DESIGN & DEVELOPMENT OF 16 INCH INLINE VORTEX FLOWMETER WITH NOISE CANCELLATION SENSOR.

Avinash Vaidya

INCONEL
Office No.15&16,Commerce Avenue Complex,
127/2, Mahaganesh Colony, Paud Road, Kothrud, Pune-411038,India
Tel: +91-20-25432965, 25464765,25469719,
email: avinash@inconelflowmeters.com; info@inconelflowmeters.com

ABSTRACT :

Our Customer required a Flowmeter which can measure Air (2000 – 12000 A.cu.meter/hr) at pulsating Pressure, varying Temperature & the meter to be installed in 16 Inch Pipeline with very low pressure loss. The meter must be highly accurate , Accuracy better than ± 1.00% of the reading & repeatable ± 0.1% over a complete measuring range. The Flow would be fluctuating & with Severe pipe vibrations.

We designed, developed & tested 16 Inch (400 mm) Inline Vortex Flowmeter having measurement Range of (1200 to 30000 A.Cu.Meter/hr) with better accuracy, repeatability & rangeability. The meter was tested in FCRI.

The requirements , criteria used while designing are discussed in details. Various available types of Flowmeters are also compared & discussed alongwith limitations of Insertion Flowmeters. The Patented Noise cancellation Sensor is described. Various types of Sensors which are routinely used in Vortex Flowmeters are compared in details.

KEYWORDS : Design, Vortex Flowmeter, 16 Inch Inline , Noise Cancellation, Sensor, Insertion, Inline, FLowmeter.

INTRODUCTION:

While designing the Inline 16 Inch Vortex Flowmeter we have considered following criteria which best suited to Customer’s requirements , the designed Flowmeter will not only be suitable but will exceed the requirements of Range, accuracy, repeatability, specifications compared to available Flowmeters in the market. While keeping the cost of the meter low compared to other alternatives.

Vortex Flowmeters have been tested in series with Turbine & Positive Displacement Gas Meters by several Industries & Government authorities.

The Vortex Flowmeters after years of testing & comparing with other types are found to have better long term stability expressed by resistance to calibration shift with Time or changes in fluid operating conditions. Test & studies are carried out world over for many years to establish Vortex Flowmeter as officially approved Custody Transfer, High Pressure Gas metering.

SELECTION OF SUITABLE FLOWMETER FROM AVAILABLE TYPES OF FLOWMETERS:

The solutions were to select between Orifice type & other differential pressure producing meters, Venturies etc. Insertion type Vortex, Annubar, Pitot tube, Averaging pitot tube, Turbine, Ultrasonic, Multipath, Nozzle etc.

The Orifice meter was considered as a economic solution however the Pressure drop across the orifice , & the required measurable range would not match. The main consideration is pressure loss, rangeability & accuracy specifications. The Price of low Differential Pressure Transmitter was also considered.

The low Differential Pressure Transmitter can have high accuracy in static calibration test in the Laboratory, However while measuring across Orifice in dynamic flowing conditions, the turbulence & dynamic fluctuations in Gas causes measurement uncertainties & scatter which were beyond the acceptable limits.

The Multipath Ultrasonic Flowmeters were considered but the cost was prohibitive though the accuracy levels are well within the required range .

Insertion meters are routinely used for measuring Flow in pipelines of 10 Inch to 108 Inch diameters.

Insertion meters are easy to install & remove by hot tap arrangement in which a isolation valve, weldneck & spool piece is used for retraction of the Insertion Probe. This method is very convenient since the installation & removal can be done at any time without shutdown of flow in pipe.

Though the Insertion meters are very convenient, but found unsuitable for this Application as the errors in Installation would have resulted in erroneous readings.

The insertion meters can be installed in existing pipeline e.g. For city water where shutdown is not possible even for a short time .

The large pipelines are normally buried underground and they are inaccessible for inspection . The location of Installation of insertion flowmeters must be selected carefully. The insertion meters with or without shroud senses the point velocities at the location.

The velocity profile at the location of insertion probe must be fully developed profile. This requires a very long straight pipe length upstream of the flowmeter. For large pipelines it is often available, normally 100 diameters straight length could be sufficient since the disturbances in flow profile are carried to several diameters of length. The flow velocities in large pipelines are often very low due to several aspects in design & consideration was for future expansion.

