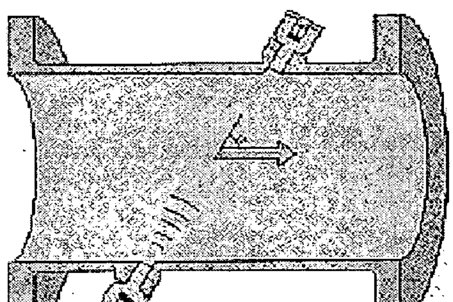


Fig 4.6: - Arrangement of two acoustic sensors in a circular section

The acoustic sensors are mounted at the pipe wall with an angle α to the mean flow (fig.4.6). The mean axial velocity is computed by the equation (see [4.8])

$$\bar{v}_{ax} = \frac{L}{2\cdot\cos\alpha}\cdot\left(\frac{1}{t_d}-\frac{1}{t_u}\right) = \frac{L}{2\cdot\cos\alpha}\cdot\left(\frac{\delta t}{(t_u-\delta t)\cdot t_u}\right)$$

[4.8]

Where L is the length of the acoustic path (distance between the two transducers) and δt denotes the transit time difference $t_u - t_d$. The actual acoustic velocity c in water is not needed for the determination of the path velocity as can be seen from equation (4.8).

The most difficult part of the measurement is the determination of the two-transit times $t_{u,d}$ with an appropriate algorithm, where the signal is digitized with an A/D converter. Special care must be given to an accurate determination of the transit time difference.

In the following two approaches for the influence of transit time measurement errors on the determination of the path velocity v_{ax} are presented.

-The first approach assumes the measurement of the absolute transit times of an up- and down stream sonic pulse (t_u and t_d) of the same acoustic path,

-The other just one absolute (t_u or t_d) and the difference transit time δt measurement.

It is shown that the accuracy of the second approach is approximately twice the accuracy of the first one.

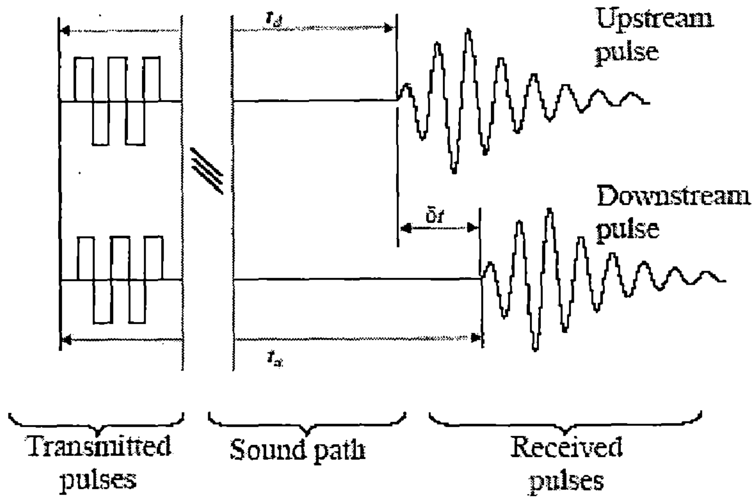


Fig 4.7: - Time difference Upstream and downstream pulse

4.3.1 TYPE OF ERRORS

There exist mainly two types of errors that occur in a measurement system, random and Systematical errors.

4.3.1.1 Random errors

The characteristic of these errors is that they are stochastical. In most cases one assumes that the errors of consecutive measurements are independent and thus are also uncorrelated. The errors are specified by a probability density function. Two different probability density functions are important in a typical data acquisition.

4.3.1.2 Normal distribution (Gaussian)

The normal probability distribution is characterized by a mean μ_N and a variance σ_n^2. This distribution is used for all kinds of unknown uncertainties. It is also a fact that the sum of *n* independent random variables which are not normal distributed, converges to a normal distribution for large *n*.

4.3.1.3 Uniform distribution

This distribution is often used in digital signal processing for A/D conversion effects and finite precision effects in computation. The error is uniformly distributed with a height of *1/Q* over a finite interval of length *Q* as shown in Fig. 4.8.

The mean of this distribution is μ_u is zero and the variance σ_u^2 is given by (see [2]):

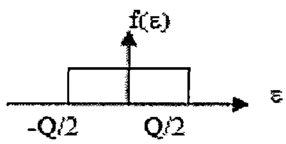


Fig 4.8: - Probability density of an uniformly distributed error variable

$$\sigma_u^2 = \int_{-\infty}^{\infty} \varepsilon^2 f(\varepsilon) d\varepsilon = \frac{1}{Q} \int_{-Q/2}^{Q/2} \varepsilon^2 d\varepsilon = \frac{1}{Q} \frac{\varepsilon^3}{3} \Bigg|_{-Q/2}^{Q/2} = \frac{Q^2}{12}$$

[4.9]

The parameter *Q* is typically the quantization step in finite precision arithmetic or in

A/D

Conversion. For *N* consecutive measurements of statistical independent data the variance of the error of the averaged results goes down as:

$$\sigma_{averaged}^2 = \frac{\sigma_{not\_averaged}^2}{N}$$

[4.10]

4.3.1.4 Systematic errors

Systematic errors are unknown but bounded, highly dependent and correlated. For example these errors are caused by deviations from device dimensions. Systematic errors cannot be detected by repeated measurements. This means that successive measurements cannot average out such errors. They can be compensated if they are known. Otherwise worst-case assumptions have to be applied for the determination of its effect.

For a single measurement it makes little difference whether the error is systematic or statistical. For systematic errors the worst bounds have to be used, while for statistical errors a worst case bound has to be specified if the distribution is gaussian (e.g. 3 times the standard deviation).

4.3.2 Signal Processing Chain

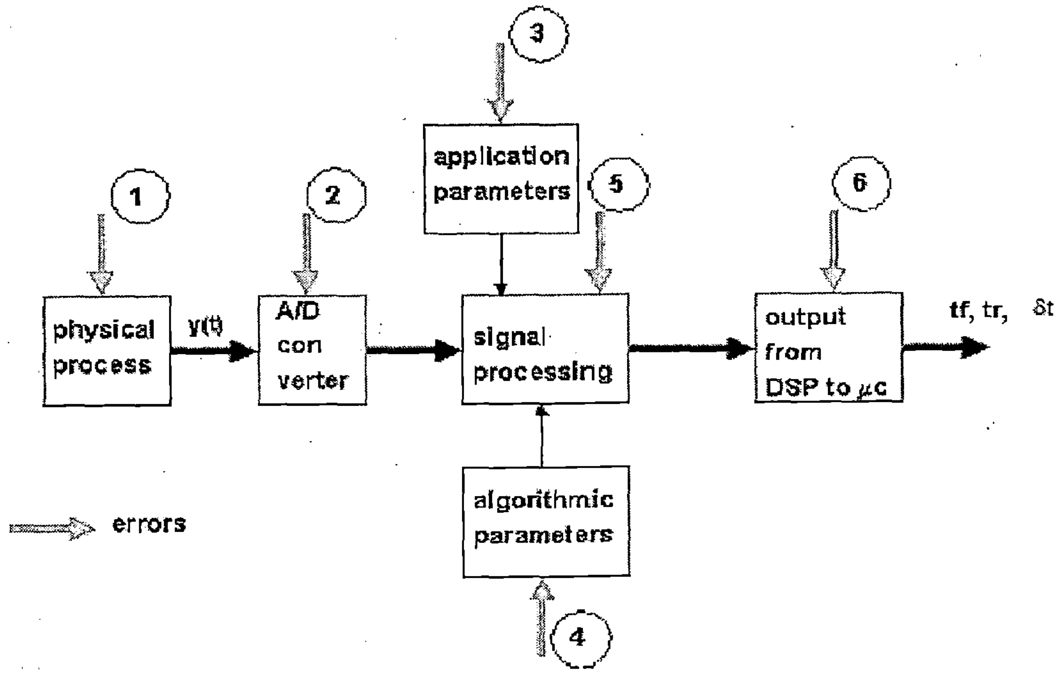


Fig 4.9: - Occurrence of errors in the measuring chain

These locations are the following:

1) Physical process: The hydraulic conditions determine the type and magnitude of errors or uncertainties. The signal varies due to various physical causes. The nature of these effects are of the statistical type with the simplified assumption of a normal distribution.

2) A/D converter: The A/D converter digitizes the incoming analog signal. The conversion to e.g.12 bits generates with not to stringent assumptions a quantization noise which is uniformly distributed.

3) *Application parameters*: These parameters are given by the configuration and can be determined to certain accuracy. They concern mainly geometrical data, e.g. the path length L and angle α.The errors generated here are of the systematic type.

4) *Algorithm*: The structure and the type of algorithm determine the existence and magnitude of systematic errors. The number of taps chosen limit for instance the performance of a FIR low pass filter.

5) *Signal processing*: This part processes the incoming data with a finite arithmetic. Therefore quantization errors occur with the quantization of the coefficients and at performing arithmetic operations. The coefficient quantization is a systematic error while the arithmetic errors can be considered statistical with a uniform distribution.
6) *Output from DSP*: This output quantization can be viewed like an A/D conversion. Either the results are quantized as fine as the intermediate results of the signal-processing path or they are quantized more coarsely. This again is considered a statistical error

After the determination of t_d, t_u and δt equation (4.8) is applied to obtain v_{ax}. For the error analysis uncertainties or inaccuracies in L, α, t_d, t_u and δt are of importance. Now we consider the following simplifications:

1) We consider only errors of the transit time determination and not of the geometrical parameters. If the geometrical parameters L and α play a role in the error analysis, then its effect will be felt twice: In the signal processing chain from the signal input $y(t)$ to the transient times and from the transient times to the path velocities.
2) For the worst-case analysis we restrict ourselves to the output quantization error ε_Q 6) only, which gives bounds to minimal and maximal errors. It must be noted that an unknown systematic offset in both absolute transit times t_u and t_d, do not affect δt, because of the subtraction of the absolute times for the determination of δt. This offset can therefore be of an order of magnitude larger than the output quantization. Only if the path length L (<0.5m) and the path velocity v_{ax} (<0.5m/s) are very small, this offset can no longer be neglected. If systematic errors in t_u and t_d do not cancel they have to be introduced as a separate error source ε_s, which can be incorporated into the output quantization source 6. The result will be a much coarser quantization, but the analysis will remain the same.
3) The statistical uncertainties of the entire signal processing chain (except the quantization 6) from the physical process to the transit times is summarized in a single noise source ε_s with normal distribution with mean μ_s and variance σ_{s2}. The output quantization ε_Q with uniform noise distribution 6) is treated separately and is considered uncorrelated to the noise source ε_s. and thus can mean and variances can be added to a single mean and variance.

