A NOVEL DOUBLE WEIGHING TANK APPROACH FOR PRECISION FLOW MEASUREMENT

Thesis

Submitted for the award of the degree of

DOCTOR OF PHILOSOPHY

by

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October 2016

CERTIFICATE

I hereby certify that the work being presented herein this thesis entitled, "**A Novel Double Weighing Tank Approach for Precision Flow Measurement**", for the award of degree of Doctor of Philosophy in Electrical and Instrumentation Engineering Department (EIED), Thapar University, Patiala, is an authentic record of my own work carried out under the supervision and guidance of Dr. Sanjay Yadav, Principal Scientist, CSIR-NPL, New Delhi and Dr. Ravinder Agarwal, Professor, EIED, Thapar University, Patiala.

The matter presented in this thesis has not been submitted either in part or in full to any university or institute for award of any degree.

(Shiv Kumar Jaiswal)

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

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ACKNOWLEDGEMENTS

At the onset, I owe my deepest gratitude to my supervisors, Dr. Sanjay Yadav and Dr. Ravinder Agarwal, who have supported me throughout my research with their patience, knowledge, suggestions, constructive criticism and keen interest. They have continued to be a source of inspiration for me and mentored me through their vast experiences. I consider myself very fortunate to have the opportunity to work with them. I am especially thankful to them for developing in me a research attitude and expanding my horizon. Without their support, this thesis would not have been completed. Whatever I know today is due to them.

I extend my wholehearted thanks to Director, NPL for his constant encouragement and permission to pursue my Ph.D. at Thapar University, Patiala and also for granting me study leave for 6 months being a residency requirement of the Ph.D. degree. I specially thank members of my Doctoral Advisory Committee consisting of Dr. S.K. Jain, Dr. Mandeep Singh and Dr. A.K. Chatterjee for their several insightful discussions and advice. My special thanks are due to my fellow senior scientists namely Dr. A.K. Bandyopadhyay, Dr. V.N. Ojha, Dr. R.K. Agarwal, Dr. Rajeev Chopra, Mr. Anil Kumar, Dr. Nahar Singh, Dr. Amish Joshi, Dr. D. Haranath and Dr. Sanjay Srivastava from CSIR-National Physical Laboratory, New Delhi for keeping me always encouraged and motivated towards my research activities. I am also thankful to Mr. Sanjay Sharma, Director, M/s. Bharti Automation Private Limited, New Delhi for helping me in the development process.

I would like to thank Mr. Chatar Singh. He always helped me in performing various experiments during office hours and beyond and also during in weekends and holidays.

I have no words to acknowledge the contributions and support received from my colleagues, friends and well wishers namely Mr. Chatar Singh, Mr. Abdul Wahid, Mr. Raman Kumar Sharma, Mr. V.K. Gupta and Mr. L. Sridhar for their unparallel help, support and suggestions.

Last but not the least, I would like to place on records that Mrs. Amita Jaiswal, my beloved wife, who has always been my constant source of inspiration and encouragement in enriching my wisdom in the world of fast expanding science and technology. Words are not suffice to express my appreciation to her in bringing up the children during my absence at home several occasions for the Ph.D. work and also for her dedicated and thought provoking advices extended to me for completion of this degree. Finally, I would like to thank my family for standing by me through all the joys and sorrows that life had to offer. My heartfelt affections are due for my children who mostly have suffered during my absence and they never brought up such issues to me.

My acknowledgements would not be complete without expressing my gratitude towards Almighty for giving me strength and health for completing this work.

Shiv Kumar Jaiswal

ABSTRACT

Water Flow Measurement Systems (WFMSs) are widely used for the measurement of flow rate of water flowmeters and also for the traceability purposes all over world. There exists basically two methods for the liquid (water) flow measurement namely gravimetric/ weighing and volumetric. Worldwide, weighing method as described in ISO 4185 is used in WFMS for calibration of different types of flowmeters. Last two decades have witnessed significant research contributions in the development of instrumentation and techniques. During these developments, special emphasis was placed on reducing the measurement errors enabling finally improving measurement uncertainty associated with flow calibration. Nowadays, flow standards of substantially low uncertainty, in the order of 0.05 % or better, are required for high accuracy flowmeters calibration wherein error and uncertainty contributions of standards transferred to meter under test (MUT) is considered almost negligible. The need of such highly accurate flow standards opens new lines for the research and developments in this field.

In a static weighing method, the main sources of measurement uncertainty are collected mass, collection time (including diverter error), and density of water. The uncertainty of the collected water mass depends upon weighing balance's indication, drift, calibration, buoyancy correction, leaks and splashes, storage effects and evaporation of water. The collection time uncertainty depends upon timer calibration, timer actuation and diverter error. The uncertainty associated with density measurements depends upon the quality of tap water and its temperature.

The associated measurement uncertainty can be improved by use of advanced instrumentation. However, it is not possible to reduce the diverter error only using better instrumentation but special mechanical designs are needed as used by several other researchers.

In order to reduce the diverter error, a unique method/ technique of multiple weighing was proposed. It motivated us to work for the development of a new standard for

traceability of flowmeters. The present investigations describe the design and development of such a unique water flow measurement system of DN100 size based on static weighing method. In a traditional WFMS, a single weighing tank and a bypass line are used. However, in present study two metallic weighing tanks each having capacity of 2500 kg, with conical shape at bottom were used to achieve faster draining. The drain time is directly dependent on diameter of the drain valve, therefore, drain valves of comparatively bigger size (diameter 200 mm, commercially known as DN200) were used to obtain faster draining to achieve lower drain time. The fishtail, nozzle and traditional diverter system were fabricated and used in the system. For increasing the collection time, in a multiple weighing system, a cyclic process is adopted wherein filling time (T_F) of the first weighing tank is always greater than the draining time (T_D) of the second tank. Further, T_D also includes adequate time given for stability of the weighing system. The increased collection time thus obtained leads to improvement of measurement uncertainty.

CONTENTS

LIST OF ABBREVIATIONS

VIM	International Vocabulary of Metrology
BIPM	International Bureau of Weights and Measures
CIPM	International Committee for Weights and Measures
MRA	Mutual Recognition Arrangement
NMS	National Measurement System
NMI	National Metrology Institute
BIS	Bureau of Indian Standards
NPLI	CSIR-National Physical Laboratory, India
D&WM	Directorate of Weights and Measures
NPL	National Physical Laboratory, UK
NIST	National Institute of Standards and Technology, USA
NMIJ	National Metrology Institute of Japan
PTB	Physikalisch-Technische Bundesanstalt, Germany
WFMS	Water Flow Measurement System
MUT	Meter Under Test
JCGM	Joint Committee for Guides in Metrology
ISO	International Organization for Standardization
IEC	International Electro-technical Commission
OIML	International Organization of Legal Metrology
SCADA	Supervisory Control and Data Acquisition
CFD	Computational Fluid Dynamics
FCRI	Fluid Control Research Institute, India
NABL	National Accreditation Board for Testing and Calibration Laboratories

1

INTRODUCTION

1.1 Metrology

Metrology ─ the science of measurement, is derived from combination of two Greek words “metron” and "logos" which literally means the study of measurement. As per International Vocabulary of Metrology (VIM) [1] published by the International Bureau of Weights and Measures (BIPM), it is defined as “the science of measurement, embracing both experimental and theoretical determinations at any level of uncertainty in any field of science and technology”. Metrology has now emerged as a challenging and essential topic and need for every country. It is fundamentally important in industry and trade, not only for the consumer but also for manufacturer because accuracy, quality and reliability of the products and measurements are equally important for both (consumer and manufacturer). Quality of product and measurement can be ensured through "*Calibration*" and "*Metrological Traceability*" of measurements. The calibration is a measurement operation that, under specified conditions, in a first step, establishes a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainties and, in a second step, uses this information to establish a relation for obtaining a measurement result from an indication [1]. The metrological traceability is the property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty [1]. An established calibration hierarchy is required in metrological traceability.

The metrology is broadly classified into three categories as follows [2];

1.1.1 Fundamental Metrology

Fundamental metrology, also called scientific metrology, is related to the establishment of measurement units, the development of new measurement methods, realization of measurement standards and the transfer of metrological traceability from these standards to users in society.

1.1.2 Applied Metrology

Applied metrology, also known as industrial metrology, is related to the application of measurement science to manufacturing and other processes and their use in society, ensuring the suitability of measurement instruments, their calibration and quality control of measurements.

1.1.3 Legal Metrology

Legal metrology is related to the regulatory requirements of measurements and measuring instruments for the protection of health, public safety, the environment, enabling taxation, protection of consumers and fair trade.

1.2 National Measurement System

The national measurement system (NMS) of a country is defined as the technical and the organizational infrastructure, which ensures a consistent and internationally recognized basis for measurement. The NMS is required;

(i) to satisfy regulatory and other domestic requirement
(ii) to improve and demonstrate the quality of products
(iii) to reduce technical barriers to trade
(iv) to facilitate international trade, and
(v) to recognize the key elements and to establish linkages with global measurement infrastructure.

It is therefore essential for every industrialized country to have a comprehensive and well-integrated national measurement infrastructure. The NMS has been classified into the following components;

(a) Formulation of standards and engineering specifications. This task is performed by Bureau of Indian Standards (BIS).

(b) Maintenance of standards of physical measurement and their dissemination to users through its calibration and testing facilities. CSIR-National Physical Laboratory (NPLI), New Delhi is responsible for this task.

(c) Enforcement of standards. Directorate of Weights and Measures (DW&M) is responsible for this task.

National standards for weights and measures are maintained by a National Metrology Institute (NMI) in the country. The NMI provides the highest level of standards for the calibration and metrological traceability in that country, for example, National Physical Laboratory (NPL) in United Kingdom, National Physical Laboratory (NPLI) in India, National Institute of Standards and Technology (NIST) in USA, National Metrology Institute of Japan (NMIJ) in Japan and Physikalisch-Technische Bundesanstalt (PTB) in Germany**.** Many NMIs have signed the *International Committee for Weights and Measures-Mutual Recognition Arrangement* (CIPM-MRA) for global acceptability of calibration and measurement certificates issued by them [3]. This provides internationally recognized traceable measurements. The NPLI has also signed the CIPM-MRA. The main objectives of CIPM-MRA are;

(i) to establish the degree of equivalence of national measurement standards maintained by NMIs

(ii) to provide for the mutual recognition of calibration and measurement certificates issued by NMIs, and

(iii) thereby to provide governments and other parties with a secure technical foundation for wider agreements related to international trade, commerce and regulatory affairs.

These objectives are achieved through participation in international comparisons and peer review of the parameters by international experts from the NMIs.

1.3 Importance of Flow Measurement

Water is one of the most important fluids used in numerous applications. The main applications include process control in industries; nuclear, thermal and hydro-electric power generation; manufacturing of drugs and pharmaceuticals, fertilizers, beverages, distilleries, petrochemicals; safety and health hazards and in aviation, agricultural, irrigation and dairy plants *etc*. The ever growing industrialization, urbanization, population and depleting ground water levels have caused drastically increasing consumption of water day by day which is severely affecting the availability of water. The fluid flow measurements are essentially required in all walks of human life. Therefore, the role of metrologists becomes very vital to develop measurement techniques for the accurate and precise measurement of quantity of water for its optimum use. It helps to quantify the exact quantity, calculate the correct tariff and to control its misuse.

1.4 Types of Flowmeters and their Calibration

The various types of flowmeters, commercially available, are electromagnetic, ultrasonic, vortex, differential pressure, positive displacement, turbine, coriolis, *etc*. The various manufacturers of these flowmeters globally are Alden Labs, Micro Motion, Endress and Houser, Krohne, ABB, Siemens, Yokogawa, OVAL Corporation, Rockwin, etc. The different flowmeters work on different principles, for example, electromagnetic flowmeter works on Faraday's law of electromagnetic induction, ultrasonic flowmeter on ultrasonic principle of time of flight, orifice flowmeter on differential pressure measurement, coriolis flowmeter on coriolis principle, turbine flowmeter on rotation of turbine, etc. However, every flowmeter shows either volume or mass output, some time both too (coriolis mass flowmeter). The volume and mass output parameters are mass flow rate, total water mass, volume flow rate and total water volume. For the determination of total water volume and volume flow rate, the density of flowing water is measured during measurement process. The volume flow rate is calculated dividing mass flow rate by the density of the water. These flowmeters are used in a number of applications based on fluid conditions. For example, electromagnetic flowmeter is used for conducting liquid. The minimum conductivity of liquid should be >5 μS/cm. If the conductivity of the liquid is lower than this value, the rate of change of flux due to flowing liquid will be very less leading to reduced induced voltage across flowmeter's electrodes as per Farade's law of electromagnetic induction and reliability of the flowmeters will be severely affected. Therefore minimum conductivity of liquid is essentially required to be maintained for proper functioning of the electromagnetic flowmeters. The ultrasonic flowmeters are generally used in application where flow measurement is to be done without inserting the flowmeter in the flow circuit (i.e. without breaking the flow circuit). Some flowmeters work in liquid, some in gas and some in both. For example, electromagnetic flowmeters work in conducting liquid. Coriolis mass flowmeters, ultrasonic flowmeters and turbine flowmeters work both in liquid and gas.

The flowmeter gives current output and frequency (pulse) output apart from its digital indication. The output of the flowmeter is automated using its current output, frequency output or its digital indication is directly read using appropriate interface.

The calibrations of these flowmeters are done in liquid or gas flow measurement systems. Some flowmeters are calibrated in liquid but used in gas, for example, coriolis mass flowmeter. The details about the various flowmeters, their operating principles, applications, installation requirements and calibration processes are reported in the references [4-5].

1.5 Research Motivation

In India, the responsibility for establishment, maintenance, upgrade and dissemination of national flow standards lies with CSIR-National Physical Laboratory, New Delhi (NPLI) as the National Metrology Institute (NMI) for India. Subsequently, NPLI has established water flow measurement system (WFMS) in joint collaboration with PTB, Germany during 1992-1998 in the flow range 0.1 m^3/h to 600 m^3/h using static-gravimetric method as per ISO 4185 [6-10]. The gas flow measurement system is established recently [11-12]. In NPLI's WFMS, there are two test rigs, namely, DN50 and DN200 for calibration of water flowmeters of different sizes ranging from 10 mm to 200 mm. This highly complex automated system comprised of lot of electronics and controls, required highly skilled manpower and resources to maintain. Accordingly, this motivated us to develop a simpler, easy to maintain, cost effective system to provide traceable measurement and calibration system indigenously. This was also aimed to develop capabilities for design and development of such primary flow standards and provide low-cost solution to Indian industries, water flow testing and calibration laboratories and water flowmeters manufactures. Accordingly, a novel WFMS of DN100 size was designed and developed. In this novel system, two weighing tanks have been used for increasing collection time of water collected in weighing tanks for improvement of measurement error and uncertainty. The system can be also operated as standard system of single weighing defined in ISO 4185 where second weighing tank works as a bypass line.

1.6 Objectives

The objectives of the present research are followings;

a) To design a water flow measurement standard having diverter error minimized to optimum level with improved measurement uncertainty

b) To develop system software for automatic operation and controls for various types of analysis like chart for repeatability of measurements, stability of flow, error and uncertainty analysis

c) Performance evaluation of the prototype compact flow measurement standard using experimental data and simulation.

1.7 Research Methodology

Keeping in view of all these objectives, the research methodology was prepared to achieve the objectives. The methodology is shown in Fig. 1.1.

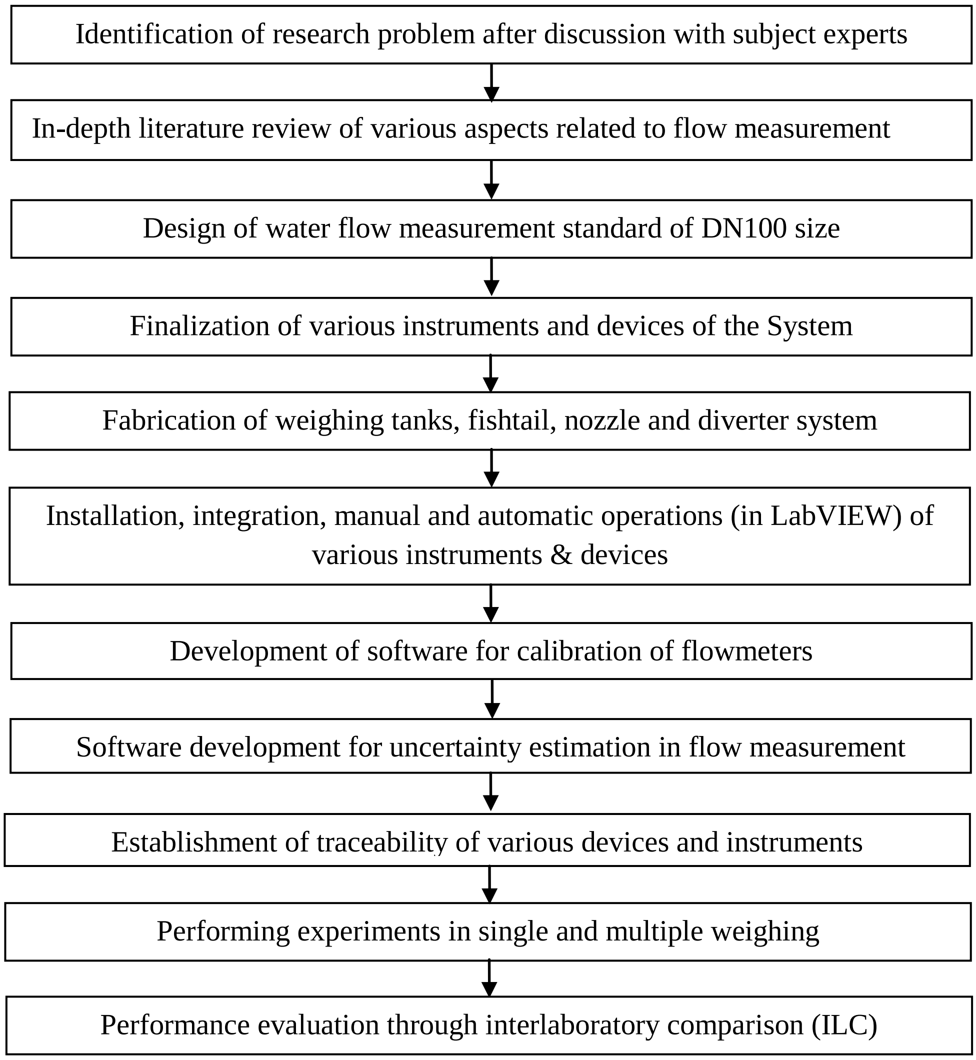


Figure 1.1: Flow chart for research methodology.

1.8 Organization of Thesis

The thesis has been organised into five chapters as given below.

Chapter 1 deals with the importance of flow measurements, flow parameters, various types of flowmeters and their calibration. The objectives and research methodology adopted to achieve the goals have been also described.

Chapter 2 covers the terse review of the literature and published works on fluid flow measurements, starting from historical background to modern fluid flow measurement facilities and state-of-the-art technologies available. During last decade, significant contribution has been made by various researchers worldwide for the improvement of accuracy of flow measurements. An effort has been made to study and summarize the work carried out by the researchers till date. The literature review helped in identifying the research problem.

Chapter 3 covers the methods of flow measurements, theoretical aspects, design details, fabrication mechanism, applied instrumentation, integration of various devices & instruments and development of software for control, data acquisition and operations of the developed system. One of the novelties of the developed system is the use of second weighing tank in place of bypass line which has resulted into the substantial increase in the collection time thereby leading to an overall improvement in the associated measurement uncertainty of the system. The advantages and disadvantages of multiple weighing method in comparison to single weighing are also discussed.

Chapter 4 discusses about the results obtained during various experiments carried out, establishment of traceability, evaluation of overall measurement uncertainty of the system and its performance evaluation through inter laboratory comparison (ILC: an internationally well established method for performance evaluation). The details of evaluation of diverter error, the main source of uncertainty, are described thoroughly. The importance of installation effect, another dominant factor in calibration of water flowmeters, is also explained. The results are discussed in reference to novelty, merits & demerits and improvement in measurement uncertainty of the system.

Chapter 5 summarizes conclusions, significance and shortcomings of the present work. Also highlighted are the suggestions and recommendations for future research work in this area.

In this chapter, a brief introduction of metrology, National Measurement System, role of NMI in metrology, importance of flow measurements, flow parameters, types of flowmeters, research objectives and research methodology have been highlighted and discussed.

2

REVIEW OF LITERATURE

2.1 History of Flow Measurement

The hydraulic structures are understood to be existed before the recorded history. The irrigation systems in Mesopotamia, check and diversion dams on the Arabian Peninsula were identified by Archaeologists about 5800 B.C. [13]. At about this time, check dams were constructed in Wadi Shumlya (southern tip of the Arabian Peninsula) to divert some of the river flow into canals. These structures are example of some of the oldest known water management structures. The first gauge (also called as *nilometer*) based measurements on water level on Nile river were recorded at several locations between Nubia and the Nile delta about 3050 B.C. In Egypt, dams and *embankments* were constructed by 2600 B.C. Its purpose was to provide river training, river diversion for land reclamation, flood protection and irrigation. During 614 A.D. to 1250 A.D., the Egypt was ruled by Arabs and *nilometers* were re-established between Aswan and Cairo. A nilometer on the southern tip of the Isle of Roda at Cairo, the best known of the Arab nilometers, was built in 715 A.D. Roda nilometer was being used for more than 1000 year until 1890 for recording maximum and minimum Nile water levels.

Romans first introduced a method for water flow, based on pipe areas, for tariff purposes for water supplied to citizen's residential areas. They were not fully aware of hydraulic discharge principle. Famous Greek Scientist, Hero was the first inventor to describe the correct relationship of flow with time, cross-sectional area, velocity and volume during first century A.D. in his book *Dioptra* which later on became the basis for flow measurement. His findings went unnoticed for almost 1500 years until Leonardo da Vinci and Castelli used these findings to express continuity equation. Even their work remained unnoticed for almost 200 years until his manuscript became public during 1690. A much awaited significant contribution for measuring velocities in rivers and canals was published by German engineer, Reinhard Woltman, in his thesis in 1790 describing the application of the spoke-vane current meter with a revolution counter to the measurement of river flow.

During 18th and 19th centuries, development and installation of weirs and flumes made flow measurements possible on irrigation canals and gauging stations were constructed on many rivers to provide records of flows. A detailed report on the historical aspects highlighted on the application of new technology for water measurement techniques is available in the literature [13]. The above techniques are for flow measurement in open channels or rivers. The weighing and volumetric techniques are used for the water flow measurements in closed conduits. The 20th century is the period when much attention and emphasis were placed on the closed conduit / channel measurements. Also, the developments of improved measurement techniques and standards, error and uncertainty estimation for both open and closed channels were implemented. The closed channel measurements are generally performed in the laboratory. The developments related to closed channel measurements are summarized in the following sections starting with flow measurement methods and techniques, sources of measurement uncertainty, improvement of accuracy of flow measurement and international status. The water flow measurement system at NPLI is also briefly described.

2.2 Methods of Flow Measurement

The water flow measurement systems (WFMSs) used for flow measurement, operate on basically two methods namely, weighing and volumetric methods as described briefly below;

2.2.1 Weighing Method

The weighing method is known as primary method. In this method, flow is realized in fundamental units of mass, length and time. In a weighing method, water is collected for a predetermined time and weighed [4, 7]. During the measurements, water flowing through the meter under test (MUT), is approximately under steady conditions of flow, pressure and temperature. The flow is determined through weighing along with the average of the flow indicated by the MUT during the collection interval. An additional flowmeter, known as a reference flowmeter, is normally used to set the test flows and to monitor the flow stability. The four parameters measured with this system are *total water mass, mass flow rate, total water volume* and *volume flow rate*.

The primary method based on weighing is well established and widely accepted method internationally [14-20]. The weighing method is again categorized into static weighing and dynamic weighing techniques.

2.2.1.1 Static Weighing method

In static weighing method, the mass of the collected water is measured after achieving the steady-state condition of the collected water [4]. Most of the WFMSs worldwide are based on static weighing due to their high accuracy.

2.2.1.2 Dynamic Weighing method

In a dynamic weighing method, the mass flow rate is determined dynamically using two positions of lever equilibrium on classical one beam scale and timer actuation periods. In the modern technique, the mass of the water being collected in a weighing tank is continuously measured as a function of time. The slope of the mass-time curve directly gives the mass flow rate [4-21]. One of the important conditions of measurement is stable flow and optimum speed of the mass indicating device for recording and plotting the data. The impact of the falling water should not affect the measurements. If it is affecting the measurement, it should be properly modelled to take into account the effect.

2.2.2 Volumetric Method

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. When a piston prover is used to measure volumetric flow, it is also primary method because volumetric flow rate is traceable to the fundamental unit of length and time and does not require density measurements [4, 22-25].

The volumetric and weighing methods are also used in gas flow measurement [26-31].

2.3 Water Flow Measurement System

The WFMS is used to calibrate the flowmeters. A simple design of WFMS consists of flow generation system, test section and weighing system as shown in Fig. 2.1 [7].

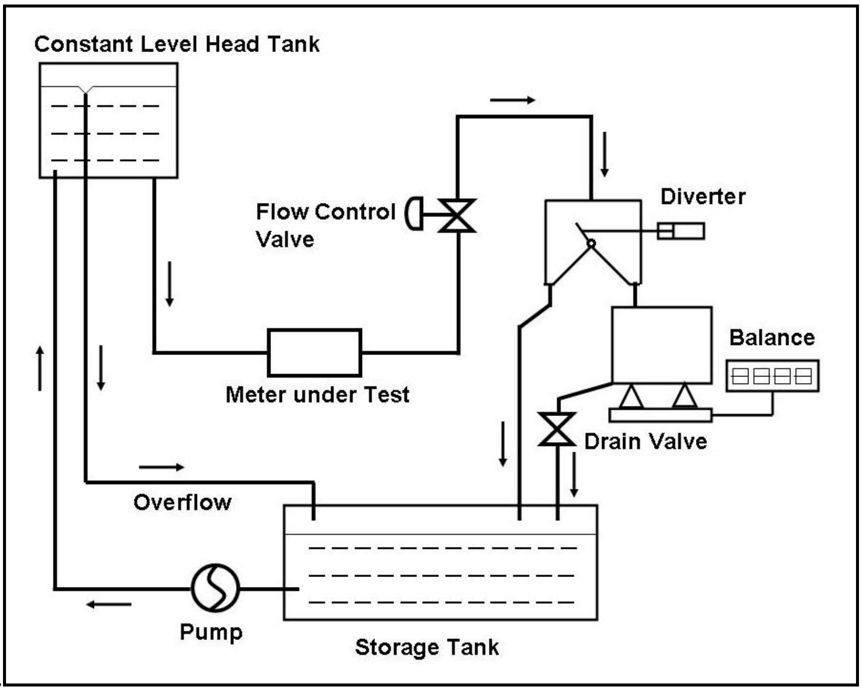


Figure 2.1: Water flow measurement system based on static weighing method.

2.3.1 Flow Generation System

It comprises of storage tank, constant level head tank, pumping system and a flow control system. The storage tank (also called as underground sump tank) is used to store large quantity of water to be pumped to test section and ultimately reaching to same place through weighing system or bypass line thus completing closed loop cycle. The storage tank is built below ground to achieve better temperature stability of the flowing medium i.e. water. The constant level overhead tank is used to maintain flow stability in the test section. If it is not used, then flow conditioner is used. It is used to improve the flow velocity profile and flow stability. The flow control valve is equipped with electro-pneumatic device to actuate it. It is used to regulate the flow through the test line. The electro-pneumatic device may be current to pressure converter or voltage to pressure converter.

2.3.2 Test Section

Test section is basically a piping system producing the required flow conditions for the MUT. The main purpose of this piping system is to obtain appropriate and fully developed flow for flowmeter operations. Therefore, flow conditioners (tube-bundle and perforated plate) are installed upstream of the flowmeter away from the MUT to avoid any flow disturbance that might affect the meter performance. The flow conditioners are not always used for test sections. The flow stability is also maintained by using appropriate upstream and downstream lengths in the test sections.

2.3.3 Weighing System

It is a precision balance with collection tank. The diverter is considered as a part of the measurement system which is used to direct flow either into the collection system or into a bypass. The bypass returns the flow to the storage tank. The measurement of flow is achieved by collecting a predefined mass of steadily flowing water over a measured time interval. During the measurement, other parameters (water temperature; air temperature, pressure and humidity) are measured for applying air buoyancy correction and density computation [31].

2.4 The Uncertainty Sources in Water Flow Measurement

In the static-gravimetric systems, the mass flow rate, q_m, is determined as follows [4];

$$q_{\mathrm{m}} = \frac{m}{t} \tag{2.1}$$

where m is the mass of water collected during time interval t. The volumetric flow, q_{v}, is derived from eq. (2.1) of mass flow rate by using known water density, ρ, as follows [4];

$$q_{\mathrm{v}} = \frac{q_{\mathrm{m}}}{\rho} = \frac{m}{t.\rho} \tag{2.2}$$

Thus, the sources of errors and uncertainties for mass flow rate measurement are mass and time. In the case of volume flow rate measurement, these sources are mass, time and density.

The relative combined standard uncertainty associated with mass flow rate measured by the WFMS is calculated by root-sum-square (RSS) method using different uncertainty components as given below;

$$u_{\mathrm{r}}(q_{\mathrm{m}}) = \sqrt{u_{\mathrm{r}}^{2}(m) + u_{\mathrm{r}}^{2}(t)} \tag{2.3}$$

where, $u_{\mathrm{r}}(q_{\mathrm{m}})$ is the relative combined standard uncertainty of the mass flow rate; $u_{\mathrm{r}}(m)$ is the relative standard uncertainty in collected water mass and $u_{\mathrm{r}}(t)$ is the relative standard uncertainty in collection time.

The relative combined standard uncertainty associated with volumetric flow rate measured by the WFMS is given below;

$$u_{\mathrm{r}}(q_{\mathrm{v}}) = \sqrt{u_{\mathrm{r}}^{2}(m) + u_{\mathrm{r}}^{2}(t) + u_{\mathrm{r}}^{2}(\rho)} \tag{2.4}$$

where, $u_{\mathrm{r}}(q_{\mathrm{v}})$ is the relative combined standard uncertainty of the volumetric flow rate and $u_{\mathrm{r}}(\rho)$ is the relative standard uncertainty in water density measurement. The $u_{\mathrm{r}}(q_{\mathrm{m}})$ and $u_{\mathrm{r}}(q_{\mathrm{v}})$ are the relative combined standard uncertainties assigned to WFMS.