The pipe must be completely visible at the point of location to ascertain the correct installation of probe & also for calibration & mapping at least four locations in one plane are required to completely map the flow profile by traversing the probe through out the diameter & by plotting the results & applying standard equations accurate measurement is possible. Practically little attention is given to the details like measurement of angle of the probe in three dimensions with respect to the centre line. It must be carefully noted that the installation of Hardware is most important as small deviation in mounting angles will reflect a large deviation from the centre line & must be controlled very carefully. Small insertion probes are susceptible to debris & dirt in the flow. A small error in installation can reflect large errors in measurements.

THE LIMITATIONS OF INSERTION FLOWMETERS FOR EXISTING APPLICATION:

1) Measures point velocities. The sensing Area of sensor or shroud compared to the area of large pipeline is considered & the measurement can be called as point measurement
2) Traversing of complete flow profile is required
3) While traversing varying blockage effect must be considered carefully
4) Compensation must be provided for the change in velocity profile against the change in Reynolds numbers
5) The natural frequency of vibration of the probe must be very high compared to measuring frequency.
6) Thermisters, Hot wire bridges, sensors are fragile & susceptible to damages within short working span due to dust, dirt & particles in the flow which tends to coat this type of sensors, this type of sensors primarily intended for short time use & not for continuous working.
7) While Installation, welding of hardware due care must be taken. For large pipelines small error in locating weldnecks produces large deviation in **Yaw & Pitch angle** as well as the shifting of center line. These errors can produce large errors in measurements.

We have designed & developed insertion type of flowmeters with our patented sensors. The Noise Cancellation feature of our sensor allow us to use our insertion probe for using upto 3000 mm dia pipelines. However for this particular application Inline Meter is suitable & recommended.

DESIGN CRITERIA :

The main consideration while designing any Flowmeter suitable for particular requirement of Customer calls for the attention towards the parameters like

1) Pipeline Size
2) Flow Range required
3) Fluid to be measured – Liquid or Gas
4) Fluid quality – clean – Dirty- Dust Laden
5) Nature of fluid – Explosive or otherwise
6) Operating Pressure
7) Operating Temperature
8) Allowable Pressure Drop across the meter
9) Fluid properties like : Viscosity, density, corrosiveness etc.
10) Compatible Material Of Construction
11) Operating conditions in the field like - explosive area location, Water emersion
12) Vibration levels at the location of the Flowmeter installation , pipe wall vibration levels due to induced vibrations from pumps, valves, mountings & transferred vibrations due to other machinery in the vicinity
13) The pulsatory nature of the flow inherent in suction blowers, compressors
14) Noise produced due to blocked flow from the closed Valve upstream/downstream
15) Oscillating flow resulting from wrongly placed valves in byepass arrangement.
16) Oscillating flow in the pipeline section in blocked pipe where flowmeter is installed & where byepass is provided before the flowmeter in upstream side, where the flow can oscillate back & forth creating false flow signals.
17) Electrical noise generated due to wrong electrical connections, ground loops formed whenever there is a large potential difference in ground levels of measuring instruments & field mounted flowmeter.
18) Galvanic protection issues
19) Lightening effects
20) Fluid noise produced by the impellers , compressors when the flow is blocked by the valves & the fluid in the pipeline oscillates, vibrates in the plain parallel to the direction of flow that is creating virtual oscillating flow signal without actual flow in the pipeline.
21) Suitable sensor design with Vibration immunity & Noise Cancellation.

The standardization of vortex flowmeter design is done by many Scientists & Researchers by extensive testing of various parameters, dimensions, shapes of bluff bodies . However the sensor part is neglected to be defined since there are several types used by various manufacturers which are proprietory in nature but there is no universal solution as there are so many parameters to be considered. Every manufacturer tries to accommodate standard sizes & flow ranges by using proprietory sensing techniques which offer comfortable signal to noise ratio to cover all the requirements.

SENSING TECHNIQUES :

The location & mounting method is selected depending on Type & Nature of the sensor.

The main objective of Sensor-Transducer used in Vortex Flowmeter is to sense the Vortices . Since the frequency of Vortices is directly proportional to Flow Rate the main aim is to detect the frequency reliably & accurately . The energy in the vortices, lift force & drag forces are also sensed alongwith the temperature to create the signal which is proportional to Mass Flow Rates.