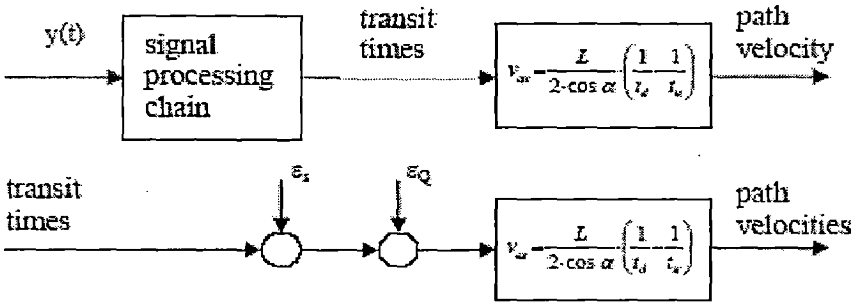


Fig 4.10 : - Error model for error propagation for path velocities determination

4.3.3 Path Velocity Error From Up- And Downstream Absolute Transit Time Measurements:

Systematic errors

Systematic errors of a function $F(x_1, x_2,..., x_n)$ with regard to errors in $x_1, x_2,..., x_n$ can be determined in a first approximation by linearization (see [3]):

$$\Delta F = F - F_0 = \sum_{k=1}^{n}\left(\frac{\partial F}{\partial x_k}\right)_{F_0}\Delta x_k \qquad x_k = x_{k,0} + \Delta x_k, \qquad k = 1,...,n$$

Systematic relative error =

$$e_{rel} = \frac{\Delta F}{F_0} = \frac{F - F_0}{F_0} = \frac{1}{F_0}\sum_{k=1}^{n}\left(\frac{\partial F}{\partial x_k}\right)_{F_0}\Delta x_k \qquad [4.11]$$

For worst-case analysis all terms have to be taken positive and for the Δx_k's the maximal possible value have to be choosen. For simplicity reason the index 0 is omitted in the forthcoming analysis.

If the two absolute transit times are measured one obtains for the path velocity from equation (14.8)

$$\bar{v}_{ax} = \frac{L}{2\cos\alpha}\left(\frac{1}{t_d} - \frac{1}{t_u}\right) = \bar{v}_{ax}(L, \alpha, t_d, t_u)$$

With equation (4.11) it follows:

$$\frac{\Delta \bar{v}_{ax}}{\bar{v}_{ax}} = \frac{\frac{L}{2\cos\alpha}\left(\frac{1}{L}\Delta L - \tan\alpha_0 \Delta\alpha - \frac{1}{t_d^2}\Delta t_d + \frac{1}{t_u^2}\Delta t_u\right)}{\bar{v}_{ax}}$$

$$\frac{\Delta \bar{v}_{ax}}{\bar{v}_{ax}} = \frac{\left(\frac{1}{L}\Delta L - \tan\alpha\ \Delta\alpha - \frac{1}{t_d^2}\Delta t_d + \frac{1}{t_u^2}\Delta t_u\right)}{\left(\frac{1}{t_d} - \frac{1}{t_u}\right)}$$

[4.12]

With the simplification $\Delta L=0$ and $\Delta\alpha=0$ we obtain:

$$relative\ error = \frac{\Delta \bar{v}_{ax}}{\bar{v}_{ax}} = \frac{\left(-\frac{1}{t_d^2}\Delta t_d + \frac{1}{t_u^2}\Delta t_u\right)}{\left(\frac{1}{t_d} - \frac{1}{t_u}\right)}$$

[4.13]

The resolution Q in absolute time is in the order of *ns*. If we assume a resolution of $Q=1ns$, then the maximum quantization error for the rounding operation is $+/-Q/2=+/-0.5ns$. For the worst case both errors Δt_u and Δt_d have a maximal value of $Q/2=0.5$ns. Equation (4.13) reduces to

$$relative\ error = \frac{\Delta \bar{v}_{ax}}{\bar{v}_{ax}} = \frac{\left(\frac{1}{t_d^2} + \frac{1}{t_u^2}\right)\frac{Q}{2}}{\left(\frac{1}{t_d} - \frac{1}{t_u}\right)} = \frac{1}{\delta t}\frac{\left(t_d^2 + t_u^2\right)}{t_u \cdot t_d}\frac{Q}{2}$$

$$\delta t = t_u - t_d$$

[4.14]

Figures 4.11,4.12 and 4.13 show the relative error as a function of path length, path velocity and time resolution Q. Fig.4.13 is a zoom of Fig. 4.12 for small velocities.

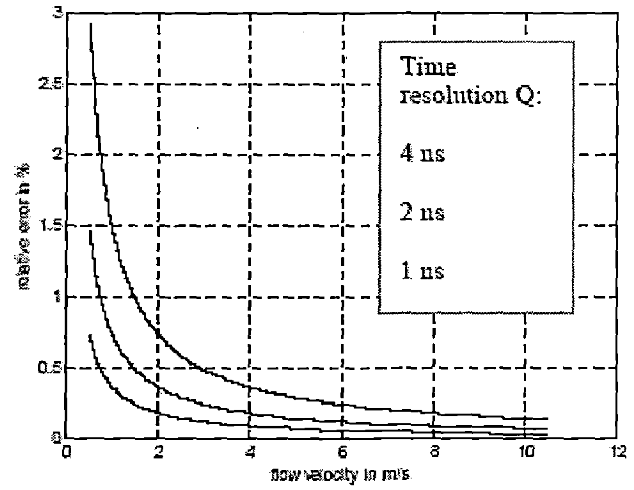


Fig 4.11 : - Error model for error propagation for path velocities determination

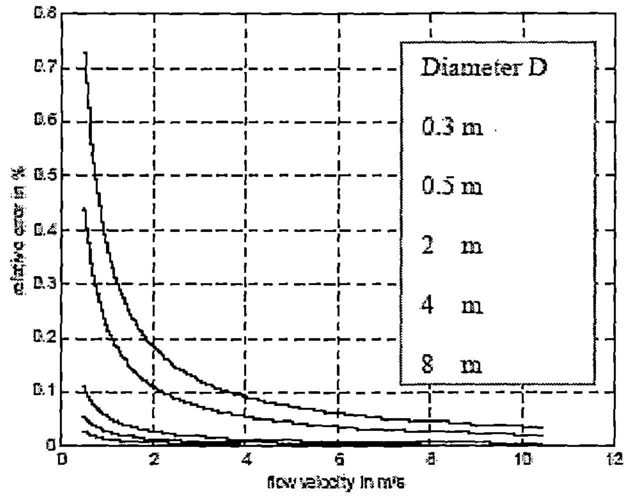


Fig 4.12 : - Relative error in velocity as a function of velocity, path length (diameter *D*) and fixed absolute time resolution *Q* of 1ns

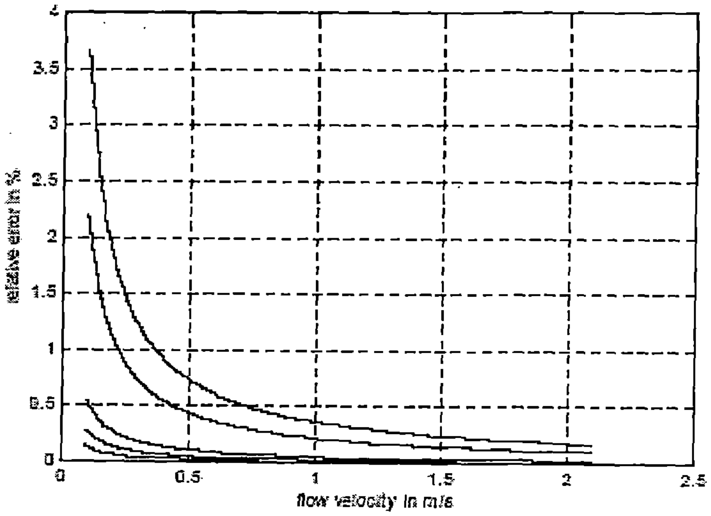


Fig. 4.13 : - Zoom of figure 4.12 for small velocities (0.1.2.1m/s)

The curves show all the same trends. For small velocities the relative error increases hyperbolically. Small time resolutions Q and large diameters reduce the relative error substantially. If we assume $t_u = t_d$, one gets from equation (4.14) the simple result:

$$relative\ error \cong \frac{\Delta \overline{v}_{ax}}{\overline{v}_{ax}} = \frac{Q}{\delta t}$$

[4.15]

The statistical error of a function $F(x_1, x_2,..., x_n)$ with regard to errors in $x_1, x_2,..., x_n$ are described by the Gaussian error propagation law. The variances of each error source are added weighted with some factors.

$$\sigma_F^2 = \sum_{k=1}^{n} \left(\frac{\partial F}{\partial x_k} \right)_{F_0}^2 \sigma_{x_k}^2$$

[5.12]

$$x_k = x_{k,0} + \Delta x_k \qquad \sigma_{x_k}^2 = E\left[(x_k - E(x_k) \ )^2 \right] = E(x_k)^2 - (x_{k,0})^2$$

Assumption Δx_k etc. to with small ed, uncorrelated $x_{k,0}, E(\Delta x_k) = 0$

(Where $E(x)$ denotes the *expected value*.) The relative variance is the given by

$$\frac{\sigma_F^2}{F_0^2} = \frac{1}{F_0^2} \sum_{k=1}^{n} \left(\frac{\partial F}{\partial x_k} \right)_{F_0}^2 \sigma_{x_k}^2$$

and the relative standard deviation

$$\sigma_{F,rel} = \sqrt{\frac{\sigma_F^2}{F_0^2}} = \frac{1}{F_0} \sqrt{\sum_{k=1}^{n} \left(\frac{\partial F}{\partial x_k} \right)_{F_0}^2 \sigma_{x_k}^2}$$

[4.16]

For the path velocity determination we assume statistical errors in the transit times only and not in the geometrical parameters. Thus one obtains the following relative standard deviation for the path velocity

$$\frac{s_v}{\overline{v}_{ax}} = \frac{\sqrt{\left(\left(\frac{1}{t_u^2} \right)^2 \sigma_u^2 + \left(\frac{1}{t_d^2} \right)^2 \sigma_d^2 \right)}}{\left(\frac{1}{t_d} - \frac{1}{t_u} \right)} = \frac{\sqrt{\left(\left(\frac{1}{t_u^2} \right)^2 \sigma_u^2 + \left(\frac{1}{t_d^2} \right)^2 \sigma_d^2 \right)}}{\left(\frac{\delta t}{t_d \cdot t_u} \right)}$$

[4.17]

Formula (4.17) can be simplified by the following assumptions:

-Both errors in the absolute transit time determination have the same statistics

-Both absolute transit times are nearly equal

Then we get for (4.17):

$$\frac{s_v}{\bar{v}_{ax}} \cong \frac{\sqrt{2}\,\sigma_{t_d}}{\delta t}$$

[4.18]

When comparing equation (4.18) with equation (4.15), one can recognize the same dependency on δt.The expression in the denominators differs, but are a mere scaling of the same curve. That means the curves of the systematic error can be used for the statistical error too. With the assumption of the error model shown in Fig.12.6, the variance of σ_{d^2} resp. σ_{u2} is given by:

$$\sigma_d^2 = \sigma_{\varepsilon_0}^2 + \sigma_{\varepsilon_s}^2$$

[4.19]

4.3.4 Path Velocity Error From One Up- Or Downstream Absolute Transit Time And The Transit Time Difference Measurement

We start from the same basic equation (4.8) and assume a measurement t_d in the downstream path and a measurement of the transit time difference δt with corresponding measurement errors Δt_d and $\Delta\delta t$:

$$v = \frac{L}{2\cos\alpha}\cdot\left(\frac{1}{t_d}-\frac{1}{t_u}\right) = \frac{L}{2\cos\alpha}\cdot\left(\frac{1}{t_d}-\frac{1}{t_d+\delta t}\right) = \frac{L}{2\cos\alpha}\cdot\left(\frac{\delta t}{t_d(t_d+\delta t)}\right) = \bar{v}_{ax}(L,\alpha,\delta t,t_d)$$

The same analysis as before yields with ΔL and $\Delta\alpha = 0$

$$\frac{\Delta\bar{v}_{ax}}{\bar{v}_{ax}} = \frac{t_d}{(t_d+\delta t)}\frac{1}{\delta t}\Delta\delta t - \frac{(2t_d+\delta t)}{t_d(t_d+\delta t)}\Delta t_d$$

[4.20]

If we assume that t_d is much larger than δt (similar to $t_d = t_u$) , then equation (13) reduces to :

$$\frac{\Delta\bar{v}_{ax}}{\bar{v}_{ax}} \cong \frac{1}{\delta t}\Delta\delta t - \frac{2}{t_d}\Delta t_d$$

[4.21]

If we compare this result with equation (4.15), we identify the first term of the right hand side of equation (4.21) with the right hand side of equation (4.15), if $\Delta\delta t$ is equal to Q. This means if the time resolution is *2ns* the rounding error for δt is ±1ns. So the second term of the right hand side of equation (4.21) makes the difference between the two measurement methods. But in most cases this term is negligible compared to the first term.