In the calibration of MUT, the volume flow rate indicated by MUT (q_{vMUT}) is compared against calculated by the standard (q_{vSTD}) and error (e) of the MUT is determined from the following equation;

$$e = \frac{(q_{\mathrm{vMUT}} - q_{\mathrm{vSTD}})}{q_{\mathrm{vSTD}}} \times 100 \tag{2.5}$$

The flowmeter error is also determined in terms of standard volume as follows:

$$e = \frac{[(q_{\mathrm{vMUT}} \times t) - V_{\mathrm{STD}}]}{V_{\mathrm{STD}}} \times 100 \tag{2.6}$$

Flowmeters have frequency (pulse) and current outputs. The flowmeters outputs are read by calibrated frequency counter and or digital multimeter during automation for averaging or totalizing the output as flowmeter readings are instantaneous and are continuously changing.

Some flowmeters are calibrated in terms of the meter *K*-factor, which is defined as follows;

$$\text{meter K-factor} = \frac{N}{V_{\mathrm{STD}}} = \frac{f}{q_{\mathrm{vSTD}}} \tag{2.7}$$

where, N is the no. of pulses output by MUT, f is the frequency output of the MUT, V_{STD} and q_{vSTD} are the volume and volume flow rate measured by WMFS.

The relative combined standard uncertainty of flowmeter error in current output mode is determined by the following equation [9-10, 31-32];

$$u_{\mathrm{r}}(e_{\mathrm{I}}) = \sqrt{u_{\mathrm{r}}^{2}(Ae) + u_{\mathrm{r}}^{2}(I) + u_{\mathrm{r}}^{2}(m) + u_{\mathrm{r}}^{2}(t) + u_{\mathrm{r}}^{2}(\rho)} \tag{2.8}$$

where, $u_{\mathrm{r}}(e_{\mathrm{I}})$ is the relative combined standard uncertainty in flowmeter error determination in current output mode, $u_{\mathrm{r}}(Ae)$ is the relative repeatability (Type A uncertainty) in the flowmeter error and $u_{\mathrm{r}}(I)$ is the relative standard uncertainty of digital multimeter in current measurement.

The relative combined standard uncertainty of flowmeter error in frequency output mode is determined by the following equation [9-10, 31-32];

$$u_{\mathrm{r}}(e_{\mathrm{f}}) = \sqrt{u_{\mathrm{r}}^{2}(Ae) + u_{\mathrm{r}}^{2}(f) + u_{\mathrm{r}}^{2}(m) + u_{\mathrm{r}}^{2}(t) + u_{\mathrm{r}}^{2}(\rho)} \tag{2.9}$$

where, $u_{\mathrm{r}}(e_{\mathrm{f}})$ is the relative combined standard uncertainty in flowmeter error determination in frequency output mode and $u_{\mathrm{r}}(f)$ is the relative standard uncertainty of frequency counter in frequency measurement.

The relative combined standard uncertainty of meter K-factor is determined as follows;

$$u_{\mathrm{r}}(K-factor) = \sqrt{u_{\mathrm{r}}^{2}(A_{\mathrm{K-factor}}) + u_{\mathrm{r}}^{2}(N) + u_{\mathrm{r}}^{2}(m) + u_{\mathrm{r}}^{2}(t) + u_{\mathrm{r}}^{2}(\rho)} \tag{2.10}$$

where, $u_{\mathrm{r}}(K-factor)$ is the relative combined standard uncertainty in flowmeter meter K-factor determination, $u_{\mathrm{r}}(A_{\mathrm{K-factor}})$ is the relative Type A uncertainty in the meter K-factor measurement and $u_{\mathrm{r}}(N)$ is the relative standard uncertainty of frequency counter in pulse measurement.

The details of various sources of uncertainty and their evaluation discussed elsewhere [9-10, 32-33] are summarized herein;

2.4.1 Collected Water Mass

The uncertainty of the collected water mass depends on the balance indication, balance drift, balance calibration, buoyancy correction, leaks and splashes, storage effects and the evaporation. The mass indicated by balance (weighing system) is corrected for buoyancy exerted by atmospheric pressure on the collected water of weighing tank. The buoyancy correction depends on air density and water density. The air density is determined by various empirical formulas as used by various researchers in this field [32-34]. For simplification of the system, the buoyancy correction factor is taken as 1.00106 for water as recommended in ISO 4185 standard.

2.4.2 Collection Time

The uncertainty of the collection time depends on the timer calibration, timer actuation and the diverter error. For a high precision timer, its calibration uncertainty is negligible and collection time uncertainty is dominated by diverter error. Timer actuation effect is very small and it has been considered as a part of diverter error. The details for the diverter error evaluation and applying correction have been given below:

In a traditional diverter design, a dividing plate is used which switches the flow from bypass line to weighing tank and *vice versa*. A traditional diverter is a diverter which has been explained in ISO 4185 standard. At the start of the collection, the diverter switches the flow from the bypass line into weighing tank. At the end of the collection interval, it switches the flow from weighing tank to bypass line. The traditional diverter has a timing error resulting from any asymmetry of the distribution of the flow exiting the nozzle and any asymmetry of the diverter motions through rectangular jet exiting the nozzle. This also results from improper alignment of the proximity (position) switches dedicated to starting and stopping the timer. Fig. 2.2 shows the condition for an error-free diverter motion in which A + D = B + C or A = C & B = D or A = B & C = D [32, 35]. The meaning of symbols used in this figure is given below [35].

t_0 = time when diverter starts to move during diverting the flow to weighing tank
t_1 = time when sensor sends a signal to trigger to start time acquisition
t_2 = time when diverter stops moving during diverting the flow to weighing tank

t_3 = time when diverter starts moving again to direct flow into bypass

t_4 = trigger signal time to stop time acquisition

t_5 = time when diverter stops during diverting the flow to bypass line

$t_d = t_2 – t_0 = t_5 – t_3$ = diverter transit time

$t_g = t_1 – t_0 = t_4 – t_3$ = trigger time

$T_T = t_5 – t_0$ = total collection time interval

$T_M = t_4 – t_1$ = measured time interval

$T_C = t_3 – t_2$ = constant flow collecting interval

Q_C = collecting flow

Q_B = bypass flow

Q_T = total flow = $Q_C + Q_B$

A = extra volume collected before the trigger time, t_1, in the opening transition

B = deficit volume missed after the trigger time, t_1, in the opening transition

C = deficit volume missed before the trigger time, t_4, in the closing transition

D = extra volume collected after the trigger time, t_4, in the closing transition

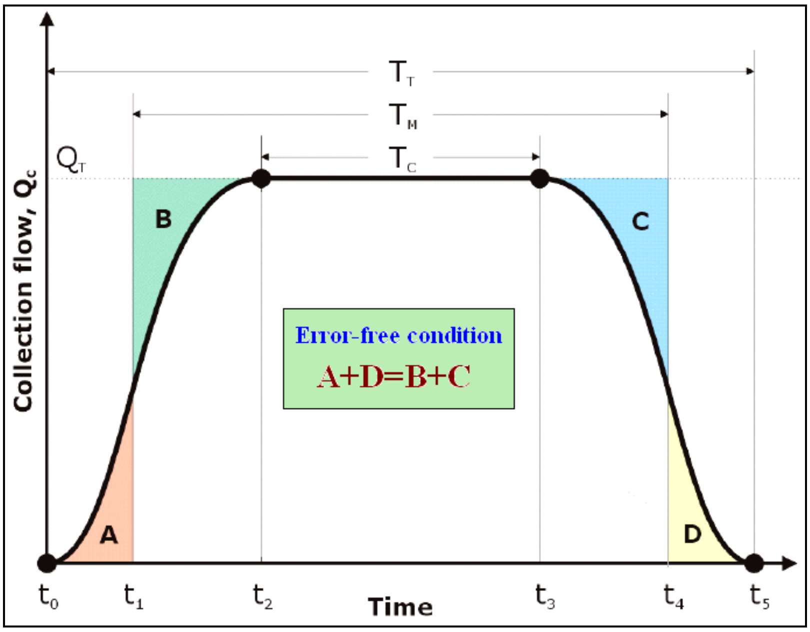


Figure 2.2: Error-free condition in a traditional diverter motion [32]. (The modified figure)

The formula for diverter error evaluation [36], represented by eq. (2.11), cited in the ISO 4185 [7] is briefly given below:

$$\Delta t = \frac{t_{\mathrm{M}}}{n-1}\left[\frac{q_0}{q_{\mathrm{n}}}.\frac{\sum_{i=1}^{n}\Delta m_{\mathrm{i}} \Big/ \sum_{i=1}^{n} t_{\mathrm{i}}}{m_0 / t_{\mathrm{M}}} - 1\right] \tag{2.11}$$

where, Δt is the diverter timing error, q_0 is average flow rate during the single-burst filling of the weighing tank with t_{M} being the metered time of flow, q_{n} is the average flow rate during the n bursts, m_0 is the mass of collected water during single-burst filling of the weighing tank and Δm_{i} is the incremental change in balance read out in t_{i} time interval during collection in the weighing tank. The time t_{i} shows individual time measurement of n increment.

The timing error correction is described herein this section. First, the weighing tank is filled to full scale m_0 during time interval of t_{M}. This is called as single-burst filling or standard run. Then the full scale m_0 is divided into n smaller steps (for example 5 to 25, large number of small steps is recommended) each of Δm_{i}. Now the weighing tank is filled in a series of n short diversions (i.e. steps) with total mass collected is $\sum_{i=1}^{n}\Delta m_{\mathrm{i}}$ and total time taken is $\sum_{i=1}^{n} t_i$. These incremental readings are taken without resetting the timer or balance output. A second single-burst filling is performed after multiple short diversions. These two single-burst fillings are averaged. Applying these acquired quantities to eq. (2.11) determines the fractional time correction Δt. The factor q_0/q_{N} takes into account any variation of flow rate. This factor should be close to unity which indicates highly stabilized flow in the flow circuit leading to smaller diverter error.

The result of this timing error correction is only valid for a given flow rate at which the above procedure is performed. This procedure must be applied to all flow rates in which calibrations are required. Thus it is a very cumbersome process. The usual practice for applying the timing correction is that the determined fractional timing correction Δt is simply added to t_{M} without performing any mechanical alignment of the proximity switches.

2.4.3 Water Density

The water used in the WFMS is usually drawn from the municipal water supply. Due to the dissolved minerals in the water, the density values vary from those of the distilled water. Normally, samples are drawn from the storage tank and their densities are measured at around ambient temperature. The uncertainty of density measurement depends upon the uncertainty of the thermometer used for temperature measurement and uncertainty of instrument (analytical weighing system or hydrometer or offline densitometer) used for density determination. Some laboratories also use online densitometers for water density measurement which show both the water temperature and density values.

2.5 Recent Advances in Water Flow Measurement

The highly accurate water flow measurements are generally based upon static weighing systems with flying-start-and-finish. For international flow measurement standards, the static weighing is preferred over the dynamic weighing due to its comparatively improved accuracy. This comparison has been based upon a rough mechanical model of a one-beam scale (i.e. classical model) [37]. The classical dynamic weighing method is also being used for coarser accuracy flow measurements. However, due to use of modern weighing system employing load cells and computer based data acquisition, algorithm, modelling and simulation, the accuracy of dynamic weighing standard has been improved up to the same level of uncertainty as in case of static weighing [37-38]. Advances in the dynamic and the static weighings are summarised herein;

2.5.1 Advances in Dynamic Weighing

Dynamic weighing standards are classified into two categories;

2.5.1.1 Classical Dynamic Weighing Standard

The classical dynamic standard is based on a rough model of a one-beam scale where calibration value is represented by two positions of lever equilibrium and timer actuation periods. In a classical dynamic weighing system, the same hydraulic circuit shown in Fig. 2.1 is used except weighing balance and diverter system. The weighing balance is basically a beam scale with a collection tank. Fig. 2.3 shows the schematic diagram of a beam weighing system manufactured by COX Instrument, USA which is used in a commercially available dynamic weighing system [37].

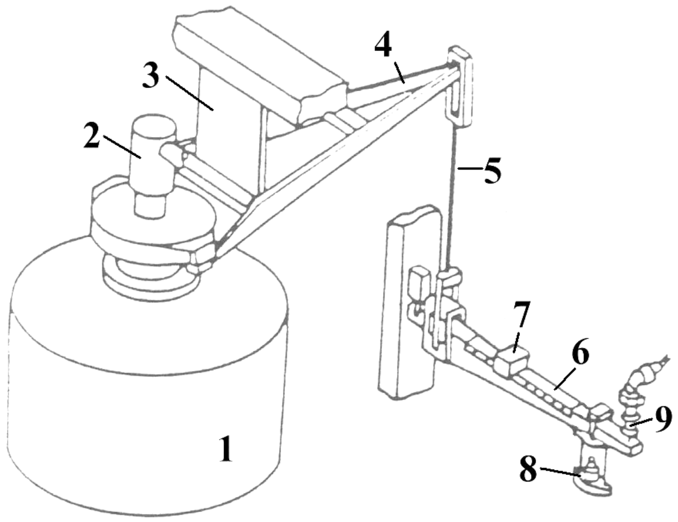


Figure 2.3: A beam weighing system (COX Instrument, USA) [37].
***(1)** Collection tank, **(2)** Fluid inlet, **(3)** Suspension assembly, **(4)** Weigh beam, **(5)** Link rod, **(6)** Tare beam, **(7)** Tare weight, **(8)** Weight pan, (**9)** Proximity switch (timer actuation)*

The operation of the system has been described in the reference [37]. The main disadvantages of this system include (i) change in impact force of falling liquid, and (ii) change in delay time when the weighing beam is moving from its rest position up to the timer actuation lever position.

2.5.1.2 Electronic Balance based Dynamic Weighing Standard

For improving the performance of classical beam scale type dynamic weighing standard, non-deflecting balance is the solution where stationary components are used for indication purposes. Therefore, non-deflecting balances have been developed using electronic load-cells / weighing cells and advanced electronics [37]. Such balances are categorized as strain-gauge force type and electromagnetic force compensation type. Fig. 2.1 shows the schematic diagram of the water flow measurement system employing load cell or electromagnetic force compensation type weighing system (or balance). Such system can be used both in static weighing and dynamic weighing. For implementation of dynamic weighing, high speed data acquisition, special modelling and simulation are required for compensating the effect of impact forces of falling liquid. In this method, the water falling on weighing tank is continuously weighed at high speed (at equal interval of approximately 50 ms or higher up to 200 ms) between the start and the end of the collection interval and large numbers of weighing readings are collected. The buoyancy correction is applied to the weighing readings. From the slope of mass-time curve, the mass flow rate is determined. This process is repeated several times to evaluate measurement uncertainty associated with repeated measurement [38-39].

A new WFMS [37] established at Physikalisch-Technische Bundesanstalt (PTB), Germany recently is capable to be used in both static and dynamic weighing. The system is consisting of three different-sized weighing systems incorporating dual-type balances, i.e. strain gauge type for fast dynamic response and electromagnetic force compensation type for static conditions for long term stability and reproducibility. The whole unit is embedded in to a single functional unit. Further, modelling on dynamic weighing calibrator was proposed for the improved measurements and for the system response behaviour. In order to utilize the benefits of dynamic weighing in water flowmeters calibration and to perform further scientific investigations to explore its use in industry, special provisions have been made by PTB to apply flying start and finish calibration for both static and dynamic weighing methods.

The research and development on dynamic weighing method is also being carried out by the researchers at the National Institute of Standards and Technology (NIST), USA [38-40]. The dynamic standard has been implemented into the static weighing standard. The uncertainty achieved with this dynamic method is found comparable to static method. The main advantage of this method is that the complex diverter system is not required. Most recently, a fully automatic dynamic weighing based water flow standard has been developed by NIST [41] in the flow range from 0.22 kg/s to 15 kg/s having associated measurement uncertainty of ±0.021 % at a coverage factor k=2. The design, modelling, development and performance verification of the system have been described.

2.5.2 Advances in Static Weighing

In static weighing method, the collection tank is weighed just before the steady water flow diversion from a bypass into the collection tank. The collection tank is weighed again after diverting the flow from the collection tank into the bypass in order to achieve steady-state conditions. Thus in static weighing, the weighing is performed only two times.

The performance of WFMS can be further improved taking in to considerations of the these factors, (i) improve the water flow stability using constant level overhead tank or flow conditioners, (ii) improve the timing error using self cancelling or error-free diverter, and (iii) develop better instrumentation and control for achieving improved accuracy. In a highly accurate WFMS, utilizing traditional diverter, the diverter timing error is a significant source of uncertainty as compared to other components i.e. mass and density of the collected water. To reduce the diverter timing error, different types of diverters have been designed and developed by various NMIs i.e. PTB, Germany; NIST, USA; NMIJ, Japan *etc*. and are being used successfully. These developments were mostly carried out during last two decades. The brief description of such developments is discussed in following sections.

2.5.2.1 PTB's Model based Diverter

In 1998, PTB, Germany presented a paper in FLOMEKO [42] for their proposed plan to establish high accuracy WFMS (called "Hydrodynamic Test Field") with targeted expanded uncertainty of total flow as ±0.02% at k=2. In order to achieve desired results, researchers at PTB first identified the design components, their specifications and design parameters. The design components thus identified were fabricated and constructed. These components include gravimetric references (special-design weighing system with integrated calibration capabilities), flow diverters, volumetric reference (compact pipe prover), density metering device and temperature sensing devices. The performances of these components were verified by individual specifying test measurements. A computer-based *Supervisory Control and Data Acquisition* (SCADA) system is used for the measurement operation, stabilizing the main process quantities (water flow rate, pressure and temperature) and monitoring of various relevant process parameters (water density, diverter actuation, balance readout and ambient-air conditions). These process and monitoring conditions are essentially required for reproducible conditions and to achieve a high degree of reproducibility in the measurement and calibration processes.

The diverter error reduction is one of the most important uncertainty components. For this purpose, computational fluid dynamics (CFD) simulations are used for the nozzle and the feeding pipe designs to achieve a symmetrical velocity profile at the liquid jet [43]. Also a new diverter system was used, in which an angular encoding transducer in combination with an appropriate electronic and storage device has been used to reduce the diverter timing error (Fig. 2.4). The further improvement in diverter performance is achieved by an electric diverter actuator which varies the variable width of the cross-sectional flow area of the diverter nozzle [36]. Several process variables were used for the design improvements and automation. The targeted measurement uncertainty (±0.02 %) could be achieved by making special arrangements for precision control of water flow rate, temperature and pressure in the calibration line (Figs. 2.5 and 2.6) [33, 44-46] and spent quite substantial time of about 9 years for these developments. In this achieved target of ±0.02 % expanded measurement uncertainty (at k=2), the contribution of the diverter error itself is ±0.008 % (at k=1). Table 2.1 shows the uncertainty budget of their new achievement. To reduce this error further, the model based diverter analysis is being carried out [47].

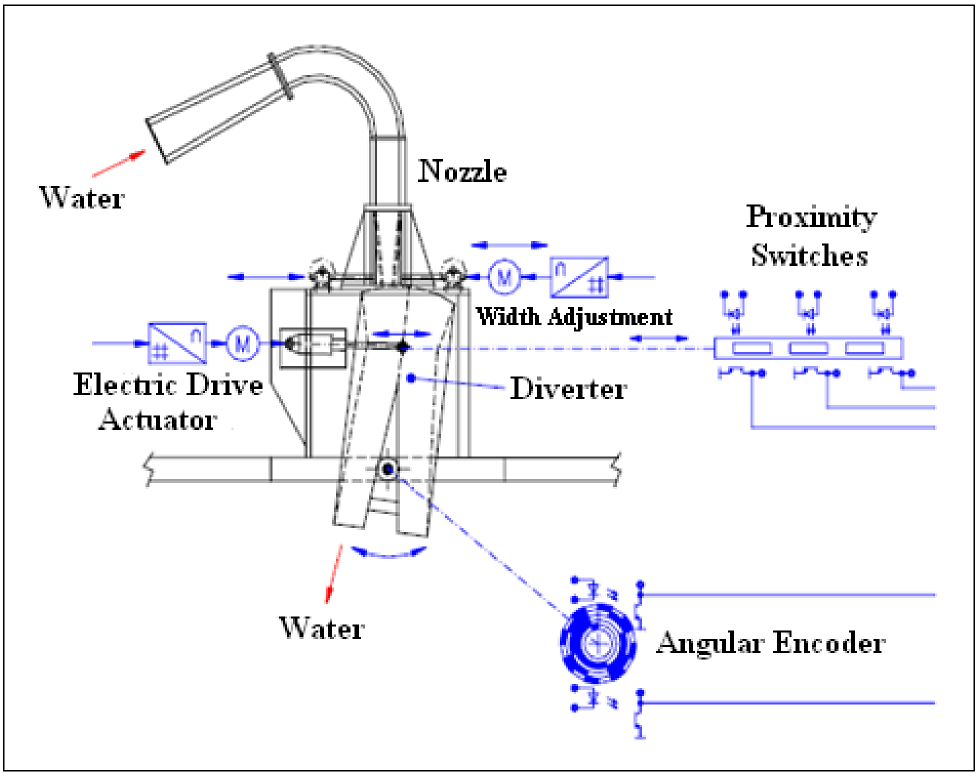


Figure 2.4: Schematic diagram of diverter drive and motion control of PTB Water Flow Measurement System [36]. (The modified figure)

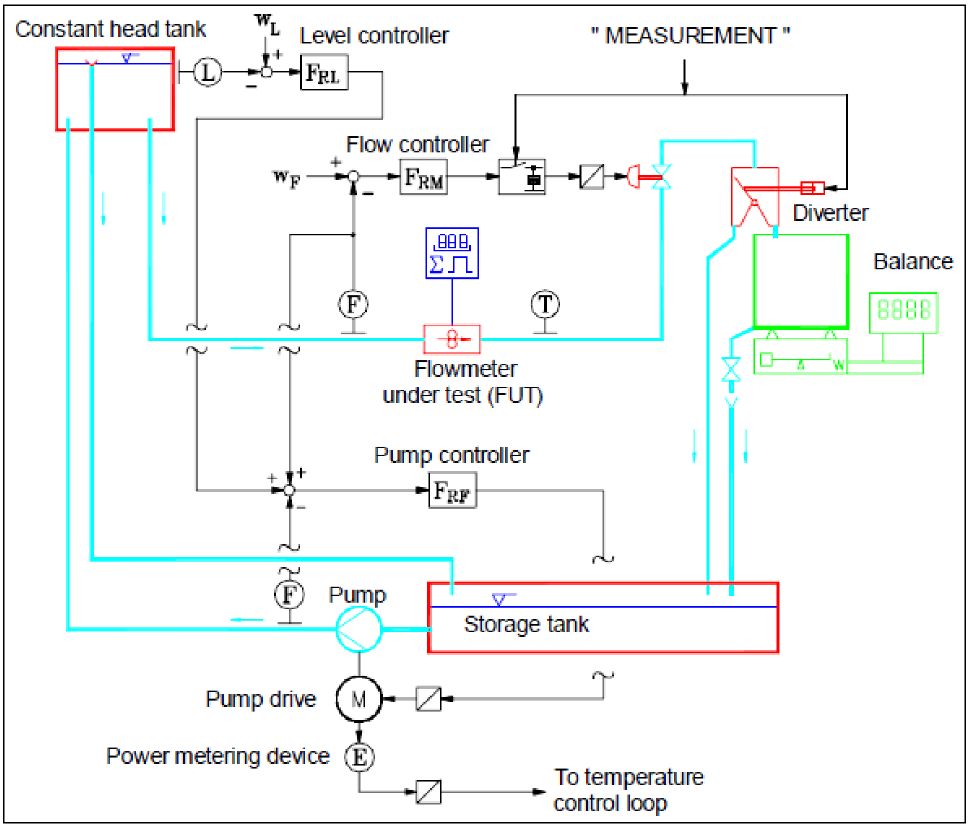


Figure 2.5: Schematic diagram of flow control loops of PTB WFMS [44].

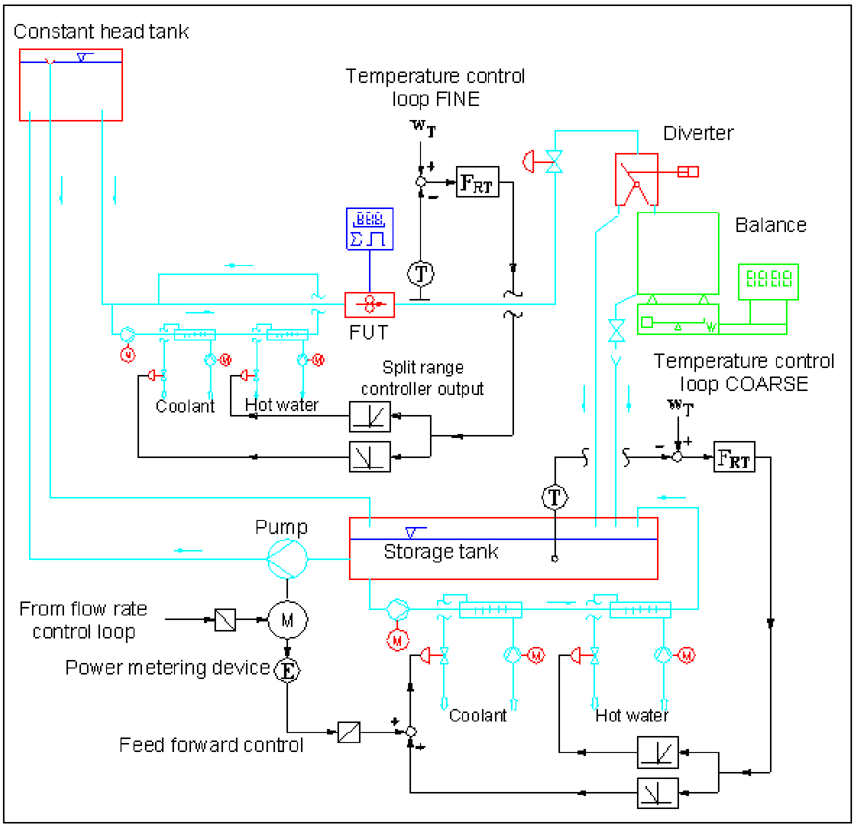


Figure 2.6: Schematic diagram of temperature control loops of PTB WFMS [44].

Table 2.1. Uncertainty budget of newly developed WFMS of PTB, Germany [33].

Sources of uncertainty	**Standard uncertainty (%)**
Mass	2.1×10^{-3}
Air buoyancy	5.5×10^{-8}
Water density	3.3×10^{-3}
Time measurement	2.3×10^{-5}
Interconnecting pipe	1.0×10^{-4}
Diverter timing error	8.0×10^{-3}
Meter under test	3.5×10^{-3}
Combined uncertainty	9.569×10^{-3}
Expanded uncertainty (at *k*=2)	$1.9137\times10^{-2}\approx$ **0.0191**

2.5.2.2 NIST's Uni-Diverter

The NIST, USA also started building their new water flow measurement system (Fig. 2.7) with improved measurement uncertainty during the same period as PTB, Germany. For this purpose, the NIST developed a self cancelling diverter called uni-directional diverter or uni-diverter that is immune to certain sources of uncertainty found in traditional diverter [35, 48].

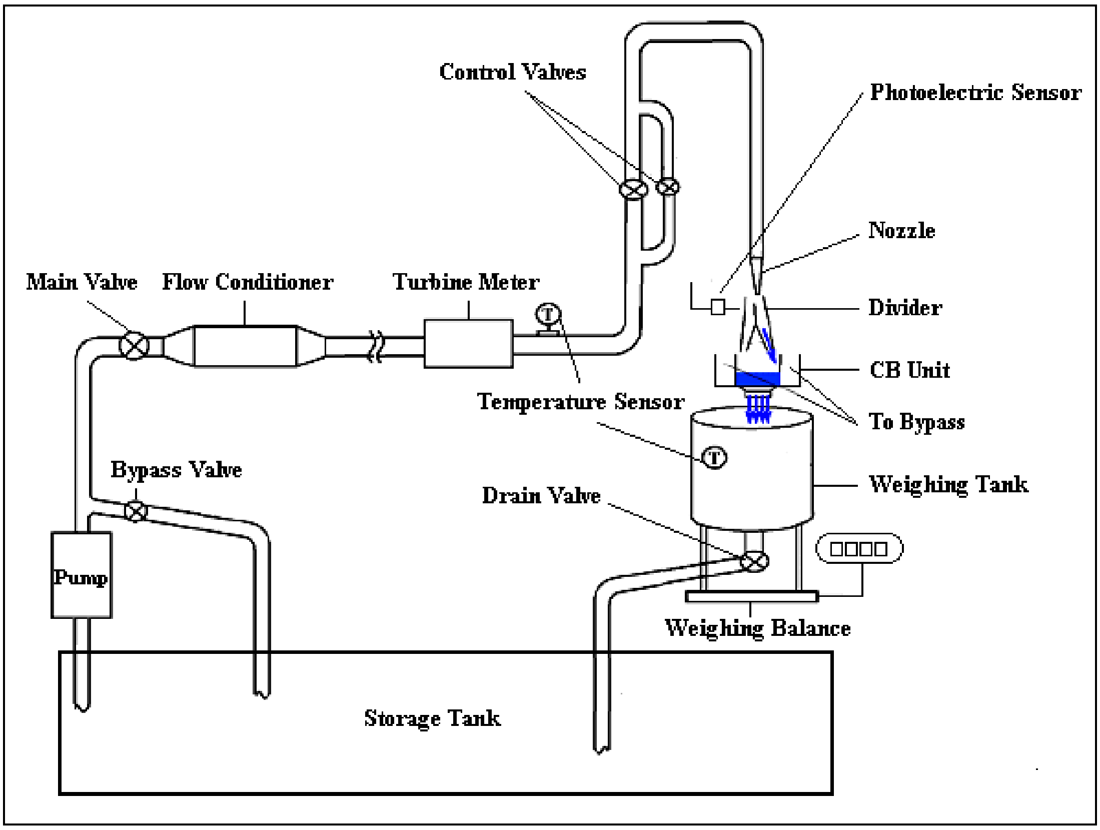


Figure 2.7: Schematic diagram of the NIST WFMS [32]. (The modified figure)

The uni-diverter moves in the same direction against liquid jet both at the beginning and at the end of water collection. The system is consisting of two active elements: (i) a traditional diverter called divider here, which cuts the flow; and (ii) a collection / bypass (CB) unit that directs the flow to the bypass or the weighing tank regardless of the divider position. The CB unit is mounted below the divider on linear bearings and can be moved horizontally under computer control. Three proximity switches are used for CB position detection and communication with computer. The CB unit consists of three separate channels and coordination of the position of the CB unit with the position of divider allows cutting the water jet in the same direction for both start and stop action during weighing tank filling (Figs. 2.8-2.9) [32]. Due to uni-directional travel of the diverter, error due to asymmetry in the divider actuated motion, the liquid jet velocity profile and the position of the diverter trigger is reduced.