Once the stable vortices are shed from the Bluff Body the sensing technique can be selected depending on the varying parameters of the Fluid which are related to Vortices. e.g. alternating Physical quantities like pressures, force, temperature, lift forces, torque etc. The passages can be formed in the Bluff Body or meter body to have cross Flow passages which are resulted from alternating pressures created by vortices. The cross flow which connects the Two sides should be avoided since this alters the Vortex Frequency. The volume & geometry of this passage or cavities plays important role in sensing. For small sizes of flowmeters since the energy associated with the vortices is low the sensing would not be proper. The transducer makes use of these dependent parameters for sensing vortices. The Signal to Noise ratio depends on these parameters & properties which are used for sensing. There are advantages & disadvantages in each type of transduction.

There are various types of sensing techniques . The sensor must be rugged & highly reliable. The NTC type of thermister embedded in glass can be used as a sensor which can be mounted directly on front face of bluff body or may be located inside the cross passage in the bluff body.

The thermister is heated by constant current & the cooling of the thermister due to fluid oscillating in the cross passage generates a signal which gives directly the frequency of vortex Shedding.

The thermister is excellent sensing method when mounted on front face where very weak flow signal is present but the advantage is at this location signal to noise ratio is very high & very clean signal is obtained. The advantage of thermister is they would not pickup the external vibrations of the pipe in any direction.

The masking thickness of sealing glass over the thermister chip must be minimal for good heat transfer thus sensing of vortices. However it limits the operating pressure & operating temperature of the fluids. The metallic probe / tube suitable for glass to metal bonding may not stand to many fluids from corrosion point of view.

The hot wire probe or thermisters can be used very successfully in a very small diameter bluff body which can be inserted in a large size pipe. The dust particles , soot which settles on these parts similar to hard deposits formed in hard water within few months of operations limits the use of these excellent sensors.

The capacitance type of sensors are also used very effectively in the measurement & sensing of vortices without going into detailed description we can say that the capacitance sensors working on principle of change in capacitance due to deflection of a member in response to pressure created by vortices, are working in the field but the problem of natural frequencies of probe & required precision machining poses problem in manufacturing & assembling of the same. The induced Noise from the body of the flowmeter, which is transferred from external sources, causes erroneous signals & limit the working range in noisy field conditions.

The differential pressure signals generated can be detected by dynamic pressure sensor located in the bluff body or outside the bluff body on diametrically opposite side of meter body. These sensors can be piezo resistive , piezo electric, or strain gauge type sensors bonded to diaphragms. These sensors may be placed in bluff body with actuation transfer mechanism to equalize on high static pressure. However these type are susceptible to pipe vibrations, induced fluid vibrations due to several sources of noise produced in the field. The so-called noise cancellation will not work due to difference in mechanical impedance of structure at the location of sensor & the geometry of sensor mounting. Finally all the attempts to make the meter work in noisy environment calls for large active filtering & active electronic circuits to detect & capture true vortex signals from the noisy spectrum , this also calls for expensive electronic & limiting the low measurable rate of flow.

Some type of sensors are placed, bonded integrally at the Top end of Bluff Body along the axis, where two strategically placed sensor pairs respond to the dynamic lift forces generated, & also to the noise component arising from disturbing vibrations transferred to meter Body.

The bending moment produced by the alternating dynamic lift forces & the bending moment due to external vibration both will produce strain in the measuring section. The positioning of sensors is so selected that the stress distribution in the sensors will produce the same ratio of Amplitudes due to Vortex Signals & the same ratio of Amplitudes due to external noise. These signals can be added effectively by suitable electronic circuitry to create Noise Free signal which represents a signal produced by vortices. **However in above arrangement the bluff body cannot be welded firmly at both ends to the meter body**. The bluff body having a large mass & hence a low resonant frequency , which limits the usage in Gas flow measurement. Also the acceleration produced due to external transferred Noise-Vibrations in the meter body will produced Noise signal which cannot be cancelled effectively.

In our Inconel's Design the Bluff Body is welded firmly to the meter Body at both ends. The passages are machined into the Bluff Body to accommodate the Sensor fitment, or the sensor can be located behind the Bluff Body. However by fitting the Sensor in the Cavity of the Bluff Body the sensor is shielded – protected from occasional physical damage. The Sensor can be fully welded to the main Body if the Customer requires Added safety.