The factor 2 in the second term means that an error in the absolute transit time has a double weight compared to an error in the transit time difference. But as already mentioned above $t_d \gg \delta t$, the second term is of no importance. As an example, the absolute transit times of the installation (with a diameter of 0.5m) at the HTA in Lucerne are of approximately 260μs for the short paths and 450μsfor the long paths and the transit time differences are for v=0,5...8m/s approximately between 0.1...2μs. Put in equation (12.14) yields for the most pessimistic case:

$$\frac{\Delta \overline{v}_{ax}}{\overline{v}_{ax}} \cong \frac{1}{0.1\mu s}\Delta\delta t - \frac{2}{450\mu s}\Delta t_d$$

That means in this case an error in δt is about 2300 times worse than the same error in t_d.

Usually the diameter of such a conduit is larger than 0.5m. In this case the error due to the measurement of the absolute transit time is really negligible.

Fig.4.12 and 4.11 show the dependency of the relative error with respect to the transit time

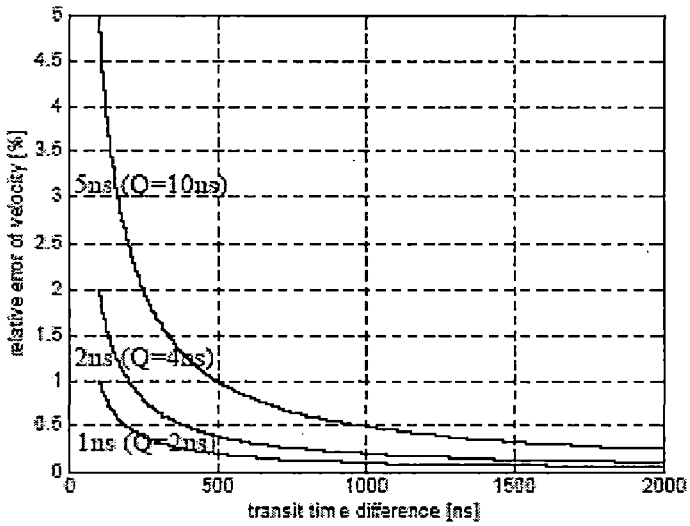


Fig 4.14 : - Relative velocity error in function of the *transit time difference* for different rounding errors in ns with the corresponding time resolution Q in brackets.

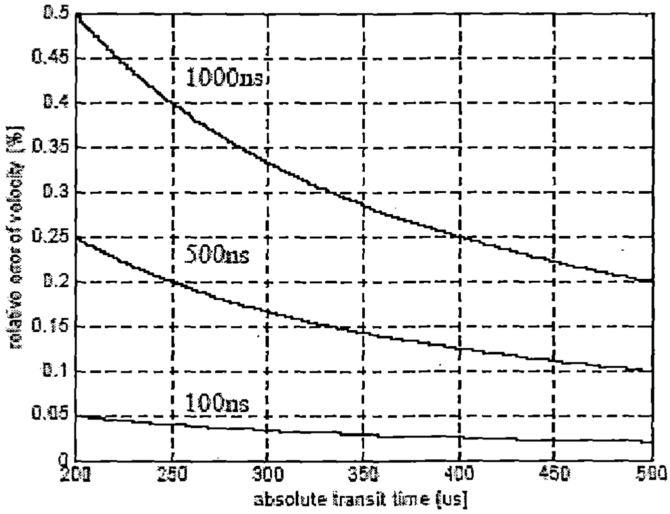


Fig. 4.15 - Relative velocity error in function of the *absolute transit time* (in μs) for different time resolution (errors) in ns.

If the relative velocity error has to be kept below 0.5% (for velocities larger than 1m/s and a diameter of 0.5m), then the transit time difference has to be determined with a time resolution of Q=1ns (Fig. 4.16) in the worst case for a single measurement. Successive measure-ment decreases the error according to the "*root-law*" of statistics (see [3]).

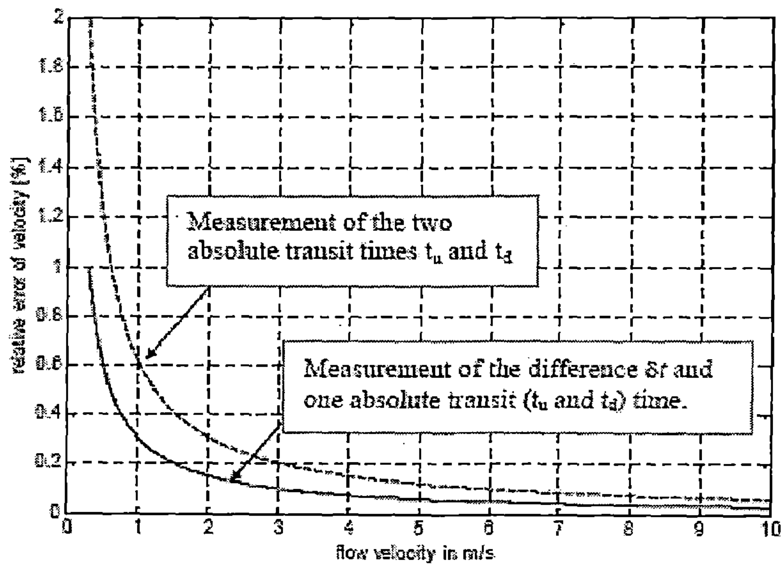


Fig.4.16 : - Comparison between the two different approaches for a fixed time resolution (Q=1ns) and diameter (0.5m).

In the first case of two absolute transit time measurements, both measurements should not have a maximal rounding error of larger then ±Q/2.

In the case of measuring the difference time and one absolute transit time the maximal rounding error could reach ±Q (Fig. 4.14), whereas the time resolution for the absolute transit time measurement has to be only in the order of *100ns*(Fig. 4.15). Hence the accuracy of the second approach is twice the accuracy of the first one.

4.3.5 Errors Due To Installation Methods

Ultrasonic flow measurement can provide an accuracy of up to ±0.5%. However, these accuracies can only be achieved if the installation of the flow meter is carefully executed. The installation error can influence the overall accuracy of the flow meter very strongly and depends on the skills of the installation crew and the surveying equipment used by the time the flow meter is installed. Very often the installation cost for a multipath flow meter can be as high as the cost of the flow meter itself.

The installation and surveying of acoustic transducers can be reduced to a sequence of measuring length and angle in space. The aim of all the surveying methods are to define the position of the drilling point of the transducer in a conduit and to measure as accurate as possible all characteristic dimensions such as path length (L), path angles (φ), and diameter (D) (figure 4.8). In cases where variable weights are used according to OWICS [VOS], the elevation levels (d) or angular position (α) need also to be measured.

The uncertainty of an acoustic discharge measurement is the sum of errors from different sources and can be divided into;

1) Installations errors 2) Integration errors (3) Instrument errors.

The instrument errors are designed in to the flow meter processing unit by the manufacture and are essentially defined by the error on the determination on the transit times.

The integration errors are influenced by the velocity distribution, the presence of the secondary flow profile and applied integration techniques. The protrusion effect can also be added to the integration error because the transducers alter the flow around it. The out of roundness of a penstock can introduced further errors on the integration but it can be neglected for out of roundness of less than 1%.

The installation errors can be characterised as the errors on the geometrical path parameters L_{wi}, and the cross section measurement. At this point, it should also be noted that when the flow meter is in operation, further errors on the geometrical path parameters and diameter could be caused by reversible deformation of the conduit due to the change in internal pressure and change in ambient temperature. A change in temperature will cause to change the diameter of the conduit but for Normal condition it can be neglected. The change in diameter due the internal pressure should only be the considered if the radial expansion is not hindered for instances by stiffening rings, saddles etc. the weight of water between to saddles can cause further errors, but it can be neglected under normal condition [VOS].

Characteristic of the installation error s is that by using modern surveying tools they can be defined and accounted for, but often the tools and the know-how are not available, and therefore these errors have to go into the instrument systematic error. The installation error is strongly influenced by the skills and know- how of the installation crew and the surveying equipment used. These errors are determined at the time the acoustic paths are installed.

