# Calibration of Electromagnetic Flowmeter Using Advanced SCADA System

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**ABSTRACT**

The Programmable Logic Controller (PLC) based Supervisory Control and Data Acquisition (SCADA) system is designed for automation, remote monitoring, signal acquisition, data logging and report generation for flow calibration and measurement process. In this paper logic and flow charts in PLC programming for execution of calibration process and controls are presented. In situ calibration of different measuring instruments used in flow calibration viz. flow meter, measuring tank load cells, calibrator tank load cells have been performed and calibration equations have been derived from their calibration curves. Gravimetric approach using flying start and stop method has been adopted for flow calibration in present study. Systematic and random error of weighing balance and flow diverter has been evaluated as per ISO 4185.

**KEY WORDS**

Calibration, measurement, SCADA, gravimetric method, uncertainty, experimental

## 1.0 INTRODUCTION

A fully automatic SCADA based Hydraulic turbine R&D laboratory has been set-up in 2016 at Alternate Hydro Energy Centre (AHEC), Indian Institute of Technology (IIT) Roorkee, Uttarakhand, India, a center of excellence for small hydropower in the country, to validate the homologous hydro models, designed and fabricated by various turbines manufactures. During the flow calibration and measurement, the main process quantities e.g. water flow rate, pressure and temperature are stabilized by logic developed in a computer-based Supervisory Control and Data Acquisition (SCADA) system, with other relevant process parameters like temperature, diverter actuation, load cell reading and ambient-air conditions, being monitored. This is an essential prerequisite to provide reproducible conditions that are necessary to achieve a high degree of reproducibility in the measurement and calibration processes.

The Programmable Logic Controller (PLC) based SCADA system is used for automation, remote monitoring, signal acquisition, data logging and report generation. The data from field instruments during calibration and measurement of flow are acquired and control commands to field devices are being sent by SCADA. The PLC also controls the process and acquire raw signal from field instruments and convert it into the secondary

output parameters. The PLC is used as the main decision making module.

## 2.0 APPLICATION OF EXISTING SCADA SYSTEM FOR CALIBRATION PROCESS

Advanced SCADA system has been designed for automation of the operations, control, data communications and acquisition, feedback, alarms, mathematical calculations and report generations in calibration process as per shown in Fig.1

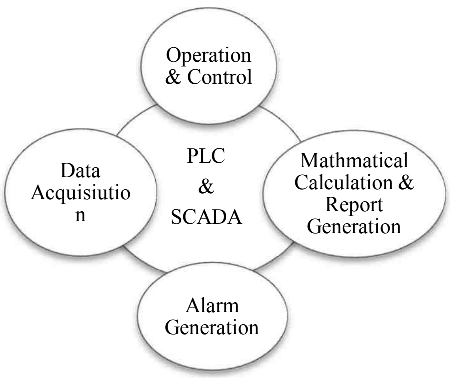



Fig.1 Application of SCADA system

Calibration of flow measurement system is being run automatically, with the capabilities of the computer-based SCADA system being utilized for automatic process control and operator interaction [14]. The operator that initiates and supervises flow meter calibration has full access to all process variables of the calibration plant with help of SCADA screen as shown Fig.2

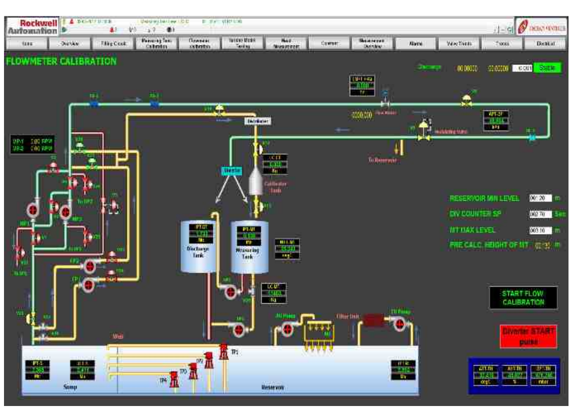
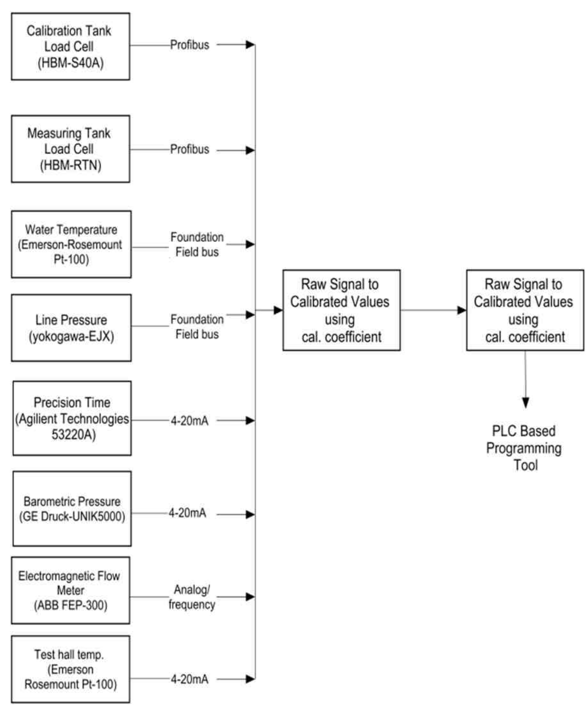



Fig.2 SCADA screen for flow meter calibration

In flow calibration and measurement, the application of PLC based SCADA system is outline in four different areas as given below:

### 2.1 Data acquisition from field instruments

In existing Scada system, various communication viz Profibus, Foundation Field bus and analog communication are used to connect the field instruments. As a standard, all data acquired from sensing and actuating devices are stored in the SCADA system's real-time data base as so-called "raw" values, i.e. no corrective functions or signal filtering operations have been applied to these process values at the moment they are being stored. Raw signal from field instruments are converted into the calibrated values by using the calibration coefficients in SCADA system. Further converted calibrated values are being averaged for a user defined time sample. Data communication and acquisition from various field instruments are shown in Fig.3

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A program has been design in PLC language as per given flow chart in Fig.4 to execute the electromagnetic flowmeter calibration process.

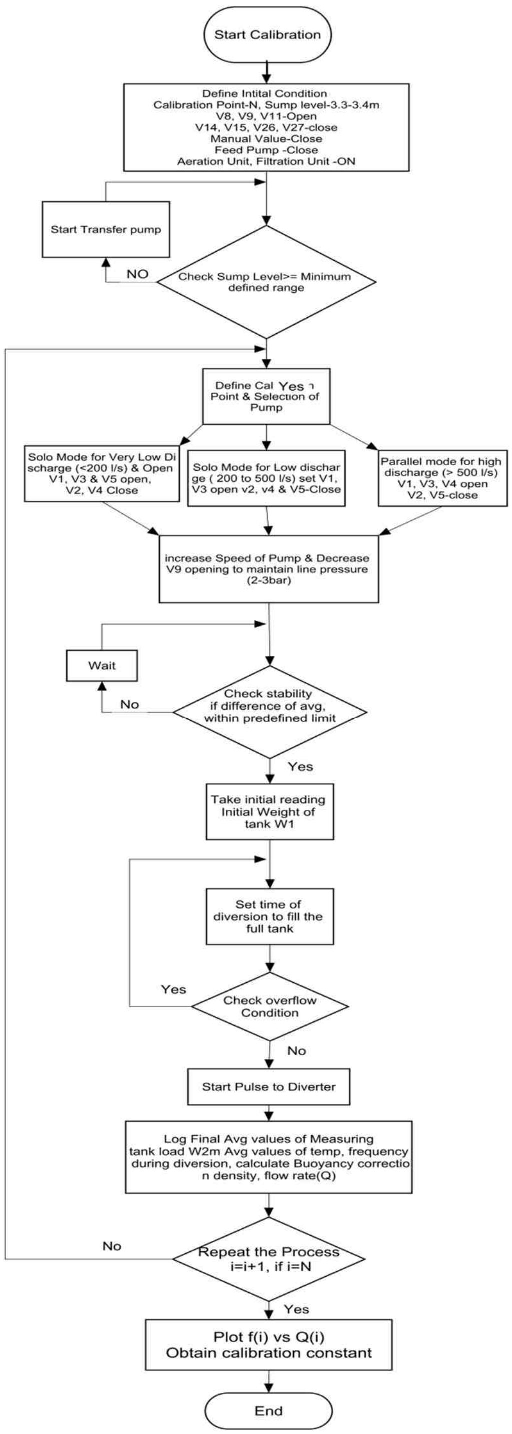


Fig. 4 Program flow for execution of calibration process

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SCADA is designed to control speed of pump, Valves, Sump level, Overflow in measuring tank during execution of flow calibration. Automatic computer-based supervision of all plant devices, e.g. the leakage-prove operation of on/off valves, guarantees to provide reliable calibration results []. The PLC based programming in the ladder logic is developed for overflow control in measuring tank using Flow chart given in Fig. 5

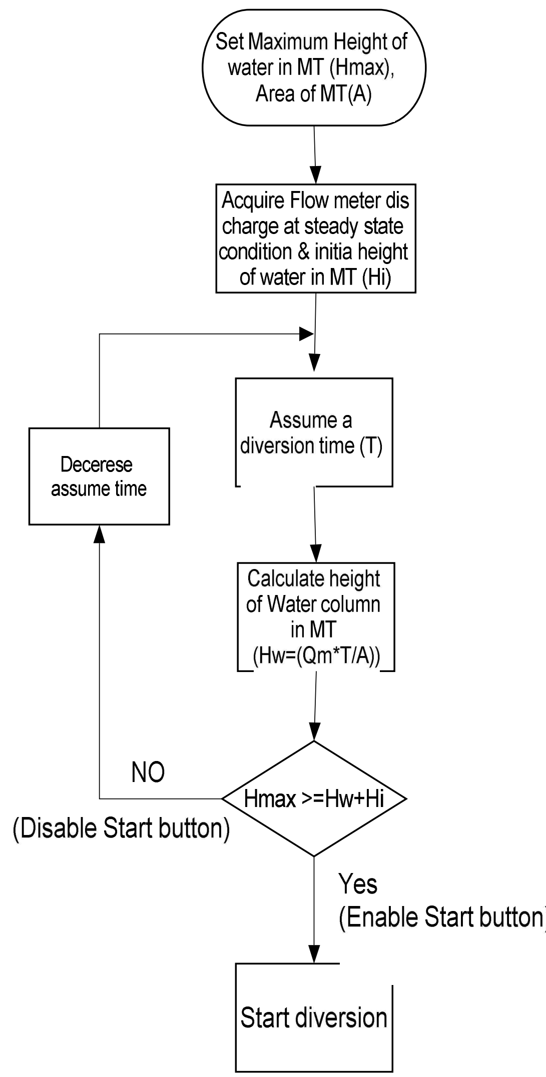


Fig. 5 Program flow chart for overflow control of water

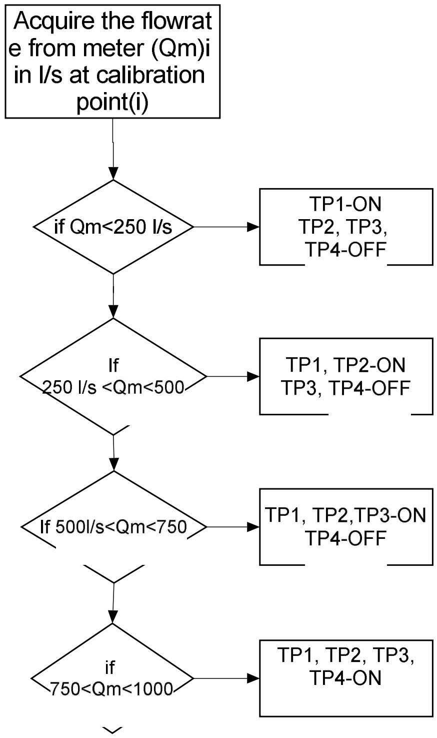


Fig. 6 Program flow chart for Sump level control

In existing SCADA there are provision for alarm generations for fault detection in any filed devices viz valves, variable frequency derives and transfer pump.