BRIEF DESCRIPTION OF NOISE CANCELING SENSOR

The Sensor device is patented by the Author in India, USA & European countries.
A sensor device for measuring frequency & Amplitude of a varying force signal is provided. The sensor device comprises of sensing elements defined by a plurality of segments symmetrically disposed about a central axis. A protective cover for housing & interface element comprising a pickup member, a planar mechanical actuator , a transfer member adapted to receive a varying signals from the pickup, Amplify the signals picked up & transfer the amplified signals to the said mechanical actuator & leads for transmitting the said output signals outside the sensing device for processing.

The above photographs & figures shows one of possible arrangements & methods, all range of products are not shown due to space constraints .

The sensing element can be Piezoelectric , Piezoresistive or strain gauge type, optical segments, etc which responds to the strain/stress produced by the quantity to be measured. As a example & for simplification of understanding of the invention of how Noise Cancellation takes place we shall consider the element to be Piezoelectric & for further simplification we shall consider outputs only from segments 1,2,3, & 4.

The varying force signal when applied to the sensing element, charge / voltage is produced in the sensing elements. The sensing segments closer to Y axis generate greater charge / Voltage compared to the segments away from the Y axis. The segment 1 will generate a lesser Charge / Voltage than segment Two & segment 4 will generate lesser charge / voltage than segment 3. In the case of Noise signals the individual segments generate equal charge / voltage, as shown in Figure No.7

Now if we take combined signal
From segment 2 & 4, the output signal will be as in Figure No.6b.

From segments 1 & 3, the output signal will be as in Figure No.6c

Now if we take the differential signal from the combined pair the output signal will be as shown in Figure No.6d

Similarly , the effect of the Noise signal shown in Figure No.7a & Figure No.7b

And combined output signals for Noise would be as in Figure No.7c

Thus the noise component is reduced to almost nil & we can extract a true signal output in the Noisy environment.

The sensor is patented in India & other countries.

1) Sensor Devices - - Indian Patent No. 208728 -- by Avinash Vaidya
2) Sensor Device for measuring frequency & Amplitude of varying force signals.—USA Patent No.7259574 -- by Avinash Vaidya
3) Sensor Devices – European countries Patent Application No.05252957.5 –by Avinash Vaidya

THE VORTEX FLOWMETER

Todor Von Karman discovered that whenever a non-streamlined body (Bluff Body) is placed in a flowing fluid, vortices are generated alternately on both sides of the Bluff body and the formation pattern is repeated resulting in a pattern named as Von Karman Vortex Street.

Vortex Shedding phenomenon occurs in nature & can be observed in everyday experiences. A Flag waving in the wind, water flowing around bridge piers & pilings, around off shore drilling platforms, & around tall buildings, aeoline tones- singing of wires in wind etc. Structural Engineers take care while designing to avoid damage to objects in the path of Vortex Street.

When a Vortex Flowmeter is fitted in a closed piping system the Vortices shed have a very weak energy & are dissipated within very short distance downstream of the meter, these are not likely to cause any damage or problems to the piping or equipment.

Strouhal (1878) made the first experimental observation of the shedding phenomenon . He showed that the shedding frequency of a vibrating wire in the wind was related to the wind velocity & wire diameter .

The strouhal number is widely used as the basic Vortex shedding correlation factor.

The Strouhal Number of the vortex shedding meter is defined as,

$$S_t = \frac{f.w}{U}$$

Where ,

f : Frequency of vortex shedding

w : Characteristic width of the bluff body

U : Fluid velocity

$$Q = \frac{f}{K} = \frac{\Pi D^2 U}{4}$$

K : K-factor for the particular meter

Q : Rate of Flow.

D : Diameter of meter

Therefore

$$K = \frac{4\,S_t}{\Pi D^2 w}$$

Experimental results show that the Strouhal number is essentially constant over wide velocity ranges & is independent of fluid properties like Pressure, Temperature, Density, Viscosity, Conductivity etc.

This property of Vortex Flowmeter is very advantageous & studied carefully by several researchers & scientists all over the world. The project for standardization has been carried out for about 8 years by NRLM & JEMIMA (Japan Electric Measuring Instruments manufacturers Association in Japan) with several collaborating manufacturers of Vortex Flowmeters.

The optimization & the Installation conditions have been obtained from several thousand parameters studied in the project & the results have been published as JEMIS 028-1998.

Among the many flowmeters dry calibration is applied to only an Orifice meter based on ISO-5167-1(1991) at present. However the discharge coefficient of an Orifice Plate depends on the diameter ratio & the Reynolds Number.