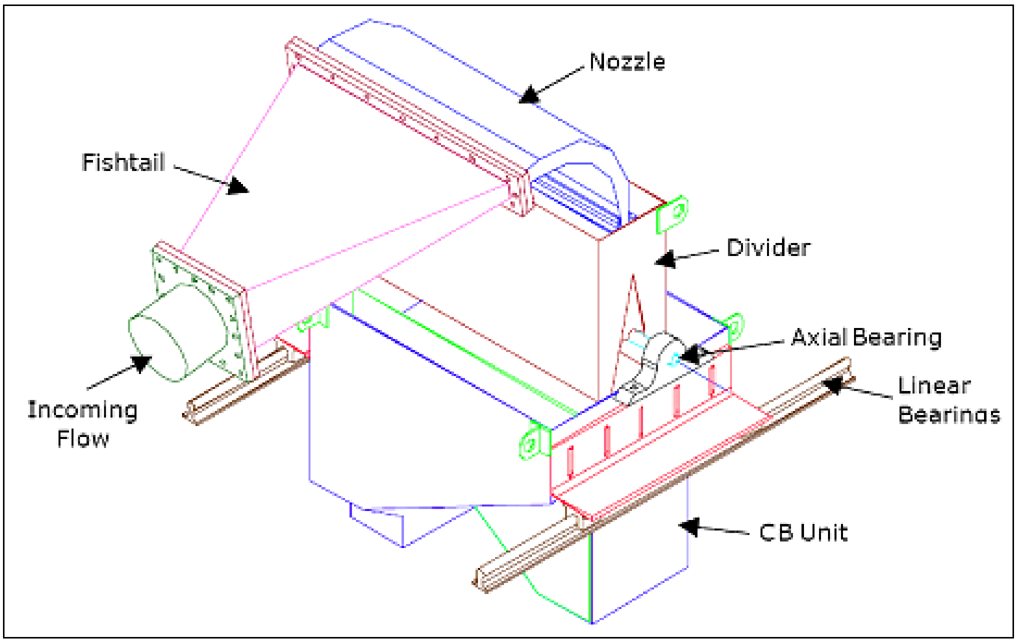


Figure 2.8: Schematic diagram showing construction of the uni-diverter of the NIST WFMS [32].

A sequential operation of the uni-diverter is depicted in Fig. 2.10. The uni-diverter's performance was tested with the traditional diverter. The uni-diverter may be operated as a traditional diverter with its CB unit stationary as shown in Figs. 2.10(a) and 2.10(f).

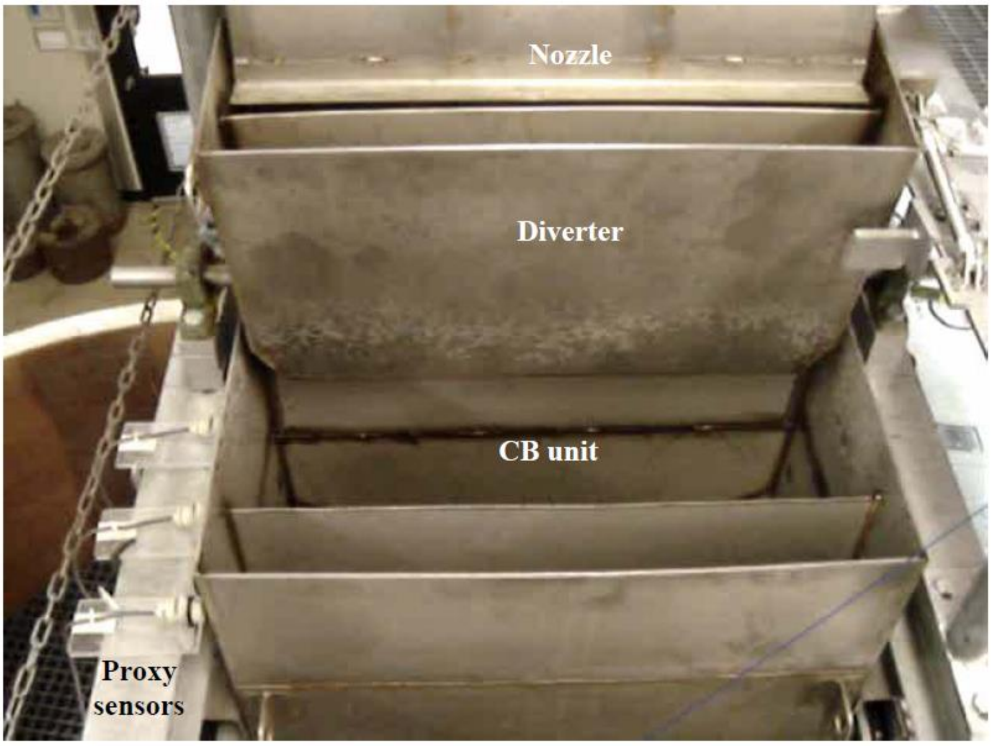


Figure 2.9: Photograph of the uni-diverter of the NIST WFMS [32].

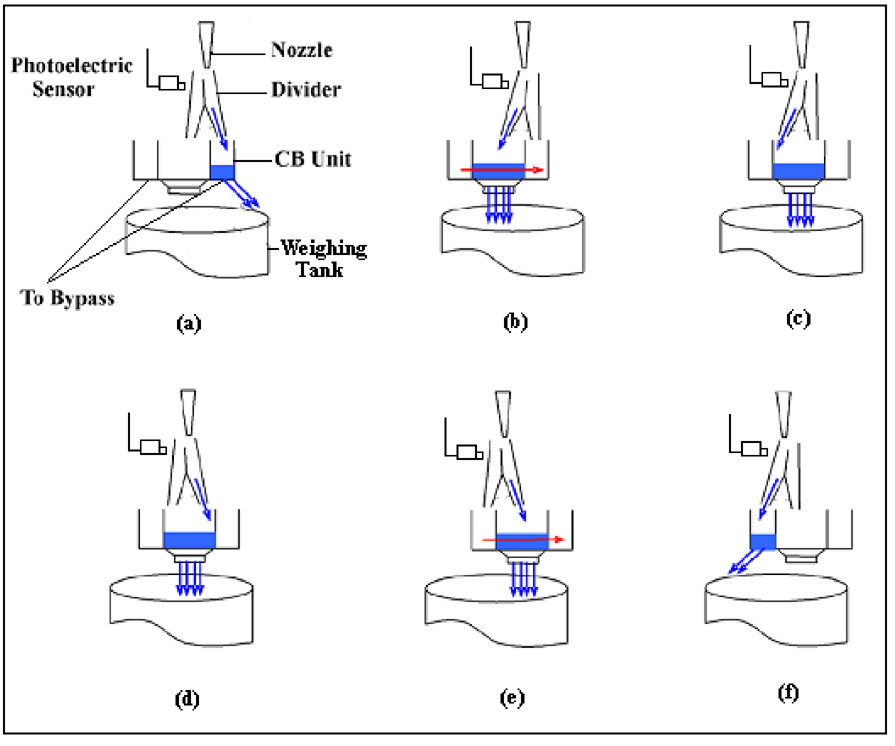


Figure 2.10: Sequential operation of the uni-diverter of the NIST WFMS [49].
(The modified figure)

The same uni-diverter was used for both uni-directional and traditional diverter motion. Fig. 2.11 shows the percentage difference between the flows determined via the uncorrected traditional diverter (Q_t) and the uni-diverter (Q_u).

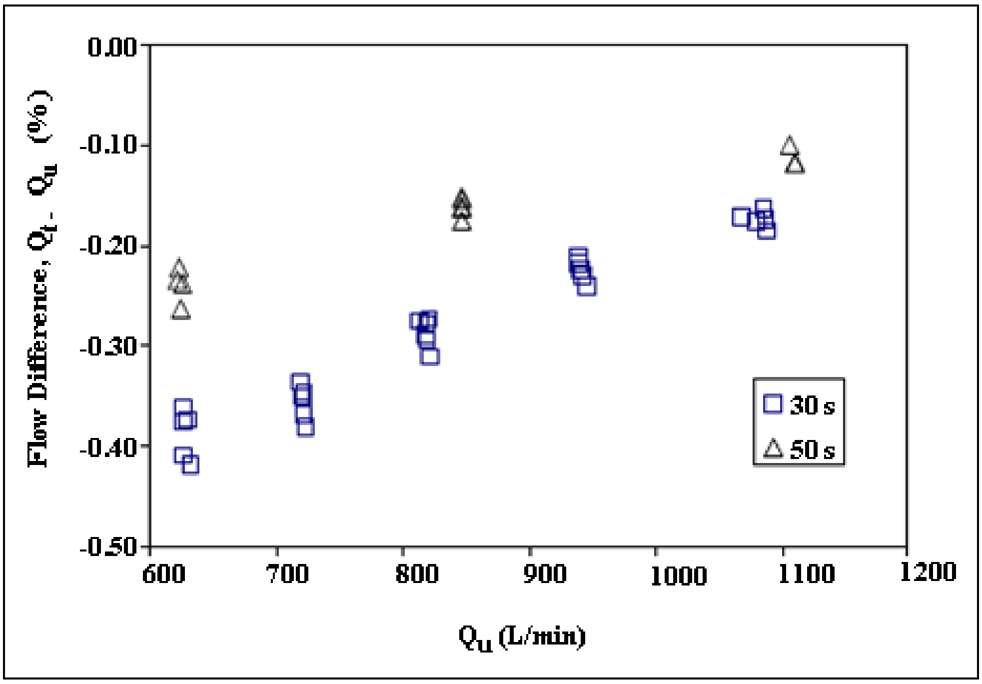


Figure 2.11: Flow difference between uncorrected traditional diverter and uni-diverter of the NIST WFMS [50]. The 30 s and 50 s are collection time. (The modified figure)

Fig. 2.12 shows the differences measured between the corrected traditional diverter and the uni-diverter. The measurement uncertainty achieved for this uni-diverter is better than ±0.01% over the flow range of 800 L/ min and more [49-50].

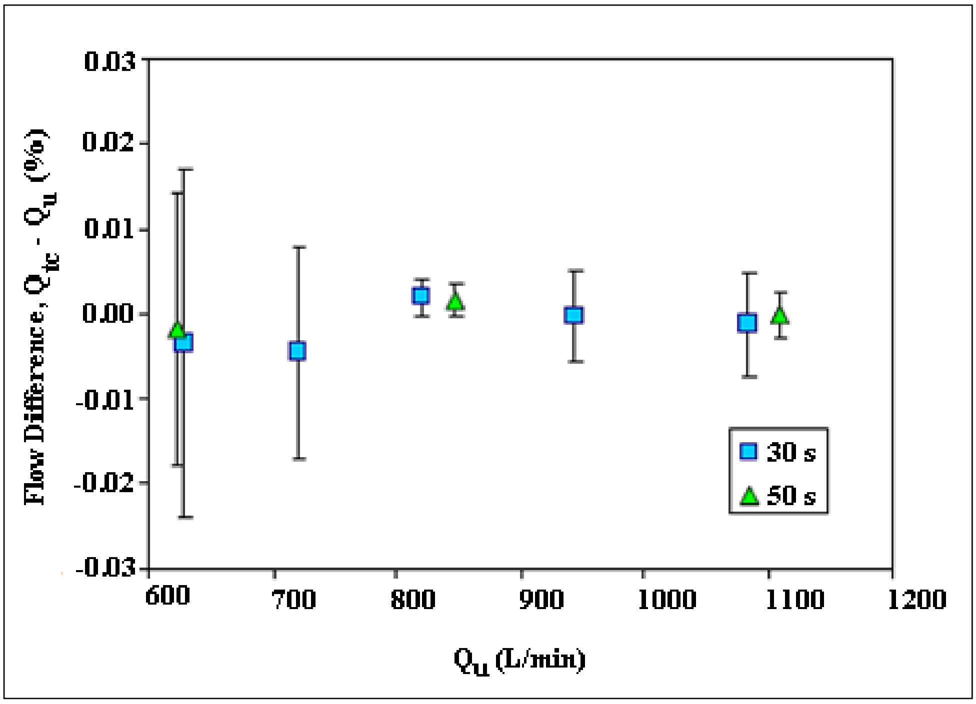


Figure 2.12: Flow difference between corrected traditional diverter and uni-diverter of the NIST WFMS [50]. The 30 s and 50 s are collection time. (The modified figure)

2.5.2.3 NMIJ's Rotating Double Wing Diverter

NMIJ, Japan also developed a new diverter system with double diverting wings to reduce the diverter timing error during the identical period of PTB, Germany and NIST, USA developments [51]. The basic concept of the new diverter system is that both wings move in the same direction against the liquid jet both at the beginning and at the end of the measurement. A combination of a ball screw and a servomotor actuates the wings accurately at a constant speed (Fig. 2.13). The smaller impact of jet on horizontal moving wings in comparison to rotating wings is also advantageous. The diverter timing error was estimated using a small prototype in a water flow circuit to make a comparison between the performance of the new system and those of traditional systems with a single diverting wing.

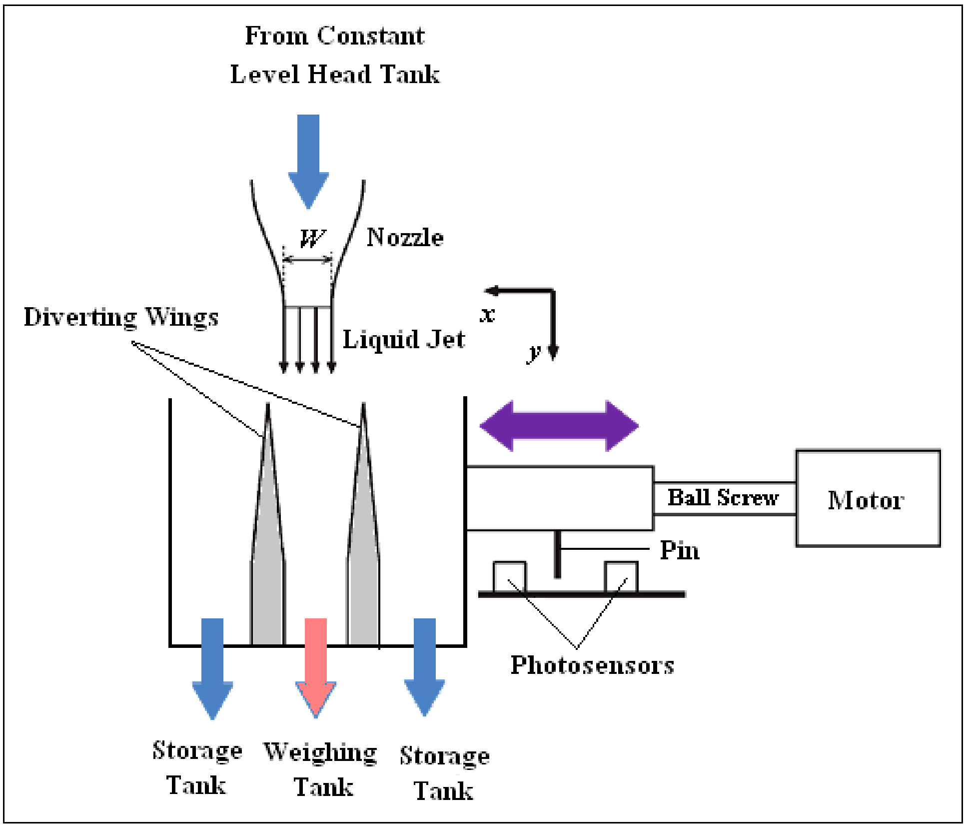


Figure 2.13: Double wing diverter of the NMIJ WFMS [51]. (The modified figure)

Fig. 2.14 shows the averaged values of the measured diverter timing error in the double-wing method. These values were estimated under different experimental conditions, i.e., various nozzle widths (10, 20 mm), undisturbed or disturbed jet, and different moving directions of the diverting wing. The estimated values were independent of the flow conditions. After the alignment of the proximity switches based on this estimated value, the diverter timing error was estimated again. These re-estimated values were less than 0.006 s, as shown in Fig. 2.14. The triggering of the timing system is easily adjusted over a wide range of flow rates by using the new diverter system. This system has been adopted for a new measurement facility for hydrocarbon flow measurements at NMIJ. This new facility for hydrocarbon flow measurement is used in the flow range 3 m^3/h to 300 m^3/h. The system applies weighing method and uses 1 t and 10 t balances. The measurement uncertainty achieved for this new diverter system of hydrocarbon flow measurement facility is better than ±0.003% over the entire flow range (Fig. 2.15).

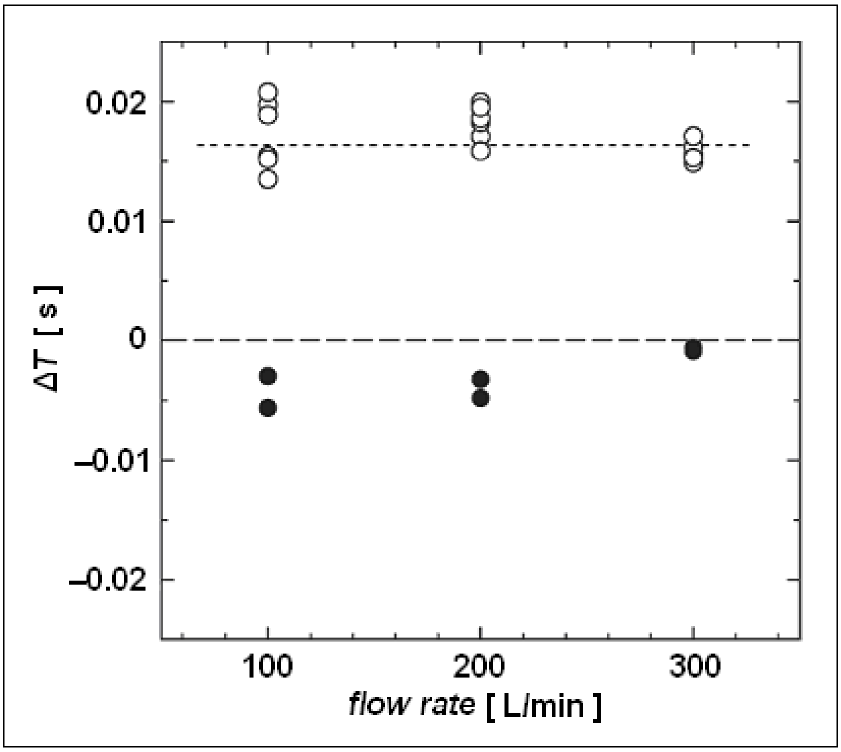
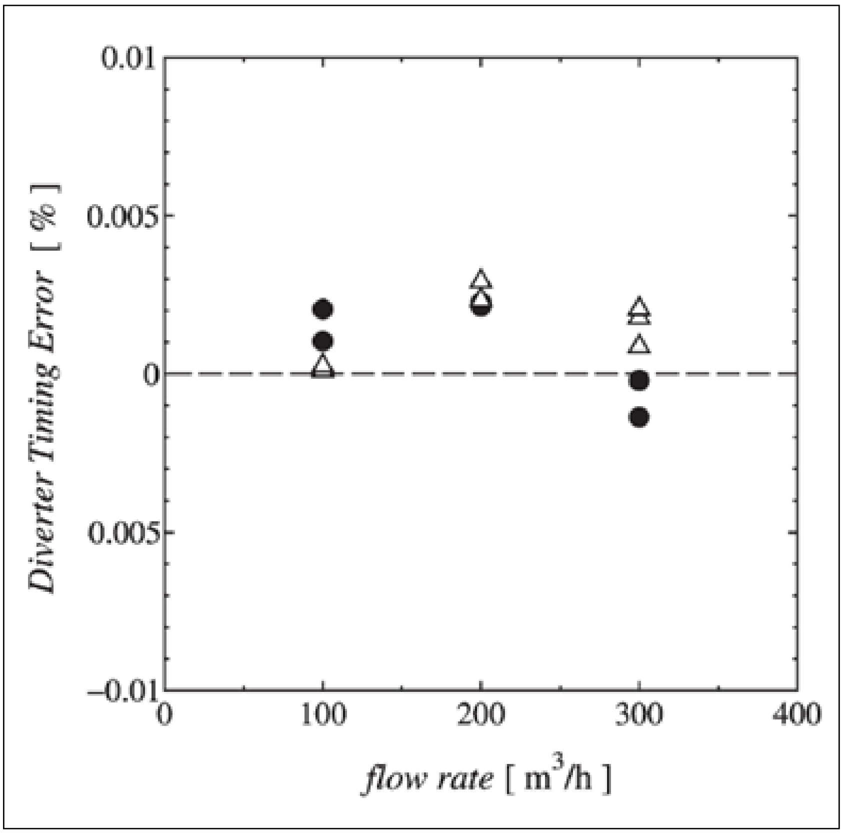
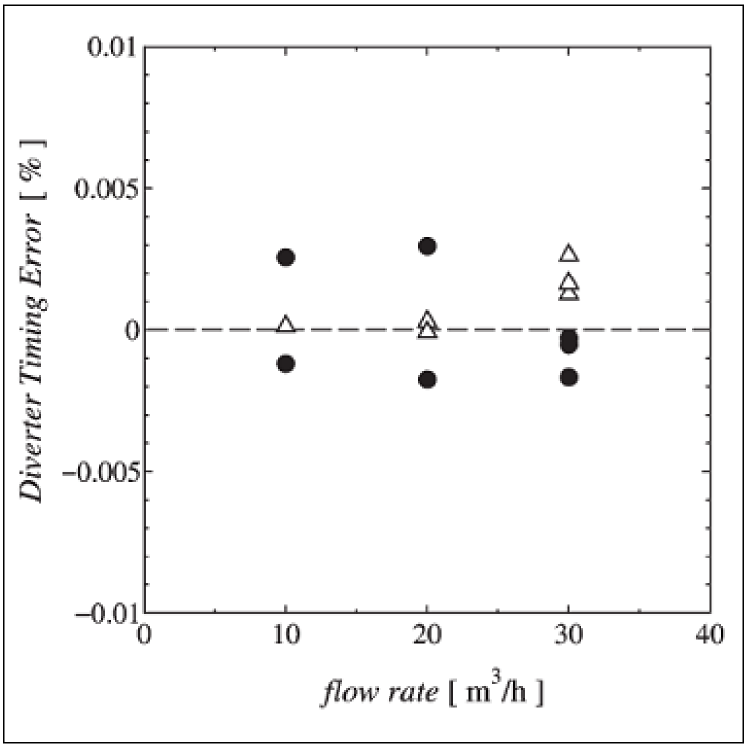


Figure 2.14: Diverter timing error with double wings in the NMIJ WFMS.
○, before adjustment; ●, after adjustment [51]. (The modified figure)



(a)



(b)

Figure 2.15: Diverter timing error for hydrocarbon flow measurement facility: (a) large diverter for 10 t balance, (b) small diverter for 1 t balance. ●, Light oil; Δ, kerosene [51]. (The modified figure)

Although, the diverter design based on double-wing method has achieved desired uncertainty levels but it has some difficulties because its end position is different from the start position as the wings travel linearly in the same direction. It must return to the start position for the next diversion. During this process, the liquid jet drops into the weighing tank because the wings pass under the liquid jet. In the test under ISO 4185, this mechanism leads to a problem in practical operation. Some solutions to prevent this unnecessary inflow have been suggested. In one of the methods, an additional diverter may be installed at the duct between the main diverter and the weighing tank. In another method, a plastic bag between the diverter wings may be used in order to prevent the unnecessary inflow. However, this involves setting the bag by hand at each diversion and its application in hydrocarbon flow measurement is very difficult and hazardous. To overcome such difficulties, a newly rotating double wing (RDW) diverter was designed and developed. This diverter system is based on the concept of symmetric diversion by two wings that move across the liquid jet in the same direction at constant speed at both start and end of measurement. One of the main advantages is that the wings are rotated to bring them to their initial position whereas in the previous design, wings are moved linearly which create the problem of achieving initial position. In this system, better adjustment of diverter trigger timing could be achieved and it is a robust mechanism. It is also in ease for implementation of an ISO 4185 test [52] in addition to all other advantages of previous system. The measurement uncertainty achieved for RDW diverter is better than ±0.002% over the entire flow range, which is considered one of the best diverter timing errors in the world. Figs. 2.16 and 2.17 show the schematic diagram and sequential operation of the RDW diverter, respectively.

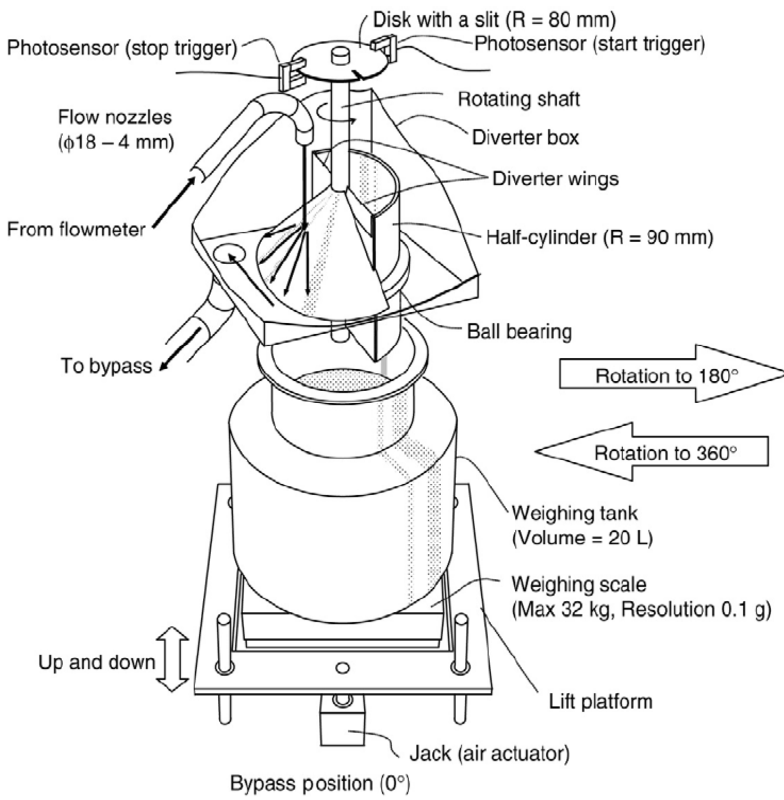


Figure 2.16: The schematic diagram of rotating double wing diverter [52].

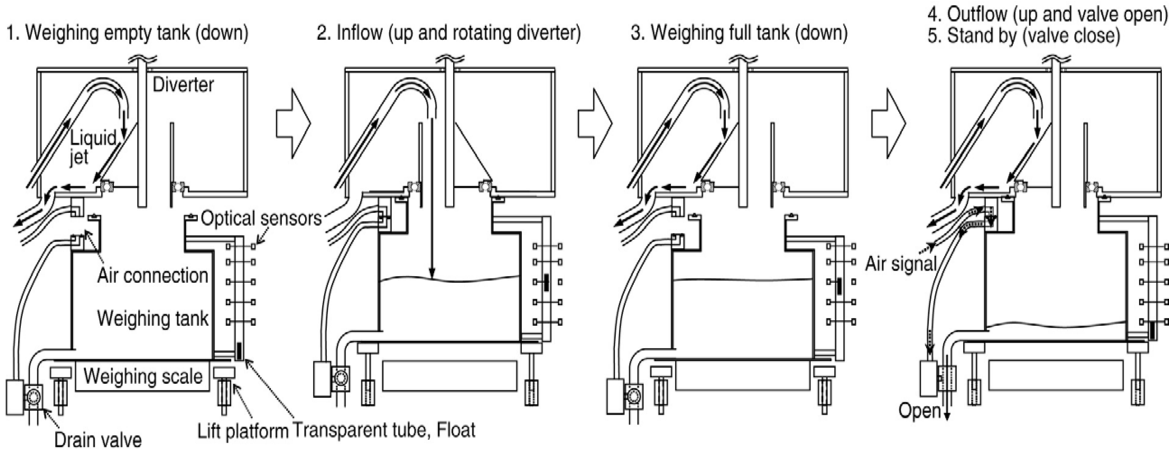


Figure 2.17: Sequence of operation of rotating double wing diverter [52].

2.6 International Status on Water Flow Measurement

Most of the developments in water flow measurement have occurred during last two decades. The recent development in the instrumentation and control has witnessed much improved measurement uncertainty of water flow measurement which is quantitatively reduced to half or better during last one decade. Worldwide, static-gravimetric system is used for water flow calibration and measurement following ISO 4185 standard. The

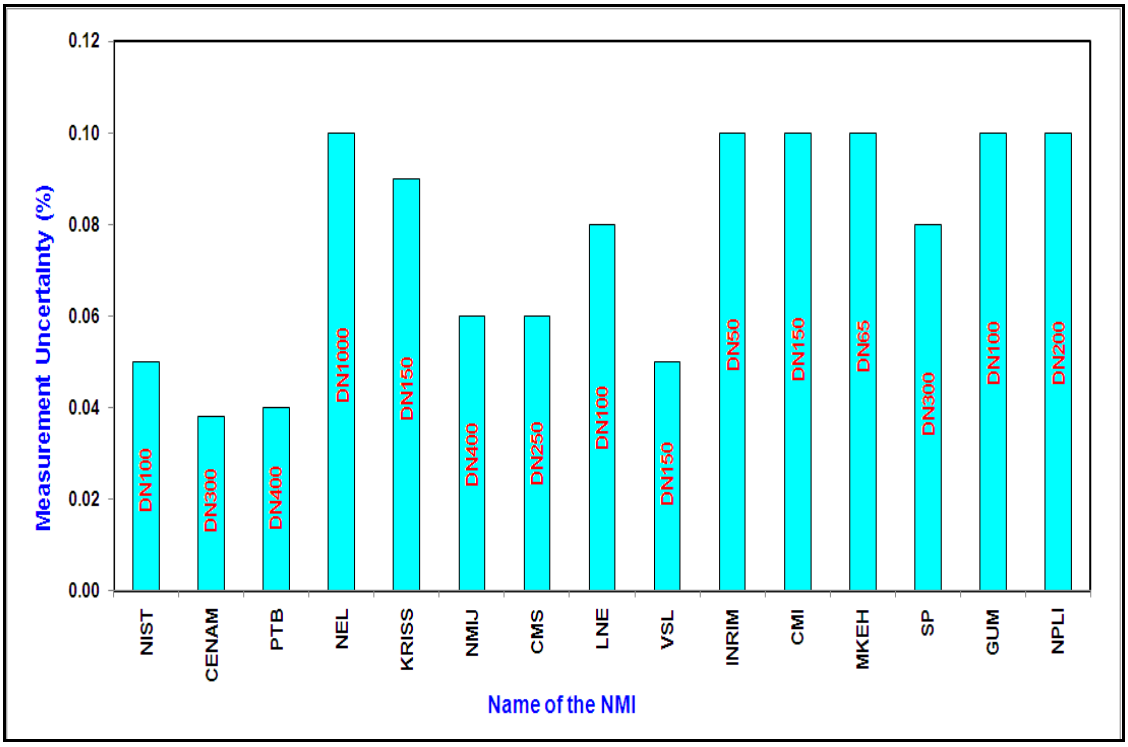
WFMSs have been established worldwide at various NMIs and other user industries, laboratories and institutes. The heavy investment and maintenance costs have limited establishment of WFMSs to only few selected NMIs and users. Table 2.2 summarizes the current status of calibration and measurement capabilities (CMCs) for volumetric flow rate of the various NMIs in the field of water flow measurement [20].