## 2.4 Mathematical calculations and report generations

Mathematical equations involved in the flow calibration process as per ISO 4185 [], for buoyancy correction, density calculation, volume flow rate are programed in the PLC & SCADA system. As water density is a function of temperature, the exact measurement of water density ($\rho$) at the temperature that occurs within flow meter calibration during a calibration run has to be performed.

$$\rho = \frac{1}{\vartheta_0.[(1-A.\rho_{abs})+8.10^6(\theta-B+C.\rho_{abs})^2-6.10^8(\theta-B+C.\rho_{abs})^3]} \quad (1)$$

Where $\vartheta_0$ is Specific volume at 0ºC, A, B and C are constant, $\rho_{abs}$ is water pressure in line, $\theta$ is temperature of water in measuring tank during diversion

$$M = W * \left\{1 + \rho_{air} * \left[\frac{1}{\rho} - \frac{1}{\rho_w}\right]\right\} \quad (2)$$

M is the corrected mass, collected in measuring tank, W is the measured weight by load Cell, $\rho_{air}$ is the density of air, $\rho$ is the density of the fluid (water), and $\rho_w$ is the density of the tank material.

Volume flow rate:

$$Q_C = \frac{M}{(t*\rho)} \quad (3)$$

$$Q_C = \frac{M}{t*\rho} \quad (4)$$

Where $Q_C$ is calibrated discharge and t is diversion time

## 3.0 FLOW CALIBRATION AND MEASUREMENT SET-UP

The working principles of flowmeters calibration are based on two basic methods namely gravimetric and volumetric methods. Gravimetric method is based on fundamental principle, known as primary method in which water is collected for a predetermined time and weighed. The weighing method is again categorized into static weighing and dynamic weighing techniques.

The two parameters measured with this system are mass flow rate and volume flow rate. For the determination of volume flow rate, the density of flowing water is measured during measurement process. The mass flow rate is then divided by the density to calculate volume flow rate. As per ISO 4185 [2-5].

In the volumetric method, water flowing through the meter under test is collected in a volumetric vessel for a predetermined time and its volume is measured, directly. Thus, volume flow rate is derived and calculated.

Since the determination of volume flow rate is measured indirectly from mass, it is treated as secondary method. The documentary standard released by ISO for flow measurement in closed conduits using volumetric method is ISO 4064 [6-8]. The primary method based on weighing is well established and widely accepted method internationally [9–12].
Calibration of the electromagnetic flow meter has been carried in open loop in which, water is pumped from a sump having the constant water level and diverted to the measuring tank for a specified period through flow diverter using gravimetric approach with flying start- and -stop method as per ISO 4185[3].

In situ calibration chain of flow measurement system is as follows:

**(a) Calibration of balance system:**
**(b) Calibration of electromagnetic flow meter:**

Calibration of flow meter was performed using gravimetric method using flying start and stop approach as per ISO-4185.

## 3.1 Calibration of balance system

### 3.1.1 Standard weights

The F2 class standard weights are used for calibration of calibrator tank load cell

### 3.1.2 Calibration of calibrator tank load cell

Calibration of calibrator tank load cell (2ton) is carried out with standard weights up to 1500 kg (72 No- 20 kg, 6 No-10 kg). The empty weight of calibrator tank is 490 kg. The output signals from load cell are logged in SCADA at 100Hz.

A curve has been plotted between output signal of load cell $(mV)_{CT}$ and applied standard weights and as shown in Fig.7 along with its regression curve as shown in Fig.8

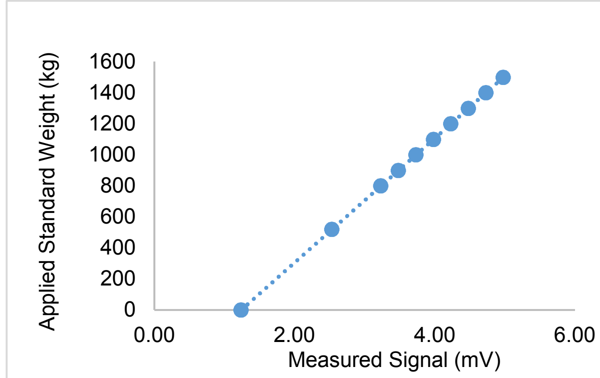


Fig.7 Calibration curve calibrator tank load cell

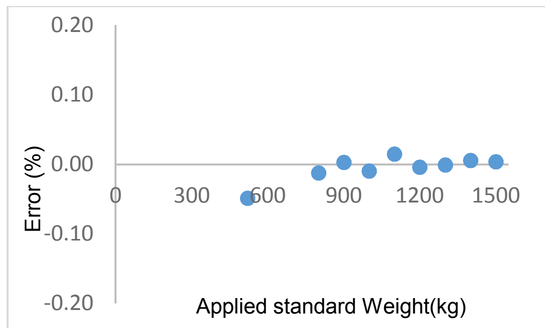


Fig. 8 Regression error of calibrator tank load cell

### 3.1.3 Calibration of Measuring Tank Load Cell

Three ring torsion type load cell of 22-ton each are placed at the bottom of measuring tank to measure the weight of water collected over a period of diversion time. These load cells are calibrated with a calibrator tank load cell.

A fix calibrated weight of water (about1300 kg) is transferred from calibrator tank to measuring tank. Initial and final output signals (mV) of load cells (measuring tank and calibrator tank) are logged SCADA system. The same is repeated until the level of measuring tank reached at maximum.

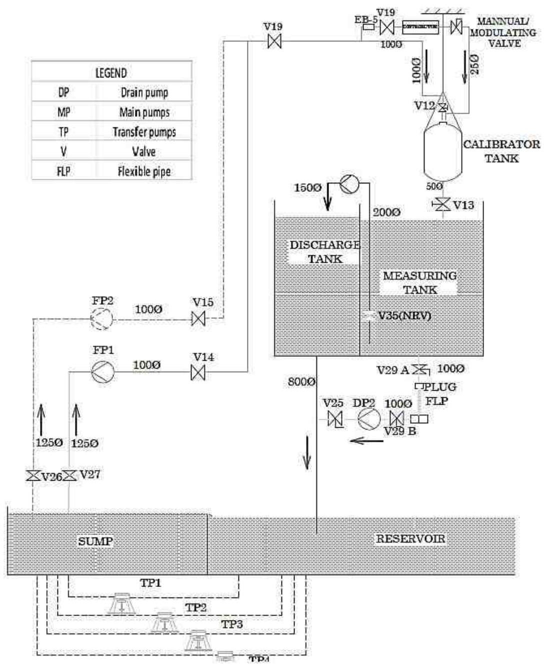


Fig.9 measuring tank load cell calibration loop

The cumulative corrected weight of water transferred by calibrator tank is plotted against the primary output signal $(mV)_{MT}$ of measuring tank load cell as shown in Fig.10. Regression error of measuring tank load cell is plotted against applied standard weight as shown in Fig.11.

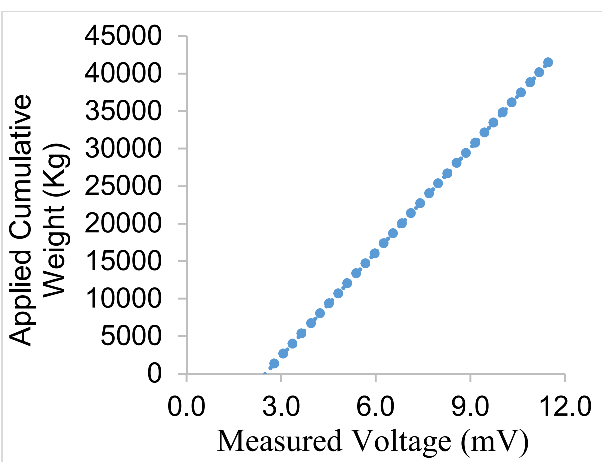


Fig. 10 calibration curve of measuring tank load cell

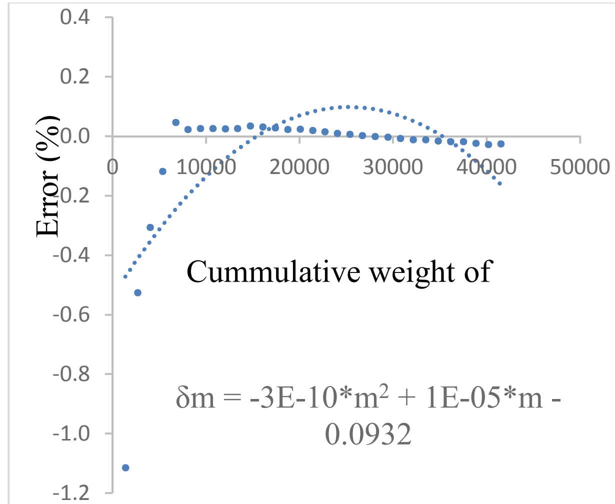


Fig. 11 Regression error of measuring tank load cell

### 3.2 Calibration of electromagnetic flow meter

Calibration of flow meter is carried out for discharge range between 100 l/s to 750 l/s by keeping sump level constant. For maintaining sump level constant, A PLC based program has been developed in ladder logic, details discuss in section…. Timing error of diverter system are obtained and used to correct the measured discharge. Water is diverted into measuring tank for a set period of time until it gets fully filled. Initial and final readings of measuring tank load cells $(mV)_{MT}$, initial and final temperature and diversion time are logged into SCADA in order to calculate the discharge. Buoyancy correction is made to the readings of a load cell to take account of the difference between the upward thrust exerted by the atmosphere and water being weighed.

Frequency $(f_F)$ signal from flowmeter during diversion period are log in SCADA and flow Calibration and regression curve are plotted in Fig.12 and Fig.13 respectively.