The influence of the angular position d_i of the transducer is studied by using numerical simulation on the angular path misalignm, ent. Voser [VOS] has shown that for a path misalignment of 0.5 and 1.0 for the outer path,at the 54 angular position, asystematic error of 0.2% and 0.32% respectively.installation errors can be studies by analyzing the influence of the geometrical parameters Lwi, φ_i, D in the quadrature integration (2)formulae. Systematic errors of a function F (x1, x2,x3-------xn) with respect to measuring errors in x1,x2, xn can be determined in a first approximation by a linerization [HeI]

Relative systematic error $$_{rel} = \frac{\Delta F}{F_0} = \frac{F - F_0}{F_0} = \frac{1}{F_0}\sum_{k=1}^{n}\left(\frac{\partial F}{\partial x_k}\right)_{F_0} \Delta x_k$$

$$x_k = x_{k,0} + \Delta x_k \qquad k = 1,..,n$$

For worst case analysis, which produces a ‘conservative “error figure, all terms have to be taken positive and for the maximal possible values have to be chosen. the statical error function cal also be described by the gaussian error propagation law which might produce a more typical value. But since many of the error sources are sysmatic, the favored Approach is to use the ‘worst case” result, particularly where accuracy guarantees are important. Discharge through the conduit is determined from integration of individual path readings, resulting in an equation which sums up the weighted path readings.

$$Q = k \cdot \frac{D}{2} \sum_{i=1}^{N} W_i \cdot \bar{v}_{axi} \cdot L_{wi} \cdot \sin\varphi_i$$

The mean axial velocity along the acoustic path I is given by the well known formulae

$$\bar{v}_{axi} = \frac{L_i}{2\cos\varphi_i}\left(\frac{1}{t_d} - \frac{1}{t_u}\right)$$

The relative systematic error can be expressed with the following formulae.

$$\frac{\Delta Q}{Q} = \frac{\frac{1}{D}\sum_{i=1}^{N} W_i \cdot \left(\frac{1}{t_{di}} - \frac{1}{t_{ui}}\right) \cdot L^2 \tan\varphi_i \Delta D + 2\sum_{i=1}^{N} W_i \cdot \left(\frac{1}{t_{di}} - \frac{1}{t_{ui}}\right) L \cdot \tan\varphi_i \cdot |\Delta L_{wi}| + \sum_{i=1}^{N} W_i \cdot \left(\frac{1}{t_{di}} - \frac{1}{t_{ui}}\right) \cdot L^2 (1 + \tan^2\varphi_i) |\Delta\varphi_i|}{\sum_{i=1}^{N} W_i \cdot \left(\frac{1}{t_{di}} - \frac{1}{t_{ui}}\right) \cdot L^2 \tan\varphi_i}$$

Table 4.3: - Errors in different installation method

	Tape Measure	**Mechanical Theodolite**	**Total station theologize**
Diameter, D	±0.10%	±0.10%	±0.10%
Path lengh, L_i	±0.18%	±0.18%	±0.18%
Path angles, ϕ_i	±1.80%	±0.35%	±0.17%
Elevation angles α_i	±0.64%	±0.13%	±0.08%
	±2.72% ±(96%)	±(0.23%) ±0.76%	±0.53% ±0.18%

Table 4.4: - Measuring error on Geometrical Parameter for the tape measure Method

Diameter, D	**Path length, L_i**	**Path angles φ_i**	**Elevation angles α_i**
± 0.1%	± 0.1%	± 0.6%	±0.5%

Diameter	**Path length L_i**	**Path Angle ϕ_i**	**Elevation angle α_i**
±0.1%	±0.1%	$\pm 0.1^0$	$\pm 0.1^0$

Angle measurement error is within $\pm$ 0.1 % which is due to the ability to set up the theodolite on the true conduit center line

Table 4.5: - Measuring on the Geometrical parameters for the mechanical theodolite method

Diameter, D	**Path length L_i**	**Path Angle ϕ_i**	**Elevation angle α_i**
$\pm$0.1%	$\pm$0.1%	$\pm 0.6^0$	$\pm 0.55^0$

Table 4.6: - Measuring Errors on the geometrical parameters on the total station theodolite method

Diameter	**Path length Li**	**Path angle ϕ_i**	**Elevation angle α_i**
$\pm$0.1%	$\pm$0.1%	$\pm 0.05^0$	$\pm 0.05^0$

Path angle measuring errors indicate that they have a large influence on the relative systematic error on the flow rate. For the full range of velocities and conduit diameters, a measuring error of 0.1^0 introduces a relative systematic error of 0.35% for path angles at 45 ^{0}, but for path angles at 60 ^{0}, the same measuring error of 0.1 ^{0} causes a relative systematic error which is considerably higher.

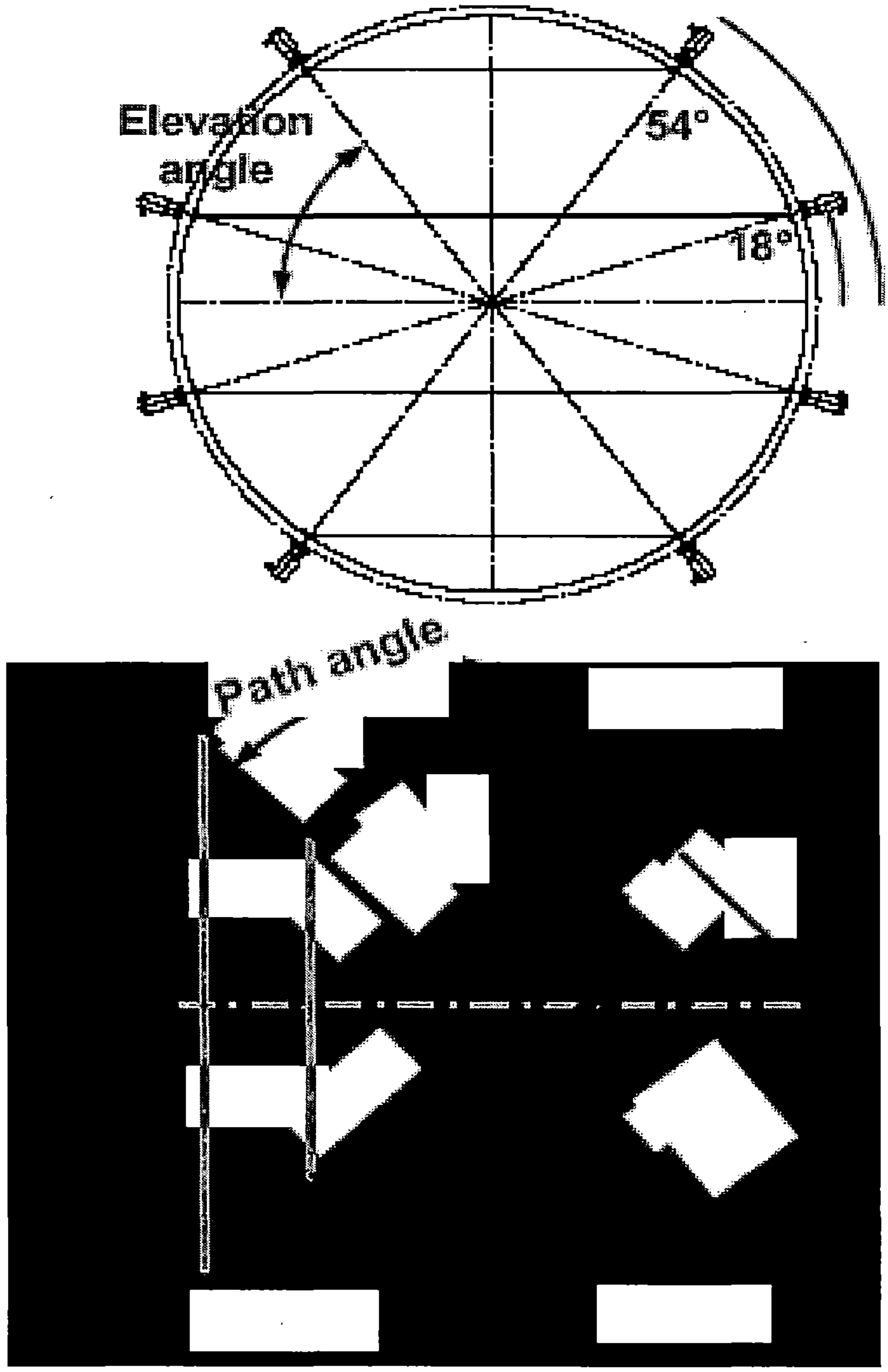


Fig 4.17: - Multipath (8path) arrangements of Transducers in a circular conduit

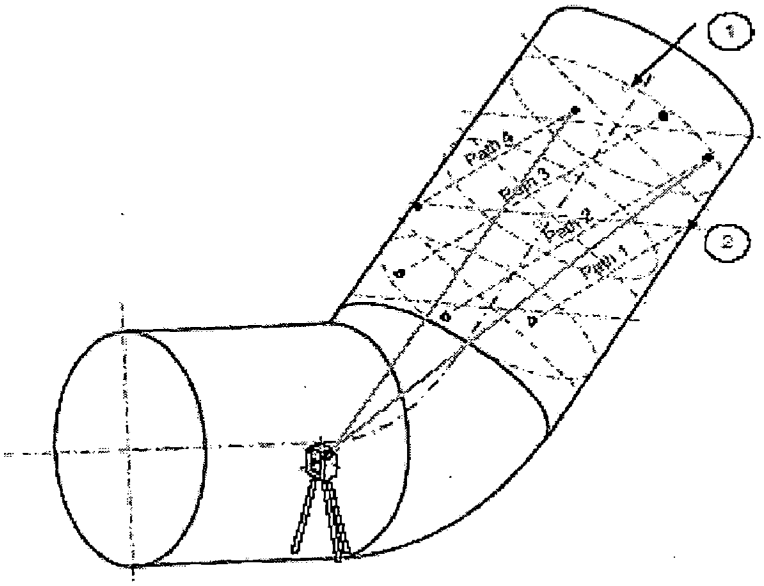


Fig 4.18: - Schematic of an installation set up with a total station theodolite

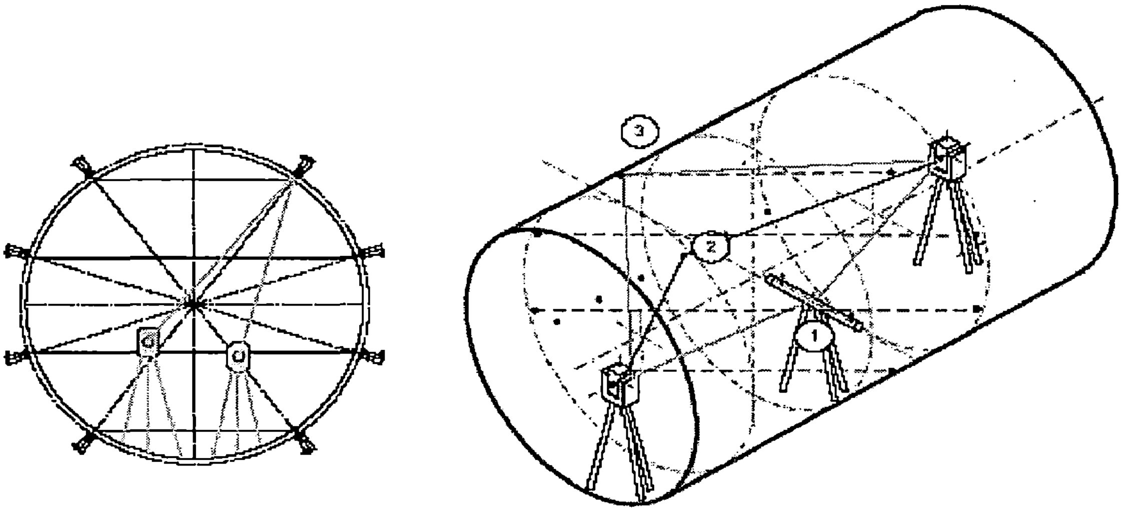


Fig 4.19: -Schematic of an installation set up with two motorized mechanical thedolite.

TRACER TIME METHOD

An alternative to Velocity measurement is the tracer dilution method. Stream discharge is determined on the basis of how much of the tracer is diluted by the flowing water. Suitable tracers have the following characteristics:

1. They readily dissolve in water at ordinary temperatures
2. They are absent in the stream or present at very low concentrations
3. They are not decomposed in the stream and is not retained or absorbed in significant quantity by plants, sediments, or other organisms
4. They can be detected in extremely low concentrations
5. They are harmless to the environment

Salts and dyes have been used in tracer studies. Fluorescent dyes, such as Rhoda mine, are commonly used tracers for hydrologic studies. Fluorometers are used to measure the concentrations of fluorescent dyes. The fluorometer measures the strength of the light emitted by the fluorescent substance.