In the case of Vortex Shedding flowmeters the dry calibration can be simpler since different sized flowmeters have a common Strouhal number based on the design & the K factor can be simply calculated from the Strouhal number & the flowmeter dimensions. There is no need to Wet calibrate the flowmeter for different fluids to be measured.

Several experiments & testing of various sizes of meters with different combinations of bluff body shapes & sizes has shown that the bluff body shape & size decides the range, linearity , signal strength & regularity of vortex shedding. The linearity & dependence of Strouhal Number against the Reynolds Number was also checked & the optimum design was finalized. Based on these experiments & data the meters are designed .

The 16 Inch meter was tested in FCRI in Air testing Laboratory. Please refer the results of the testing & Photographs.

Figure No.8- Results of Calibration for 16 Inch Inline Vortex Flowmeter
Figure No.9- Calibration chart of testing results.
Figure No.10- Photograph of 16 Inch VFM under testing.

We routinely manufacture Inline & Insertion type Vortex Flowmeters upto 118 Inch (3000 mm) pipeline diameters for Air, Gas, Liquids with accuracy better than
± 1.00% of the reading all over the span & repeatability of ± 0.1%.

REFERENCES :

[1] R.W.Miller – Flow Measurement Engineering Hand Book.

[2] H.J.Kastner – Officially Approved Gas Metering In W-GERMANY . The establishment of the Vortex Meter - J . International Symposium on Fluid Flow measurement Publications - 1986

[3] T.B.Morrow, D.L.George, M.G.Nored and E.B. – Operational Factors that affect Orifice Meter Accuracy Key findings from Muti-Year Study. Gas Research Institute Report. GRI-00/0141

[4] J.J.Miau, C.C,Hu,J.H.Chow – Response of a Vortex Flowmeter to impulsive Vibrations - J. Flow Measurement and Instrumentations – 2000-41-49

[5] Tomotsu Igarashi – Performance of New type Vortex Shedder for Vortex Flowmeter- J. Proceeding of 6th Triennial International Symposium on Fluid Control Measurement-2000

[6] Curtis Gulaga – Vortex Shedding Meters - Technical Paper C B Engineering Ltd.Canada.

[7] Donald Ginesi – Vortex Shedding Flowmeters - Technical Paper. CALDON publication.

[8] E.Van Bokhorst,M.C.A.M.Peters and C.H.L.Limpens – Impact of pipe vibrations on Vortex FLowmeters under operating conditions. 4th International Symposium on Fluid Flow Measurement.

[9] Walt Seidl – Installation & Operation errors in Gas measurements-72nd International School of Hydrocarbon measurement.

[10] JEMIS 028-1998 – Methods of Flow Measurement by Vortex FLowmetere

[11] M.Takamoto and Y.Terao – Standardization of flowmeters – 4th International Symposium on fluid flow measurement - 1999

[12] ISO / TR 12764 1997- Flow Rate measurement by means of Vortex Flowmeters inserted in circular cross section conduits running full.

[13] Heimo Inalainen, Jouko Halttunen – Vortex Signal Analysis – Proceedings of IMEKO

[14] D.W.Clarke, T.Ghaoud.- A dual phase – locked loop for Vortex Flow metering. Flow Measurement and Instrumentation Vol 14.pp1-11, March 2003.

[15] Takamoto M., Utsumi H., Watanabe N., and Terao Y. – Installation effects on Vortex Shedding Flowmeters. J.Flow measurement and Instrumentation.Vol 4 No.4, 277/285 (1993)

[16] D.F.White, A.E.Rodley and C.L. Mc Murtrie.- The Vortex Shedding Flowmeter. J. Flow its measurement and control in science & Industry-ISA-1974

[17] Xin Fu, Bizhong Xia and Huayong Yang – A computational Fluid Dynamics approach to Noise Immunity improvement of Vortex Flowmeter. SAE technical papers.

[18] Stephen M. Price. Donald R. Smith – Sources and remedies of High Frequency piping vibration and Noise. Proceedings of the Twenty-Eighth Turbomachinery Symposium 1999.

[19] Hongiian Zhang et.al. – A study of Mass Flow rate measurement based on the Vortex Shedding principle- J- Flow measurement and Instrumentation 17 (2006) 29-38

[20] R.W.Miller.Foxboro Company – US Patent No.3972232 Vortex FLowmeter Apparatus.