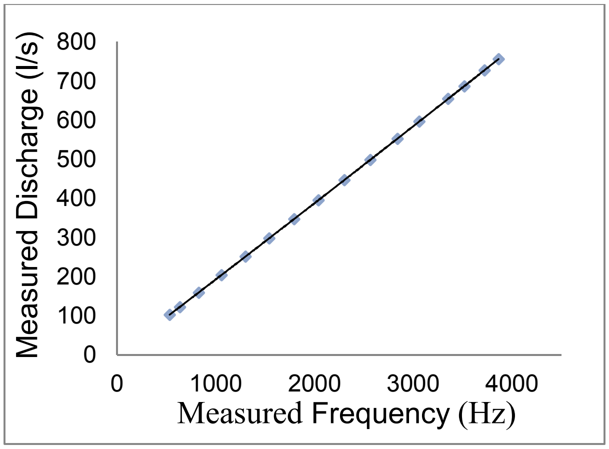


Fig.12 Flow meter calibration curve

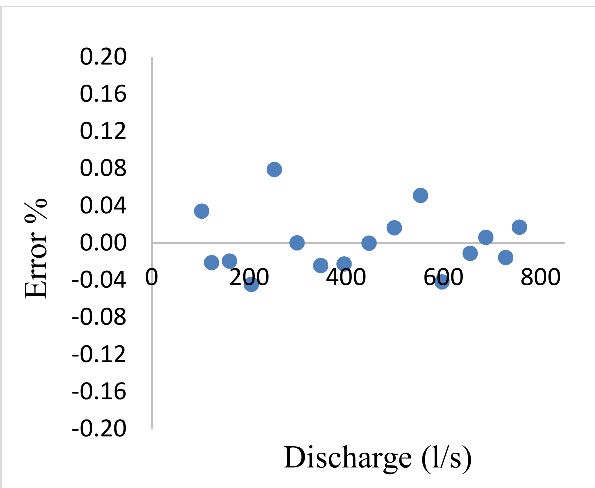


Fig.13 regression error of flow meter

Calibration equations of electromagnetic flowmeter, measuring tank load cell and calibrator tank load cell are tabulated in Table-1.

Table-1 Calibration equation of flow parameters

| Instrument | Calibration equation |
|---|---|
| Calibrator tank load cell | $(W_{CT})_C = 400.76 * (mV)_{CT} - 495.82$ |
| Measuring tank load | $(W_{MT})_C = 4622.57 * (mV)_{MT} - 11523.86$ |
| Flow meter | $Q_C = 3 * 10^{-7} * f_F^2 + 0.191448 * f_F + 1.318646$ |

These calibration equations are used in Ladder logic based PLC programming to convert raw signal into calibrated values.

## 4.0 UNCERTAINTY ANALYSIS

The uncertainty associated with a discharge measurement is obtained by combining the uncertainties arising from the sources. Although "systematic" errors have been distinguished from "random" errors, the probability distribution of the possible values of each systematic component is essentially Gaussian, and, in accordance with IS0 5168.

The combination of all the uncertainties may be made by the root-sum-square method. As per ISO 4185, the systematic, random uncertainty and total uncertainty in discharge measurement is given by (as per ISO 4185(1980)) Eq.5, Eq.6 and Eq.7 respectively.

$$e_{Qs} = \sqrt{[(e_s)_b]^2 + [(e_s)_p]^2 + [(e_s)_d]^2 + [(e_s)_\varepsilon]^2 + [(e_s)_t]^2} \tag{5}$$

where $E_s$ is the overall system uncertainty; $(e_s)_b$ uncertainty due to the weighing machine; $(e_s)_\varepsilon$ is the buoyancy correction; $(e_s)_p$ is the systematic uncertainty due to diverter system; $(e_s)_t$ is systematic uncertainty due to the timing device; $(e_s)_d$ systematic uncertainty in the measurement of density.

$$(e_{QR})_{95} = \sqrt{[(e_R)_b]^2 + [(e_R)_p]^2} \tag{6}$$

where, $(e_R)_b$ Random uncertainty is the difference between two weighing observations; $(e_R)_p$ is the random uncertainty due diverter system; the random uncertainty in density measurement $(e_R)_d$ is neglected

$$(e_{QT}) = \sqrt{[(e_{QR})_{95}]^2 + [e_{Qs}]^2} \qquad (7)$$

In the present study buoyancy effect has been calculated as per Eq.2 in the measuring tank and correction has been made in the total collected weight of water in measuring tank. Systematic error $(e_s)_t$ in time measurement is neglected

In present setup, F2 class weight, calibrator tank and measuring tank constitute the weighing system. Systemic uncertainty of measuring tank load cell is calculated using Eq.8 and Eq.9 as per ISO-4185.

$$\delta m = -3E\text{-}10{*}m^2 + 1E\text{-}05{*}m - 0.0932 \qquad (8)$$

$$\delta(\Delta m) = \delta m_2 - \delta m_1 \qquad (9)$$

Correction on measurement in diversion time is also carried out as per method given in ISO-4185 as shown in Fig.14. Value obtained from the curve Δt= 0.0217s is adjusted in the total diversion time during flow meter calibration.

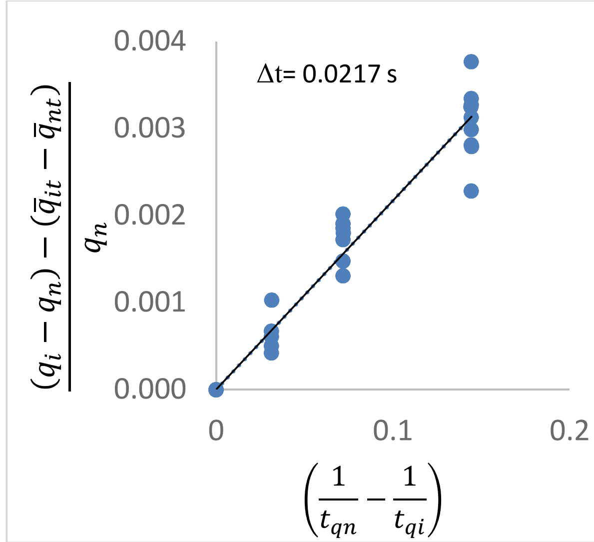


Fig.14 diversion time correction

Systematic uncertainties of each instrument/parameter are given in Table-2.

Table 2-Systemic uncertainties in flow measurement

| S. No | Components | | | Uncer. (%) |
|---|---|---|---|---|
| 1. | weighing system | Standard weights | 0.0045 | 0.070 |
| | | Calibrator tank load cell | 0.05 | |
| | | Measuring tank load cell | 0.0489 | |
| 2. | Timing device | | | Negligible |
| 3. | Density | | | 0.010 |
| 4. | Diverter system | | | 0.049 |
| 5. | Buoyancy | | | corrected |
| Systemic uncertainty in flow measurement | | | | 0.0860 |

The repeatability of the movement (random error) of the flow diverter is determined experimentally by setting the flow-rate to a steady value and then carried out series of 10 diversions for a fixed diversion period to provide a series of 10 estimations of the flow- ate This exercise is repeated for several

different diversion periods and, from the standard deviation of each series of measurements, the 95 % confidence limits have been be evaluated as per ISO-4185 and are shown in Fig.15.

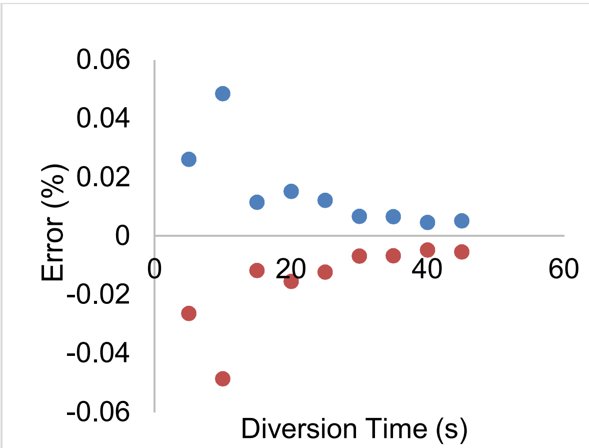


Fig.15 Random error in diverter time

For evaluation of random error of weighing system, the standard deviation of the distribution of points about the best-fit curve shown in Fig.11 is calculated with 95 % confidence limits of the distribution determined using Student's t-table. This value of confidence limits is multiplied by square root of two (since the determination of the mass of water collected in measuring tank during a diversion is obtained from the difference between two weighing) as per ISO-4185. Random error of flow diverter system and weighing system are found as ±0.0262616 and ±0.0485% respectively.
Total random error in flow measurement during calibration is calculated using Eq.7 and found out as 0.0551%. Systematic uncertainty of flow measurement during calibration is 0.0860% and regression error at 700 l/s is found 0.02% from flow calibration curve. The total uncertainty in flow measurement at 700 l/s is found as ±0.104%.

## 5.0 CONCLUSIONS

The real-time data base as an inherent component of the SCADA system being applied for the automated operation of the test field provides capabilities these special capabilities are a prerequisite to execute the flow calibration process and control the flied instruments. In-situ calibration of measuring instruments viz calibrator tank load cell, measuring tank load cell, flowmeter has been performed. Calibration equations, regression curves have been obtained. Uncertainty analysis has been performed as per ISO 4185 at 700 l/s flowrate and systematic error, random error and regression error has been found 0.086%, 0.055% and 0.02% respectively. The total uncertainty in flow measurement at 700 l/s is found as ±0.104%.