Tracer dilution techniques are more difficult to use than current meter techniques and under most conditions, the results are less reliable. The dilution method should only be used when conditions are unfavorable for current meter discharge measurement, such as in rough channels that exhibit highly turbulent flow.

5.1 THEORY OF TRACER METHODS

In tracer dilution methods, a tracer is injected into a stream and subject to dilution by the stream. The stream discharge can be determined from the rate of injection, the concentration of the tracer in the injection solution, and the downstream concentrations. There are two primary methods for discharge determination using tracer dilution principle:

a) The constant rate injection method

b) Sudden injection method. (Integration method)

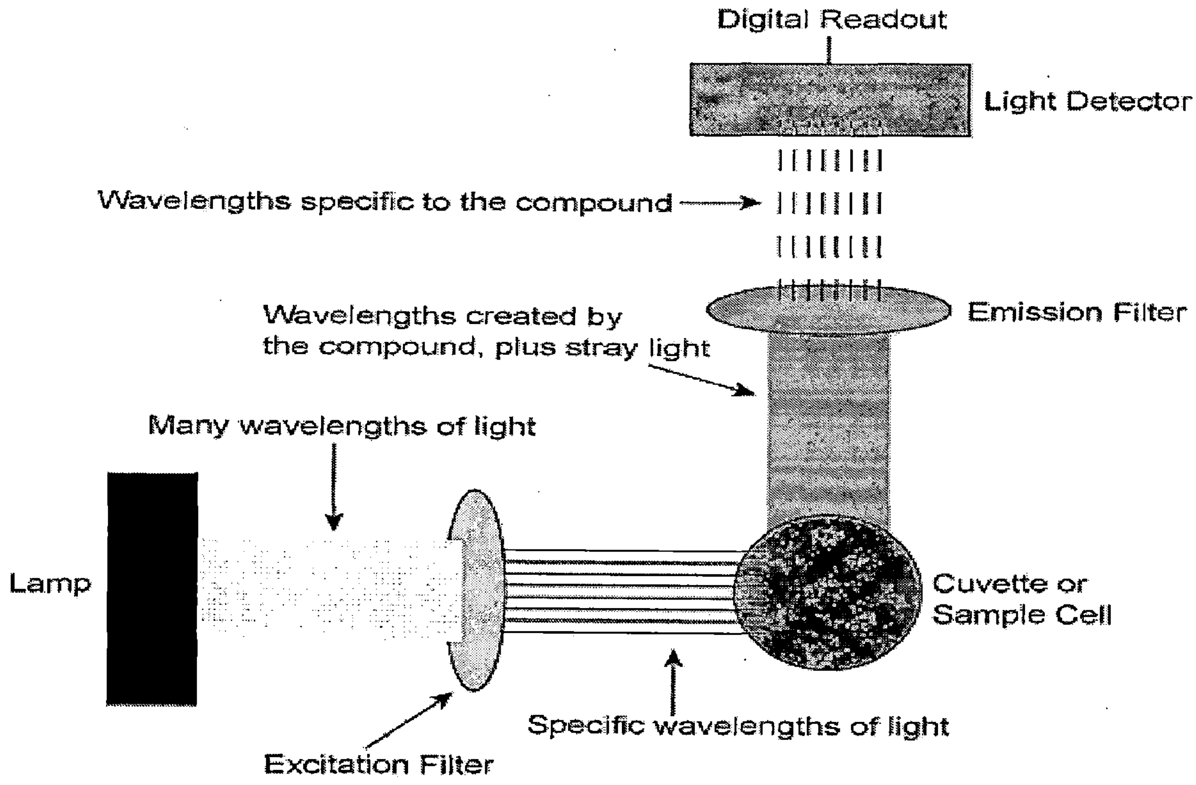


Figure 5.1: - Basic operation of a fluorometer

In the constant rate injection method, the tracer solution is introduced to the stream at a constant flow rate over a period sufficiently long to achieve a constant concentration of the tracer in the stream flow and at the downstream sampling locations. The instantaneous injection of a slug of tracer solution is the basis of the sudden injection method. The determination of the total mass of tracer at a sampling cross section determines, indirectly, the stream discharge. Also, if the cross sectional area of the stream or conduit is constant, the sudden injection method may also be used to determine the velocity of flow.

The third method is known as the "transit-time method", is based on a measurement of the time taken for a tracer to travel a specified distance between two cross-sections in a pipe or in an open channel. However, in the present state of knowledge, and for the purpose of this standard, only the constant-rate-injection method and transit-time method, in closed conduit, are recommended. Moreover, the transit-time method is to be preferred to the constant-rate-injection method, due to the spurious and random errors, which can arise when using the later.

Standards are available for these methods using both radioactive and non-radioactive tracers. The methods are particularly suitable where there are relatively long lengths of penstock available or where additional mixing of the tracer may be obtained by inclusion of the machine in the measuring length or the installation of mixing pyrometers, as the machine alone does not provide sufficient mixing. [14]

5.2 TRACER DILUTION TECHNIQUES

5.2.1 Constant Rate Injection Method

A constant rate injection system is illustrated in Figure 5.2.The principle of this method of discharge measurement is the continuous injection of tracer into the main water flow at a steady measured rate and the determination of the resulting concentration of the tracer, relative to its initial concentration, at a point far enough down stream to ensure thorough mixing. Provided the tracer is introduced into the stream for a sufficiently long period of time, the concentration variation at a downstream cross section will resemble a concentration time curve similar to Figure 5.3.

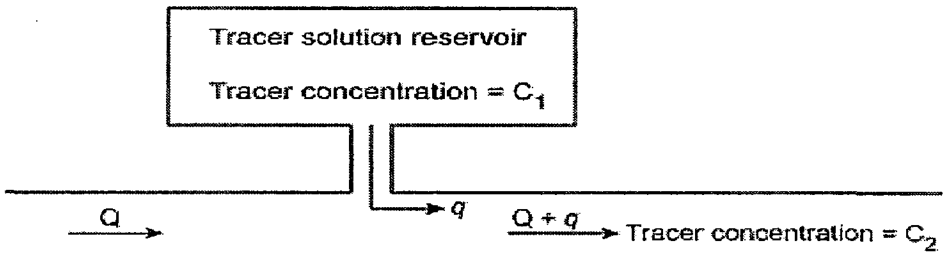


Figure 5.2: - Constant rate tracer injection system.

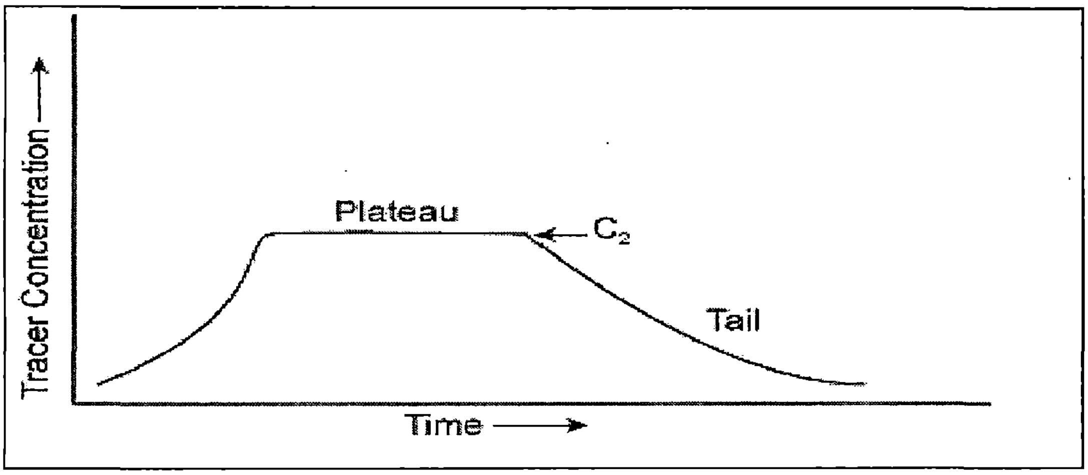


Fig 5.3: - Typical concentration curve with constant tracer injection.

It is not necessary to know the geometric characteristic of the pipe but it is essential to ensure that reverse or side currents do not exist which could abort some of the tracer.

Also the concentration of tracer in natural water must be constant and not exceed 15% of the concentration at the sampling point during injection of the tracer. Radioactive and non-radioactive tracers can be used.

The discharge Q can be determined from:

$$Q = q\,\frac{C_1 - C_2}{C_2 - C_O} \qquad [5.1]$$

Where:

Q is the discharge to be measured

q is the discharge of tracer solution injected

C_O is the initial concentration of tracer in natural water

C_1 is the concentration of tracer in injected fluid

C_2 is the concentration of tracer in the sampling station

5.2.2 Sudden Injection Method

The instantaneous injection of a slug of tracer solution produced a downstream concentration time curve similar to Figure 5.4

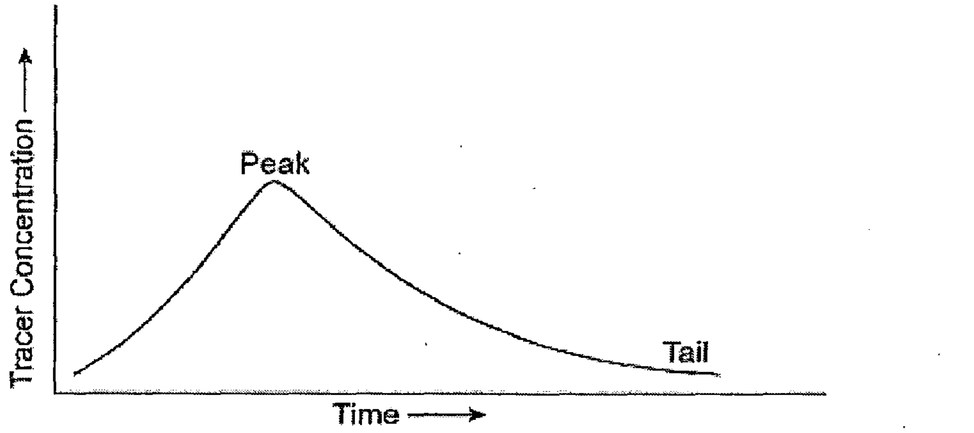


Fig 5.4: - Typical concentration curve with sudden tracer injection.

5.2.3 Accuracy of Tracer Dilution Method

There are three primary sources of error in the tracer dilution methodology, turbidity interference, loss of tracer, and insufficient tracer mixing. Turbidity can either increase or decrease the recorder tracer concentrations (fluorescence) depending on the relative concentrations of tracer and turbidity. The effects of turbidity can be minimized by allowing sample to stand long enough to facilitate the settling of suspended solids.

Conservation of mass is the basis for the determination of stream discharge in the tracer dilution method. The accuracy of the discharge calculation is adversely affected if some of the tracer is lost. Tracer losses are typically the result of adsorption and chemical reaction between the tracer and streambed material, suspended sediments, dissolved material in the river water, plants, or other organisms. The amount of tracer loss via adsorption varies primarily with the type of tracer, and the type and concentration of suspended and dissolved solids in the water. The best tracer is that which is least affected by the absorption process.