[21] Takeniro Sawayama, Yokogawa Electric Works – US Patent No.4248098 Flow metering Apparatus.

[22] Tamuza et al., Yokogawa – US Patent No.4437350 Vortex Flow metering Apparatus.

[23] Hyok S. Lew – US Patent No.4835436 Piezo Electric Impulse Sensor

[24] Khalifa, Schlumberger Ind. – US Patent No. 4864868 Vortex FLowmeter Transducer

[25] Igor Getman, et. al. – US Patent No. 6352000 Vortex Flow Sensor

[26] Avinash Vaidya – Indian Patent No. 208728 - Sensor Devices

[27] Avinash Vaidya – US Patent No 7259574 - Sensor Devices for measuring frequency & amplitude of varying force signals.

[28] Avinash Vaidya - European Patent Application No: 05252957.5 - Sensor Devices

Fig. No.1 Photograph of one of the sensors

Fig. No. 2 - Sensor fitted in a BOSS having passages

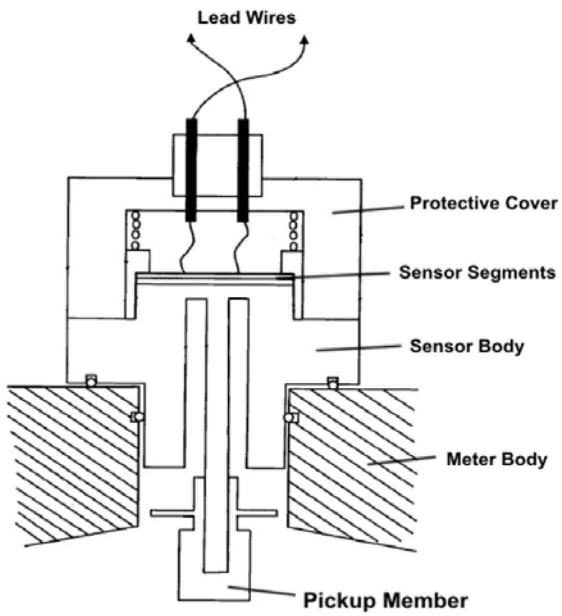

Fig. No.3

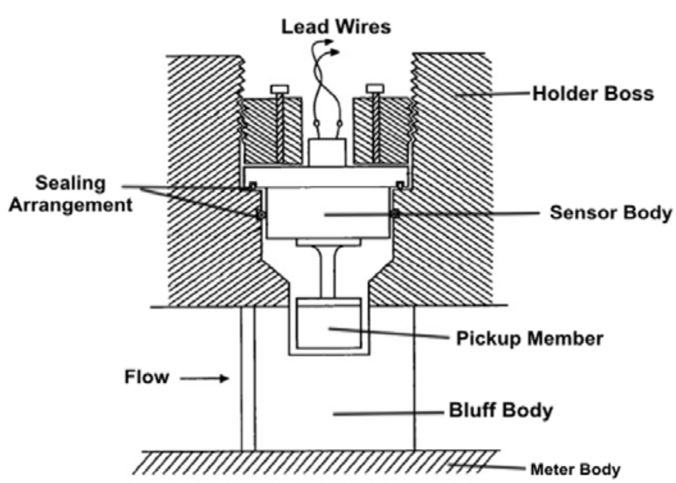

Fig. No.4

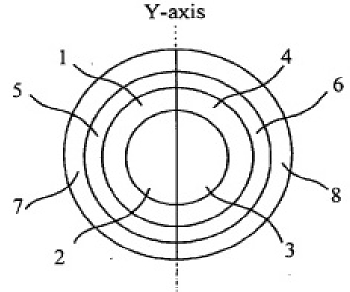

FIG - 5a

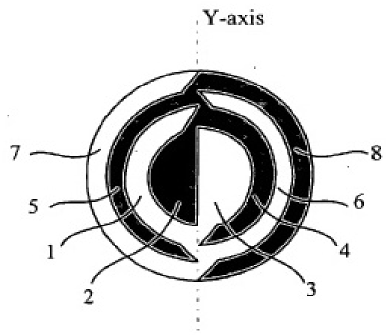