**Acknowledgement:**

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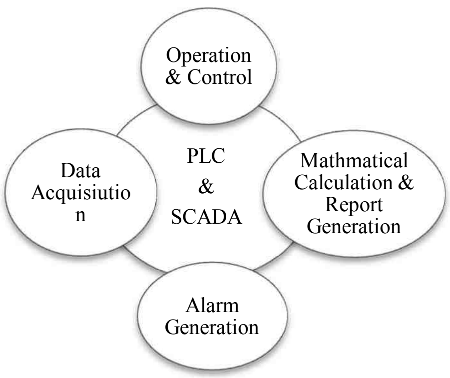


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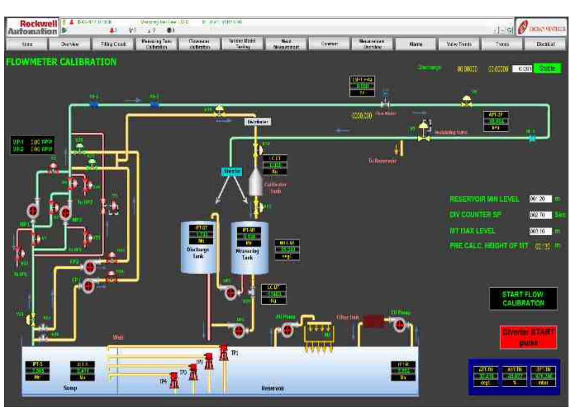


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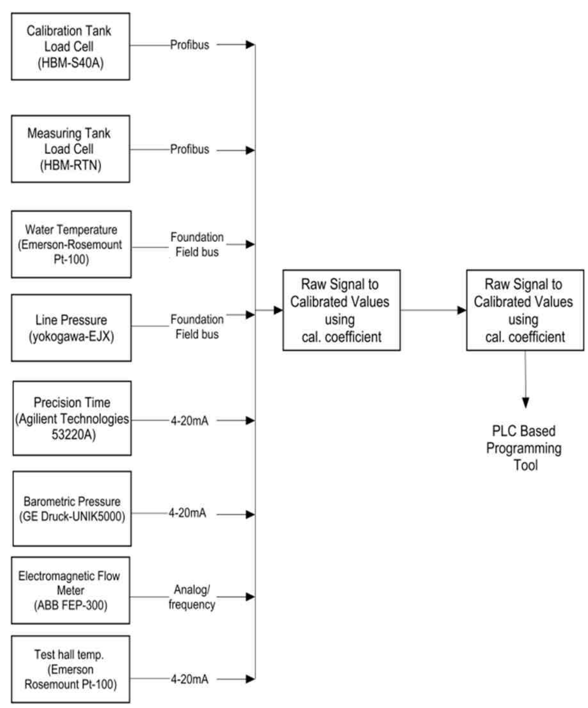


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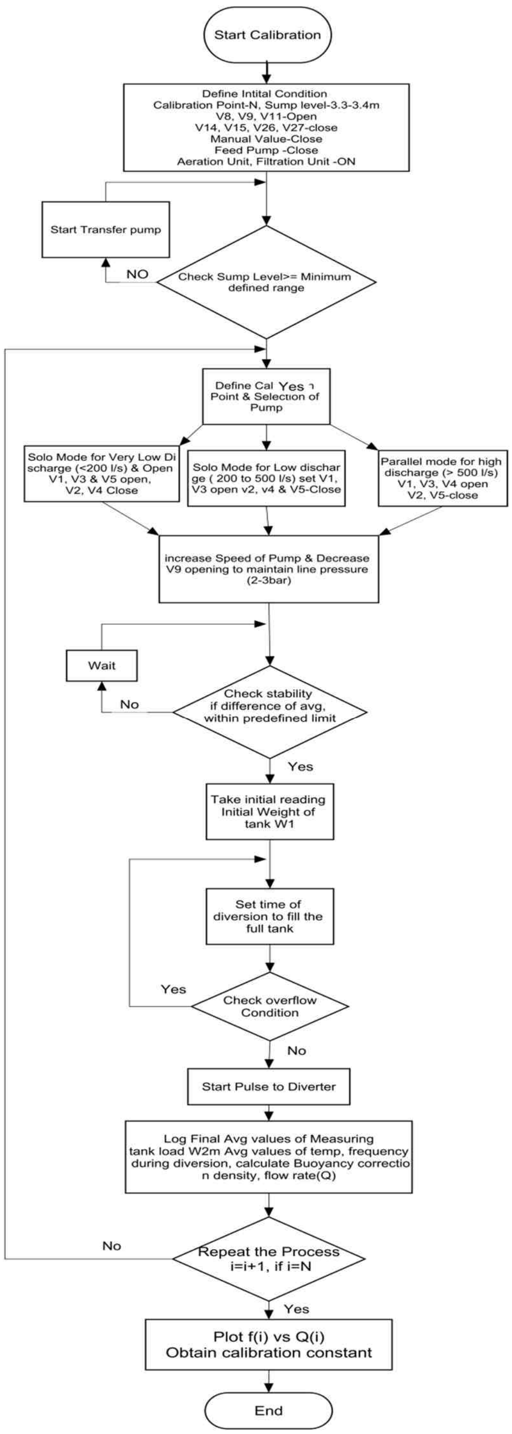


Fig. 4 Program flow for execution of calibration process

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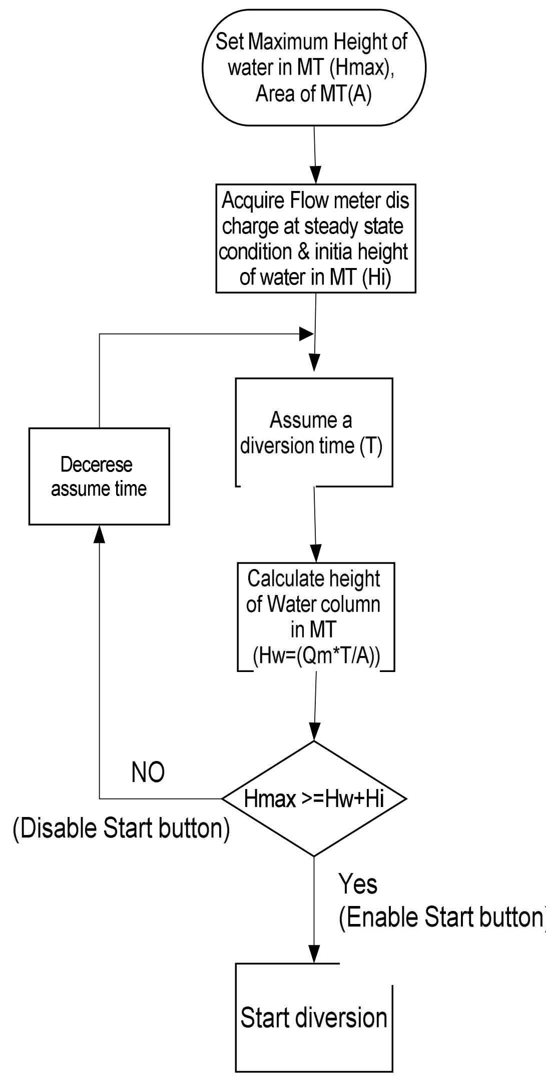
SCADA is designed to control speed of pump, Valves, Sump level, Overflow in measuring tank during execution of flow calibration. Automatic computer-based supervision of all plant devices, e.g. the leakage-prove operation of on/off valves, guarantees to provide reliable calibration results []. The PLC based programming in the ladder logic is developed for overflow control in measuring tank using Flow chart given in Fig. 5

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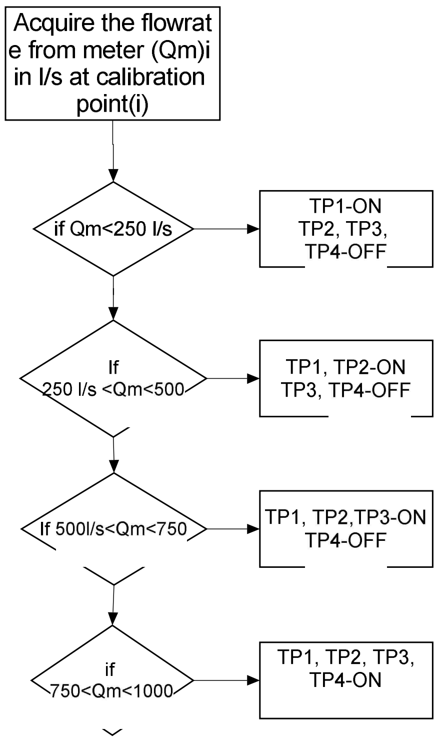


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In existing SCADA there are provision for alarm generations for fault detection in any filed devices viz valves, variable frequency derives and transfer pump.

## 2.4 Mathematical calculations and report generations

Mathematical equations involved in the flow calibration process as per ISO 4185 [], for buoyancy correction, density calculation, volume flow rate are programed in the PLC & SCADA system. As water density is a function of temperature, the exact measurement of water density ($\rho$) at the temperature that occurs within flow meter calibration during a calibration run has to be performed.

$$\rho = \frac{1}{\vartheta_0.[(1-A.\rho_{abs})+8.10^6(\theta-B+C.\rho_{abs})^2-6.10^8(\theta-B+C.\rho_{abs})^3]} \quad (1)$$

Where $\vartheta_0$ is Specific volume at 0ºC, A, B and C are constant, $\rho_{abs}$ is water pressure in line, $\theta$ is temperature of water in measuring tank during diversion

$$M = W * \left\{1 + \rho_{air} * \left[\frac{1}{\rho} - \frac{1}{\rho_w}\right]\right\} \quad (2)$$

M is the corrected mass, collected in measuring tank, W is the measured weight by load Cell, $\rho_{air}$ is the density of air, $\rho$ is the density of the fluid (water), and $\rho_w$ is the density of the tank material.

Volume flow rate:

$$Q_C = \frac{M}{(t*\rho)} \quad (3)$$

$$Q_C = \frac{M}{t*\rho} \quad (4)$$

Where $Q_C$ is calibrated discharge and t is diversion time

## 3.0 FLOW CALIBRATION AND MEASUREMENT SET-UP

The working principles of flowmeters calibration are based on two basic methods namely gravimetric and volumetric methods. Gravimetric method is based on fundamental principle, known as primary method in which water is collected for a predetermined time and weighed. The weighing method is again categorized into static weighing and dynamic weighing techniques.

The two parameters measured with this system are mass flow rate and volume flow rate. For the determination of volume flow rate, the density of flowing water is measured during measurement process. The mass flow rate is then divided by the density to calculate volume flow rate. As per ISO 4185 [2-5].

In the volumetric method, water flowing through the meter under test is collected in a volumetric vessel for a predetermined time and its volume is measured, directly. Thus, volume flow rate is derived and calculated.

Since the determination of volume flow rate is measured indirectly from mass, it is treated as secondary method. The documentary standard released by ISO for flow measurement in closed conduits using volumetric method is ISO 4064 [6-8]. The primary method based on weighing is well established and widely accepted method internationally [9–12].

Calibration of the electromagnetic flow meter has been carried in open loop in which, water is pumped from a sump having the constant water level and diverted to the measuring tank for a specified period through flow diverter using gravimetric approach with flying start- and -stop method as per ISO 4185[3].

In situ calibration chain of flow measurement system is as follows:

**(a) Calibration of balance system:**

**(b) Calibration of electromagnetic flow meter:**

Calibration of flow meter was performed using gravimetric method using flying start and stop approach as per ISO-4185.

### 3.1 Calibration of balance system

#### 3.1.1 Standard weights

The F2 class standard weights are used for calibration of calibrator tank load cell

#### 3.1.2 Calibration of calibrator tank load cell

Calibration of calibrator tank load cell (2ton) is carried out with standard weights up to 1500 kg (72 No- 20 kg, 6 No-10 kg). The empty weight of calibrator tank is 490 kg. The output signals from load cell are logged in SCADA at 100Hz.