Photochemical decay is another possible source of tracer loss. It varies with the tracer material used and the residence time in direct sunlight. The losses are usually negligible with fluorescent dyes if the residence time is limited to a few hours.

Examination of Equation 5.1 show that if tracer mass is lost or destroyed by any means between the injection and sample point, the flow will be overestimated. An underlying assumption in the tracer dilution method is the complete vertical and horizontal mixing of the tracer with the ambient fluid. Vertical mixing usually occurs rapidly compared to lateral mixing. As a result, long reaches are typically needed for complete lateral mixing of the tracer. The mixing distance will also vary with the hydraulic characteristics of the reach. It has been shown that ice cover can significantly reduce the mixing capacity of a stream reach (Engmann and Kellerhals, 1974).

In the constant rate injection method, complete mixing has occurred when the concentration, C_2, shown in Figure 5.3 has the same value at all downstream sampling locations. Complete mixing has occurred in the sudden injection method when the area beneath the concentration time curve (Figure5.4) has the same value at all points in the downstream sampling cross section. In either approach, for a reach of given geometry and stream discharge, the length of time for adequate mixing of the tracer is the same.

Complete or perfect mixing is seldom the goal since it requires an extremely long channel and a long period of injection or sampling. There exists an optimum mixing length for a given stream reach and discharge. If too short a distance is used, there is an inaccurate accounting of the tracer mass as it passes the sampling site. In contrast, too great a distance will produce excellent results but only if it is feasible to sample for an extended period of time. The optimum mixing length is the length that produces adequate mixing for accurate discharge measurements, but does not require an unusually long duration of injection or sampling.

These concepts are illustrated in the Figure 5.5. In the short sampling reach set of curves, adequate mixing occurs, and the tracer cloud must be sampled for its entire time of passage at several lateral locations in the channel, A, B, C. It is generally regarded that at least three sampling points should be used at each sampling site. Also as shown in the Figure 5.5, optimum sampling reach and long sampling reach of curves, the tracer cloud resulting from sudden injection must be sampled at the sampling site from the time of its first appearance there until the time, T_t, of is disappearance from the sampling cross section. In the constant rate of injection methodology, a plateau will first be reached at all points in the cross section at time T_t after injection begins at the injection site. The duration of injection must be at least equal to T_c; injection should continue long enough thereafter to ensure adequate sampling of the plateau.

In the long sampling reach, sampling at time S would result in a false conclusion that mixing was poor and the minimum required sample period, T_c, is extremely long. This results in excessive sampling costs. With good measuring techniques and flow conditions, the estimated systematic uncertainty at 95% confidence level should be about 1% to 2%.

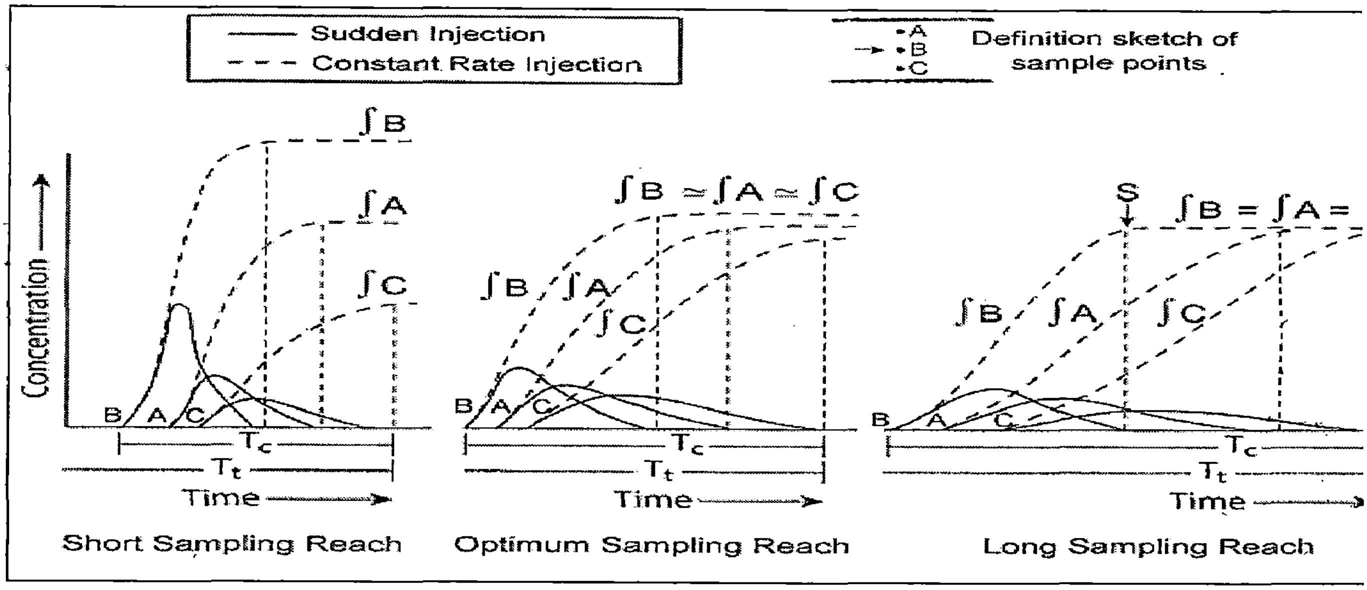


Figure 5.5: - Tracer concentration curves under a variety of injection and sample reach lengths.

PITOT TUBE METHOD

6.1 WORKING PRINCIPLE

The Pitot tube (named after Henri Pitot in 1732) measures a fluid velocity by converting the kinetic energy of the flow into potential energy. The conversion takes place at the stagnation point, located at the Pitot tube entrance (see the schematic below). A pressure higher than the free-stream (i.e. dynamic) pressure results from the kinematic to potential conversion. This "static" pressure is measured by comparing it to the flow's dynamic pressure with a differential manometer. Pitot tubes may be used to measure the dynamic pressure, from which the local velocity may be obtained, at each of a sufficient number of points in the cross-section to permit computation of the discharge by velocity area method.

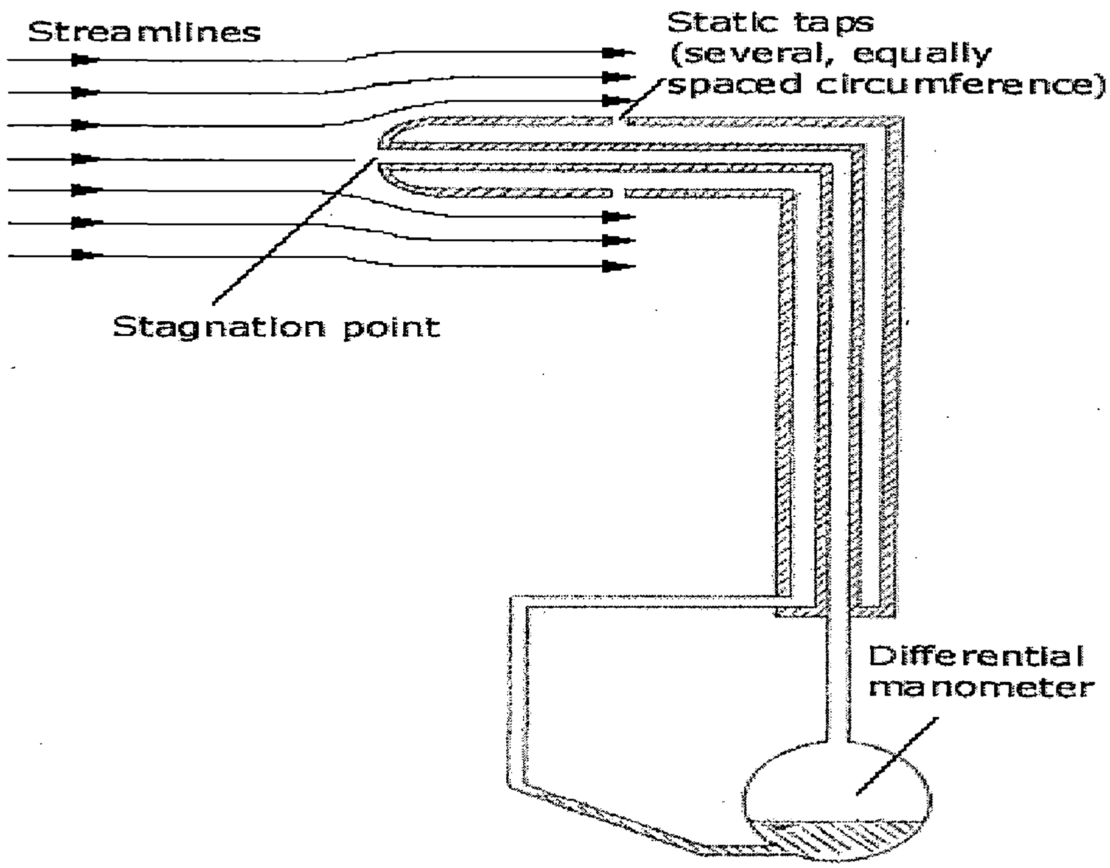


Fig.6.1 Cross-section of a Typical Pitot Static Tube

Since the dynamic pressure varies with the square of the velocity, the accuracy of the measurement decreases rapidly with decreasing velocity. In practical terms this restricts the use of pitot tubes to flow in closed conduits where the velocity is not too low and the water is free of suspended matter. The flow rate can be determined from the difference between the static and dynamic pressures, which is the velocity head of the fluid flow. An annular consists of several pitot tubes placed across a pipe to provide an approximation to the velocity profile, and the total flow can be determined based on the multiple measurements. [24]

6.2 GENERAL REQUIREMENTS

Converting the resulting differential pressure measurement into a fluid velocity depends on the particular fluid flow regime the Pitot tube is measuring. Specifically, one must determine whether the fluid regime is incompressible, subsonic compressible, or supersonic. ISO 3966 covers the design, installation and use of standardized pitot tubes. Only the clauses relating to incompressible fluid shall be used for testing under this standard. Any significant blockage must be taken into account. ISO 3966 shall be used only with the standardized pitot static tubes, described there in which are equipped with a single total pressure tap and one or more static pressure taps. Such tubes may be used uncelebrated and the flow coefficient is assumed to be unity.