Table 2.2. International status on water flow measurement [20].

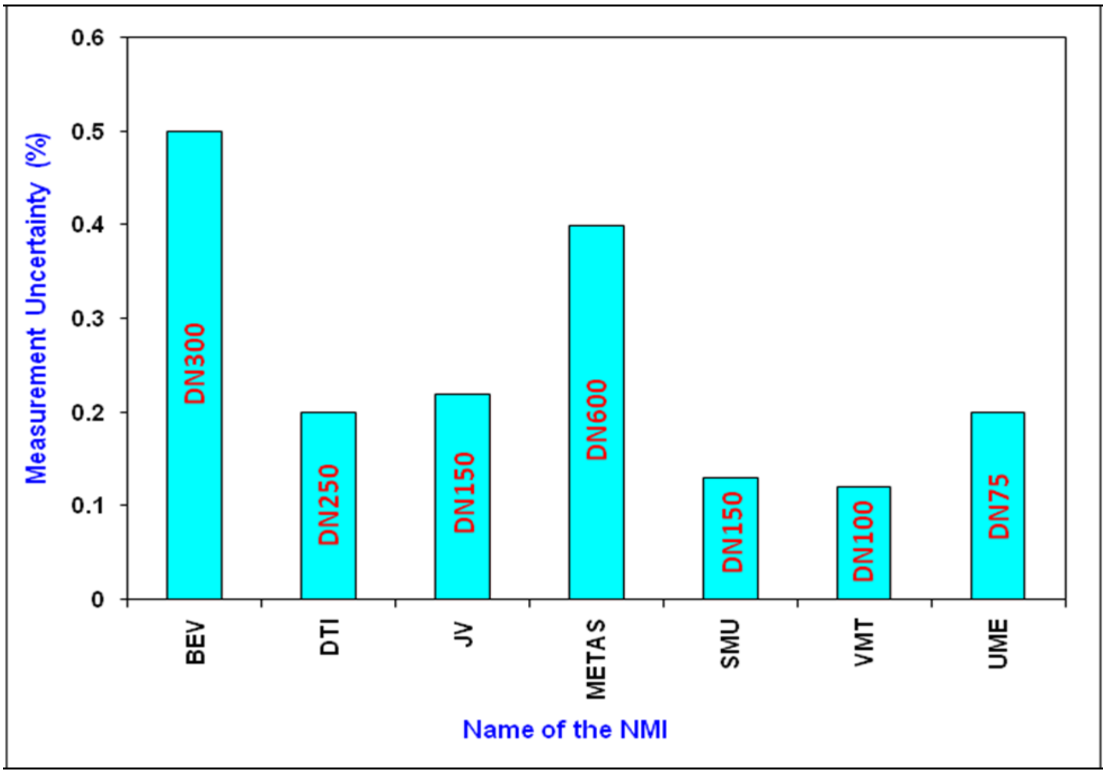
S. No	Name of the NMI/ Lab.	Pipe size (mm)	Uncertainty at *k*=2 (%)	Remarks
1.	NIST, USA	100	0.05	Last Peer Reviewed in 2014
2.	CENAM, Mexico	300	0.038	Last Peer Reviewed in 2014
3.	PTB, Germany	400	0.04	Last Peer Reviewed in 2012
4.	NEL, UK	1000	0.10	Last Peer Reviewed in 2013
5.	KRISS, Korea	150	0.09	Last Peer Reviewed in 2015
6.	NMIJ, Japan	400	0.06	Last Peer Reviewed in 2015
7.	CMS, Taiwan	250	0.06	Last Peer Reviewed in 2008
8.	LNE, France	100	0.08	Last Peer Reviewed in 2012
9.	BEV, Austria	300	0.07 0.50	Last Peer Reviewed in 2012
10.	VSL, The Netherland	150	0.05	Last Peer Reviewed in 2007
11.	VMT/VMC, Lithuania	100	0.11	Last Peer Reviewed in 2012
12.	INRIM, Italy	50	0.10	Last Peer Reviewed in 2014
13.	CMI, Czech Republic	150	0.10	Last Peer Reviewed in 2012
14.	METAS, Switzerland	600	0.40	Last Peer Reviewed in 2015
15.	SMU, Slovakia	150	0.12	Last Peer Reviewed in 2015
16.	JV, Norway	150	0.22	**
17.	MKEH, Hungary	65	0.10	Last Peer Reviewed in 2012
18.	DTI, Denmark	250	0.20	Last Peer Reviewed in 2013
19.	UME, Turkey	75	0.20	Last Peer Reviewed in 2013
20.	SP, Sweden	300	0.08	Last Peer Reviewed in 2012
21.	GUM, Poland	100	0.10	Last Peer Reviewed in 2013
22.	NPLI, India	200	0.10 (original system) [52]	It was revived during 2008-2009 and presently its upgrade has been planned. Not peer reviewed.

** No information is available about peer review status.

Fig. 2.18 shows calibration and measurement capabilities of the NMIs in the graphical form. It is to be noted that in some places, the capabilities (i.e. uncertainty) of the NMIs are better than given in Appendix–C of CIPM MRA. The CMC is generally not the best measurement capability (BMC) but it is coarser to cover the requirement of normal customers. For example, PTB has achieved the uncertainty of 0.019% up to flow range 400 m^3/h but it offers the uncertainty of 0.04% for the whole flow range. Similarly, NIST has best measurement capability of 0.033% for flow measurement up to DN100 but its CMC shows 0.05% uncertainty to cover the requirement of normal customers.



(a)



(b)

Figure 2.18: Graphical representation of CMCs of various NMIs in water flow measurement, (a) measurement uncertainty up to 0.1% and (b) measurement uncertainty above 0.1%.

2.7 Water Flow Measurement Standard at NPLI

The NPLI WFMS comprising of two Test Rigs of sizes DN50 and DN200, was established in a joint collaboration with PTB, Germany during 1992-1998 under NPLI-PTB Technical Collaboration Program for calibration of different types of water flowmeters having electrical output (i.e. electromagnetic, ultrasonic, vortex, turbine, mass flow types etc.) in the flow range 0.1 m^3/h to 600 m^3/h using static-gravimetric method as per ISO 4185 [6, 53]. The WFMS was non-operational for few years. It was revived during 2008-2009 [54]. Fig. 2.19 shows the data acquisition chart of the revived system. Now, the system has become technologically obsolete. Hence, its maintenance and operation are financially and technologically unviable. Also its traceability is a problem. Therefore, its upgrade has been planned using state-of-the-art instrumentation and control systems to make it comparable to advanced NMIs and provide traceable calibration and measurement services to Indian users.

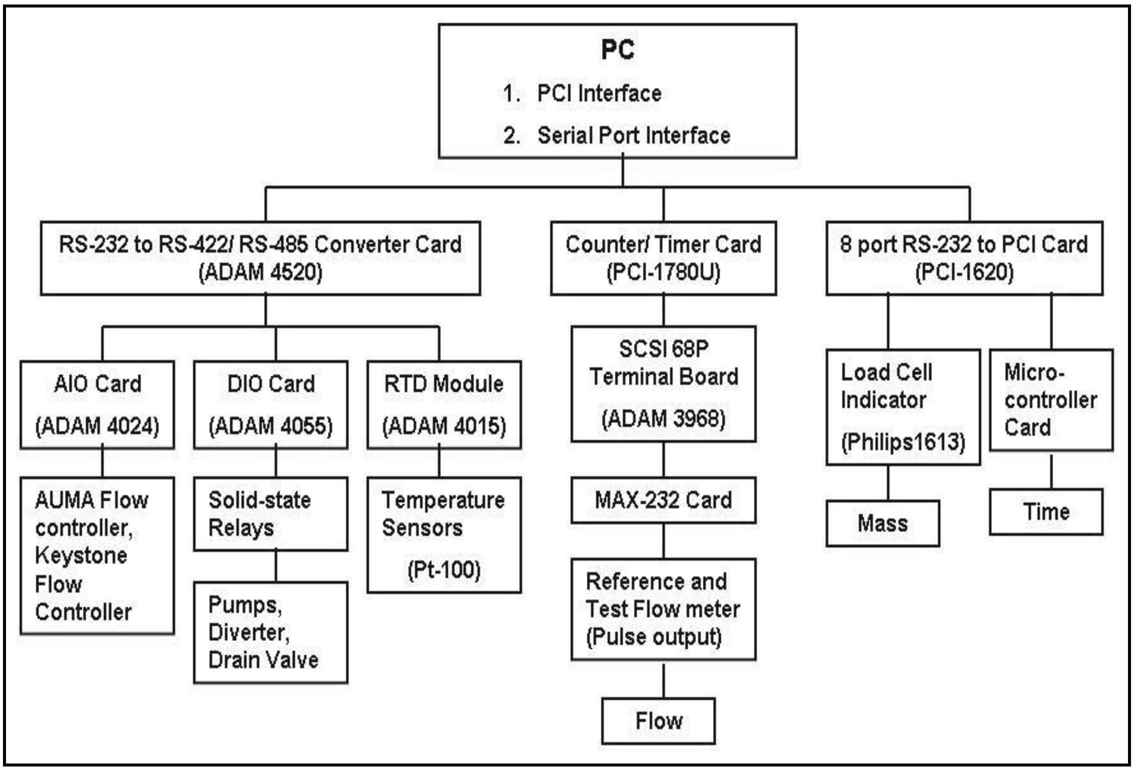


Figure 2.19: Data Acquisition Chart of the Revived WFMS at NPLI [54].

As a follow up of the upgrade, a new prototype automatic water flow measurement standard (i.e. primary standard) of size DN100 has been designed and developed. A novel design technique has been implemented to reduce the diverter error which is a major source of uncertainty. The prototype system would serve as a low-cost solution for Indian water meters manufacturing associations, water flow calibration laboratories and other users. The details of the new system have been given in next chapter.

In this chapter, a brief review of the literature and published works on fluid flow measurements, starting from historical background to modern fluid flow measurement facilities and state-of-the-art technologies available have been discussed. Also the significant contributions made by various researchers worldwide for the improvement of accuracy of flow measurements have been described. The literature review helped in identifying the research problem.

3

METHOD, DESIGN, FABRICATION, INSTRUMENTATION AND OPERATION

3.1 Theoretical Aspects of Multiple Weighing

The weighing system is designed by considering the maximum flow rate and minimum collection time. For a minimum collection time, the time uncertainty is fixed, *e.g.*, for collected mass of 2000 kg (*i.e.* 2 t), collection time is 80 s at a flow rate of 90 m^3/h. The diverter timing error evaluated as per ISO 4185 [7] is 20 ms, then relative timing error is determined as 0.025%. The diverter timing error is considered as an uncertainty component in collection time. The collection time uncertainty consists of diverter error and timer calibration uncertainty. In case of high precision timer, its calibration uncertainty is negligible as compared to diverter error, therefore, collection time uncertainty and diverter error are considered equal. This error is almost exhaustive and further reduction in collection time is almost impossible in a single weighing system wherein bypass line is used. To reduce the timing error, the increase in the collection time by collecting large mass of water is essentially required. Finally, it results into an increase in the size of collection tank.

The method for measuring the volumetric flow rate is based on fundamental principle involving SI units of mass, length and time. The mass flow rate, q_m and the volume flow rate, q_v are defined in Chapter 2 as eqns. (2.1-2.2). The relative combined standard uncertainty in mass flow rate, $u_r(q_m)$ and volume flow rate, $u_r(q_v)$ are determined using eqns. (2.3-2.4) described in Chapter 2. From eqns. (2.1) and (2.3), it is clearly evident that error and uncertainty of mass flow rate are functions of collected mass and collection time. Also, eqns. (2.2) and (2.4) reveal that error and uncertainty of volume flow rate are functions of collected mass, collection time and density of the fluid. The measurement uncertainty of density depends upon the particular density meter used in the measurement process. It is taken as a fixed value for a particular instrument. Therefore, the only options available for improvements of uncertainty are related to mass and time. It is feasible only by enhancing the collected mass of water during collection time interval. During collection intervals, the changes in the water's density are small because the temperature changes are small and the thermal expansion of water is small. Since uncertainty associated with density measurement (determined by particular density meter) is a fixed value, therefore, calibration details have been shown in mass flow rate, which involves the improvement parameters of collected mass and collection time.

In this method, two weighing tanks of identical dimensions are used. The essential requirement for the proper functioning of the method is that filling time (T_F) of the one weighing tank must be greater than drain time (T_D) of the another tank. The sufficient stabilization time for weighing system is included in the drain time. The filling of one tank and drain process of another tank starts simultaneously. Moments the first tank fills, the diverter starts its operation and diverts the flow to the second tank and it starts filling. While it is filling, the weighing process of the first tank is completed. At this moment, the tank one starts to drain out, completes in a certain time interval and then its drain valve is closed. This complete process of both the tanks is continued in a cyclic manner. Fig. 3.1 shows the concept of multiple weighing based flow measurement using double weighing tanks.

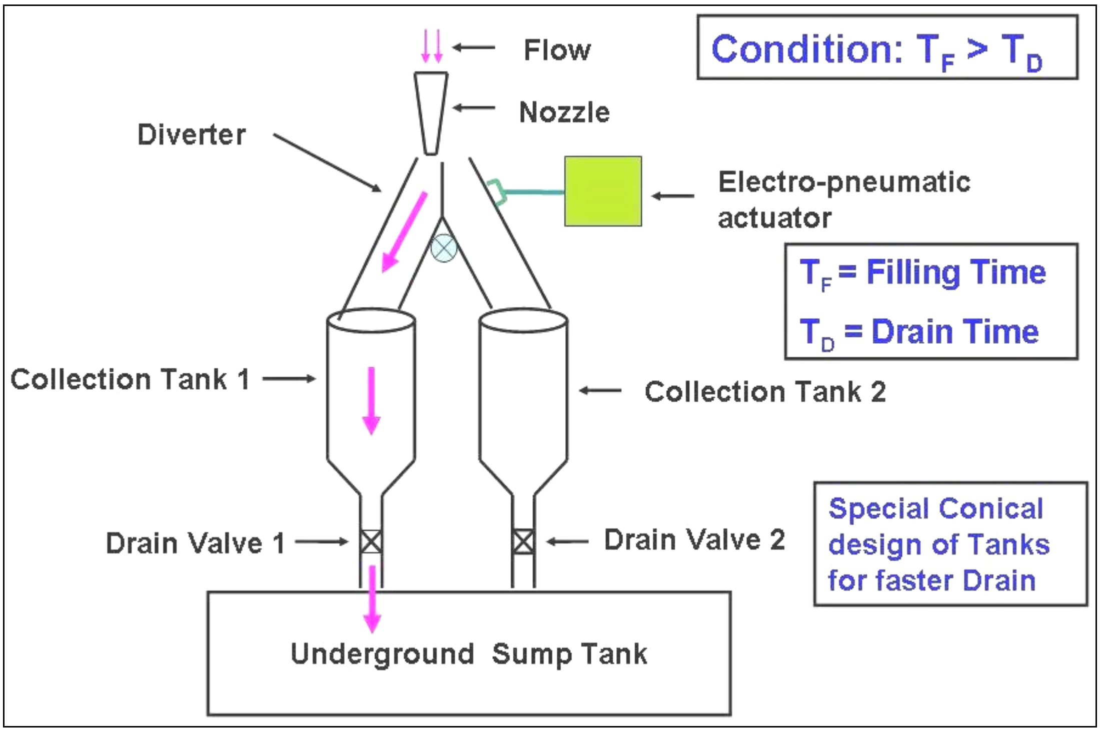


Figure 3.1: Operating principle of double weighing tank based WFMS.

If collected mass (*m*) in a time interval (*t*) is for one cyclic process and it is repeated '*n*' number of times, then total collected mass and collection time are increased '*n*' times. Therefore, the total mass collected (*M*), is estimated as $M = \sum m_i$ (i=1 to *n*). Similarly, the total collection time (*T*), is determined by $T = \sum t_i$ (i=1 to *n*). Since the water flow is directed between two weighing tanks without any splashing and leakage, therefore, the combination of collection tanks and attached weighing balances act like the equivalent single weighing balance of capacity '*n*' times. Now, it is clearly evident that collected mass and collection time are sufficiently increased and hence the uncertainty associated with mass and time is improved considerably.

3.2 Design, Fabrication and Integration of New WFMS

The design of developed prototype water flow measurement system is based on gravimetric method following specifications of all design components as per ISO 4185 standard [7]. A block diagram of the newly designed and developed system is shown in Fig. 3.2.

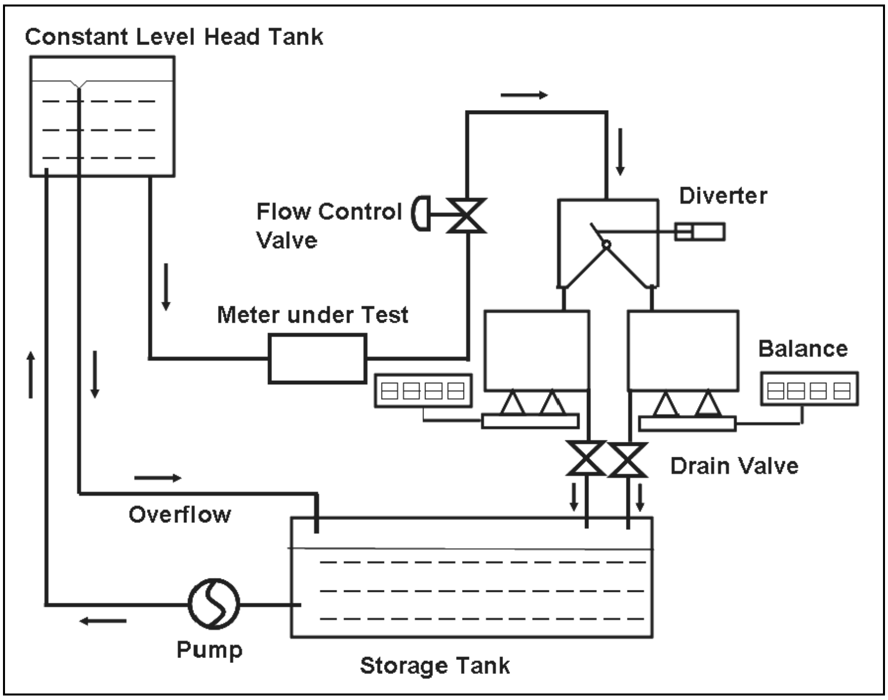


Figure 3.2: Block diagram of newly developed WFMS.

In the present system based on gravimetric principle, a unique method of multiple weighing technique is used wherein utilizing two weighing tanks. System is mainly consisting of several components, devices and instruments namely load cells, load cell indicators, dead weights, diverter, fishtail, nozzle, pumping system, air compressor system, manifold valves, control panels, electromagnetic flowmeters, ball valves, flow control valve, collection tanks, high precision frequency counter, timer, digital multimeter, digital thermometer (i.e. PT-100 sensor with RTD calibrator), aneroid barometer, pressure gauge, automation hardware and software. A number of devices and components like weighing tanks, diverter, fishtail, nozzle, pipe adaptors and various fittings were fabricated as per design parameters. All the components, devices and instruments were integrated thereafter. The individual or combination of component, device and instrumentation are briefly described here.

3.2.1 Underground Sump Tank

The WFMS is a closed loop flow system. The underground sump tank, also called storage tank, is made of a cemented concrete structure. Its size is (25×3×3) m and thus having total storage capacity of 225 m^3 water. The temperature stability of the storage tank is found to be better than ±1 °C/h for calibrating medium i.e. water. It is constructed to supply required flow rate with stable temperature in the flow line. For evacuating the sump tank, a submersible pump of 3 kW capacity has been provided.

3.2.2 Pumps, Manifold Valves and Constant Level Overhead Tank (CLOHT)

There are three constant velocity vertical pumps (make: KSB), each of 37 kW (50 hp). These pumps can be operated individually or in combinations as per requirement, to pump water from the underground sump tank to constant level over head tank (CLOHT) of 25 meter height through a customized manifold (DN300). The head and flow capacity of the each pump are 30 m and 240 m^3/h, respectively. The capacity of all the three pumps together is 720 m^3/h. The windings of each pump are connected in delta configuration. Each pump operates on 3-phase, 400 V AC, 50 Hz electric supply. Fig. 3.3 shows the photograph of the pumping system.

Figure 3.3: Pumps and manifold valves of New WFMS.

The CLOHT constructed at a height of 25 meter having storage capacity of 21 m^3, is in a position to supply water to the test rig up to a maximum flow to enable to calibrate different types of flow meters. The selected height and its effective capacity are adequate to take care of all losses due to various fittings and also providing the desired flow rate up to 600 m^3/h. There exists a weir for maintaining the water level constant well within ±6 mm. The main features of the CLOHT are maintaining the level constant, water surface free from ripples, restricting the formation of swirl, highly stable flow and constant head to the test rigs. The diameter of pumping line is 300 mm. There exists an overflow line of 200 mm diameter. Fig. 3.4 shows the photograph of CLOHT. From the CLOHT, a separate manifold (DN400) is derived which splits the flow into two separate pipelines of 50 mm and 200 mm [6]. Direct pumping line is used by closing the manifold valves of input and output pipes of CLOHT. During direct pumping, higher flow with increased pressure is obtained but stability of flow is poorer as compared to flow obtained through CLOHT. The effective pressure obtained at test rig for 25 m height CLOHT is about 2.5 bar. Admittedly, the flow generation system is of the earlier WFMS, however, the 100 mm test rig is the new development.

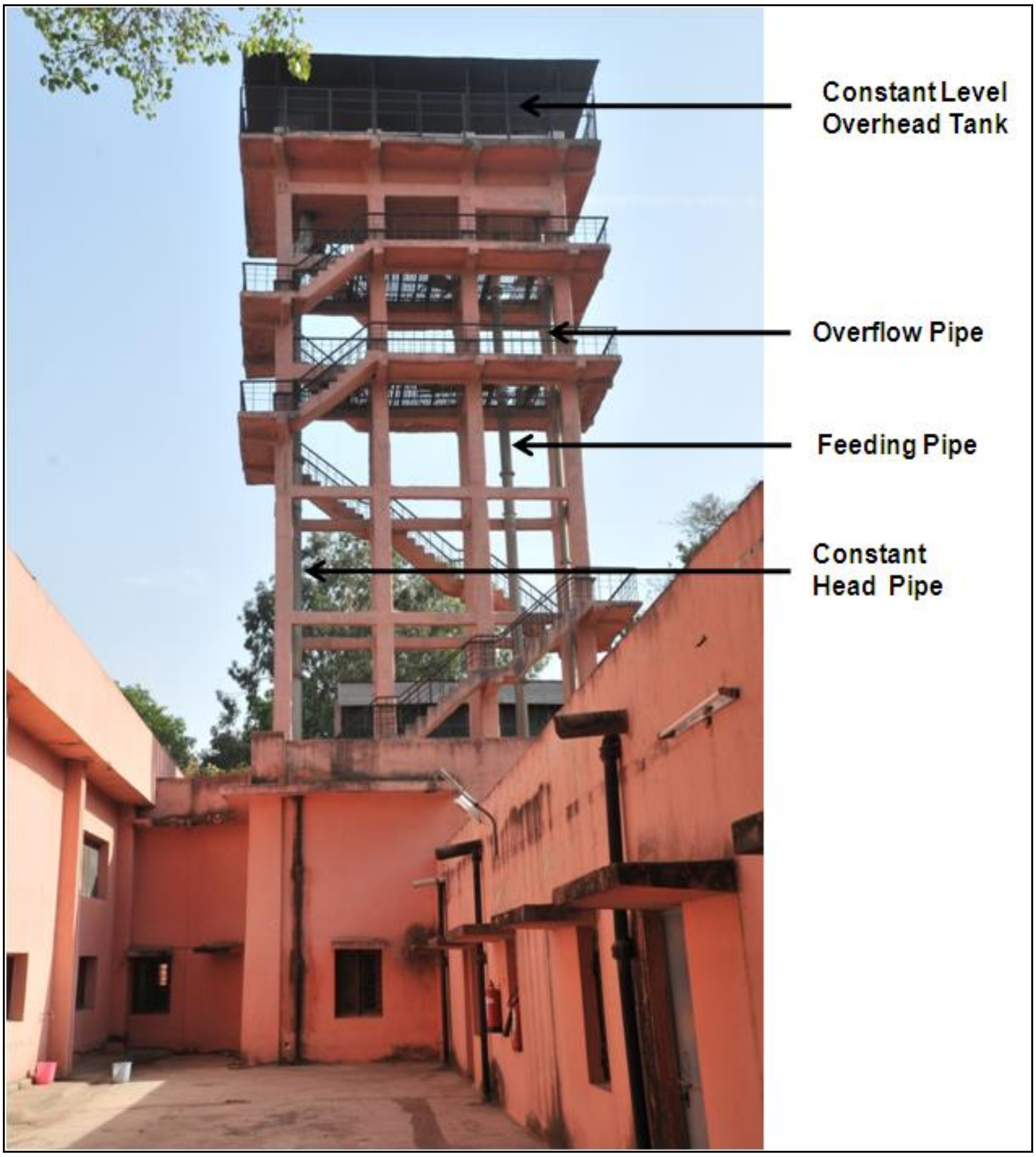


Figure 3.4: Constant level overhead tank for new WFMS.

3.2.3 Air Compressor System

There is an air compressor system (make: Kaeser, model: SK26) of 15 kW capacity. Its flow rate capacity and pressure rating are 2.5 m^3/min and 10 bar, respectively. It has been integrated with refrigerated type dryer and air receiver of 500 L capacity to supply dry air for operation of electro-pneumatic type diverter, drain, ball and flow control valves. Fig. 3.5 shows the photograph of the air compressor system.

3.2.4 Control Panel

The control panel (Fig. 3.5) is housed with main switch, MCBs, MCCB, DOL Starter, contactors with thermal overload protection, 24 V DC power supply and two fans. The panel is made operational through main switch. The MCBs and MCCB are used for control of air compressor, refrigerated type dryer, 3 kW submersible pump and 24 V DC power supply. The 24 V DC power supply is used for electro-pneumatic operation of 6 manifold valves (3 connected in series with pumps, 2 with input and output pipes of CLOHT and 1 with direct pumping pipe bypassing CLOHT). The DOL starter is used for operation of 3 kW submersible pump to evacuate the underground sump tank. The contactors with thermal overloads are used for operations of 37 kW pumps. The fans have been connected to input power supply through MCB before main switch of control panel for cooling purpose, avoiding electric spark over and reducing the humidity level inside.

Figure 3.5: Air compressor system for new WFMS.

3.2.5 Weighing Systems

The each weighing system consists of four load cells (make: ADI Artech), a load cell indicator (make: Weighing Solution and Instrumentation) and a collection tank (also called weighing tank). These load cells are shear beam type, each of 1000 kg capacity, thus enabling total capacity to 4000 kg. The weight and storage capacity of the weighing tank are 800 kg and 2500 kg, respectively. It is used for weighing the collected water in the weighing tank. The output of all four load cells are combined and fed to the load cell indicator and output is displayed. The maximum limit set on the load cell indicator is 2500 kg to accommodate the weight of the weighing tank. Although capacity of tank is 2500 kg, it is used up to 2000 kg with a resolution of 0.2 kg, in the present case to avoid any overflow. The conical (V) shape design of the weighing tanks at the bottom end allows the faster draining, which is required in case of multiple weighing (Fig. 3.6). Two such identical weighing systems were developed (Fig. 3.7). A metallic plate made of mild steel has been suspended beneath weighing tank for simplification of calibration of weighing system (Fig. 3.8).

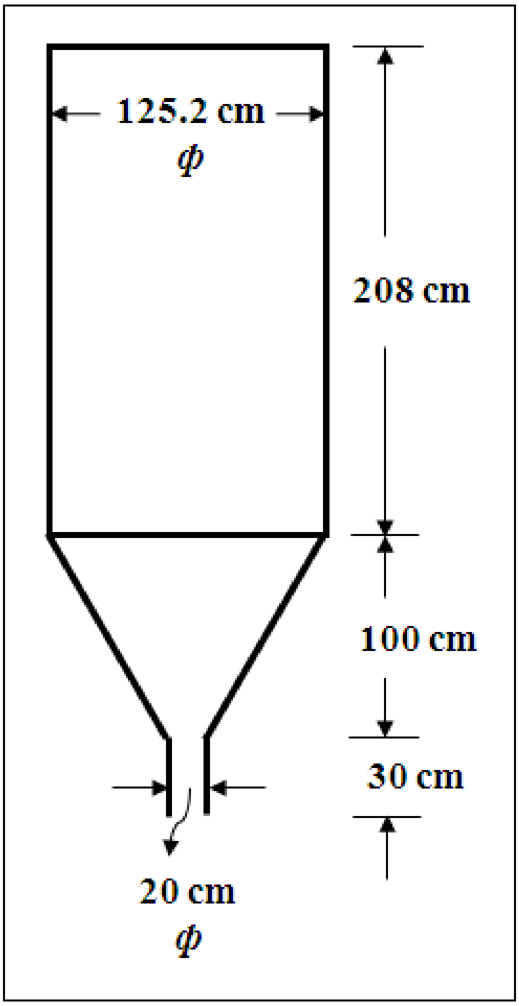


Figure 3.6: Schematic diagram of weighing tank with design parameters.