A curve has been plotted between output signal of load cell $(mV)_{CT}$ and applied standard weights and as shown in Fig.7 along with its regression curve as shown in Fig.8

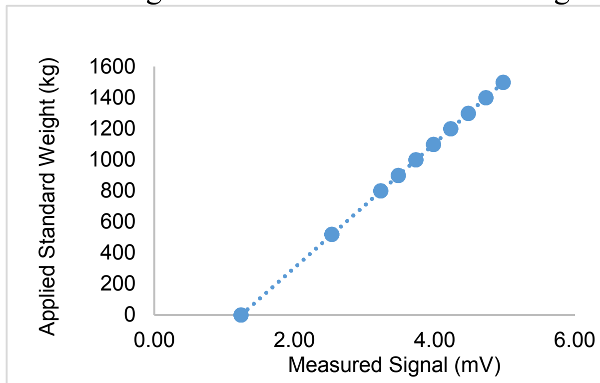


Fig.7 Calibration curve calibrator tank load cell

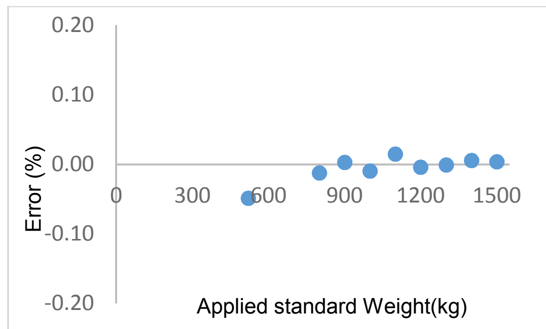


Fig. 8 Regression error of calibrator tank load cell

#### 3.1.3 Calibration of Measuring Tank Load Cell

Three ring torsion type load cell of 22-ton each are placed at the bottom of measuring tank to measure the weight of water collected over a period of diversion time. These load cells are calibrated with a calibrator tank load cell.

A fix calibrated weight of water (about1300 kg) is transferred from calibrator tank to measuring tank. Initial and final output signals (mV) of load cells (measuring tank and calibrator tank) are logged SCADA system. The same is repeated until the level of measuring tank reached at maximum.

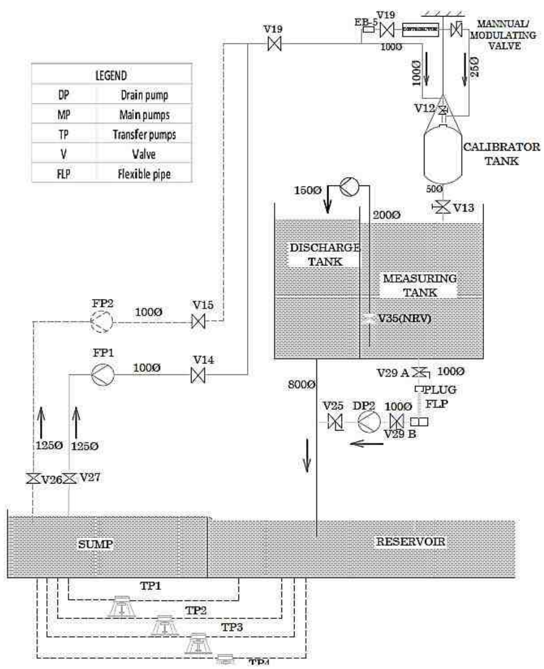


Fig.9 measuring tank load cell calibration loop

The cumulative corrected weight of water transferred by calibrator tank is plotted against the primary output signal $(mV)_{MT}$ of measuring tank load cell as shown in Fig.10. Regression error of measuring tank load cell is plotted against applied standard weight as shown in Fig.11.

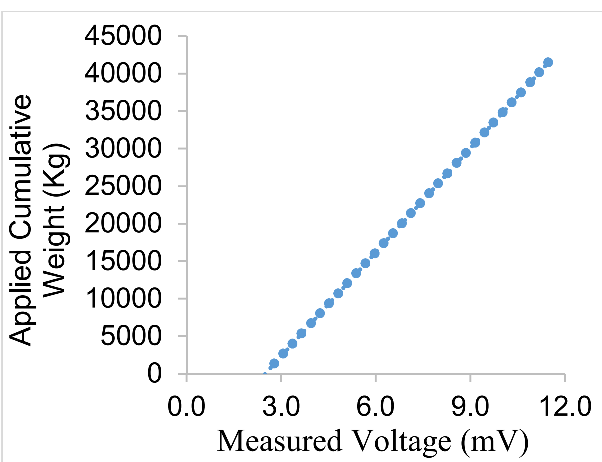


Fig. 10 calibration curve of measuring tank load cell

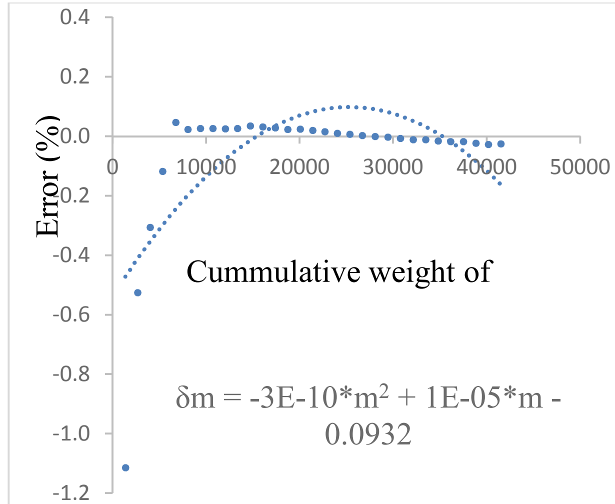


Fig. 11 Regression error of measuring tank load cell

### 3.2 Calibration of electromagnetic flow meter

Calibration of flow meter is carried out for discharge range between 100 l/s to 750 l/s by keeping sump level constant. For maintaining sump level constant, A PLC based program has been developed in ladder logic, details discuss in section…. Timing error of diverter system are obtained and used to correct the measured discharge. Water is diverted into measuring tank for a set period of time until it gets fully filled. Initial and final readings of measuring tank load cells $(mV)_{MT}$, initial and final temperature and diversion time are logged into SCADA in order to calculate the discharge. Buoyancy correction is made to the readings of a load cell to take account of the difference between the upward thrust exerted by the atmosphere and water being weighed.

Frequency $(f_F)$ signal from flowmeter during diversion period are log in SCADA and flow Calibration and regression curve are plotted in Fig.12 and Fig.13 respectively.

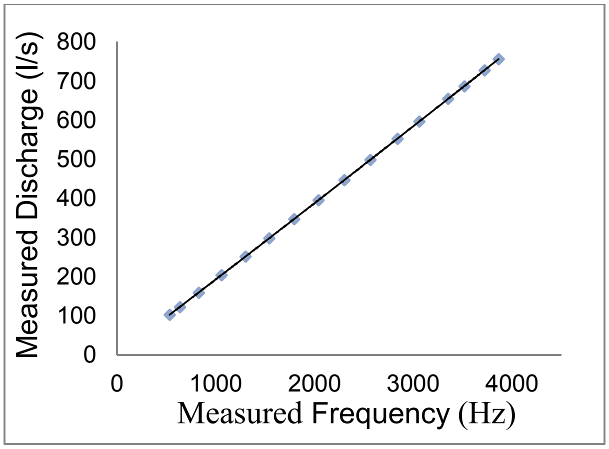


Fig.12 Flow meter calibration curve

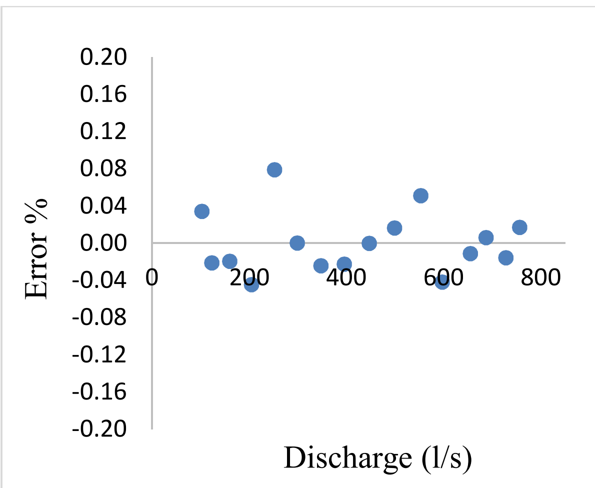


Fig.13 regression error of flow meter

Calibration equations of electromagnetic flowmeter, measuring tank load cell and calibrator tank load cell are tabulated in Table-1.

Table-1 Calibration equation of flow parameters

| **Instrument** | **Calibration equation** |
|---|---|
| Calibrator tank load cell | $(W_{CT})_C = 400.76 * (mV)_{CT} - 495.82$ |
| Measuring tank load | $(W_{MT})_C = 4622.57 * (mV)_{MT} - 11523.86$ |
| Flow meter | $Q_C = 3 * 10^{-7} * f_F^2 + 0.191448 * f_F + 1.318646$ |

These calibration equations are used in Ladder logic based PLC programming to convert raw signal into calibrated values.

## 4.0 UNCERTAINTY ANALYSIS

The uncertainty associated with a discharge measurement is obtained by combining the uncertainties arising from the sources. Although "systematic" errors have been distinguished from "random" errors, the probability distribution of the possible values of each systematic component is essentially Gaussian, and, in accordance with IS0 5168.

The combination of all the uncertainties may be made by the root-sum-square method. As per ISO 4185, the systematic, random uncertainty and total uncertainty in discharge measurement is given by (as per ISO 4185(1980)) Eq.5, Eq.6 and Eq.7 respectively.

$$e_{Qs} = \sqrt{[(e_s)_b]^2 + [(e_s)_p]^2 + [(e_s)_d]^2 + [(e_s)_\varepsilon]^2 + [(e_s)_t]^2} \tag{5}$$

where $E_s$ is the overall system uncertainty; $(e_s)_b$ uncertainty due to the weighing machine; $(e_s)_\varepsilon$ is the buoyancy correction; $(e_s)_p$ is the systematic uncertainty due to diverter system; $(e_s)_t$ is systematic uncertainty due to the timing device; $(e_s)_d$ systematic uncertainty in the measurement of density.

$$(e_{QR})_{95} = \sqrt{[(e_R)_b]^2 + [(e_R)_p]^2} \tag{6}$$

where, $(e_R)_b$ Random uncertainty is the difference between two weighing observations; $(e_R)_p$ is the random uncertainty due diverter system; the random uncertainty in density measurement $(e_R)_d$ is neglected

$$(e_{QT}) = \sqrt{[(e_{QR})_{95}]^2 + [e_{Qs}]^2} \qquad (7)$$

In the present study buoyancy effect has been calculated as per Eq.2 in the measuring tank and correction has been made in the total collected weight of water in measuring tank. Systematic error $(e_s)_t$ in time measurement is neglected

In present setup, F2 class weight, calibrator tank and measuring tank constitute the weighing system. Systemic uncertainty of measuring tank load cell is calculated using Eq.8 and Eq.9 as per ISO-4185.

$$\delta m = -3E\text{-}10*m^2 + 1E\text{-}05*m - 0.0932 \qquad (8)$$

$$\delta(\Delta m) = \delta m_2 - \delta m_1 \qquad (9)$$

Correction on measurement in diversion time is also carried out as per method given in ISO-4185 as shown in Fig.14. Value obtained from the curve Δt= 0.0217s is adjusted in the total diversion time during flow meter calibration.