FIG - 5b

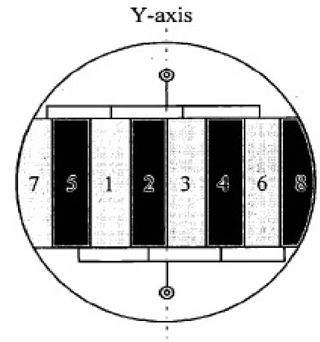

FIG - 5c

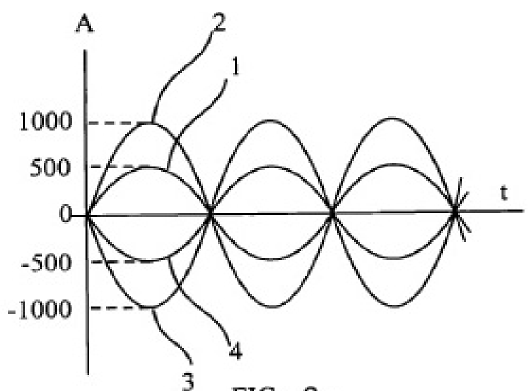

FIG - 6a

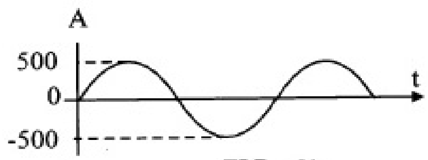

FIG - 6b

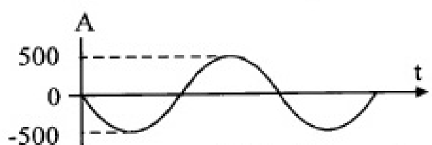

FIG - 6c

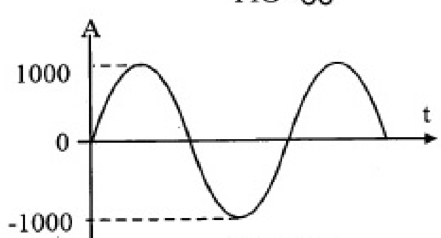

FIG - 6d

Fig. No. 6

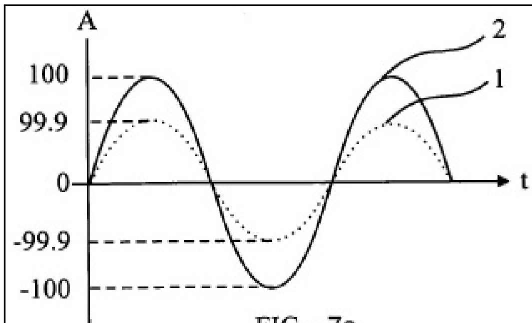

FIG - 7a

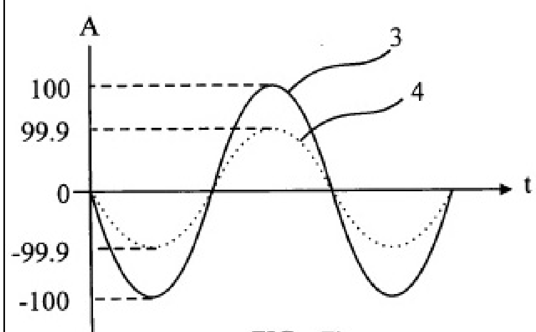

FIG - 7b

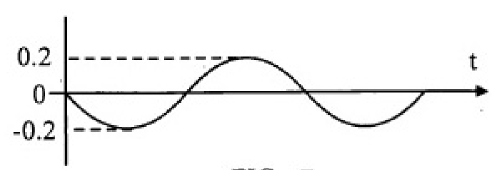

FIG - 7c

Fig. No.7

Results of Calibration for 16 inch INLINE VFM

Sl. No.	Actual flow rate* q_a (m^3/h)	K-Factor K (Pulses/m^3)	Type A Standard uncertainty, ur(y) (best fit) (Pulses/m^3)	Bias error G(y) (Pulses/m^3)	Type A Standard uncertainty, $u_r(y)$ (combined) (Pulses/m^3)
1	2	3	4	5	6
1	1076.30	16.45	----	----	----
2	1253.79	19.81	0.023	0.101	0.124
3	1429.36	19.77	0.022	0.096	0.118
4	1784.99	19.76	0.021	0.086	0.107
5	2139.48	19.76	0.019	0.076	0.095
6	2496.94	19.92	0.018	0.065	0.084
7	2853.84	19.76	0.017	0.055	0.072
8	3552.43	19.83	0.015	0.035	0.050