Figure 3.7: Weighing systems of new WFMS.

Figure 3.8: Plates and drain valves connected with the weighing systems.

After closing of drain valve, the dripping from the weighing tank was studied. There is no leakage from the weighing tank. In case of incomplete draining of the weighing tank, draining effect is monitored with load cell indicator. Before every measurement, the initial reading of the weighing system is recorded. For determination of total collected mass, the initial reading is deducted from the final mass reading. In this way, the partial draining/ dripping of weighing tank is taken care.

3.2.6 Drain Valves

The each weighing tank is connected with a DN200 size drain valve (make: Rotex) for draining the water to sump tank (Fig. 3.8). This butterfly type valve is integrated with solenoid for its electro-pneumatic operation using 220 V AC, 50 Hz electric power supply. The drain valves are operated automatically using National Instrument's digital input output (DIO) card.

3.2.7 Test Section

Test section is comprised of a 100 mm piping system (110 D upstream and 30 D downstream lengths, where D is internal diameter of the pipeline) for obtaining optimum and fully developed flow and better flow stability. The new experimental WFMS has been developed by deriving a separate line of 100 mm from the 400 mm manifold (Fig. 3.9).

Figure 3.9: New DN100 Test Rig along with old DN50 and DN200.

3.2.8 Reference and MUT Flowmeters

The MUT is installed in the test line. There are 2 ball valves (make: Aira Euro) installed before and after the MUT, considering the installation requirements of the flowmeters. These ball valves are used for opening and closing the MUT section. To calibrate the MUT at zero flow, the MUT section is closed by these valves for stable zero flow in the MUT section. These valves are also used for closing the input flow in the test line during any repair and maintenance. The upstream and downstream lengths are more than 50 D and 30 D for the MUT. These upstream and downstream lengths are sufficient to meet the installation requirements of any type of flowmeter (Fig. 3.10). Since CLOHT has been used for better flow stability, the use of flow conditioner is avoided in the pipeline. The adopters of different sizes are fabricated to install the MUT. The adjustable dismantling joint (make: Kejriwal Castings) has been installed in the MUT section for providing gap in the pipeline during MUT installation. After downstream ball valve, a 100 mm electromagnetic flowmeter (make: Krohne) has been installed after due consideration of straight length requirement of this flowmeter. This flowmeter is known as a *reference flowmeter* and it is used to set the flow in the test line and to monitor the flow stability (Fig. 3.11)

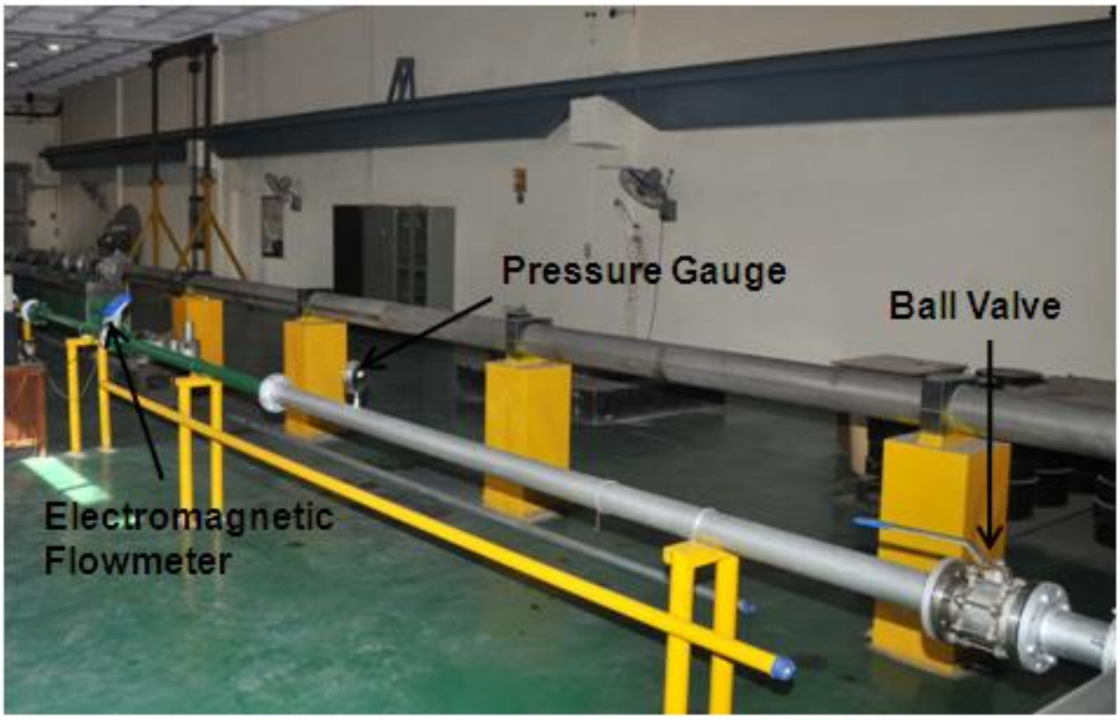


Figure 3.10: Upstream section of MUT flowmeter.

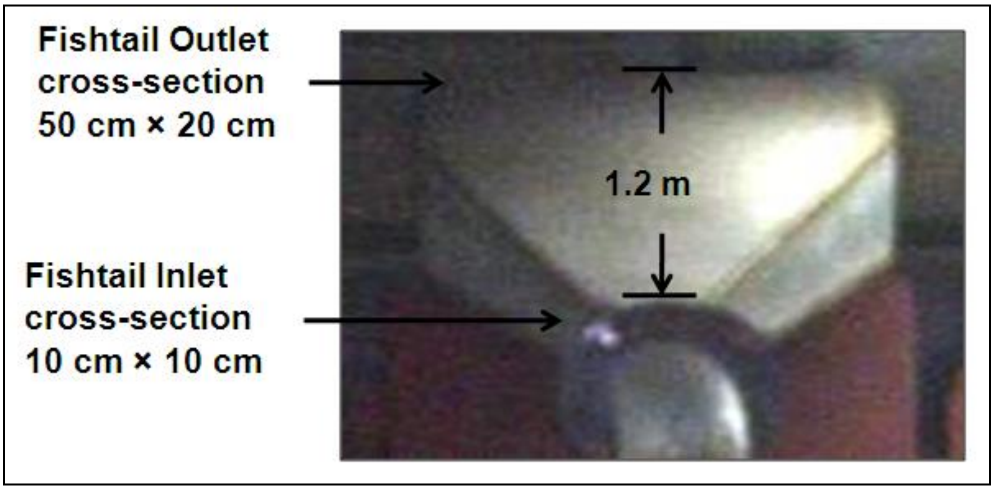
Figure 3.11: Photograph showing reference flowmeter and flow control valve.

3.2.9 Flow Control Valve

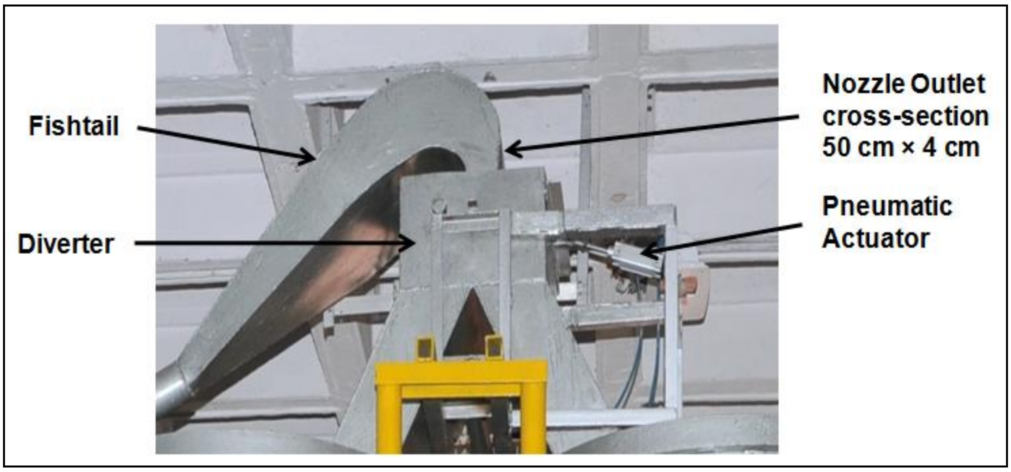
The diaphragm type 100 mm flow control valve (make: Dembla) has been used in downstream side of reference flowmeter for control of flow of the test line. The current to pressure converter has been integrated with flow control valve which operates on (4-20) mA (Fig. 3.11). This valve is manually controlled by a (4-20) mA current source (make: Aarohi) which has a course and fine control knob for setting the current and finally adjusting the flow in the test line. The resolution of this current source is 0.001 mA.

3.2.10 Fishtail and Nozzle

The fishtail is used to alter the flow from circular to rectangular cross-section of the nozzle. The objective of the fishtail and the nozzle is to provide thin sheet of water which does not splash during operation of the diverter. The fishtail and nozzle have been designed and fabricated. Fig. 3.12 shows the fishtail and nozzle of new WFMs.



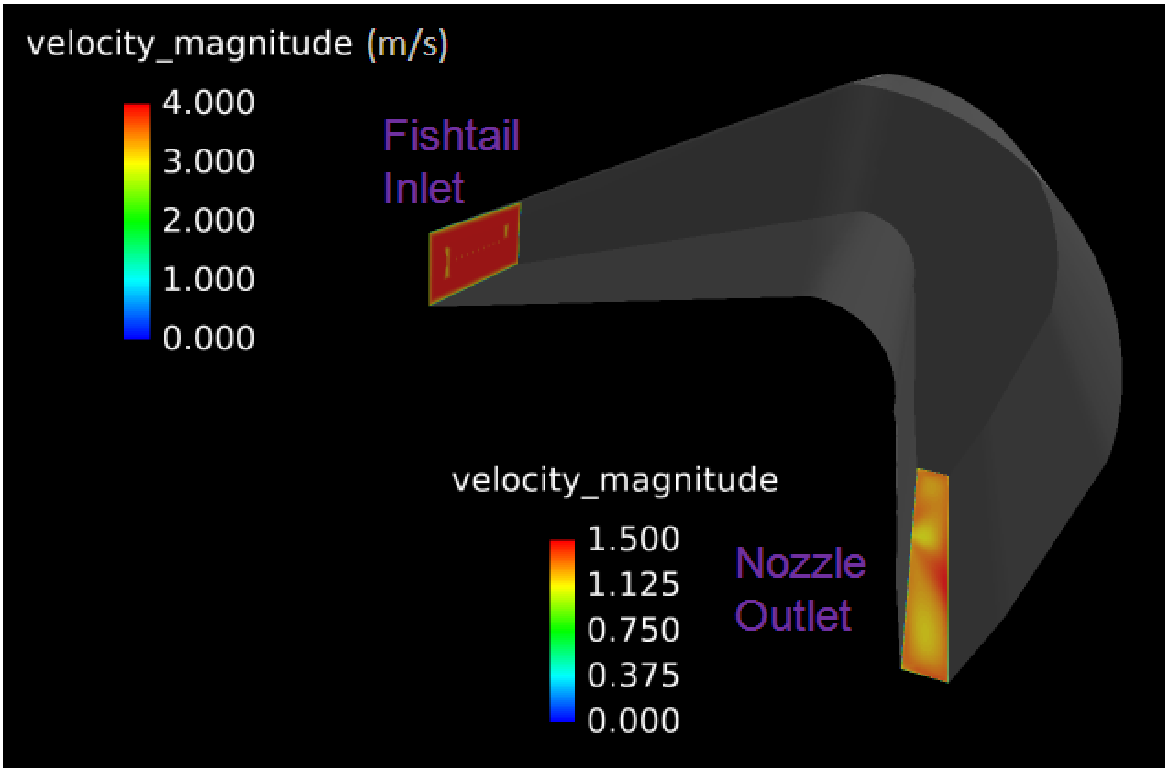
(a)



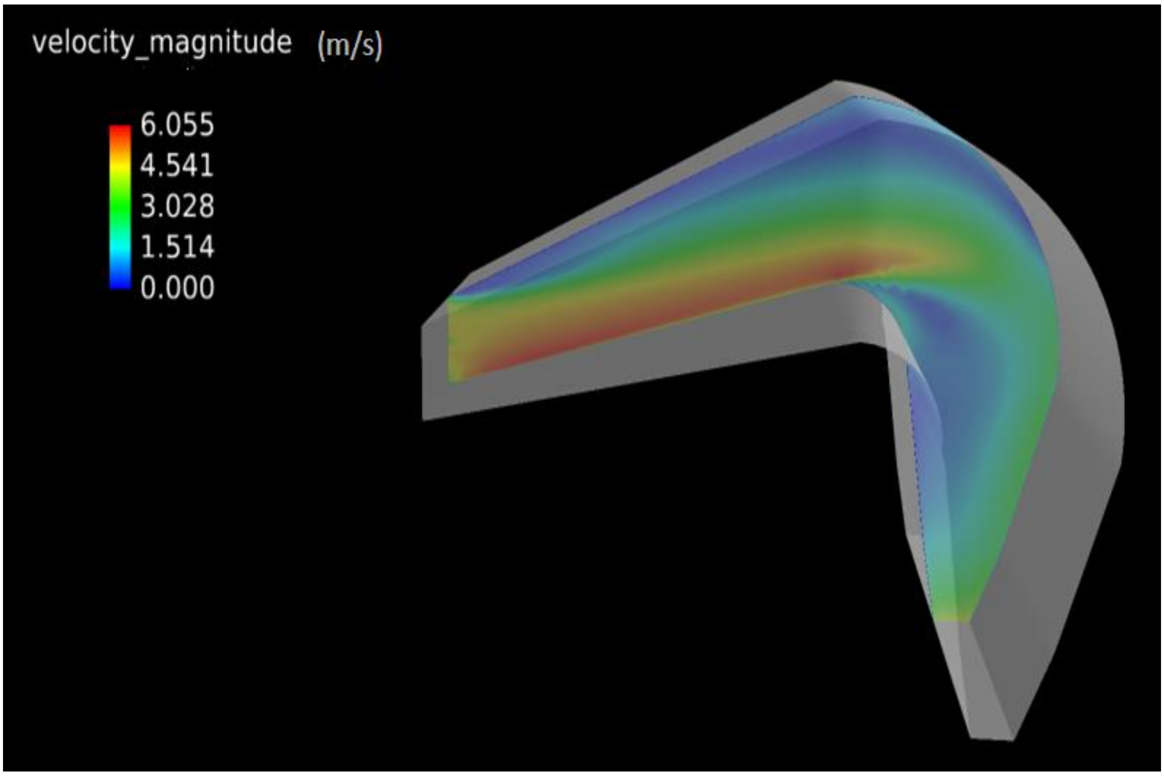
(b)

Figure 3.12: Fishtail, nozzle and diverter of new WFMS.

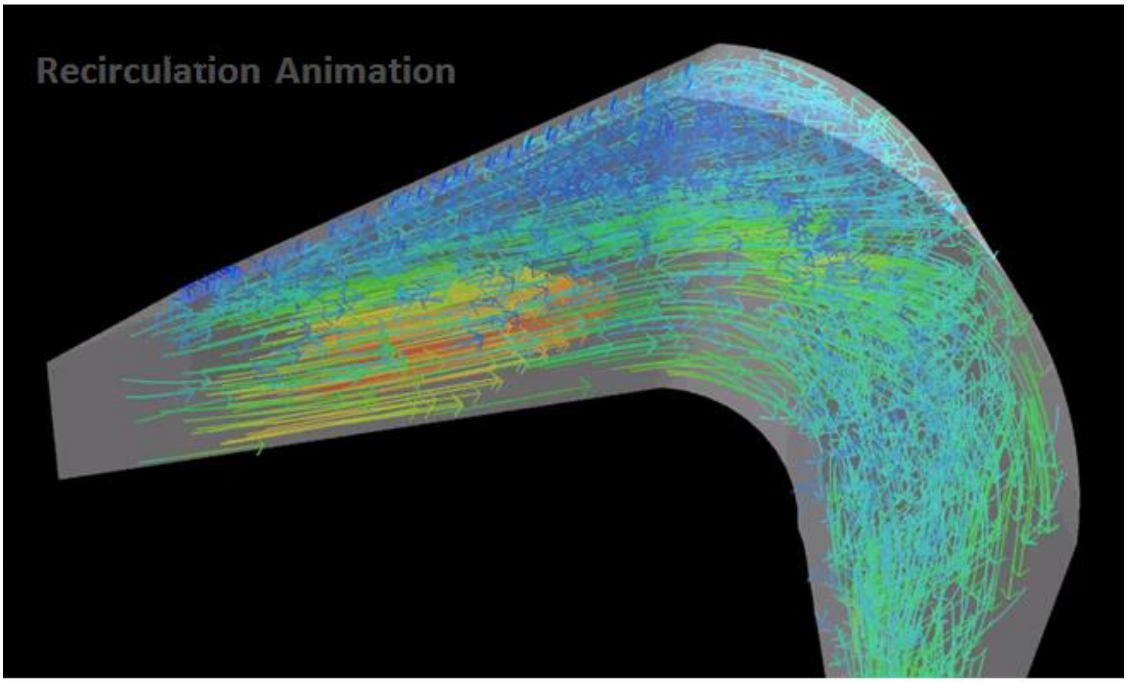
The flow nozzle (length 50 cm and width 4 cm), is having aspect ratio of 12.5. The velocity distribution of water flowing through fishtail and nozzle was studied through Computational Fluid Dynamics (CFD) simulation. Fig. 3.13 shows the flow velocity distribution at fishtail and nozzle inlet and outlet. From the simulation results, it is concluded that flow velocity decreases after entering the fishtail due to increased area. This helps in achieving the thin sheet of water with reduced velocity so that water does not splash during diverter operation. From the re-circulation animation, it is observed that water flowing through fishtail collides with fishtail outlet wall and its some portion bounce backs [Fig. 3.13 (c)]. To minimize this effect further, the fishtail and nozzle assembly is fabricated with higher curvature. The performance of fishtail and nozzle assembly is found satisfactory in the present design.



(a) Flow velocity distribution at fishtail inlet and nozzle outlet.



(b) Cut-away view of fishtail and nozzle in z-axis showing velocity distribution.



(c) Recirculation animation of water flowing through fishtail and nozzle.

Figure 3.13: Characterization of fishtail and nozzle at turbulent flow condition.

3.2.11 Diverter System

The function of a diverter is to divert the flow from bypass line to collection tank and *vice versa* in a traditional system where single weighing tank and a bypass line are used. However, in double weighing tank based system, the function of the diverter is to divert the flow from first weighing tank to second weighing tank and *vice versa*. The diverter system has been designed and fabricated in the present work. The angle of diversion is about 7.5º from vertical axis. Pneumatic actuated piston-cylinder (PC) assembly and solenoid, are used for diverter operation. The PC assembly, also known as pneumatic actuator, is controlled through pressure regulator which in turn controls the speed of diverter. The proximity switch connected with the timer, has been installed with diverter system for measuring the collection time. The operation of the diverter is automated using NI DIO card. Figs. 3.14 and 3.15 depict the design parameters and photograph of the diverter system, respectively. Diverter being a mechanical device, takes some time for diversion which results in to an error in collection volume. Due to this error, the diverter error comes into picture. The diverter error is considered as an uncertainty in the calibration time. Faster diverter actuation, longer time (i.e. large collection tank) and symmetric timer actuation are main processes commonly used to minimize the diverter error. For diverter error estimation, the use of a single proximity switch is advantageous for easy triggering of the frequency counter. The earlier system contains 3 proximity switches which require automation for triggering.

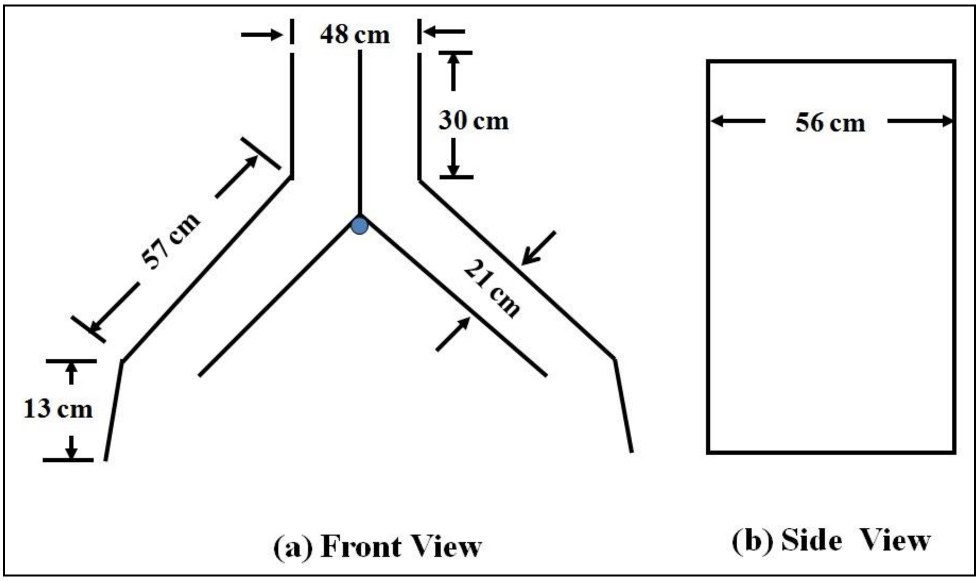


Figure 3.14: Schematic diagram of diverter with design parameters.

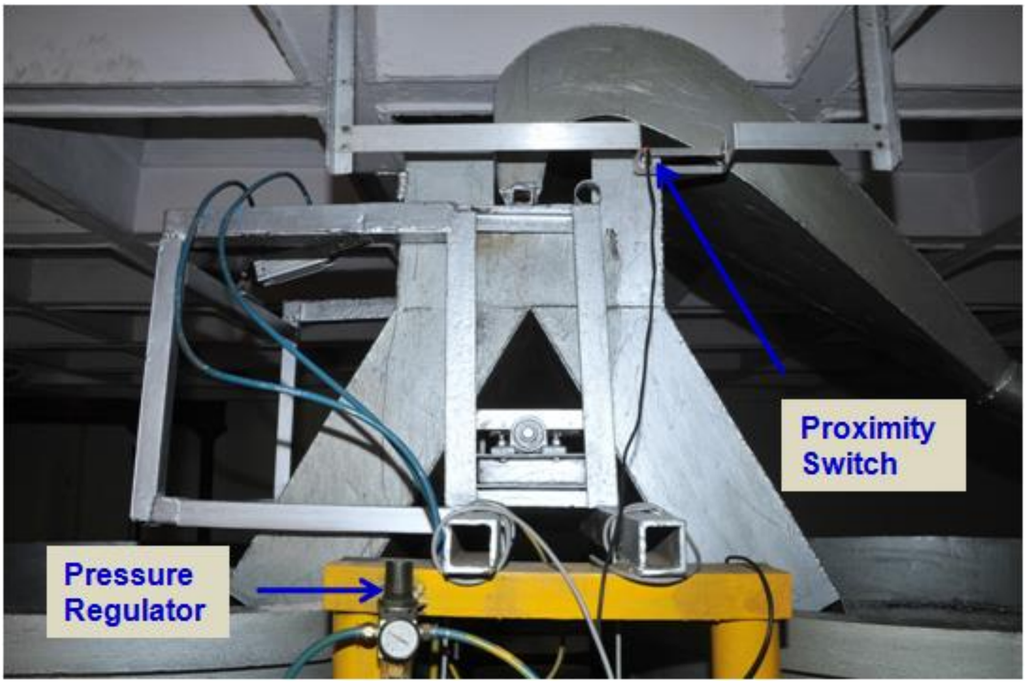


Figure 3.15: Diverter system for collection time measurement.

3.2.12 Digital Thermometer

The digital thermometer (make: Yantrika) comprising of the PT-100 sensor and RTD (resistance temperature detector) calibrator, is used for measuring water temperature during measurements. Its resolution is 0.1 ºC. The Fluke make digital thermometer is also used for temperature measurement due to its high resolution (0.001 ºC) and high accuracy. Measurement of water temperature is essentially required to determine the water density through weighing balance or offline densitometer.

3.2.13 Mass Standards for Weighing System

There are total 20 weights, 10 made of mild steel (Class M1) while another 10 of cast iron (Class M2), in the denomination of 50 kg each. These weights are used for calibrating the weighing systems. The traceability of these weights is achieved by calibrating them against appropriate national standards of mass and balances.

3.2.14 Aneroid Barometer

The aneroid barometer (make: Oakton, model: WD-033116-80) is used to measure ambient pressure (Fig. 16). The resolution of the barometer is 1 mbar. The barometer also has provision of displaying atmospheric temperature reading in the room. The barometric pressure is one of the three parameters required for air density computation.

Figure 3.16: Aneroid barometer.

3.2.15 Digital Temperature and Relative Humidity Indicator

The digital temperature and humidity indicator (make: IRA, model: Humitherm 842 MR) is used to monitor ambient temperature and relative humidity which are also required for air density computation as per NIST formula [32] given in eq. (3.1);

$$\rho_a = \frac{[(0.348444 \times P) - h(0.00252 \times T - 0.020582)]}{(273.15 + T)} \quad (3.1)$$

where ρ_a = air density (kg/ m^3), P = air pressure (mbar), h = relative humidity of the air (%rh) and T = air temperature (°C). The air density is finally used for calculation of air buoyancy correction in mass determination for weighing system.

3.2.16 Timer / Frequency Counter

The timer / frequency counter (make: Agilent, model: 53131A) is used to measure the filling time of weighing tank. Its resolution is 1 ns. When diverter is switched from bypass to weighing tank, the proximity switch triggers the timer by sensing the movement of the diverter and timer starts to record collection time measurements. When weighing system reaches to desired collected mass, the diverter is switched back from weighing tank to bypass line. The proximity switch senses the diverter movement and triggers the timer i.e. timer is stopped. The indicated time by the timer is the total collection time. Due to this reason, static gravimetric WFMS is also called flying-start-flying-finish type system because triggering of timer occurs during the diverter motion. In the WFMS, low resolution (1 ms) Aarohi make timer has been also used (Fig. 3.17). The minimum requirement for timer resolution according to ISO 4185 standard is 10 ms or better. The frequency counter is also used for reading the frequency output of the flowmeter.

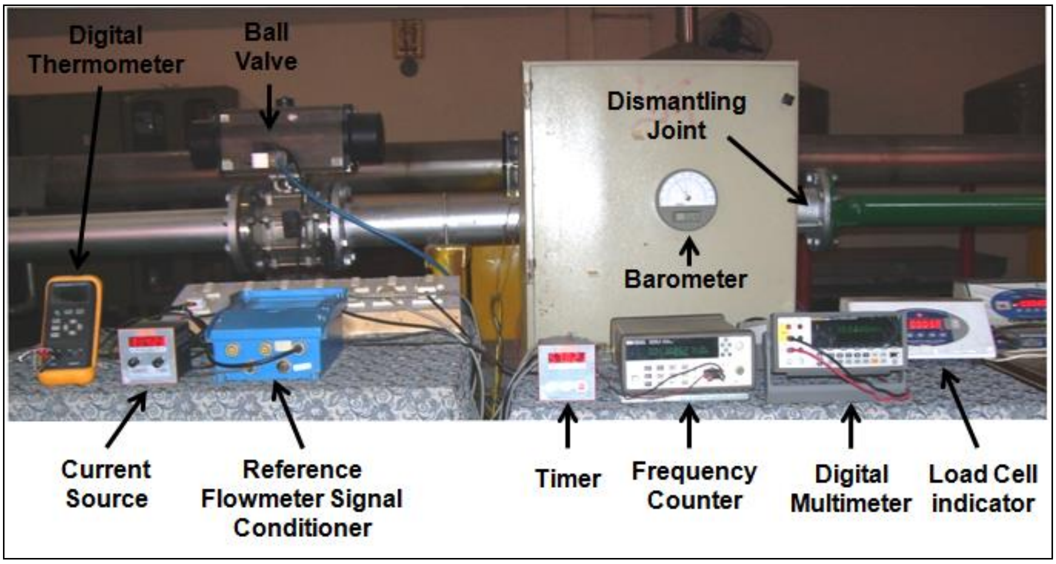


Figure 3.17: Photograph showing PC based flow measurement system.

3.2.17 Digital Multimeter

The digital multimeter (make: Fluke, model: 8846A) is used in the system (Fig. 3.17) to read the current output of the flowmeters. It has resolution of 0.00001 mA and 0.0001 mA at 10 mA and 100 mA ranges, respectively. The contribution of the resolution to the total uncertainty is 0.0002% to 0.00005% which is considered negligible in comparison to manufacturer specification of 0.05% accuracy [55]. Its error is determined by calibration process of digital multimeter against high precision calibrator. The error is then corrected through automation program developed for flowmeter calibration. Finally, uncertainty associated with measurement, achieved through calibration is included in the uncertainty budget.

3.2.18 Pneumatic Tubing and Pressure Regulator

The appropriate pressure tubing, regulator and air filter of pressure rating up to 10 bar were used in the test rig to supply dry air for the actuation and operation of ball valve, drain valves, diverter and flow control valve. For the distribution of the air, a special air manifold was fabricated.

3.2.19 Pressure Gauge

The pressure gauge (make: Yantrika) is used to monitor the test line to estimate the filling of pipeline. Its range is (0-4) bar. When CLOHT is completely filled up, the pressure gauge shows the constant water pressure of about 2.5 bar.

Table 3.1 shows the name of the instruments and devices of new WFMS and their uses.

Table 3.1. List of various items of new WFMS and their uses.