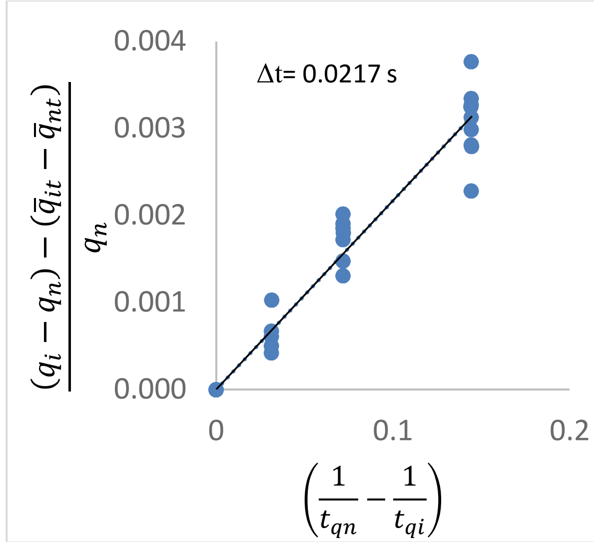


Fig.14 diversion time correction

Systematic uncertainties of each instrument/parameter are given in Table-2.

Table 2-Systemic uncertainties in flow measurement

| S. No | Components | | | Uncer. (%) |
|---|---|---|---|---|
| 1. | weighing system | Standard weights | 0.0045 | 0.070 |
| | | Calibrator tank load cell | 0.05 | |
| | | Measuring tank load cell | 0.0489 | |
| 2. | Timing device | | | Negligible |
| 3. | Density | | | 0.010 |
| 4. | Diverter system | | | 0.049 |
| 5. | Buoyancy | | | corrected |
| Systemic uncertainty in flow measurement | | | | 0.0860 |

The repeatability of the movement (random error) of the flow diverter is determined experimentally by setting the flow-rate to a steady value and then carried out series of 10 diversions for a fixed diversion period to provide a series of 10 estimations of the flow- ate This exercise is repeated for several

different diversion periods and, from the standard deviation of each series of measurements, the 95 % confidence limits have been be evaluated as per ISO-4185 and are shown in Fig.15.

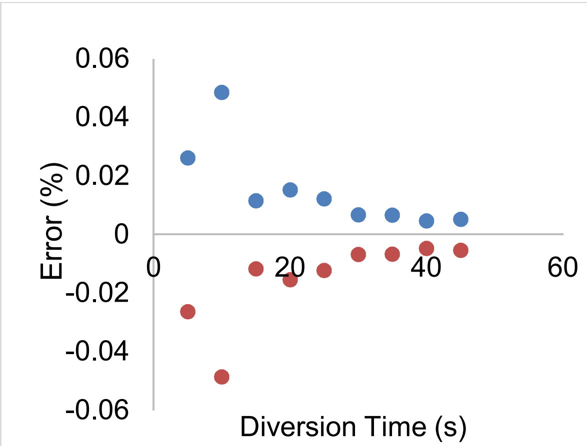


Fig.15 Random error in diverter time

For evaluation of random error of weighing system, the standard deviation of the distribution of points about the best-fit curve shown in Fig.11 is calculated with 95 % confidence limits of the distribution determined using Student's t-table. This value of confidence limits is multiplied by square root of two (since the determination of the mass of water collected in measuring tank during a diversion is obtained from the difference between two weighing) as per ISO-4185. Random error of flow diverter system and weighing system are found as ±0.0262616 and ±0.0485% respectively.

Total random error in flow measurement during calibration is calculated using Eq.7 and found out as 0.0551%. Systematic uncertainty of flow measurement during calibration is 0.0860% and regression error at 700 l/s is found 0.02% from flow calibration curve. The total uncertainty in flow measurement at 700 l/s is found as ±0.104%.

## 5.0 CONCLUSIONS

The real-time data base as an inherent component of the SCADA system being applied for the automated operation of the test field provides capabilities these special capabilities are a prerequisite to execute the flow calibration process and control the flied instruments. In-situ calibration of measuring instruments viz calibrator tank load cell, measuring tank load cell, flowmeter has been performed. Calibration equations, regression curves have been obtained. Uncertainty analysis has been performed as per ISO 4185 at 700 l/s flowrate and systematic error, random error and regression error has been found 0.086%, 0.055% and 0.02% respectively. The total uncertainty in flow measurement at 700 l/s is found as ±0.104%.


**Acknowledgement:**

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# Calibration of Electromagnetic Flowmeter Using Advanced SCADA System

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## ABSTRACT

The Programmable Logic Controller (PLC) based Supervisory Control and Data Acquisition (SCADA) system is designed for automation, remote monitoring, signal acquisition, data logging and report generation for flow calibration and measurement process. In this paper logic and flow charts in PLC programming for execution of calibration process and controls are presented. In situ calibration of different measuring instruments used in flow calibration viz. flow meter, measuring tank load cells, calibrator tank load cells have been performed and calibration equations have been derived from their calibration curves. Gravimetric approach using flying start and stop method has been adopted for flow calibration in present study. Systematic and random error of weighing balance and flow diverter has been evaluated as per ISO 4185.

## KEY WORDS

Calibration, measurement, SCADA, gravimetric method, uncertainty, experimental

## 1.0 INTRODUCTION

A fully automatic SCADA based Hydraulic turbine R&D laboratory has been set-up in 2016 at Alternate Hydro Energy Centre (AHEC), Indian Institute of Technology (IIT) Roorkee, Uttarakhand, India, a center of excellence for small hydropower in the country, to validate the homologous hydro models, designed and fabricated by various turbines manufactures. During the flow calibration and measurement, the main process quantities e.g. water flow rate, pressure and temperature are stabilized by logic developed in a computer-based Supervisory Control and Data Acquisition (SCADA) system, with other relevant process parameters like temperature, diverter actuation, load cell reading and ambient-air conditions, being monitored. This is an essential prerequisite to provide reproducible conditions that are necessary to achieve a high degree of reproducibility in the measurement and calibration processes.

The Programmable Logic Controller (PLC) based SCADA system is used for automation, remote monitoring, signal acquisition, data logging and report generation. The data from field instruments during calibration and measurement of flow are acquired and control commands to field devices are being sent by SCADA. The PLC also controls the process and acquire raw signal from field instruments and convert it into the secondary

output parameters. The PLC is used as the main decision making module.

## 2.0 APPLICATION OF EXISTING SCADA SYSTEM FOR CALIBRATION PROCESS

Advanced SCADA system has been designed for automation of the operations, control, data communications and acquisition, feedback, alarms, mathematical calculations and report generations in calibration process as per shown in Fig.1

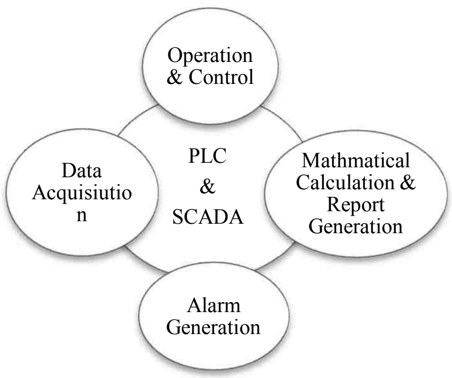


Fig.1 Application of SCADA system

Calibration of flow measurement system is being run automatically, with the capabilities of the computer-based SCADA system being utilized for automatic process control and operator interaction [14]. The operator that initiates and supervises flow meter calibration has full access to all process variables of the calibration plant with help of SCADA screen as shown Fig.2

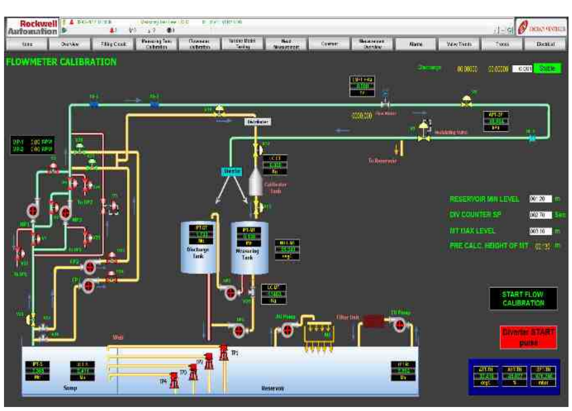


Fig.2 SCADA screen for flow meter calibration

In flow calibration and measurement, the application of PLC based SCADA system is outline in four different areas as given below:

### 2.1 Data acquisition from field instruments

In existing Scada system, various communication viz Profibus, Foundation Field bus and analog communication are used to connect the field instruments. As a standard, all data acquired from sensing and actuating devices are stored in the SCADA system's real-time data base as so-called "raw" values, i.e. no corrective functions or signal filtering operations have been applied to these process values at the moment they are being stored. Raw signal from field instruments are converted into the calibrated values by using the calibration coefficients in SCADA system. Further converted calibrated values are being averaged for a user defined time sample. Data communication and acquisition from various field instruments are shown in Fig.3

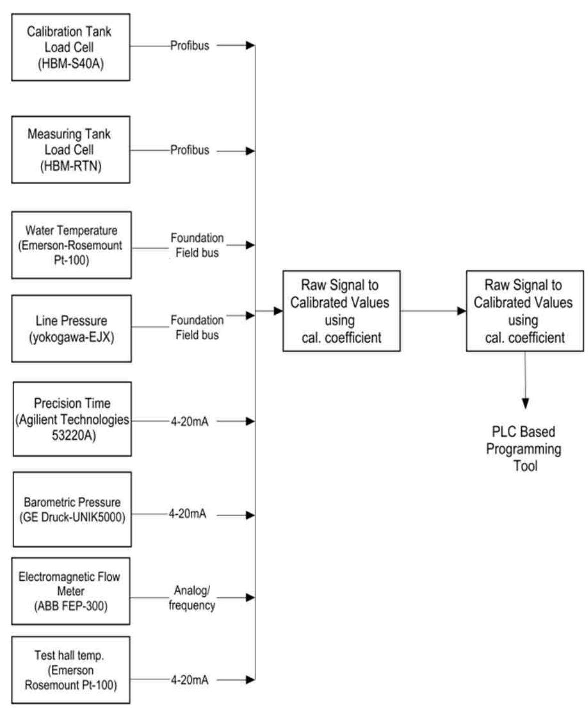


Fig.3 Data acquisition and communication to various field instruments

### 2.2 Execution of calibration process

A program has been design in PLC language as per given flow chart in Fig.4 to execute the electromagnetic flowmeter calibration process.