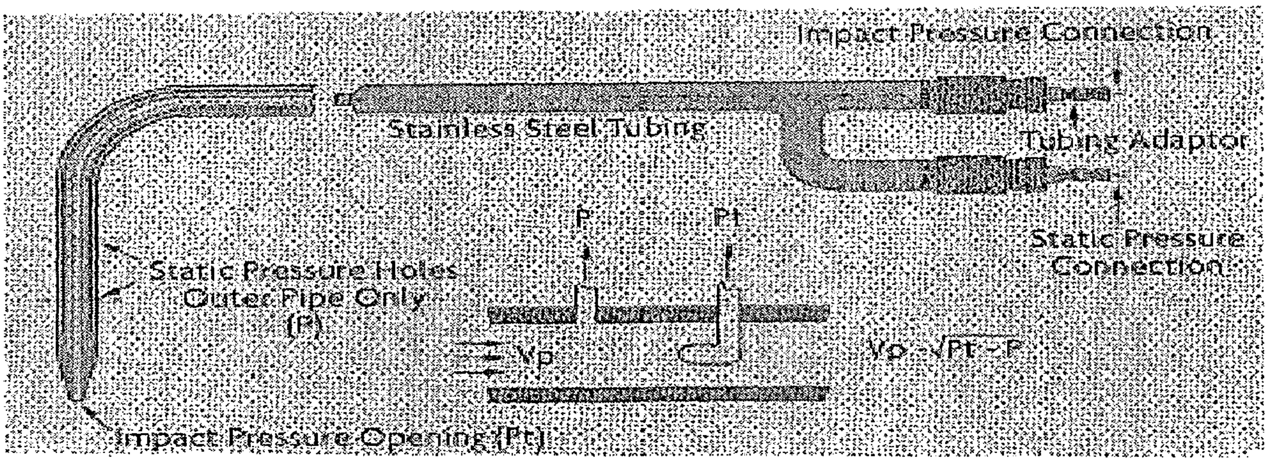


Fig 6.2 Pitot tube measuring two Pressure

6.3 VELOCITY CALCULATION

A flow can be considered incompressible if its velocity is less than 30% of its sonic velocity. For such a fluid, the Bernoulli equation describes the relationship between the velocity and pressure along a streamline,

$$\frac{V^2}{2g} + z + \frac{p}{\rho g} = C \qquad [6.1]$$

Evaluated at two different points along a streamline, the Bernoulli equation yields,

$$\frac{v_1^2}{2g} + z_1 + \frac{p_1}{\rho g} = \frac{v_2^2}{2g} + z_2 + \frac{p_2}{\rho g} \qquad [6.2]$$

If $z_1 = z_2$ and point *2* is a stagnation point, i.e., $v_2 = 0$, the above equation reduces to,

$$\frac{v_1^2}{2} + \frac{p_1}{\rho} = \frac{p_2}{\rho}$$

The velocity of the flow can hence be obtained,

$$v_1 = \sqrt{\frac{2(p_2 - p_1)}{\rho}}$$

Or more specifically,

$$v = \sqrt{\frac{2(p_{stagnation} - p_{static})}{\rho}} \qquad [6.3]$$

6.4 UNCERTANITY OF MEASUREMENT

The above equation is typically valid for incompressible (constant density) flow. High velocities (V) will lead to increasing errors. Presence of suspended matters in the fluid is another source of error. With good measuring techniques and flow conditions, the estimated systematic uncertainty at 95% confidence level should be about 1.5 to 2.5%.

COMPARISION OF VELOCITY MEASUREMENT BY TWO METHODS

7.1 SITE SELECTION FOR OPEN CHANNEL DISCHARGE MEASUREMENT

The selection of a suitable site for making a discharge measurement will greatly affect the accuracy of that measurement. The stream should be straight above and below the measuring section with the main thread of flow parallel to the banks. As a rule, the stream should be straight for at least three channel widths above and below the selected section. The streambed should be free of large rocks, pier, weeds, or other obstructions that will cause turbulence or create a vertical component in measured velocity. In this dissertation work the site, which is selected is canal situated at Badrabad. Velocity observations are made at each vertical preferably at the same time as measurement of depth, especially in the case of unstable beds. If unit width discharge is required, it is generally computed from the individual observations. In the integration method (2.4.4), the mean velocity is obtained directly. The discharge is computed either arithmetically or graphically by summing the products of the velocity and corresponding area for a series of observations in a cross-section. The section (2.7, 2.8) discusses the various methods used for open-channel discharge calculation using the propeller-current meters, as recommended by ISO-748 and IS-1192, [18, 19].

The basic idea regarding all the methods, described below is that a smooth curve is drawn for the determination of velocity profile along the depth and width of the section. Fig. 2.8 explains the above-mentioned scheme, for the discharge calculation. There are various methods in which the velocity profile in the vertical transects can be plotted [11, 12]. The smooth curve for the same can either be plotted by curve fitting methodology or by using some interpolating scheme.

7.2 MEASUREMENT POINTS

Measurement of the discharge for a turbine requires that a location in the open-channel be chosen as the measurement plane, and a number of sampling sections be established across it. In most of the cases flow in channel was non-uniform along the width and depth. So Velocity-Area Integration method was used to get the absolute value of discharge in the channel .The channel was divided into horizontal and vertical planes and the current meters are placed in these specific points to obtain the count, which in turn is converted to point velocities.

These matrix of point velocities will be the input to MATLAB program, which is given through excel data sheet in a specified format. The MATLAB program developed here is a generalized one, which will accept any number of point velocities and can calculate the absolute discharge.

For the development of methodology of discharge calculation on computer and the verification of program developed, data from the test run was used. The test was aimed at the measurement of discharge in open-channel using propeller current meters. The channel was rectangular in shape and dimension of channel were 6.42m total width and total depth of 0.45m from the water surface.

Since the flow in the channel was not uniform, a matrix of measuring points was formed, which is shown in Fig. 7.2. An arrangement of 12 points in rectangular section was proposed for the acquisition of velocities from the open channel. The number of transects required to sample in the vertical is achieved by placing the transducer array attached to a movable frame, which was moved horizontally downwards to required elevations. It is assumed that the discharge during the sampling intervals was constant.

Four current meters were located at the depths of 0.10m, 0.20m and 0.30m, from water surface and laterally they were placed at distances of 1.284 m, 2.568m, 3.852m, a 5.136m from the right side of channel. As described in section, (7.2) a matrix of 3X4 = 12 current meters locations was formed that gives the flow velocities (point velocities) at these locations. At every depth, the revolutions made by the four current meters, over the 120s interval were counted electronically. Eight sets of such readings were taken at four minute intervals at one depth and the average flow velocity of water was worked out at the twenty current meters locations as shown in the table [1].

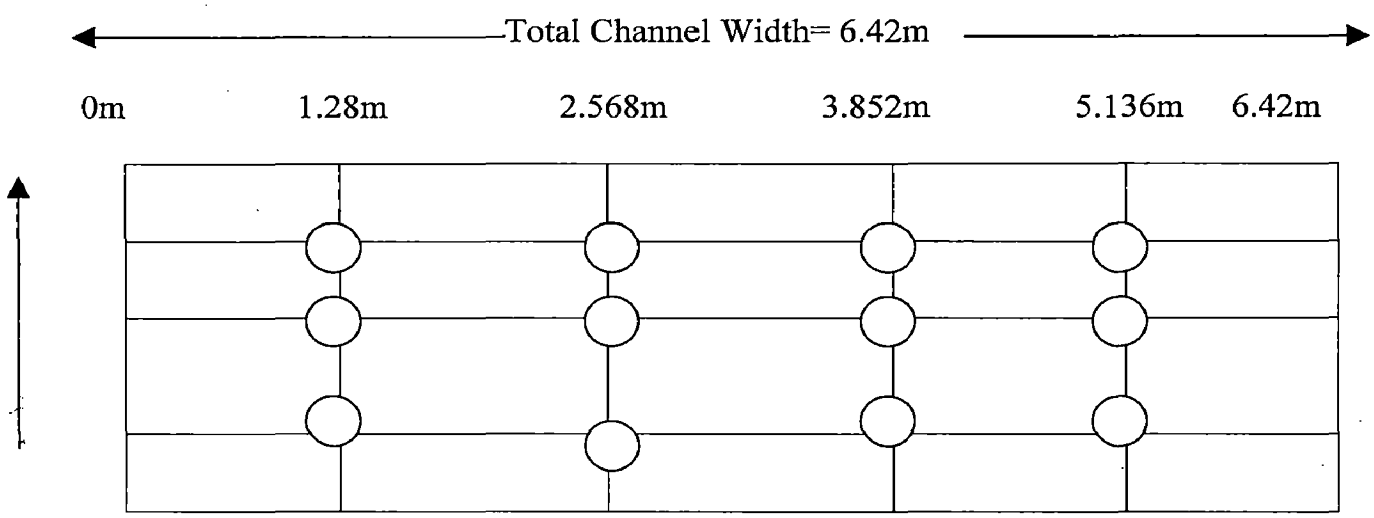


Fig. 7.1: - Matrix (3 X 4) of Measuring Points formed in the Open-Channel.

The placement of current meters in a flow channel will depend on the condition of the flow existing there. If the flow is very much irregular, then the number of measuring points should be increased. The 3X 4 matrix. The local point velocity measured by the current meters is tabulated in Table 7.1. In Table 7.2 the local point velocity measured by Horizontal Acoustic Doppler Current Profiler meter are tabulated.

Table 7.1: - Point Velocities Measured By Current Meters in the Open-Channel

WIDTH/ DEPTH (m)	1.284	2.568	3.852	5.136
0.1m	0.1695625	0	0.2880625	0.27965
0.20m	0.1690625	0	0.3007875	0.2607875
0.30m	0.20065	0	0.2814125	0.2625

able 7.2: - Point Velocities Measured By Horizontal acoustic Current Meter Profiler

WIDTH/ DEPTH (m)	1.284	2.568	3.852	5.136
0.1m	0.184	0.216	0.275	0.167
0.20m	0.174	0.247	0.280	0.255
0.30m	0.198	0.24	0.27	0.255

7.3 DISCHARGE CALCULATION

7.3.1 Current Meter Method

From the measured velocity at local points as shown in Fig 7.1, the average velocity and corresponding discharge of the channel is calculated. The average velocity depends on the value of power law coefficient, m, as mentioned in chapter 2, section 2.5.3. The value of m has been taken from 3 to 7 and average velocity and discharge are calculated. Calculation of average velocity is done by two interpolation methods, namely Cubic Spline and Cubic interpolation scheme and listed in Table 7.3. The Standard Deviation (SD) in velocity and discharge are also calculated.

Table 7.3: - Calculation of SD of discharge and velocity

m	By Cubic spline interpolation method		By Cubic interpolation method	
	Discharge (Cumec)	Avg. Velocity (m/s)	Discharge (Cumec)	Avg. Velocity (m/s)
3	0.451604495	0.156318620	0.451776856	0.1563782818
4	0.471572999	0.163230526	0.471761808	0.1632958837
5	0.485101737	0.167913374	0.485301501	0.1679825203
6	0.494867772	0.171293794	0.495075341	0.1713656426
7	0.502247048	0.173848061	0.502460463	0.1739219325
SD	± 1.83%.	± 0.635%	±1.798%.	± 0.617%

7.3.2 Horizontal Acoustic Current Meter Profiler Method

The same principle for calculating average velocity and SD are used here. But there is a difference in measuring the velocity in the local points as shown in fig 7.1. the results are listed in Table 7.4.

Table 7.4: - Standard deviation of discharge and velocity

m	By Cubic spline interpolation method		By Cubic interpolation method	
	Discharge (Cumec)	Avg. Velocity (m/s)	Discharge (Cumec)	Avg. Velocity (m/s)
3	0.426644973	0.147679118	0.425445784	0.147264030
4	0.445834088	0.154321249	0.444593767	0.153891923
5	0.458838908	0.158822744	0.457571213	0.158383943
6	0.468228694	0.162072929	0.466994147	0.161627370
7	0.479324726	0.164529154	0.474022879	0.164078532
SD	$\pm$ 1.72%	$\pm$ 0.5975 %	$\pm$1.723%	$\pm$0.46%

The Horizontal Acoustic Doppler Current Profiler also gives average velocity at different observation time and different depths. It can also give the SD of different velocities along the flow direction. From the values of average horizontal velocities discharge can be calculated as follows.