S. No.	Name of the device / component / instrument	Used for
1.	Underground sump tank	temperature stability of calibrating medium i.e. water and as a water source for flow
2.	Pumps	generating the flow
3.	Manifold valves	opening and closing of desired pipe line
4.	Constant level overhead tank	supplying swirl free and stable flow in the pipe line
5.	Air compressor system	supplying dry air for pneumatic operation of the electro-pneumatic valves
6.	Control panel	operation of pumps, air compressor system and manifold valves
7.	Mass standards	calibration of weighing system
8.	Weighing systems	weighing of water collected in tank
9.	Drain valves	draining the weighing tanks
10.	Electromagnetic flowmeters	MUT and reference flowmeter
11.	Reference flowmeter	indication of flow rate in the pipe line and to monitor the flow stability
12.	Ball valves	opening and closing of MUT section without disturbing flow velocity profile of MUT
13.	Flow control valve	adjusting the flow in the pipe line
14.	(4-20) mA current source	regulating the flow control valve through current to pressure converter
15.	Fishtail and nozzle assembly	changing flow from circular to rectangular cross-section and providing thin sheet of water to avoid splashing during diverter operation
16.	Diverter system	switching the flow from bypass line to weighing tank and *vice versa*
17.	Digital thermometer	water temperature measurement
18.	Digital temperature and relative humidity indicator	ambient temperature and relative humidity measurement in the laboratory
19.	Barometer	ambient pressure measurement in the laboratory
20.	Timer / frequency counter	measuring filling time of weighing tank
21.	Frequency counter	measuring frequency (pulse) output of the flowmeters
22.	Digital multimeter	measuring current output of the flowmeters
23.	Analytical balance	measuring water density
24.	Pressure tubing, pressure regulator and air filter	supplying dry air for the actuation and operation of various types of valves
25.	Pressure gauge	Indication of CLOHT and pipe line filling and water pressure monitoring
26.	Personal computer	automation, control and data acquisition
27.	Digital input output (DIO) card	automation of diverter and drain valves
28.	Submersible pump	evacuating underground sump tank for its cleaning

Fig. 3.18 shows the photograph of the complete set-up where old DN50 and DN200 test rigs are also visible.

Figure 3.18: Complete DN100 Test Rig. Also shown are DN50 and DN200.

3.3 Development of Software for Control, Data Acquisition and Operations

The calibration process of the flowmeters has been made automatic. The different devices and instruments like load cell indicators, digital multimeter, frequency counter, timer, diverter and drain valve have been automated in NI LabVIEW software. For diverter and drain valve operations, the NI DIO card has been used. The load cell indictors (of weighing systems) are automated through RS-232 interface. The high precision frequency counter and digital multimeter are automated through their GPIB (IEEE-488) interface. For automation of diverter and drain valve, the circuit was designed consisting of 24 V DC power supply and relays. These diverter and drain valves are automated through NI DIO card. Fig. 3.19 shows the data acquisition and control chart of New WFMS.

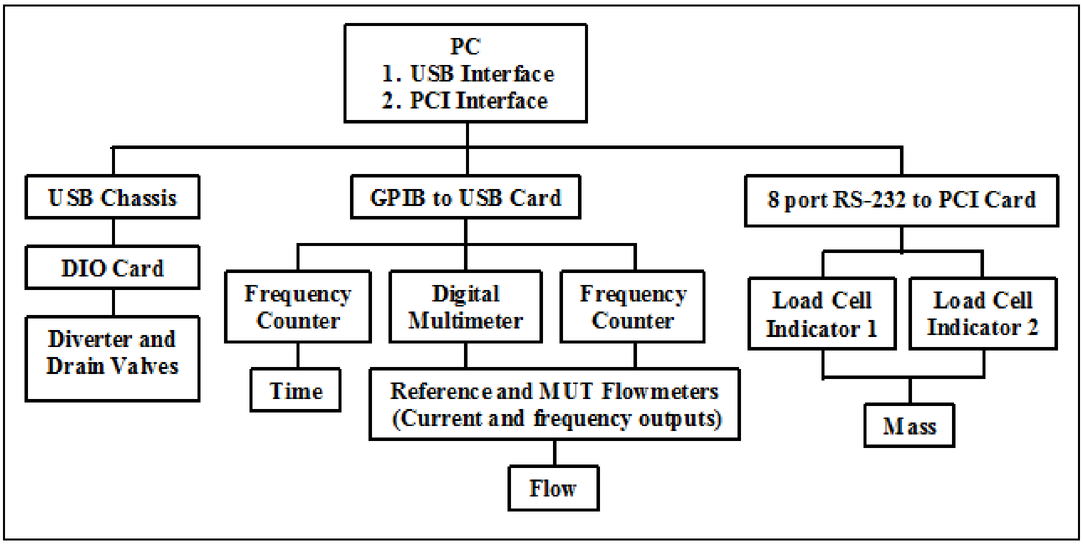


Figure 3.19: Data acquisition and control chart of new WFMS.

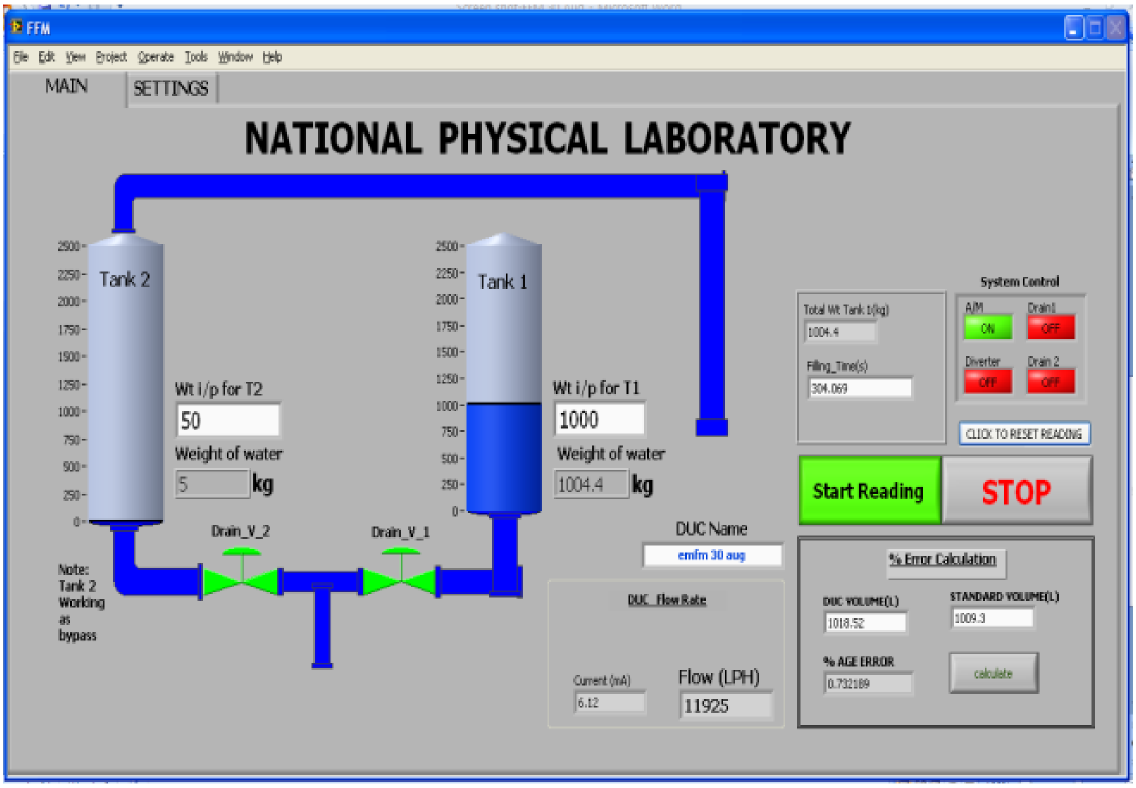
The MUT flowmeters have current and frequency (pulse) outputs which are averaged or totalized through data acquisition system during their calibration. The digital multimeter changes the current to flow rate through following eq.;

$$q_x = \frac{(I_x - I_0)}{(I_{FS} - I_0)} \times q_{FS} \tag{3.2}$$

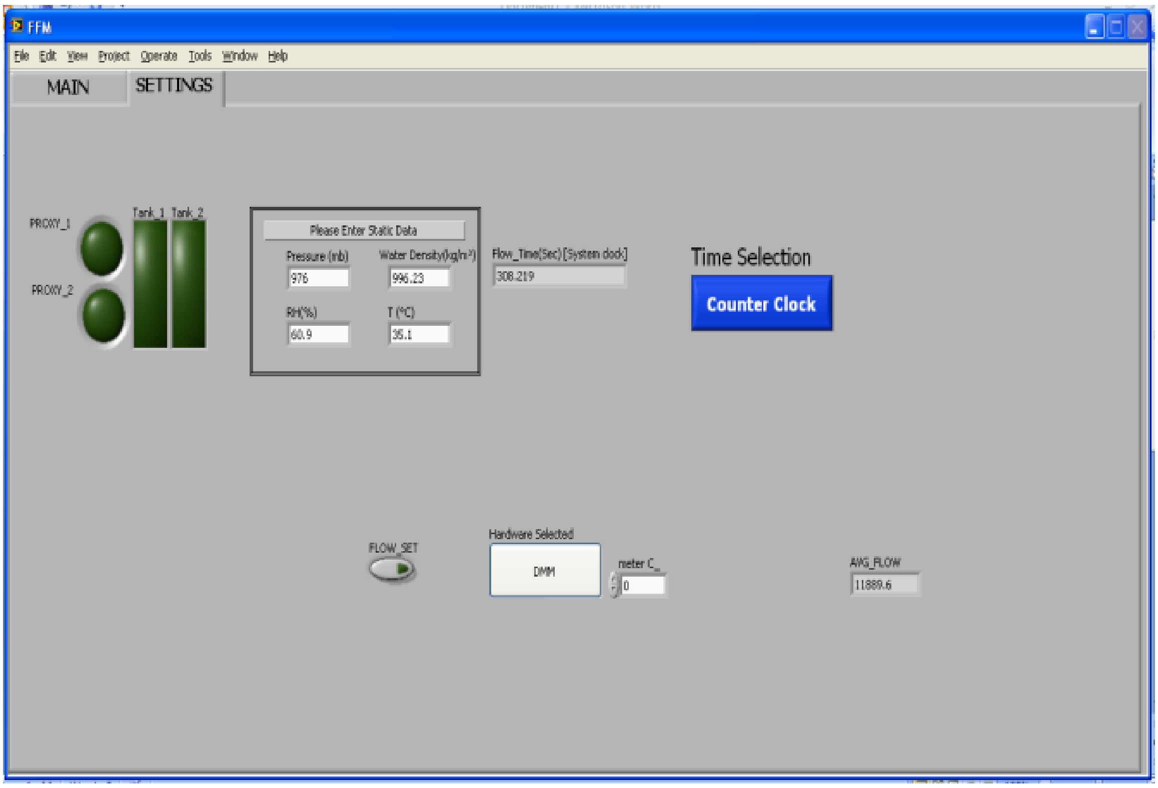
where, q_x is the volume flow rate at current I_x; I_0 is the current at zero flow and q_{FS} is the full scale volume flow rate at full scale current I_{FS}. Most of the flowmeters give (4-20) mA output, so eq. (3.2) becomes

$$q_x = \frac{(I_x - 4)}{(20 - 4)} \times q_{FS} \tag{3.3}$$

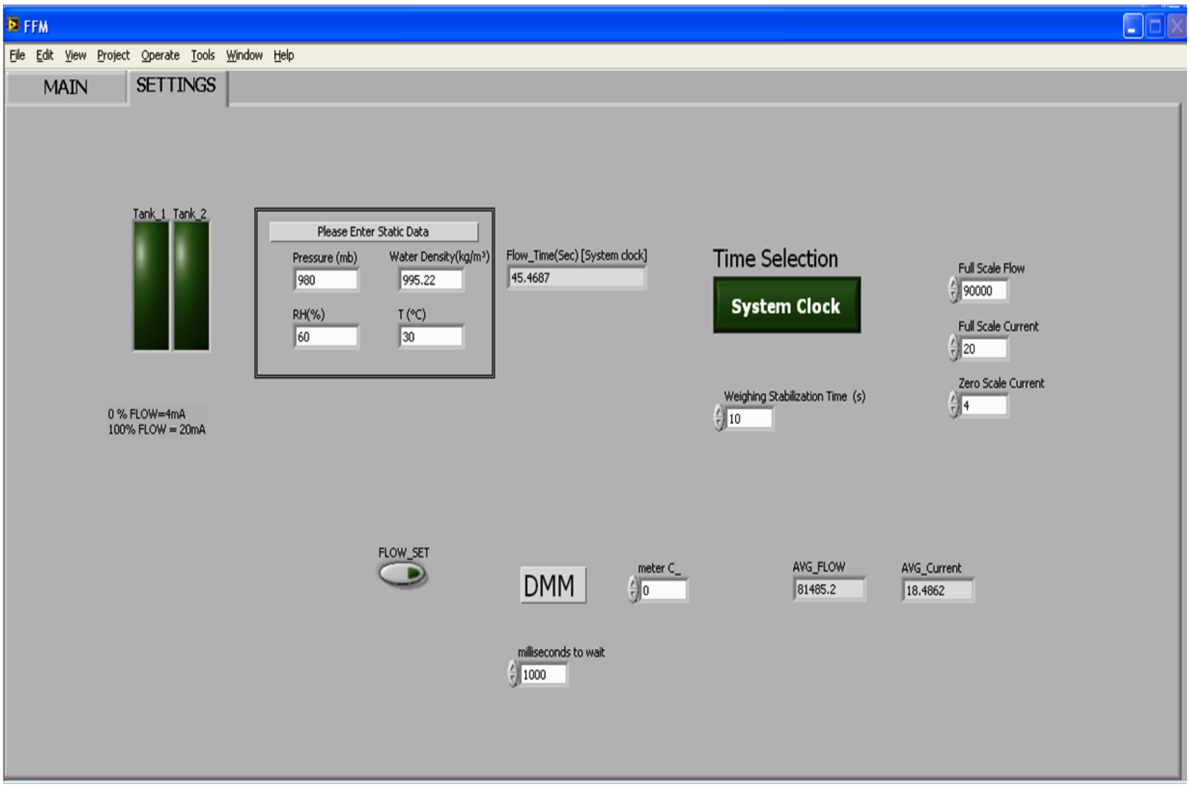
Fig. 3.20 shows the screen shot of flowmeter calibration in current output mode using single weighing method where weighing tank 2 has been used as a bypass line. In the WFMS, the electromagnetic flowmeter of DN80 size has been used as MUT. Although it is designed for flow rate of 45 m^3/h, its flow range was changed to 90 m^3/h without disturbing meter constant. Also, inside the program, full scale flow rate was defined built in, not showing in the software [Fig. 3.20 (b)]. Later on, program was made generalized type providing more options like zero flow current, full scale current, full scale flow, weighing system stabilization time, digital multimeter reading update time [Fig. 3.19 (c)]. An option has been provided for choosing collection time measurement using universal counter / timer or PC clock. From the calibration of digital multimeter, if the error of the flowmeter is estimated to be more than uncertainty, it is corrected before measurements through software program. There is a provision of selection of Automatic / Manual (A/M) mode. In case of static data, the data is fed as input and then program will automatically calculate the error of the flowmeter and all the data are stored in the database (Fig. 3.21).



(a)

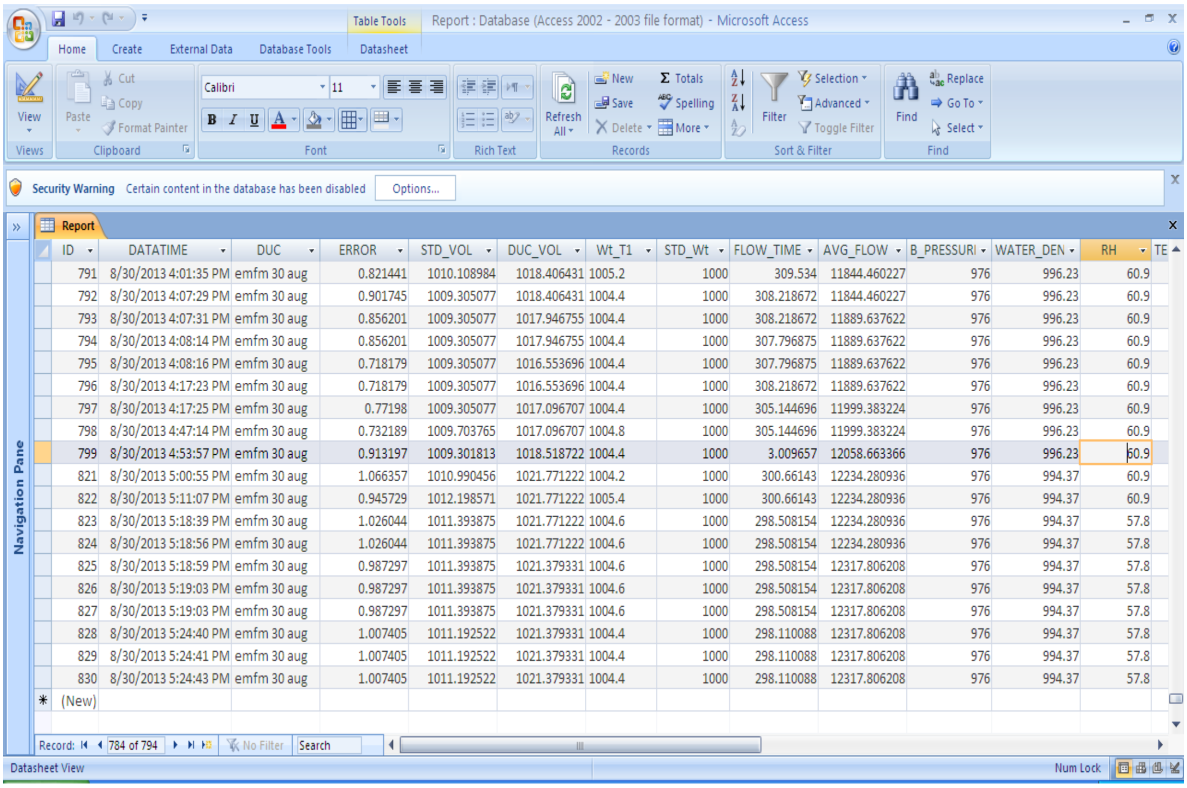


(b)



(c)

Figure 3.20: Screen shots of the automation software developed for single weighing tank in current output mode.



ID	DATATIME	DUC	ERROR	STD_VOL	DUC_VOL	Wt_T1	STD_Wt	FLOW_TIME	AVG_FLOW	B_PRESSURI	WATER_DEN	RH
791	8/30/2013 4:01:35 PM	emfm 30 aug	0.821441	1010.108984	1018.406431	1005.2	1000	309.534	11844.460227	976	996.23	60.9
792	8/30/2013 4:07:29 PM	emfm 30 aug	0.901745	1009.305077	1018.406431	1004.4	1000	308.218672	11844.460227	976	996.23	60.9
793	8/30/2013 4:07:31 PM	emfm 30 aug	0.856201	1009.305077	1017.946755	1004.4	1000	308.218672	11889.637622	976	996.23	60.9
794	8/30/2013 4:08:14 PM	emfm 30 aug	0.856201	1009.305077	1017.946755	1004.4	1000	307.796875	11889.637622	976	996.23	60.9
795	8/30/2013 4:08:16 PM	emfm 30 aug	0.718179	1009.305077	1016.553696	1004.4	1000	307.796875	11889.637622	976	996.23	60.9
796	8/30/2013 4:17:23 PM	emfm 30 aug	0.718179	1009.305077	1016.553696	1004.4	1000	308.218672	11889.637622	976	996.23	60.9
797	8/30/2013 4:17:25 PM	emfm 30 aug	0.77198	1009.305077	1017.096707	1004.4	1000	305.144696	11999.383224	976	996.23	60.9
798	8/30/2013 4:47:14 PM	emfm 30 aug	0.732189	1009.703765	1017.096707	1004.8	1000	305.144696	11999.383224	976	996.23	60.9
799	8/30/2013 4:53:57 PM	emfm 30 aug	0.913197	1009.301813	1018.518722	1004.4	1000	3.009657	12058.663366	976	996.23	60.9
821	8/30/2013 5:00:55 PM	emfm 30 aug	1.066357	1010.990456	1021.771222	1004.2	1000	300.66143	12234.280936	976	994.37	60.9
822	8/30/2013 5:11:07 PM	emfm 30 aug	0.945729	1012.198571	1021.771222	1005.4	1000	300.66143	12234.280936	976	994.37	60.9
823	8/30/2013 5:18:39 PM	emfm 30 aug	1.026044	1011.393875	1021.771222	1004.6	1000	298.508154	12234.280936	976	994.37	57.8
824	8/30/2013 5:18:56 PM	emfm 30 aug	1.026044	1011.393875	1021.771222	1004.6	1000	298.508154	12234.280936	976	994.37	57.8
825	8/30/2013 5:18:59 PM	emfm 30 aug	0.987297	1011.393875	1021.379331	1004.6	1000	298.508154	12317.806208	976	994.37	57.8
826	8/30/2013 5:19:03 PM	emfm 30 aug	0.987297	1011.393875	1021.379331	1004.6	1000	298.508154	12317.806208	976	994.37	57.8
827	8/30/2013 5:19:03 PM	emfm 30 aug	0.987297	1011.393875	1021.379331	1004.6	1000	298.508154	12317.806208	976	994.37	57.8
828	8/30/2013 5:24:40 PM	emfm 30 aug	1.007405	1011.192522	1021.379331	1004.4	1000	298.110088	12317.806208	976	994.37	57.8
829	8/30/2013 5:24:41 PM	emfm 30 aug	1.007405	1011.192522	1021.379331	1004.4	1000	298.110088	12317.806208	976	994.37	57.8
830	8/30/2013 5:24:43 PM	emfm 30 aug	1.007405	1011.192522	1021.379331	1004.4	1000	298.110088	12317.806208	976	994.37	57.8
(New)												

Figure 3.21: Screen shot of database of stored measurement data.

In the manual mode, the program displays the indicated values of the weighing systems and digital multimeter. In order to check the proper functioning of the system, the diverter and drain valves can be operated in manual mode. However, DMM display shows the data but not the averaging which is required for automatic operations. There is a provision in the program for monitoring the flow stability of line using "***Flow Set***" icon [Fig. 3.20 (b) and (c)]. Fig. 3.22 shows the plot of flow verses time to monitor flow stability. From the "***Flow Stability***" icon given at desktop of PC, the data of the flow stability can be accessed and standard deviation of flow rate can be determined.

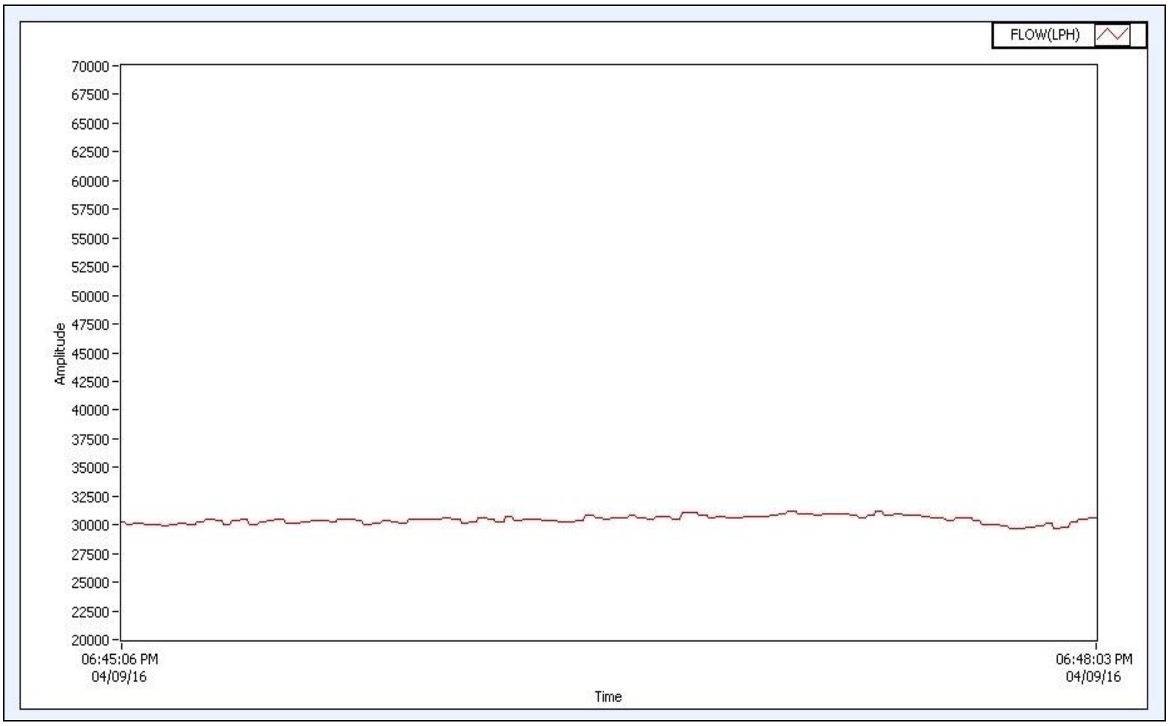


Figure 3.22: Graph of flow rate verses time for flow stability.

The MUT flowmeters' frequency output is measured and averaged by frequency counter or digital multimeter (Fluke 8846A digital multimeter is having this facility). In the program, the static data such as full scale frequency, full scale flow rate, zero flow rate frequency are defined. Even frequency offset can be also taken care by the program. Frequency output is converted to the flow rate using the following eq. (3.4);

$$q_x = \frac{(f_x - f_0)}{(f_{FS} - f_0)} \times q_{FS} \tag{3.4}$$

where, q_x is the volume flow rate at frequency f_x; f_0 is the frequency at zero flow and q_{FS} is the full scale volume flow rate at full scale frequency f_{FS}. Normally full scale frequency output of the most of the flowmeters are used in the range of (5-10) kHz.

Similarly, the software has been developed for frequency output of the flowmeter. Fig. 3.23 shows the screen shot of the flowmeter calibration in the frequency mode. Frequency (pulse) mode of operation of the flowmeter is the most accurate method because accuracy of frequency counter used to measure frequency output is very high as compared to digital multimeter. The best measurement uncertainty is always applicable for frequency output unless and otherwise stated.

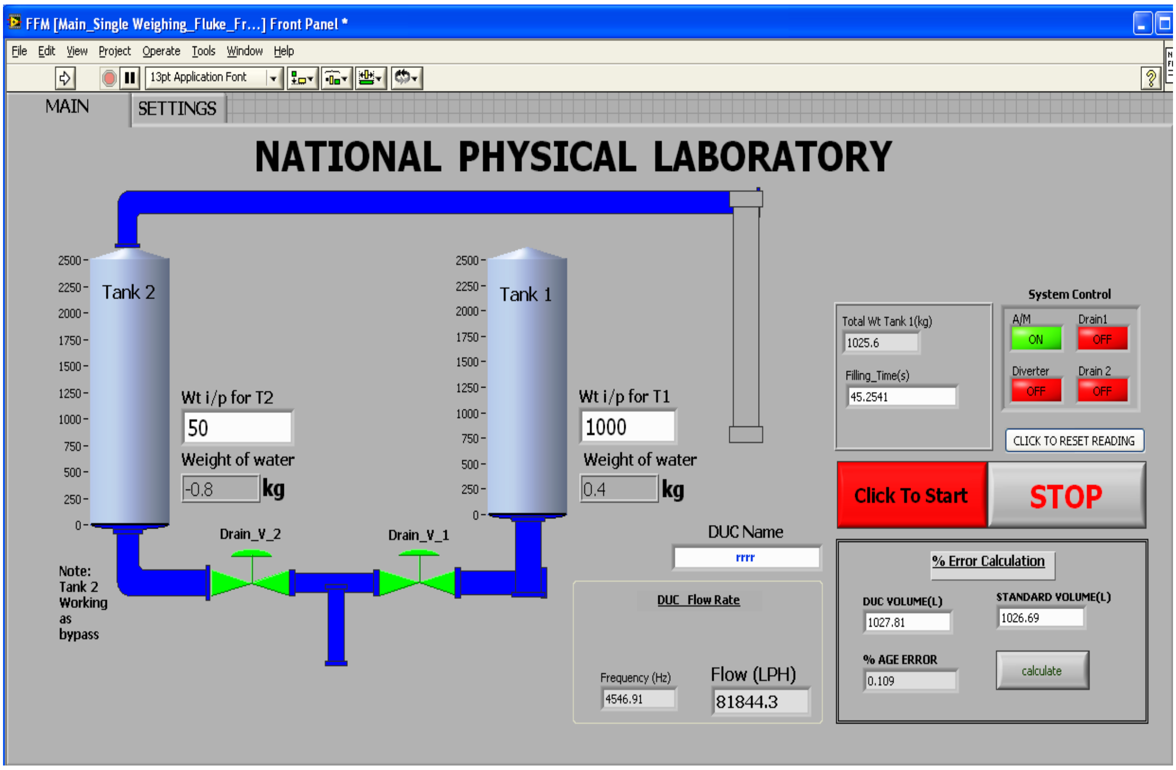
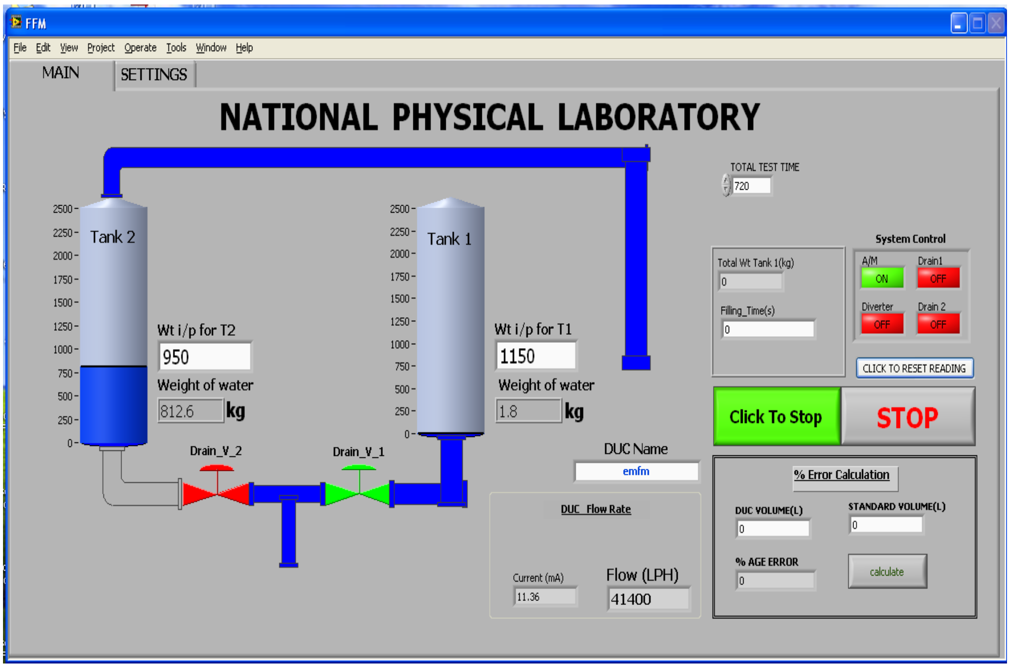
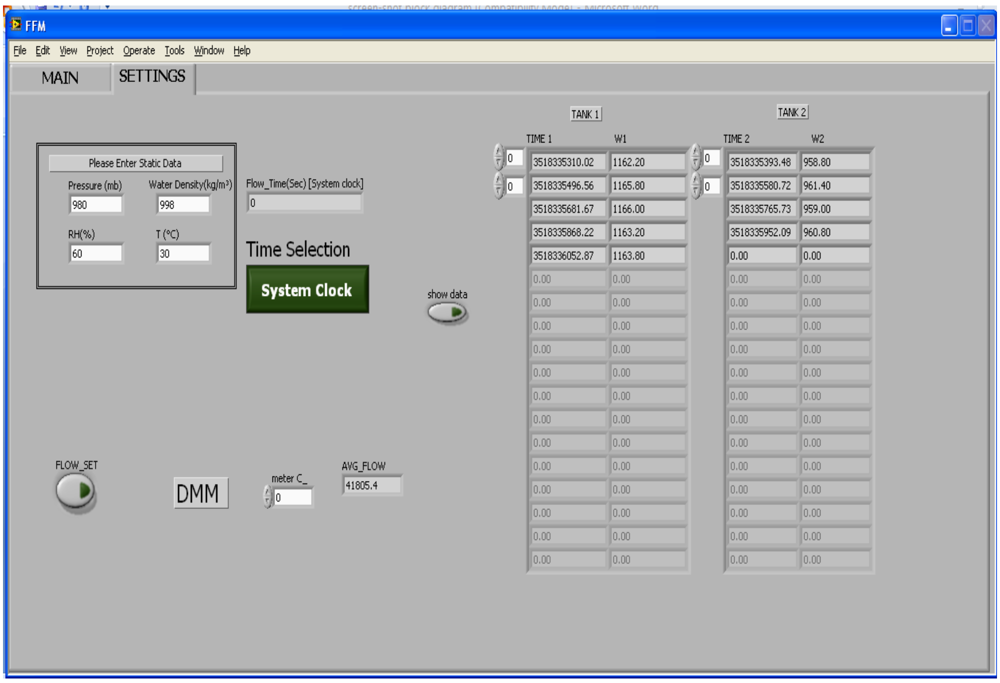


Figure 3.23: Screen shot of the automation software developed for single weighing tank in frequency output mode.