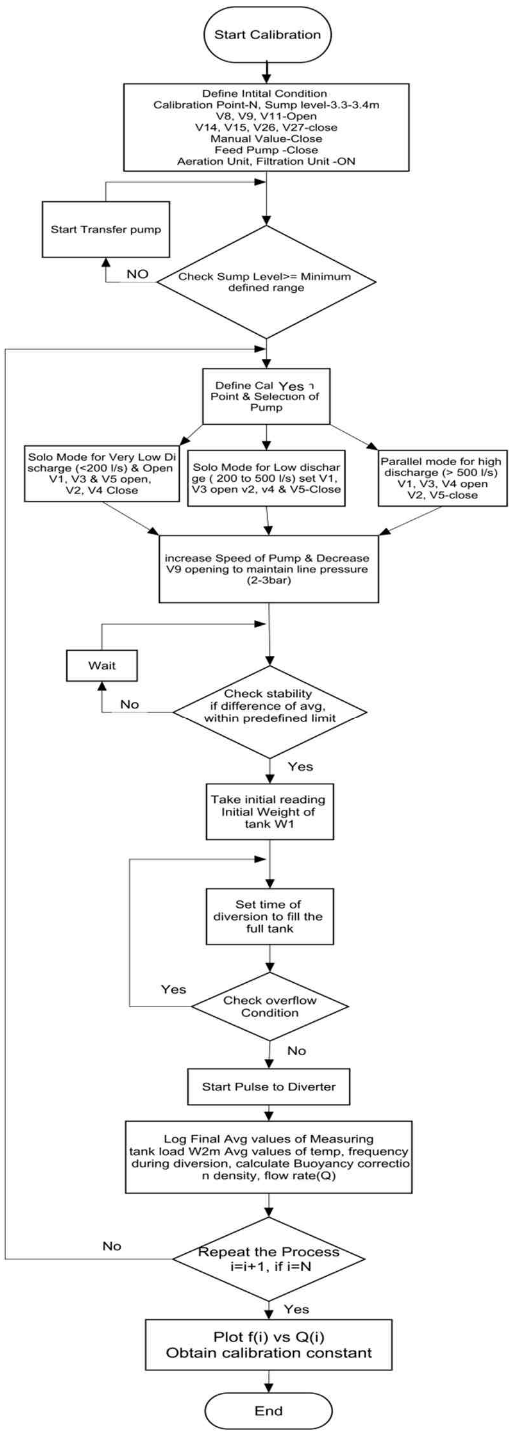


Fig. 4 Program flow for execution of calibration process

## 2.3 Control of Operation & Alarm generation

SCADA is designed to control speed of pump, Valves, Sump level, Overflow in measuring tank during execution of flow calibration. Automatic computer-based supervision of all plant devices, e.g. the leakage-prove operation of on/off valves, guarantees to provide reliable calibration results []. The PLC based programming in the ladder logic is developed for overflow control in measuring tank using Flow chart given in Fig. 5

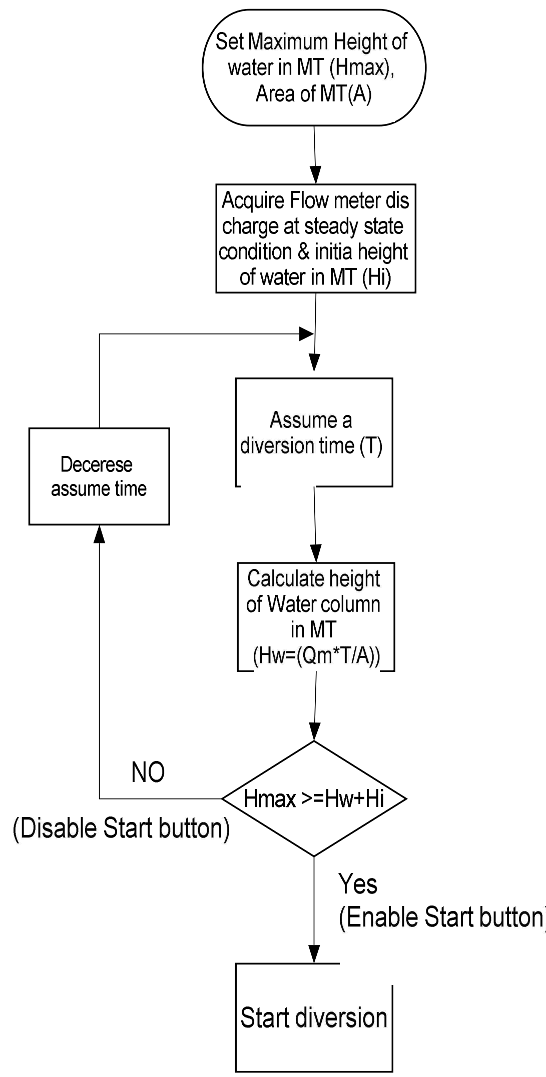


Fig. 5 Program flow chart for overflow control of water

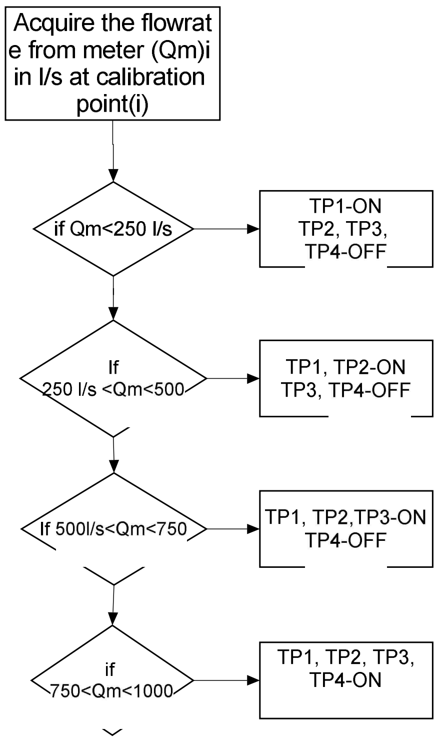


Fig. 6 Program flow chart for Sump level control

In existing SCADA there are provision for alarm generations for fault detection in any filed devices viz valves, variable frequency derives and transfer pump.

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Where $\vartheta_0$ is Specific volume at 0ºC, A, B and C are constant, $\rho_{abs}$ is water pressure in line, θ is temperature of water in measuring tank during diversion

$$M = W * \left\{1 + \rho_{air} * \left[\frac{1}{\rho} - \frac{1}{\rho_w}\right]\right\} \quad (2)$$

M is the corrected mass, collected in measuring tank, W is the measured weight by load Cell, $\rho_{air}$ is the density of air, ρ is the density of the fluid (water), and $\rho_w$ is the density of the tank material.

Volume flow rate:

$$Q_C = \frac{M}{(t*\rho)} \quad (3)$$

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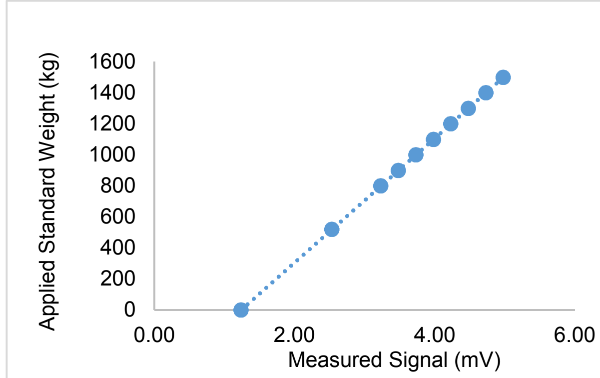


Fig.7 Calibration curve calibrator tank load cell

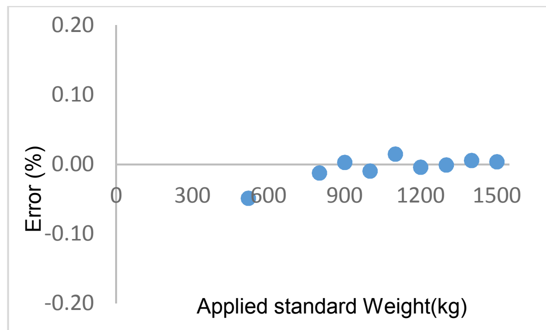


Fig. 8 Regression error of calibrator tank load cell

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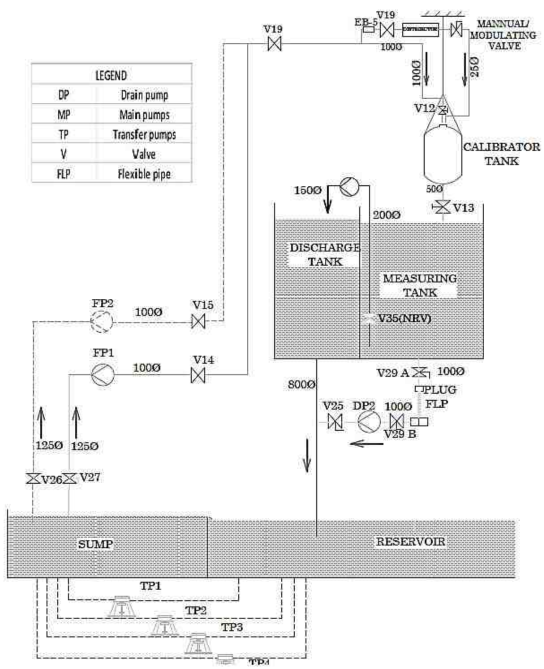


Fig.9 measuring tank load cell calibration loop

The cumulative corrected weight of water transferred by calibrator tank is plotted against the primary output signal $(mV)_{MT}$ of measuring tank load cell as shown in Fig.10. Regression error of measuring tank load cell is plotted against applied standard weight as shown in Fig.11.

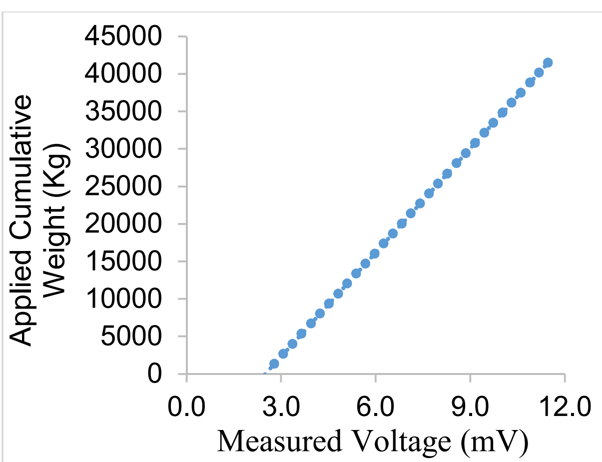


Fig. 10 calibration curve of measuring tank load cell

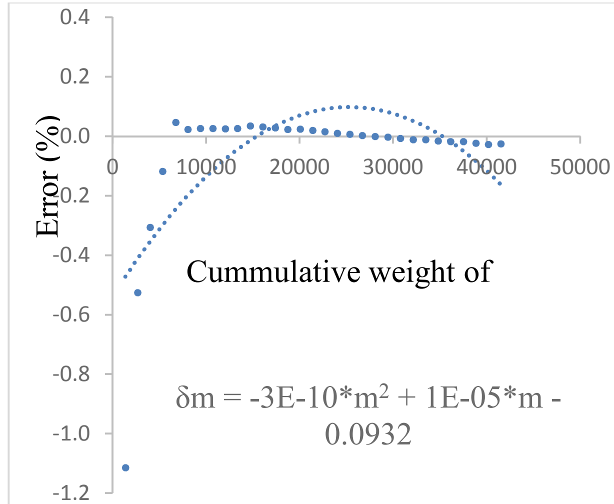


Fig. 11 Regression error of measuring tank load cell

### 3.2 Calibration of electromagnetic flow meter

Calibration of flow meter is carried out for discharge range between 100 l/s to 750 l/s by keeping sump level constant. For maintaining sump level constant, A PLC based program has been developed in ladder logic, details discuss in section…. Timing error of diverter system are obtained and used to correct the measured discharge. Water is diverted into measuring tank for a set period of time until it gets fully filled. Initial and final readings of measuring tank load cells $(mV)_{MT}$, initial and final temperature and diversion time are logged into SCADA in order to calculate the discharge. Buoyancy correction is made to the readings of a load cell to take account of the difference between the upward thrust exerted by the atmosphere and water being weighed.