Width of Channel 6.42m

Depth of Channel 0.45m

Area of channel = 6.42*0.45 = 2.889 m^2

Discharge = Area of channel* velocity.

The results are listed in Table 7.5 below.

Table 7.5 :- Measurement of average velocity by H-ADCP method

Sl. No.	Velocity	Std Dev	Discharge
1	0.230	0.077	0.66447
2	0.244	0.065	0.704916
3	0.228	0.067	0.658692
4	0.248	0.070	0.716472

From the given values of SD, average SD can be calculated as follows

Average Std Deviation for Velocity = (0.077+0.065+0.067+0.07)/4

= .06975.

Standard Deviation For discharge $=[(0.003906/4)-(-0.07511/4)^2]^{0.5}$

= 0.0249781.

7.4 COMPARISON BETWEEN CURRENT METER METHOD AND HORIZONTAL ACOUSTIC DOPPLER CURRENT PROFILER

The SD in values of average velocity and discharge obtained from current meter method and horizontal acoustic Doppler current profiler (H-ADCP) methods have been compared here. The results are listed in Table 7.6 and 7.7 respectively.

Table 7.6: - Uncertainty in velocity measurements by two different methods

	Cubic Spline Scheme	Cubic Interpolation Scheme
Current Meter	± 0.635%	±.617%
H-ADCP	± 0.5975 %	± 0.46%

Table 7.7: - Uncertainty in Discharge Measurements by twon different methods

	Cubic Spline Scheme	Cubic Interpolation Scheme
Current Meter	±1.83%	±1.798%
H-ADCP	± 1.72%	**±1.723%**

CONCLUSIONS AND RECOMMENDATIONS

8.1 CONCLUSIONS

In the present thesis work the comparison of the velocity of flow in a rectangular cross section channel located at Badrabad is done by using the current meter and horizontal acoustic doppler current profiler (H-ADCP). The standard deviation of the velocity and discharge of the flow in the channel has been calculated and from this the uncertainty in these two methods are compared. From these following conclusions has been drawn.

(i) Uncertainty in Velocity measurement by current meter method within range of order of ±0 .635% and ±0.617%.

(ii) Uncertainty in Velocity measurement by horizontal acoustic Doppler current profiler (H-ADCP) of order of ±0.5975 % and ±0.4% in H-ADCP method.

(iii) Uncertainty in discharge measurement by current meter method within of order of ± 1.83%-& ± 1.798%.

(iv) Uncertainty in discharge measurement by horizontal acoustic Doppler current profiler (H-ADCP) greater than that is in order ±1.72% & ± 1.723% in H –ADCP Method.

(v) It is clear that by using the horizontal acoustic Doppler current profiler (H-ADCP), uncertainty in the measurement is lesser than the current meter. Hence Horizontal acoustic Doppler current profiler (H-ADCP) is more accurate than current meter.

8.2 RECOMMENDATIONS

The following are the recommendations done from the comparison of the velocity measurement in the rectangular channel by using current meter and horizontal acoustic doppler current profiler (H-ADCP) to measure the velocity. They are as follows

i. Even though Horizontal acoustic doppler current profiler (H-ADCP) is more accurate than current meter. The cost of Horizontal acoustic doppler current profiler (H-ADCP) is much higher than the current meter.

ii. The uncertainty in the current meter is with in the permissible range. For the small hydro applications, where cost plays a major role current meter can be used.

iii. It is preferred to use Horizontal acoustic doppler current profiler (H-ADCP) where the accuracy is utmost concern.

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ANNEXURE

Screen snap shots of the horizontal acoustic doppler current profiler software are given below

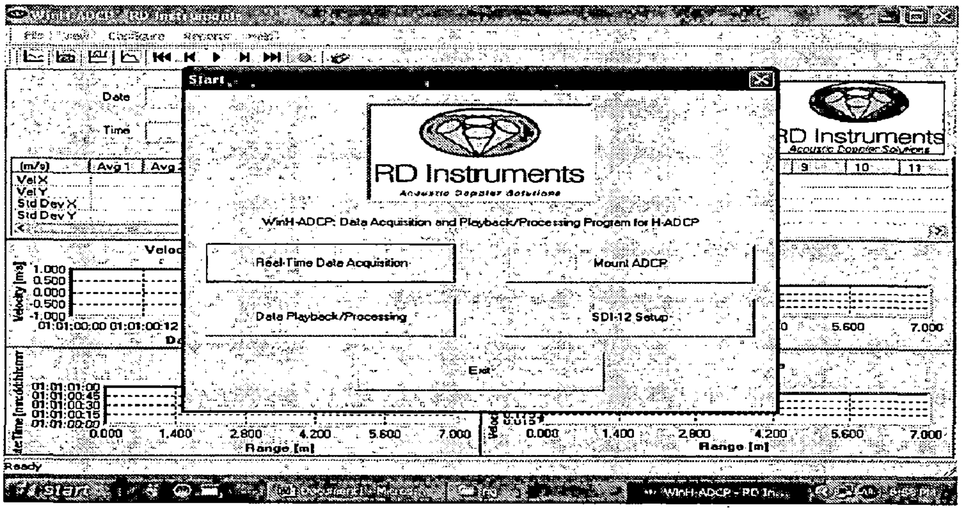

Fig.i: - Screen snapshot of horizontal acoustic doppler current profiler software

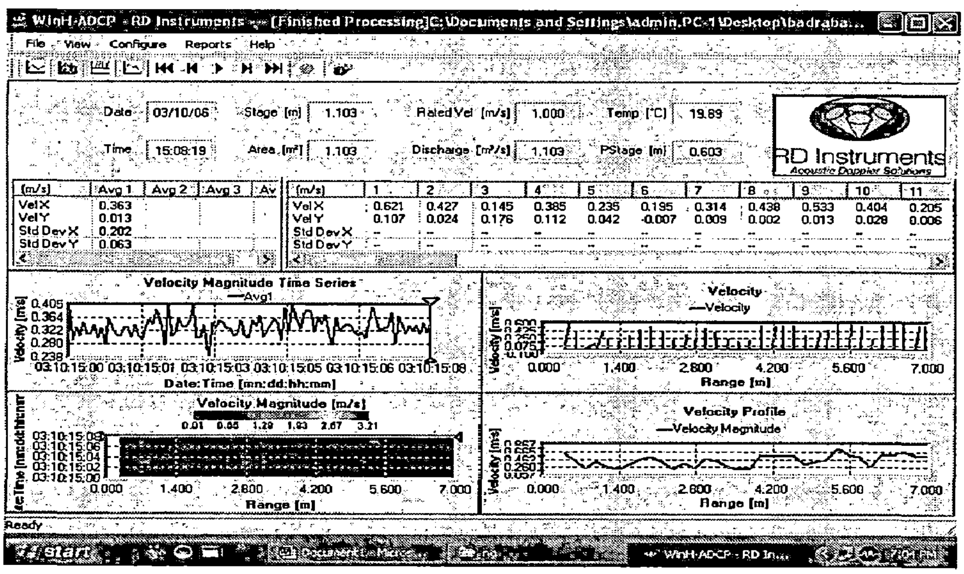

Fig.ii:- Snap showing Velocity magnitude at depth 0.30m

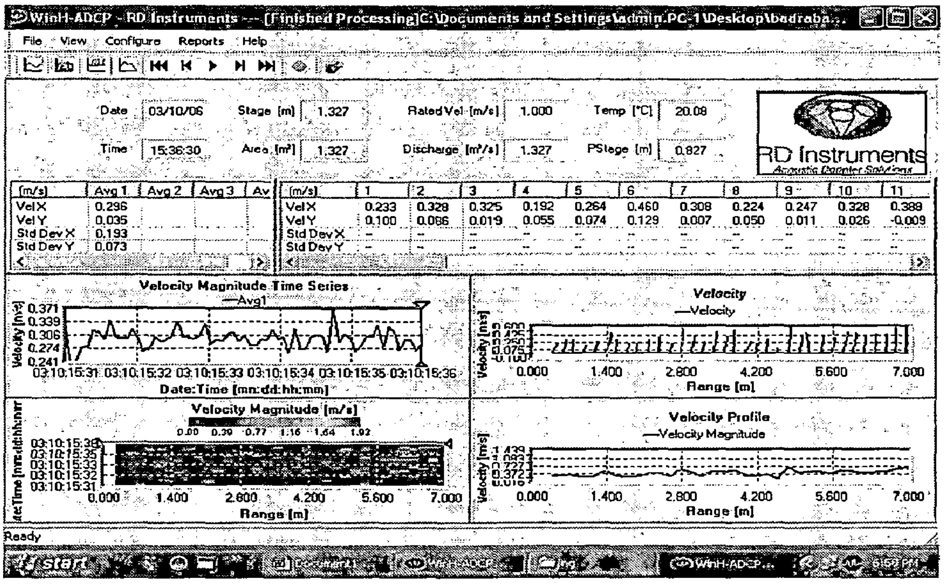

Fig. iii:- Snap showing Velocity magnitude at depth 0.20m

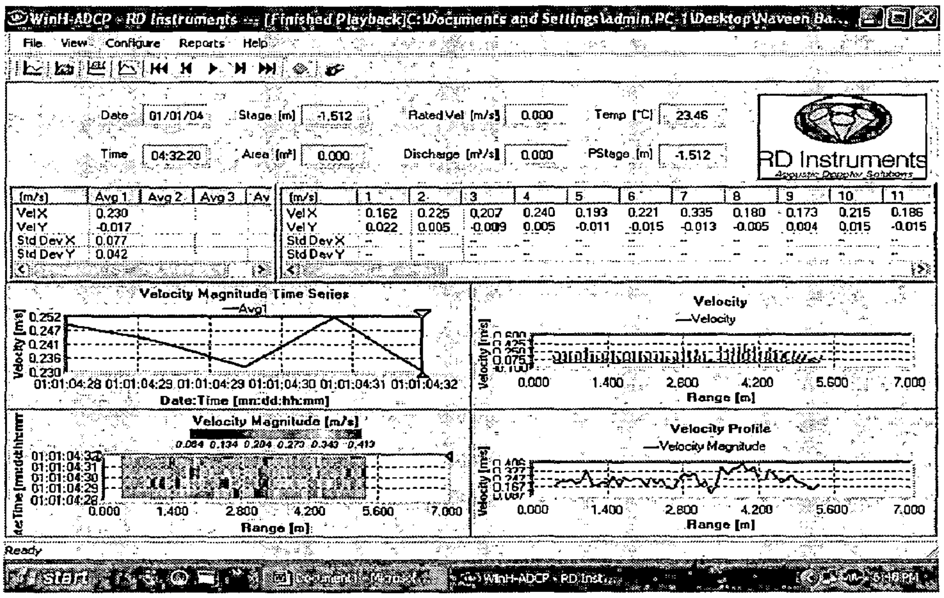

Fig.iv:- Snap showing Velocity magnitude at depth 0.10m