To implement multiple weighing technique employing two weighing tanks, a fixed timing mode of operation has been adopted where collection time is determined from targeted collected mass and flow rate at which measurement has to be done, *e.g.*, the targeted collected mass (using double weighing tanks) is 10,000 kg at nominal flow rate of 40 m^3/h, then total collection time is 900 s assuming water density to be 1000 kg/m^3. Fig. 3.24 shows screen shot of the automation software developed for double weighing tank in current output mode. In this program, the total collection time shown in Fig. 3.24 (a) is 720 s, and instantaneous flow rate is shown as 41,400 L/h (41.4 m^3/h). Mass setting for Tank 1 is 1150 kg and for Tank 2 is 950 kg. These settings were done after multiple experiments to optimize the measurement process. The average flow rate and masses of Tank 1 and Tank 2 in multiple weighing process can be seen in Fig. 3.24 (b).



(a)



(b)

Figure 3.24: Screen shot of automation software developed for double weighing tanks in current output mode.

In the present study, the uncertainty estimation in flow measurement has been carried out adopting globally accepted methods of uncertainty evaluation [7, 9-10]. The software has been developed for this purpose (Fig. 3.25).

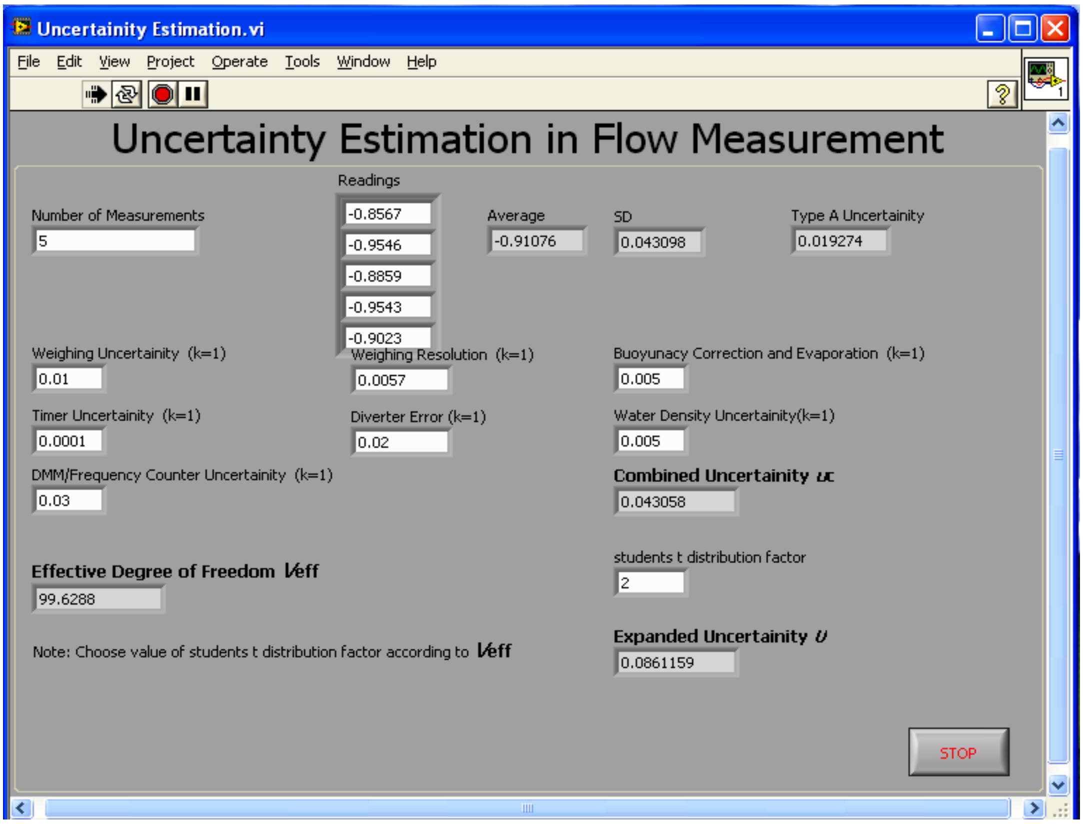


Figure 3.25: Screen shot of uncertainty estimation software developed for flow measurement.

3.4 Operation of the WFMS in a Single Weighing Mode

The WFMS can be operated in a single weighing mode by making one of the two weighing systems as a bypass line. The process of making flow measurement in a single weighing mode consists of the following steps:

i) Flowmeter under test is mounted in the test section. All the static parameters of MUT flowmeter i.e. full scale flow rate, full scale current or frequency output nominal values, zero flow current or frequency output, etc. are appropriately defined in the automation program. The mass of water to be collected in the weighing system is also defined.

ii) The weighing tank 2 acts as a bypass line and its drain valve is kept open. The drain valve of weighing tank 1 is then closed. The flow control valve is adjusted to achieve the desired flow rate through pipeline and MUT. The system is then continued to run for about 15-20 min. for stability of water temperature in the pipe line and also for removal of trapped air in the pipe line to avoid incorrect measurement. The trapped air in the pipe line is generally more effective at low flow rate.

iii) Weighing system 1 is then either adjusted to zero value through taring process or measured its initial mass.

iv) After clicking of **"Start"** in the automation program, the measurement process is started. The diverter is switched from bypass (weighing tank 2) to weighing tank 1 to collect water in the weighing tank 1 and pulse output given by proximity switch triggers to start the timer to initiate the collection time measurement.

v) During calibration, the initial water temperature in the pipeline between the MUT and the weighing tank and the laboratory air temperature, relative humidity and pressure (for buoyancy corrections to the collected mass measurement) are recorded. If one is not having additional instrumentation for ambient temperature, relative humidity and pressure measurement, then standard buoyancy correction factor of 1.00106 can be used in the calculation of mass flow rate.

vi) As soon as the defined collected mass is reached in weighing tank 1, the diverter is automatically diverted to switch the flow from weighing tank 1 to bypass line (weighing tank 2) and pulse output given by proximity switch stops the timer. Thus timer displays total collection time.

vii) The final mass of water in the weighing tank is recorded after allowing sufficient time for its stabilization. After recording the final mass, the weighing tank is automatically drained.

viii) The final water temperature is recorded after completion of the measurement. The average of initial and final water temperatures is taken. The online densitometer directly reads the water temperature and its density. So, if one has online densitometer, then the water temperature and density are directly measured and noted in the calibration sheet.

ix) The collection time measured by the timer and the average flow rate of MUT determined by digital multimeter/ frequency counter in the automated measurement are recorded.

x) After completion of experiment, the data are analyzed for determination of flowmeter error/ meter k-factor along with uncertainty.

3.5 Operation of the WFMS in a Multiple Weighing Mode

The WFMS is operated in a multiple weighing mode using both weighing systems. Initially, one of the weighing systems acts as a bypass line and subsequently it is used for weighing. The PC clock is used as timer for collection time measurement. The cyclic weighing process is adopted and normally it consists of the following steps:

i) The MUT is mounted in the test section. All the static parameters of the MUT i.e. full scale flow rate, full scale current output nominal values, zero flow current output, etc. are appropriately defined in the automation program. Also the total mass of water to be collected and total test time are defined in the automation program. Here, Tank 1 and Tank 2 have been denoted as T1 and T2, respectively.

ii) The masses to be collected in Tank 1 and Tank 2 are set as WS1 and WS2 respectively.

iii) Tank 2 is initially chosen as bypass line. The drain valve of Tank 1 is closed. The flow control valve is adjusted to achieve the desired flow through the pipe line and the MUT. The system is then continued to run for about 15-20 min. for stability of water temperature in the pipe line and also for removal of trapped air in the pipe line to avoid incorrect measurement.

iv) Weighing system T1 is then either adjusted to zero value through taring process or measured its initial mass.

v) After clicking of **“Start”** in the automation program, the measurement process is started and the diverter is automatically switched from Tank 2 to Tank 1 position and Tank 1 starts filling. The multimeter starts averaging the current output of the flowmeter. As long as Tank 1 is filling, during this time, the drain valve of Tank 2 is closed and it is ready for filling. Just before filling, its initial mass value is recorded.

vi) As soon as the mass value of Tank 1 reaches preset value i.e. WS1, the diverter is automatically switched from Tank 1 to Tank 2 position and Tank 2 starts filling. After stabilization of Tank 1 reading (10 s provided in the program), its final mass value is noted and the drain valve of Tank 1 is automatically opened. After draining of Tank 1, its drain valve is automatically closed and Tank 1 is ready for filling. Just before filling, the initial mass value of Tank 1 is recorded.

vii) As soon as the mass value of Tank 2 reaches preset value i.e. WS2, the diverter is automatically switched from Tank 2 to Tank 1 position and Tank 1 starts filling. After stabilization of Tank 2 reading, its final mass value is noted and the drain valve of Tank 2 is automatically opened. After draining of Tank 2, its drain valve is automatically closed and Tank 2 is ready for filling. Just before filling, the initial mass value of Tank 2 is recorded. This cyclic filling and draining continues till total set time is reached.

viii) During the last cycle, when Tank 1 (or Tank 2) is filling (depending on value of total collection time) and total collection time is elapsed, the diverter is automatically switched from Tank 1 (or Tank 2) to Tank 2 (or Tank 1) by a stop command of preset timer. The drain valve of Tank 2 (or Tank 1) is automatically opened to work as bypass line. Digital multimeter stops the averaging of flowmeter current output. Then the mass of Tank 1 (or Tank 2) is recorded and measurement process is completed.

ix) As done in the single weighing mode, the ambient temperature, relative humidity and barometric pressure; water temperature are recorded for air buoyancy correction determination. The water density measurement is done using analytical balance.

x) After completion of experiment, the data are analyzed for determination of flowmeter error along with uncertainty.

3.6. Advantages and Disadvantages of Multiple Weighing

3.6.1 Advantages

i. Larger water mass can be collected resulting in to larger collection time. This leads to reduction or improvement in the diverter error.

ii. In case of non-functioning of either of the weighing systems, another weighing system of the two can be used and flow measurement can be continued which is very advantageous.

iii. The totalizer type water meters can be calibrated at higher flow as it does not require determination of collection time.

iv. Diverter error is calculated only once for verification purpose and no need to repeat for further measurements.

v. Only one time use of frequency counter for time measurement is needed and subsequently measurements are carried out using PC clock as timer. The use of PC clock as timer is applicable for longer collection time (above 350 s) where the effect of stability is less than 0.01%. The accuracy of PC clock is taken care through its calibration against frequency counter.

vi. The present system is a simpler one as compared to techniques used by several researchers/ NMIs for diverter error reduction utilizing complex instrumentation and designs.

3.6.2 Disadvantages

i. The use of two weighing systems (balance + tank) increases the overall cost of WFMS. However, for achieving improved measurement uncertainty one can compromise with slightly higher cost.

ii. For calibration of flowmeters in frequency output mode, the hardware trigger for such a large number of triggering in multiple weighing is not possible. The software triggering of the flowmeter output can be performed because the small timing error due to forward and backward motion of diverter is negligible as compared to such a large collection time.

iii. It is a time consuming method and comparatively high power is consumed due to continuous pumping of water.

In this chapter, theoretical aspects, design details, fabrication of components/ devices, integration, instrumentation, automation and operation of the developed system have been described and discussed. The advantages and the disadvantages of the multiple weighing method have also been highlighted.

4

RESULTS AND DISCUSSION

4.1 Metrological Traceability of Individual Instrument used with New WFMS

The various instruments used in the WFMS i.e. weighing systems (each system consists of four load cells, one weighing tank and one load cell indicator), mass standards, digital multimeter, universal frequency counter, PT-100 sensor with RTD calibrator, digital temperature and relative humidity indicator and barometer were calibrated against appropriate national standards of respective parameters. The brief description of their traceability is given below;

4.1.1 Mass Standards

The 10 nos. of mild steel mass standards (dead weights) of class M1 and 10 nos. of cast iron mass standards of class M2 were calibrated using appropriate national standards of mass and weighing balance as per OIML R-111 document standard wherein uncertainty requirement of reference mass is better than one-third of its maximum permissible error [56-57]. The expanded uncertainty (at k=2) associated with measurement of mass of 50 kg each weight was found to be ±2.5 g which is less than one-third of the maximum permissible error for class M1 (8 g) and Class M2 (16 g).

4.1.2 Weighing Systems

Both the weighing systems of 2000 kg capacity each, were calibrated up to 1000 kg by using above referred (section 4.1.1) 20 nos. of mild steel and cast iron traceable reference mass standards following OIML R-76 document standard [58-59]. The reference mass standards used for weighing system calibration fulfill the metrological requirements of OIML R-111 document standard. The individual uncertainty or sum of the uncertainties of reference mass standard(s) is / are better than one-third of the maximum permissible error of 2000 kg weighing system for the applied load. For calibration beyond 1000 kg and up to 2000 kg, a calibration technique of equivalent mass of water is used (Fig. 4.1)

[7]. As per this technique, the weighing system was calibrated up to 1000 kg by using reference mass standards. Thereafter, reference masses were removed and water was filled up to same 1000 kg mass value as displayed by weighing system indicator. Thus weighing system represents the reference mass standards of 1000 kg. Now step by step, 50 kg reference mass standards were placed on the weighing system and the weighing system was loaded up to 2000 kg. At each load, the weighing system indicator reading is noted against the set value. This was done in unloading sequence too. The average of two readings (weight up and weight down) of the weighing system were taken and compared against reference mass standards values. Similarly, the second weighing system was calibrated. The measurement uncertainty of each weighing system was found to be ±0.2 kg (at k=2) from 50 kg to 2000 kg. The error of weighing system at different loads is found to be within its maximum permissible error.

Figure 4.1: Calibration of the weighing system using reference mass standards.

After calibration of weighing system, its performance was checked without flow whether actuating the drain valve (opening/ closing operation) of the weighing system changes the weighing system reading. For this purpose, first the weighing system reading was recorded in drain valve open position. After closing of its drain valve, the weighing system reading was again recorded. The difference between the final and initial observations is the effect of actuation of drain valve. This step was repeated 10 times in about 1 minute interval. The change of +1.0 kg in weighing system reading was observed every time from open position to close position of the drain valve. This result is expected as pneumatic pressure is applied through tubes to the weighing system during operation. This is the reason that drain valve of the weighing system is normally closed before collecting the liquid (water) in the weighing system and its initial reading recorded. In case, this process is not carried out, it will introduce the error of drain valve actuation.

4.1.3 Digital Thermometer

The digital thermometer (make: Yantrika) was calibrated using standard platinum resistance thermometer (SPRT) in the temperature range 0-50 ºC and its expanded uncertainty was found to be ±0.2 ºC (at k=2).

4.1.4 Digital Temperature and Relative Humidity Indicator

The digital temperature and relative humidity indicator (make: IRA) was calibrated using two pressure RH generator in the temperature range 15-30 ºC and relative humidity (RH) range 30-70 %. The expanded uncertainty in temperature and RH measurement was found to be well within ±0.2 ºC and ±0.4 % (at k=2).

4.1.5 Aneroid Barometer

The aneroid barometer (make: Oakton) was calibrated using multifunction pressure indicator in the barometric range and its expanded uncertainty was found to be ±1 mbar (at k=2).

4.1.6 Frequency Counter

The universal frequency counter (make: Agilent) was calibrated in frequency mode by locking its 10 MHz reference frequency to cesium frequency standard using comparison method. The expanded uncertainty in 10 MHz frequency measurement was found to be ±0.03 Hz (at *k*=2).

4.1.7 Digital Multimeter

The digital multimeter (make: PREMA) was calibrated using high precision multifunction calibrator employing comparison method. Its expanded uncertainty in the current range (4-20) mA was found to be ±0.01 mA (at *k*=2). Later on, digital multimeter (make: Fluke) was used in the measurement. Its expanded uncertainty in the current range (4-20) mA was found to be ±0.00018 mA to ±0.0015 mA (at *k*=2).

4.2 Uncertainty Evaluation of WFMS

All the calibrated instruments described in ***Section 4.1*** are used for metrological characterization of the WFMS. The flow is realized through collected water mass, collection time and water density parameters, therefore, the uncertainty contribution of these parameters are discussed and finally uncertainty associated with measurement using WFMS is evaluated.

4.2.1 Collected Water Mass Uncertainty

The uncertainty of the collected water mass depends on the weighing balance indication, balance drift, balance calibration, buoyancy correction, leaks and splashes, storage effects and the evaporation. The expanded uncertainty of the weighing system from 500 kg to 2000 kg is found to be ±0.2 kg (at *k*=2). The buoyancy correction is applied to the collected mass values by measuring ambient air temperature, relative humidity and barometric pressure; water temperature and water density during measurement process. The drift of the balance (weighing system) is not included in the uncertainty budget but may be considered later on after acquiring sufficient data over the time. The effects of leaks and splashes are assumed negligible as there are no leaks and splashes observed in the system during measurement. The storage and evaporation effects are not studied in the present investigation. However, combined contribution of buoyancy correction uncertainty, storage and evaporation effects is taken as ±0.005 % (at k=1) as reported by other researchers [32-33].

4.2.2 Collection Time Uncertainty

The main uncertainty contributions for the collection time are timer calibration and diverter error. For the time measurements, a frequency counter of nano second resolution has been used and its relative uncertainty is estimated to be better than 0.0001% (at k=1). The diverter error has been evaluated using eq. (2.11) as per ISO 4185 standard [7]. Table 4.1 shows the data of diverter error without proximity switch adjustment.

The plot of diverter error thus evaluated without proximity switch adjustment is shown in Fig. 4.2. The PC clock synchronized to NPLI Time Server, has been used as timer along with frequency counter for improvement in the diverter error. The PC clock is also used as timer in multiple weighing technique. The combined use of PC clock and frequency counter result into reduction of diverter error considerably and it is found to be within 0.025% (at k=1) for the flow range 30 % to 100%. This method is applicable where provision for the adjustment of proximity switch is not available. In the diverter error determination, normally large number of short diversions (as many as up to 25) is carried out. At flow rate of 90 m^3/h, the diverter error has been estimated with 5 and 10 short diversions. From the Table 4.1, it is clear that diverter error decreases as number of short diversions increases.

Table 4.1. Diverter error evaluation at various flow rates without adjustment of proximity switch.

S. No.	Nominal flow rate q m^3/h	**Single burst filling**					**Multiple diversion**					**Diverter Error ms (%)**		
		Initial mass W_1 kg	Final mass W_2 kg	Collection time t_M s		Average flow rate q_0 m^3/h	Initial mass W_1 kg	Final mass W_2 kg	Collection time t_i s		Average flow rate q_N m^3/h	Universal counter (UC)	PC counter	Average of UC & PC Time
				Universal counter	PC counter				Universal counter	PC counter				
1.	10	1.2	2001.2	721.522327	721.1090	10.1890	1.4	399.8	142.945102	142.625	10.2610	-536.1 (-0.0743)	11.2 (0.0015)	-262.8 (-0.0365)
2.		Repeat of single burst filling after multiple diversion					1.2	399.2	145.072744	144.641	10.1219			
3.		1.0	2001.8	722.16247	721.7500	10.1853	1.2	400.0	145.019944	144.766	10.1188			
4.							1.0	400.4	143.080477	142.672	10.3076			
5.							1.0	400.4	144.924225	144.562	10.1423			
6.	30	1.2	1997.8	249.890255	249.5780	29.1486	1.0	400.6	48.870903	48.5156	29.8312	-174.4 (-0.0702)	153.5 (0.0619)	-10.8 (-0.0044)
7.		Repeat of single burst filling after multiple diversion					1.0	401.8	50.597916	50.2969	29.0498			
8.		1.0	2000.8	246.9422311	246.6410	29.5528	1.2	400.0	48.980734	48.8594	29.6919			
9.							1.0	399.8	51.726806	51.3594	28.2397			
10.							1.0	399.6	48.816743	48.3437	29.8957			
11.	50	0.8	2019.4	147.912021	147.547	49.8552	1.0	411.4	30.502254	30.2031	49.3444	-200.2 (-0.1347)	163.2 (0.1100)	-19.4 (-0.0131)
12.		Repeat of single burst filling after multiple diversion					0.8	400.8	29.612166	29.2500	49.7871			
13.		0.8	2021.2	149.451392	149.1250	49.3966	0.8	400.6	29.241411	28.8437	50.1168			
14.							0.8	405.6	30.146716	29.8125	49.3254			
15.							0.8	409.6	30.001793	29.5937	50.0062			
16.	70	0.8	2025.4	108.0980604	107.750	68.4641	1.0	425.4	22.764957	22.4685	68.3535	-166.9 (-0.1538)	120.6 (0.1114)	-23.9 (-0.0221)
17.		Repeat of single burst filling after multiple diversion					1.0	407.0	21.760246	21.4687	68.3675			
18.		0.6	2028.4	108.932066	108.609	67.9151	1.0	394.8	21.200976	20.8750	68.4134			
19.							0.8	392.8	20.854942	20.5156	69.1018			
20.							0.8	408.0	22.470803	22.2387	66.6614			
21.	90	1.2	2016.8	84.493211	84.1875	87.0509	1.2	401.8	16.859808	16.5655	86811.3	-126.6 (-0.150)	180.2 (0.2132)	26.8 (0.0317)
22.		Repeat of single burst filling after multiple diversion					1.2	400.4	16.820987	16.5625	86.5621			
23.		1.0	2007.2	84.549820	83.9687	86.6839	1.2	401.2	17.027261	16.7187	86.6918			
24.							1.0	406.4	17.287496	16.8125	86.4430			
25.							1.2	396.4	16.789238	16.3437	86.7574			

26.		0.2	2008.8	84.800984	84.5625	86.7054	0.4	197.0	8.261374	8.17188	86.9500			
27.		Repeat of single burst filling after multiple diversion					0.4	199.2	8.498416	8.28125	86.7656			
28.		0.6	2012.8	84.883744	84.6562	86.8275	0.4	194.4	8.348760	8.10938	86.9203			
29.							0.2	200.6	8.577519	8.32813	87.1500			
30.	90						0.2	205.4	8.743123	8.46875	86.9000	-114.2	84.0	-16.2
31.							0.2	201.6	8.628626	8.40625	86.9438	(-0.1347)	(0.0994)	(-0.0191)
32.							0.4	201.2	8.705057	8.48438	86.4984			
33.							0.4	205.2	8.740833	8.52438	86.7562			
34.							0.4	204.2	8.519628	8.45313	86.6312			
35.							0.6	203.8	8.731188	8.50000	86.5969			

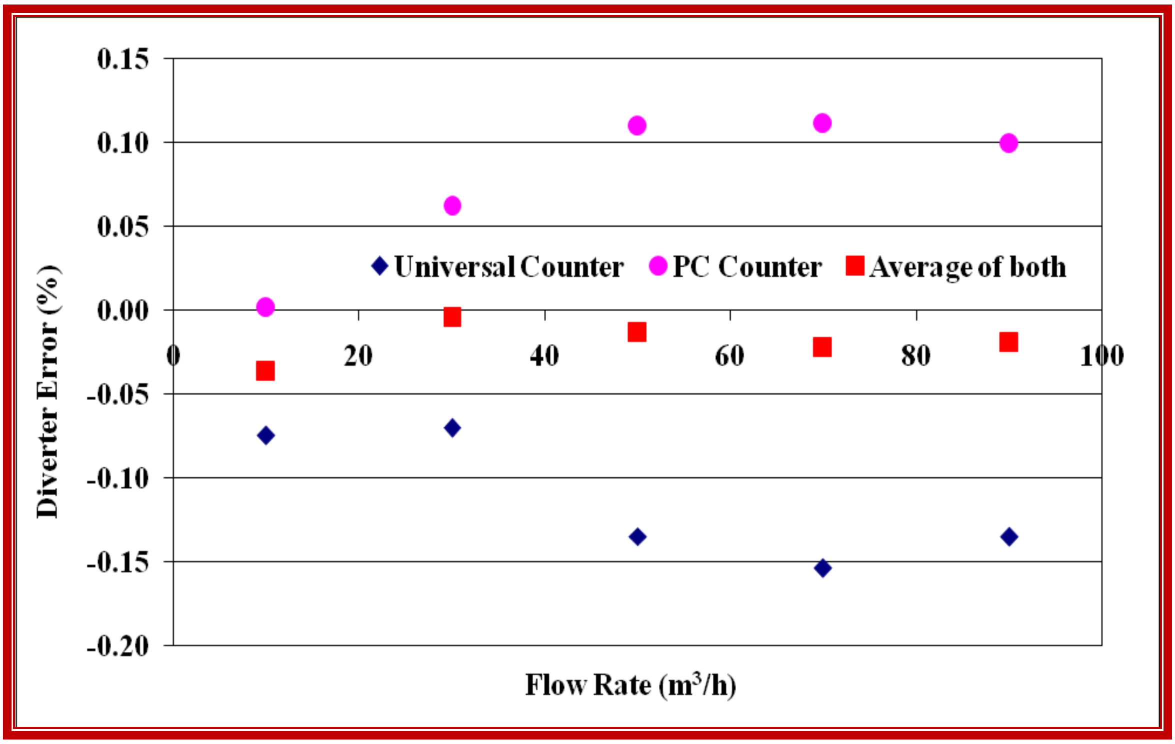


Figure 4.2: Plot of diverter error verses flow rate without adjustment of proximity switch.

The proximity switch was adjusted several times for optimizing the diverter error and after each adjustment; diverter error was re-evaluated using universal frequency counter. After adjustment of proximity switch, the diverter error is found to be within 0.02% (at *k*=1) in the flow range 10 m^3/h to 90 m^3/h. Table 4.2 show the data of diverter error after proximity switch adjustment and Fig. 4.3 shows the plots of diverter errors.

Table 4.2. Diverter error evaluation at various flow rates after adjustment of proximity switch (collection time measured by universal frequency counter).