Frequency $(f_F)$ signal from flowmeter during diversion period are log in SCADA and flow Calibration and regression curve are plotted in Fig.12 and Fig.13 respectively.

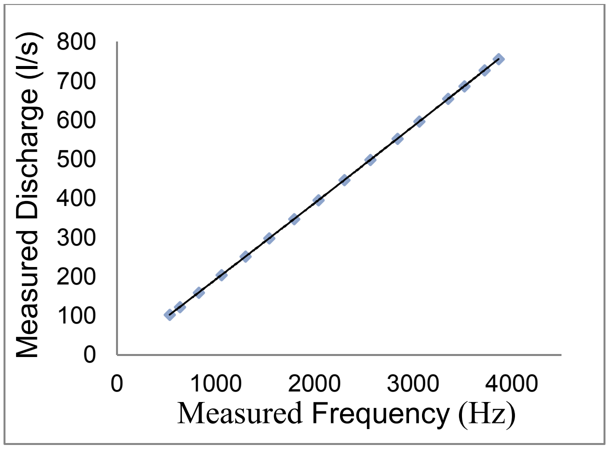


Fig.12 Flow meter calibration curve

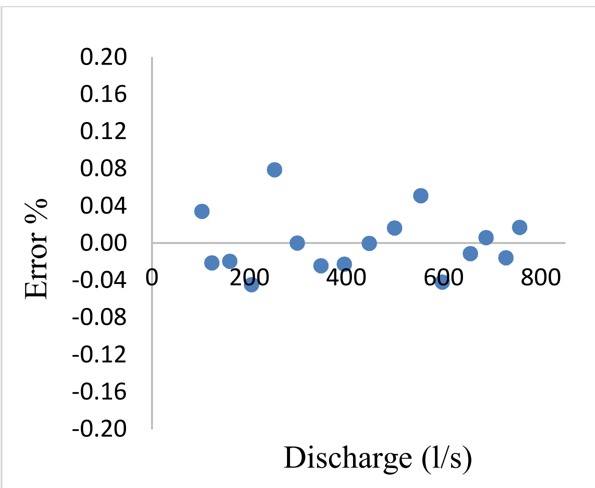


Fig.13 regression error of flow meter

Calibration equations of electromagnetic flowmeter, measuring tank load cell and calibrator tank load cell are tabulated in Table-1.

Table-1 Calibration equation of flow parameters

| **Instrument** | **Calibration equation** |
|---|---|
| Calibrator tank load cell | $(W_{CT})_C = 400.76 * (mV)_{CT} - 495.82$ |
| Measuring tank load | $(W_{MT})_C = 4622.57 * (mV)_{MT} - 11523.86$ |
| Flow meter | $Q_C = 3 * 10^{-7} * f_F^2 + 0.191448 * f_F + 1.318646$ |

These calibration equations are used in Ladder logic based PLC programming to convert raw signal into calibrated values.

## 4.0 UNCERTAINTY ANALYSIS

The uncertainty associated with a discharge measurement is obtained by combining the uncertainties arising from the sources. Although "systematic" errors have been distinguished from "random" errors, the probability distribution of the possible values of each systematic component is essentially Gaussian, and, in accordance with IS0 5168.

The combination of all the uncertainties may be made by the root-sum-square method. As per ISO 4185, the systematic, random uncertainty and total uncertainty in discharge measurement is given by (as per ISO 4185(1980)) Eq.5, Eq.6 and Eq.7 respectively.

$$e_{Qs} = \sqrt{[(e_s)_b]^2 + [(e_s)_p]^2 + [(e_s)_d]^2 + [(e_s)_\varepsilon]^2 + [(e_s)_t]^2} \tag{5}$$

where $E_s$ is the overall system uncertainty; $(e_s)_b$ uncertainty due to the weighing machine; $(e_s)_\varepsilon$ is the buoyancy correction; $(e_s)_p$ is the systematic uncertainty due to diverter system; $(e_s)_t$ is systematic uncertainty due to the timing device; $(e_s)_d$ systematic uncertainty in the measurement of density.

$$(e_{QR})_{95} = \sqrt{[(e_R)_b]^2 + [(e_R)_p]^2} \tag{6}$$

where, $(e_R)_b$ Random uncertainty is the difference between two weighing observations; $(e_R)_p$ is the random uncertainty due diverter system; the random uncertainty in density measurement $(e_R)_d$ is neglected

$$(e_{QT}) = \sqrt{[(e_{QR})_{95}]^2 + [e_{Qs}]^2} \quad (7)$$

In the present study buoyancy effect has been calculated as per Eq.2 in the measuring tank and correction has been made in the total collected weight of water in measuring tank. Systematic error $(e_s)_t$ in time measurement is neglected

In present setup, F2 class weight, calibrator tank and measuring tank constitute the weighing system. Systemic uncertainty of measuring tank load cell is calculated using Eq.8 and Eq.9 as per ISO-4185.

$$\delta m = -3E\text{-}10 * m^2 + 1E\text{-}05 * m - 0.0932 \quad (8)$$

$$\delta(\Delta m) = \delta m_2 - \delta m_1 \quad (9)$$

Correction on measurement in diversion time is also carried out as per method given in ISO-4185 as shown in Fig.14. Value obtained from the curve Δt= 0.0217s is adjusted in the total diversion time during flow meter calibration.

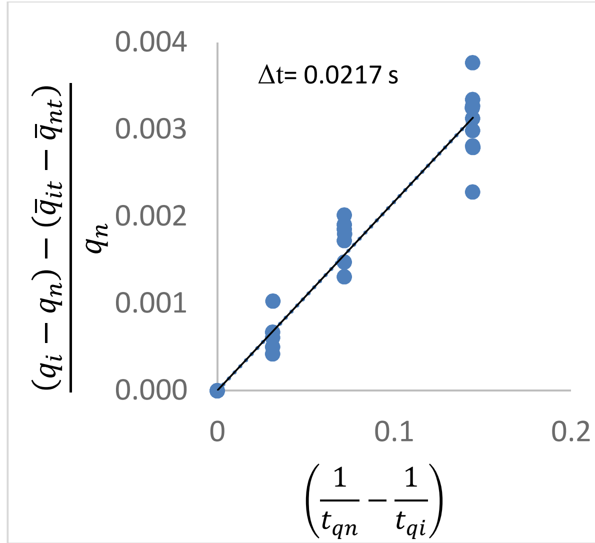


Fig.14 diversion time correction

Systematic uncertainties of each instrument/parameter are given in Table-2.

Table 2-Systemic uncertainties in flow measurement

| S. No | Components | | | Uncer. (%) |
|---|---|---|---|---|
| 1. | weighing system | Standard weights | 0.0045 | 0.070 |
| | | Calibrator tank load cell | 0.05 | |
| | | Measuring tank load cell | 0.0489 | |
| 2. | Timing device | | | Negligible |
| 3. | Density | | | 0.010 |
| 4. | Diverter system | | | 0.049 |
| 5. | Buoyancy | | | corrected |
| Systemic uncertainty in flow measurement | | | | 0.0860 |

The repeatability of the movement (random error) of the flow diverter is determined experimentally by setting the flow-rate to a steady value and then carried out series of 10 diversions for a fixed diversion period to provide a series of 10 estimations of the flow- ate This exercise is repeated for several

different diversion periods and, from the standard deviation of each series of measurements, the 95 % confidence limits have been be evaluated as per ISO-4185 and are shown in Fig.15.

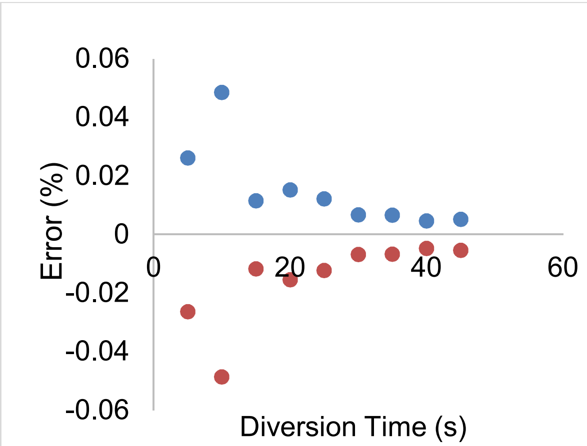


Fig.15 Random error in diverter time

For evaluation of random error of weighing system, the standard deviation of the distribution of points about the best-fit curve shown in Fig.11 is calculated with 95 % confidence limits of the distribution determined using Student's t-table. This value of confidence limits is multiplied by square root of two (since the determination of the mass of water collected in measuring tank during a diversion is obtained from the difference between two weighing) as per ISO-4185. Random error of flow diverter system and weighing system are found as ±0.0262616 and ±0.0485% respectively.
Total random error in flow measurement during calibration is calculated using Eq.7 and found out as 0.0551%. Systematic uncertainty of flow measurement during calibration is 0.0860% and regression error at 700 l/s is found 0.02% from flow calibration curve. The total uncertainty in flow measurement at 700 l/s is found as ±0.104%.

## 5.0 CONCLUSIONS

The real-time data base as an inherent component of the SCADA system being applied for the automated operation of the test field provides capabilities these special capabilities are a prerequisite to execute the flow calibration process and control the flied instruments. In-situ calibration of measuring instruments viz calibrator tank load cell, measuring tank load cell, flowmeter has been performed. Calibration equations, regression curves have been obtained. Uncertainty analysis has been performed as per ISO 4185 at 700 l/s flowrate and systematic error, random error and regression error has been found 0.086%, 0.055% and 0.02% respectively. The total uncertainty in flow measurement at 700 l/s is found as ±0.104%.

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