9	4235.86	19.88	0.014	0.016	0.030
10	5599.89	19.61	0.014	0.023	0.038
11	6890.23	19.67	0.018	0.060	0.078
12	6893.53	19.67	0.018	0.060	0.078
13	6890.95	19.67	0.018	0.060	0.078
14	6891.27	19.69	0.018	0.060	0.078
15	6892.10	19.67	0.018	0.060	0.078
16	8069.82	19.57	0.022	0.094	0.116
17	9266.41	19.59	0.027	0.128	0.155
18	8655.06	19.61	0.024	0.111	0.135
19	5596.73	19.68	0.014	0.023	0.038
20	2855.37	19.71	0.017	0.055	0.072
21	1429.16	19.79	0.022	0.096	0.118
Mean K-factor, K ($1250 \leq q_a < 10000$ m^3/h)				**19.72**	**Pulses/m^3**
Type A uncertainty (maximum) while using mean				*0.155*	*Pulses/m^3*
Expanded uncertainty, U (k=2.09)				***0.33***	*Pulses/m^3*

** Actual flow rate corrected to test meter conditions.*

Note: Sl No. 1 is not considered for uncertainty anlaysis

Fig. No.8 – Results of calibration for 16 inch INLINE VFM

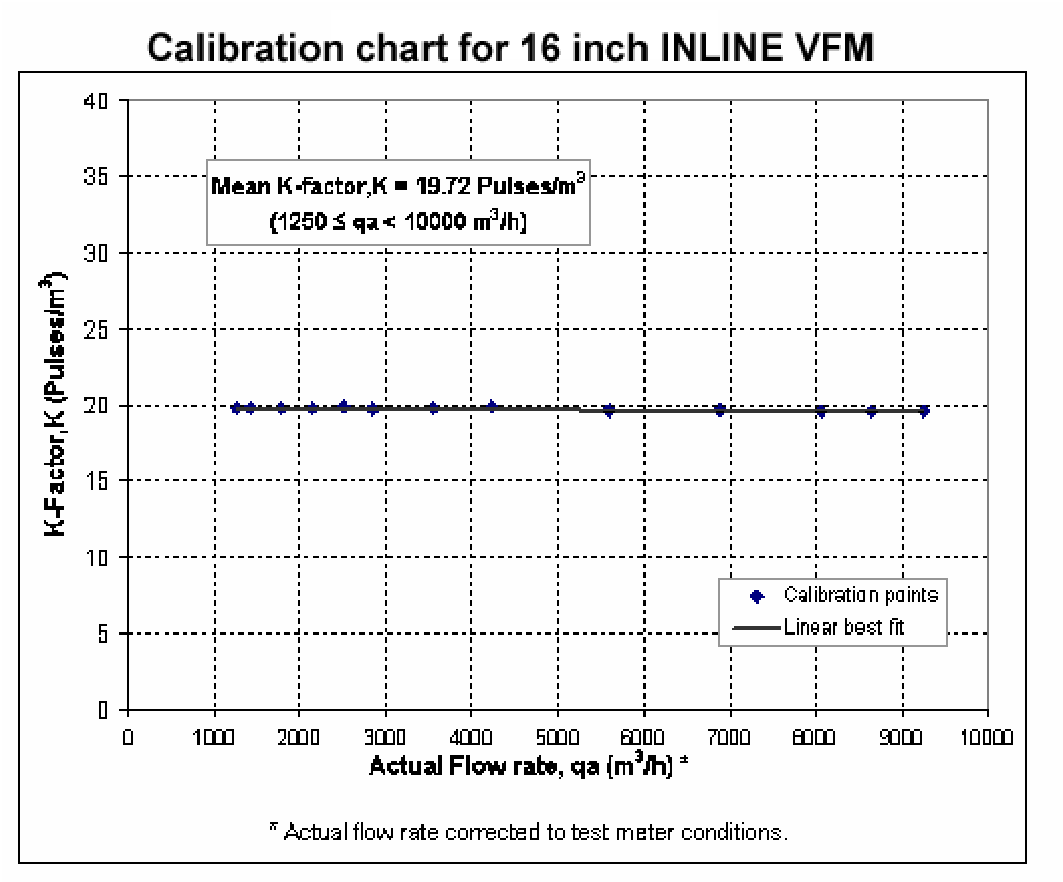

Fig. No. 9 – Calibration chart of testing results

Fig. No. 10 – 16 inch VFM UNDER TESTING