S. No.	Nominal flow rate q m^3/h	Single burst filling				Multiple diversion				Diverter Error ms %
		Initial mass W_1 kg	Final mass W_2 kg	Collection time t_M s	Average flow rate q_0 m^3/h	Initial mass W_1 kg	Final mass W_2 kg	Collection time t_i s	Average flow rate q_N m^3/h	
1.	10	0.0	1999.8	719.850946	9.99616	0.8	200.6	71.289258	10.0633	-34.7 (-0.0048)
2.		Repeat of single burst filling after multiple diversion				0.8	201.0	70.858347	10.1627	
3.		0.6	2000.6	711.871548	10.0955	0.8	199.4	72.587014	9.81255	
4.						0.8	200.0	71.844128	9.99433	
5.						0.8	199.8	70.725647	10.1114	
6.						0.8	199.0	70.199201	10.1972	
7.						0.6	199.8	71.915956	9.95636	
8.						0.6	199.8	70.682471	10.0585	
9.						0.8	200.8	71.257956	10.0909	
10.						0.6	200.6	73.139345	9.86887	
11.	30	0.4	1996.8	241.158813	29.7853	0	204.6	24.903509	29.7672	-41.5 (-0.0172)
12.		Repeat of single burst filling after multiple diversion				0	200.4	24.850256	29.0859	
13.		0.2	1994.2	244.898355	29.3681	0	203.6	24.697555	29.5300	
14.						0	200.8	24.411493	29.7326	
15.						0	202.8	25.400261	29.0404	
16.						0	203.0	24.897599	29.6671	
17.						0	202.6	24.268000	29.8008	
18.						0	199.6	23.823633	29.9152	
19.						0	200.4	24.902651	29.0481	
20.						0	203.2	24.898523	29.5658	

21.	50	0.6	1992.4	142.911275	50.2803	0.6	193.8	13.556829	50.4934	10.0 (0.0070)
22.		Repeat of single burst filling after multiple diversion				0.4	195.0	13.896614	51.0811	
23.		0.2	1995.4	140.212975	51.3324	0.6	196.2	13.565066	51.7767	
24.						0.6	197.2	14.116354	50.8205	
25.						0.4	200.8	14.416723	50.6193	
26.						0.4	198.6	14.167618	50.6354	
27						0.4	196.0	13.594539	50.9943	
28.						0.4	199.4	14.170792	49.8105	
29.						0.4	200.0	14.207999	51.1341	
30.						0.4	199.6	14.318192	50.4663	
31.	70	0.4	2007.6	104.539182	69.1766	0.8	209.2	10.673445	70.5105	8.6 (0.0083)
32.		Repeat of single burst filling after multiple diversion				0.8	206.6	10.489629	70.7274	
33.		0.6	2002.4	101.686951	70.8674	0.8	196.2	10.125542	69.7235	
34.						0.8	201.0	10.252309	70.5413	
35.						0.6	204.0	10.440988	70.6017	
36.						0.6	202.4	10.309603	70.6664	
37.						0.6	203.6	10.205295	69.7557	
38.						0.6	201.2	10.269759	70.8484	
39.						0.6	202.2	10.027681	71.2824	
40.						0.6	200.8	10.295958	70.6760	
41.	90	0	2005	82.658007	87.5902	0.4	206.0	8.596153	87.9153	14.5 (0.0175)
42.		Repeat of single burst filling after multiple diversion				0.4	207.8	8.244064	88.1848	
43.		0.4	2001.2	83.045078	87.0732	0.4	204.8	8.513991	88.0937	
44.						0.4	203.4	8.397720	87.8643	
45.						0.4	207.6	8.322447	87.7876	
46.						0.4	196.8	8.194318	87.3998	
47.						0.4	200.0	8.428880	87.3659	
48.						0.4	201.2	8.409511	87.4267	
49.						0.4	199.8	7.956040	87.8708	
50.						0.4	204.4	8.100687	88.6566	

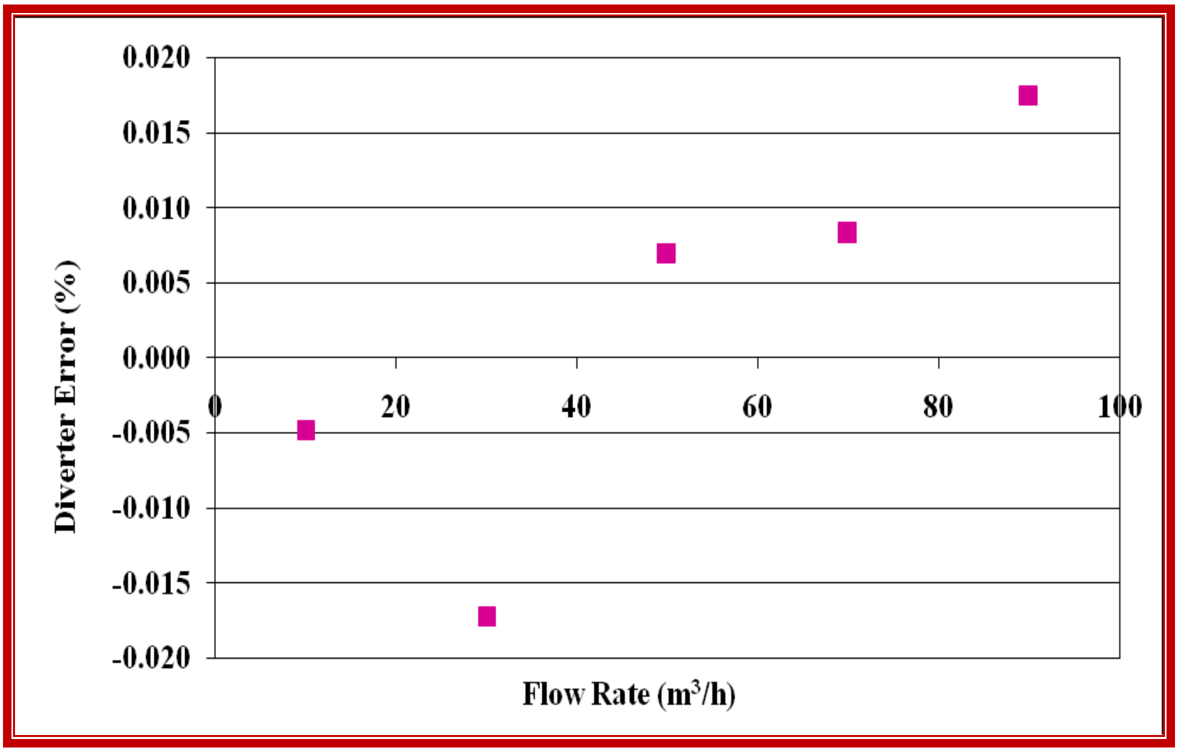


Figure 4.3: Plot of diverter error verses flow rate after adjustment of proximity switch.

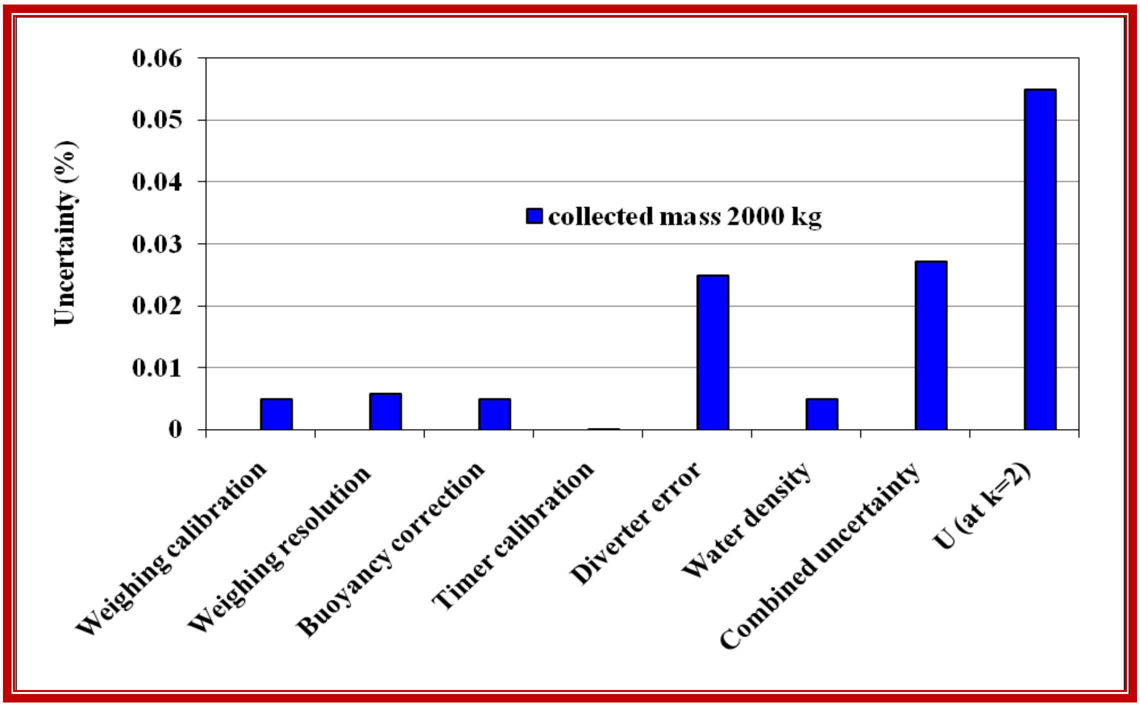
4.2.3 Water Density Uncertainty

The routine municipal water supply water is used in the experiments. The water density is determined using weighing method and its relative expanded uncertainty is estimated as 0.01% (*k*=2).

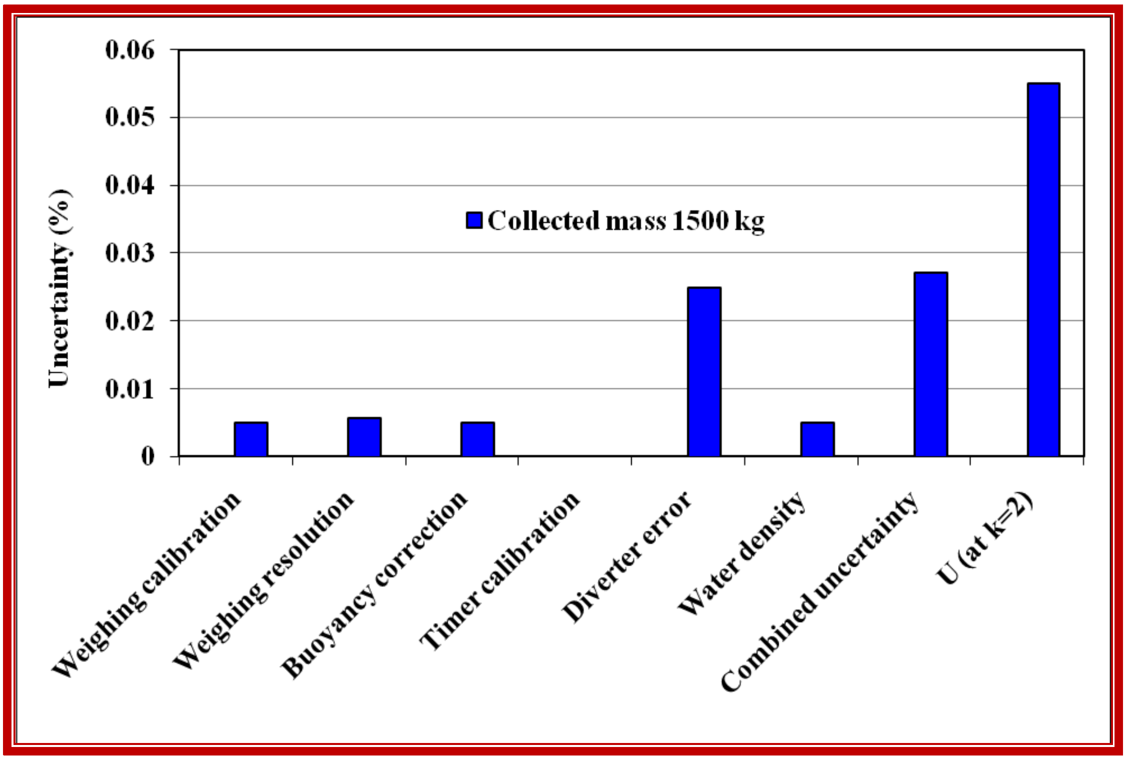
The uncertainty due to repeatability of MUT and digital multimeter / frequency counter (depending upon current or frequency output) is not included. Accordingly, the overall system uncertainties at 2000 kg, 1500 kg, 1000 kg and 500 kg collected water mass are estimated as 0.055%, 0.056, 0.061% and 0.081% (at *k*=2), respectively. The uncertainty budget of the new WFMS is summarized in Table 4.3. Fig. 4.4 shows the plot of uncertainty of the WFMS from 500 kg to 2000 kg collected mass.

Table 4.3. Uncertainty budget of new WFMS of size DN100.

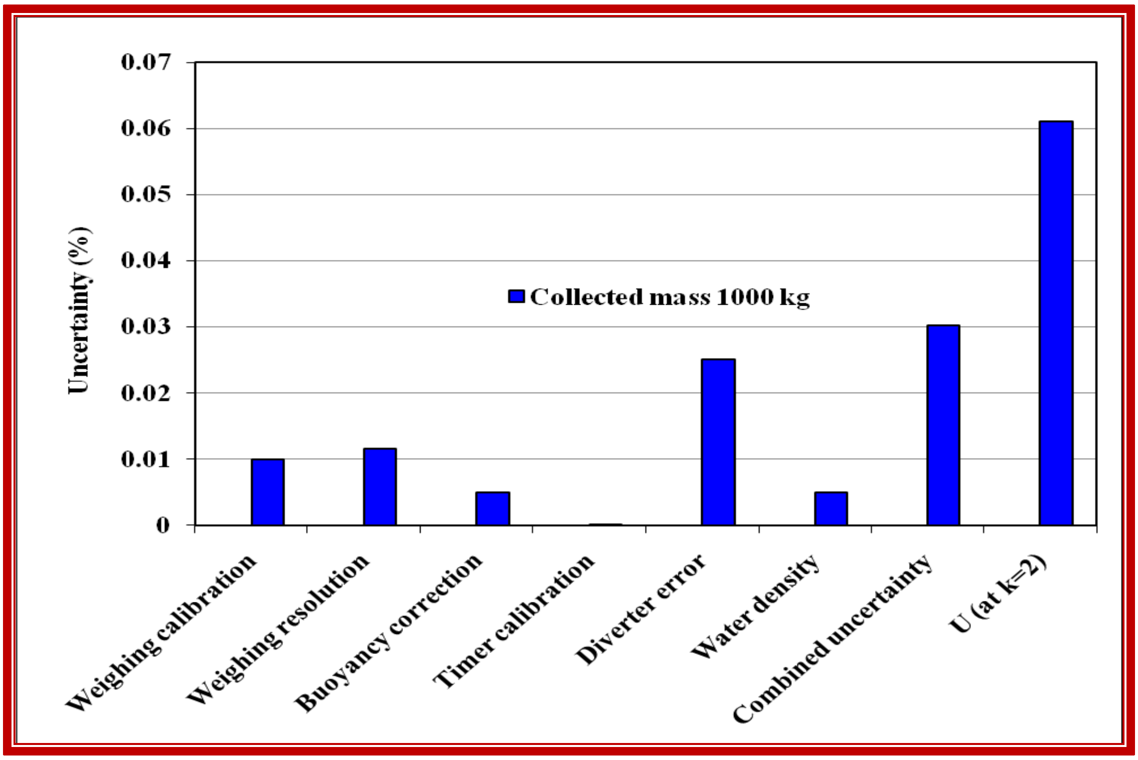
Sources of uncertainty	**Collected water mass** [Relative standard uncertainty (%)]			
	2000 kg	**1500 kg**	**1000 kg**	**500 kg**
1. Weighing tank calibration	0.005	0.0067	0.01	0.02
2. Resolution (indication) of weighing system	0.0058	0.0077	0.0116	0.0231
3. Buoyancy correction, storage and evaporation effects	0.005	0.005	0.005	0.005
4. Timer calibration	0.0001	0.0001	0.0001	0.0001
5. Diverter timing error	0.025	0.025	0.025	0.025
6. Water density determination	0.005	0.005	0.005	0.005
Relative combined uncertainty (u_c)	0.0271	0.0279	0.0302	0.0401
Relative expanded uncertainty (U) at k = 2	0.055	0.056	0.061	0.081



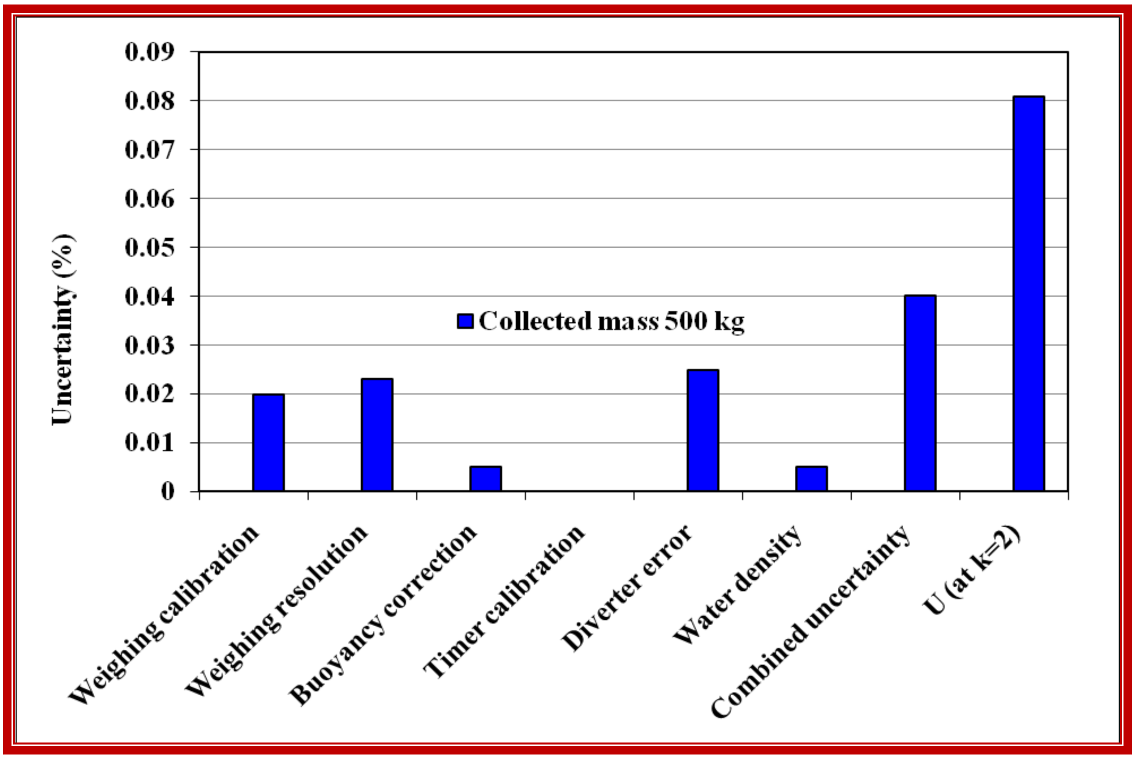
(a)


0.06
0.05
0.04
0.03
0.02
0.01
0
Uncertainty (%)
Collected mass 1500 kg
Weighing calibration
Weighing resolution
Buoyancy correction
Timer calibration
Diverter error
Water density
Combined uncertainty
U (at k=2)

(b)


0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
Uncertainty (%)
Collected mass 1000 kg
Weighing calibration
Weighing resolution
Buoyancy correction
Timer calibration
Diverter error
Water density
Combined uncertainty
U (at k=2)

(c)



(d)

Figure 4.4: Plot of uncertainty of WFMS at various collected masses.

4.3 Experimental Results using Single Weighing and Multiple Weighing Methods

4.3.1 Single Weighing

The calibration of a flowmeter requires data acquisition and evaluation of current output and pulse (frequency) output using digital multimeter and frequency counter, respectively. An electromagnetic flowmeter (MUT) of 80 mm size, make Krohne was calibrated using WFMS. The estimated relative expanded measurement uncertainty including all the uncertainty components was found to be ±0.105 % at k=2 at 90 m^3/h. The detailed uncertainty budget of electromagnetic flowmeter at 90 m^3/h is given in Table 4.4 whereas Fig. 4.5 shows the uncertainty budget in graphical form. The uncertainty of digital multimeter shown in Table 4.4 and Fig 4.5 is basically dominated by resolution (0.01 mA in the range 4 mA to 20 mA) of PREMA 6000 model which is estimated as ±0.05 % (at k=2) in the present investigation.

Table 4.4. Uncertainty budget of electromagnetic flowmeter calibration at 90 m^3/h in current output mode where PREMA 6000 model digital multimeter is used.

Sources of uncertainty	Collected water mass [Relative standard uncertainty (%)]
	2000 kg
1. Weighing tank calibration	0.005
2. Resolution (indication) of weighing system	0.0058
3. Buoyancy correction, storage and evaporation effect	0.005
4. Timer calibration	0.0001
5. Diverter timing error	0.025
6. Water density determination	0.005
7. Digital multimeter calibration	0.025
8. Repeatability (Type A uncertainty) of flowmeter	0.037
Relative combined uncertainty (u_c)	0.0523
Relative expanded uncertainty (U) at k = 2	0.105

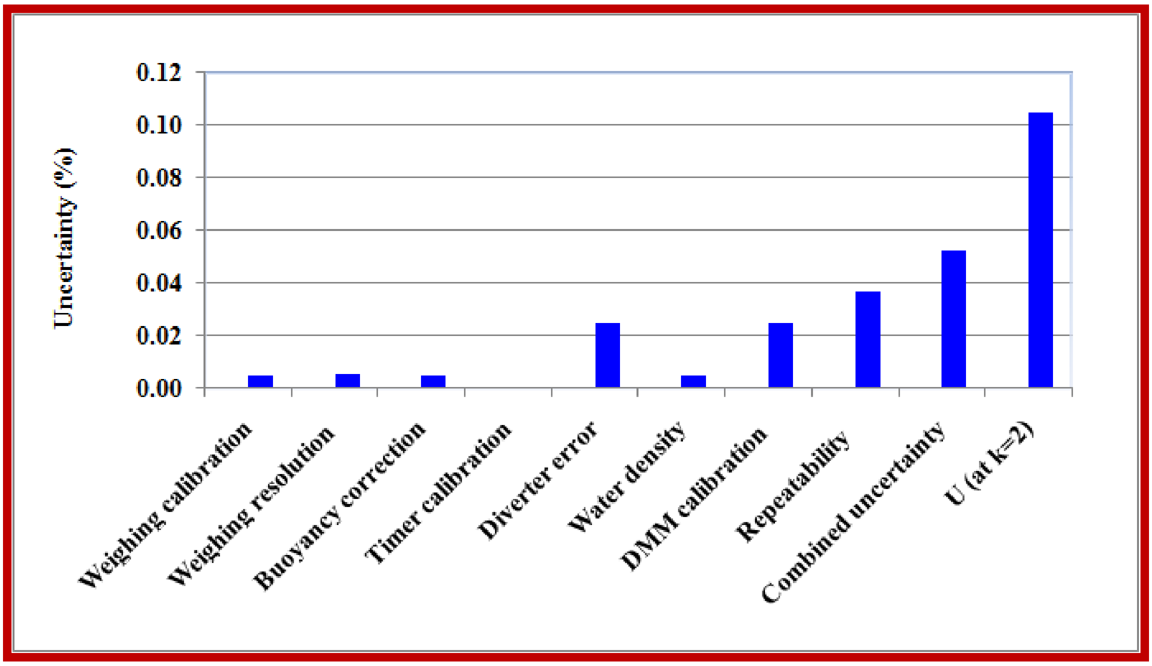


Figure 4.5: Plot of uncertainty of WFMS at 90 m^3/h inclusive of uncertainty of flowmeter data acquisition device (i.e. old PREMA DMM).

Thereafter, a high precision 6½ digit multimeter model Fluke 8846A has been used to get high accuracy and low uncertainty in output current measurement. Its measurement uncertainty is ±0.00018 mA to ±0.0015 mA in (4-20) mA range which contributes to ±0.0075 % at 20 mA. Table 4.5 and Fig. 4.6 show uncertainty budget of WFMS with Fluke 8846A model digital multimeter in tabulated and graphical forms respectively

Table 4.5. Uncertainty budget of electromagnetic flowmeter calibration at 90 m^3/h in current output mode where Fluke 8846A digital multimeter is used.

Sources of uncertainty	**Collected water mass** [Relative standard uncertainty (%)]
	2000 kg
1. Weighing tank calibration	0.005
2. Resolution (indication) of weighing system	0.0058
3. Buoyancy correction, storage and evaporation effect	0.005
4. Timer calibration	0.0001
5. Diverter timing error	0.025
6. Water density determination	0.005
7. Digital multimeter calibration	0.005
8. Repeatability (Type A uncertainty) of flowmeter	0.031
Relative combined uncertainty (u_c)	0.0415
Relative expanded uncertainty (U) at k = 2	0.083

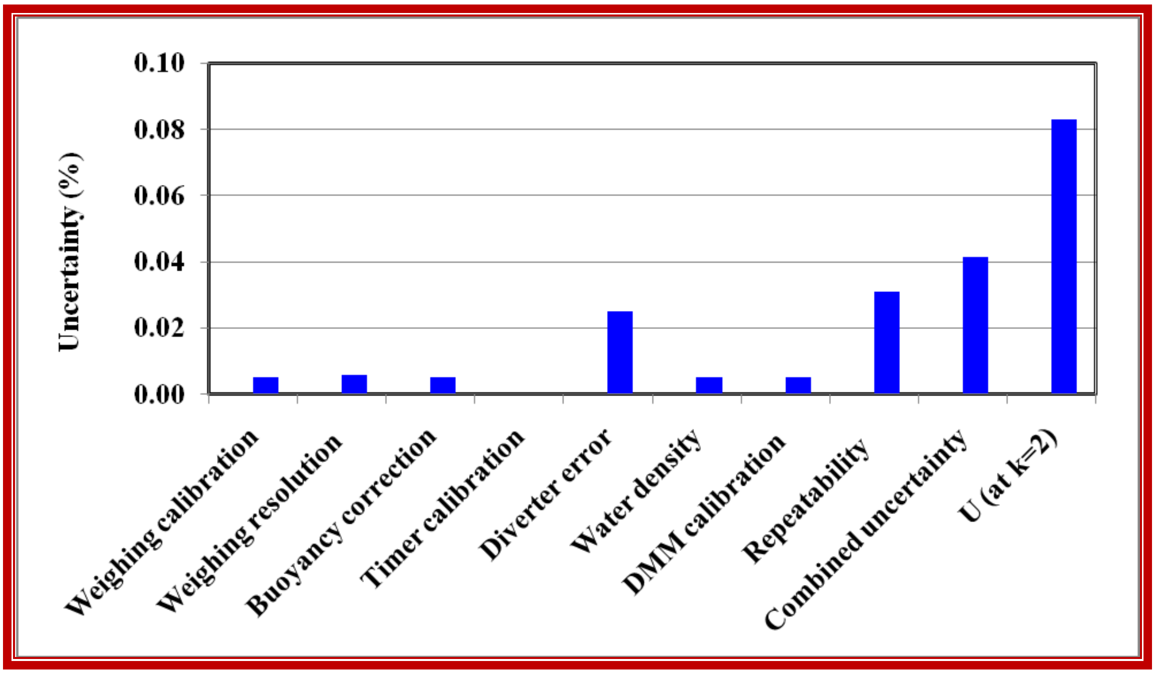


Figure 4.6: Plot of uncertainty of WFMS at 90 m^3/h inclusive of uncertainty of flowmeter data acquisition device (i.e. New Fluke DMM).

4.3.2 Multiple Weighing

For multiple weighing, both the weighing systems have been used. The PC clock is used for time measurement. This PC clock is calibrated using universal frequency counter employing comparison method where time difference between the universal counter and PC counter is added to PC counter and PC counter becomes calibrated timer with diverter error determined through universal counter assigned to it. The stability of the PC counter/ timer has been also determined at various collection times by varying the flow rates

(Table 4.6). It is clearly evident from the data that standard deviation (short-term stability) of PC timer is in the range of 0.018% to 0.007% for collection time interval of 110 s to 340 s. It is concluded that water should be collected for sufficiently longer time interval (above 350 s) in multiple weighing method to keep the stability effect of PC counter/ timer within 0.01%.

Table 4.6 Calibration and Stability (Standard Deviation) Data of PC Counter/ Timer

S. No.	Nominal Flow Rate q m^3/h	Collection time measured by Universal Counter t_{UC} s	PC Counter t_{PC} s	Difference UC & PC $t_{UC}- t_{PC}$ s	Standard Deviation σ ms	Standard Deviation σ %
1.	50	110.372670	110.062	0.310670	19	0.018
2.		109.487152	109.187	0.300152		
3.		109.609111	109.259	0.350111		
4.		109.733641	109.406	0.327641		
5.		109.577955	109.266	0.311955		
6.		109.176487	108.875	0.301487		
7.	30	121.375857	121.141	0.234857	17	0.014
8.		119.204710	118.922	0.282710		
9.		121.089180	120.828	0.261180		
10.		119.108619	118.844	0.264619		
11.		121.096247	120.844	0.252247		
12.		118.705879	118.437	0.268879		
13.	10	341.721343	341.516	0.205343	23	0.007
14.		340.475239	340.250	0.225239		
15.		335.572072	335.344	0.228072		
16.		332.305729	332.102	0.203729		
17.		329.639931	329.375	0.264931		
18.		329.053431	328.812	0.241431		

For prototype WFMS, the concreted drain line of old DN50 Test Rig has been used which can handle the maximum flow rate up to 80 m^3/h. Although, we have higher drain capacity using a 2500 kg weighing tank and 200 mm drain valve but due to limitation of concreted drain line, the diameter of the connecting metallic drain pipe has been reduced from 200 mm to about 100 mm. Due to this, the draining time increases from about 18 s to 72 s for 2000 kg water. This is the reason that the multiple weighing experiment was performed at the flow rate of 40 m^3/h using a weighing capacity of 1000 kg.

The data of flowmeter error calculation in single and multiple weighing has been given in Table 4.7. The diverter error has not been corrected and proximity switch not adjusted for optimizing the diverter error. The PREMA 6000 model digital multimeter was used for flowmeter current output measurement. The comparative results of error and uncertainty in single and multiple weighing has been given in Table 4.8. In this error and uncertainty, the digital multimeter uncertainty has been excluded to show the effect of collection time uncertainty. If one is having advanced electromagnetic flowmeter (for example, Krohne Optiflux model) for directly reading its digital flow rate indication through appropriate interface, then digital multimeter and frequency counter are not required to read the flowmeter's current and frequency outputs. Thus the uncertainty of flowmeter data acquisition device (i.e. digital multimeter and frequency counter) does not come into picture.

Table 4.7. Data of calibration of electromagnetic flowmeter in multiple weighing mode at flow rate of 40 m^3/h.

S. No.	Collected mass target kg	Tank1 collected mass m_{tank1} kg	Tank 2 collected mass m_{tank2} kg	Collected mass $= m_{tank1} + m_{tank2} + \ldots$ kg	Collection time (PC counter) t s	Water temp. T ºC	Water density ρ kg/m^3	Standard volume flow rate Q_S m^3/s	Standard volume flow rate Q_S LPH	MUT volume flow rate Q_M LPH	Flowmeter Error %
1.	1000	1002.2 (m_1)	-	1002.2 (m_1)	90	29.5	996.18	0.01119	40284.38	40494.2	0.521
2.	2000	1014 (m_1)	1035.6 (m_2)	2049.6 (m_1+m_2)	180	29.3	996.26	0.011442	41189.79	40896	-0.713
3.	3000	1083.4 (m_1) 755.6 (m_3)	1080.2 (m_2)	2919.2 ($m_1+m_2+m_3$)	270	29.5	996.18	0.010865	39113.38	38902	-0.540
4.	4000	1082.0 (m_1) 1082.0 (m_3)	1080.2 (m_2) 709.6 (m_4)	3953.8 ($m_1+m_2+m_3+m_4$)	360	29.4	996.18	0.011037	39731.72	39503.1	-0.575
5.	5000	1163.2 (m_1) 1163.0 (m_3) 807.2 (m_5)	959.4 (m_2) 958.0 (m_4)	5050.8 ($m_1+m_2+m_3+m_4+m_5$)	450	29.5	996.18	0.011279	40604.38	40290.6	-0.773
6.	6000	1163.6 (m_1) 1162.0 (m_3) 1161.4 (m_5)	959.0 (m_2) 959.0 (m_4) 719.8 (m_6)	6124.8 ($m_1+m_2+m_3+m_4+m_5+$ m_6)	540	29.5	996.18	0.011398	41032.06	40724.1	-0.751
7.	7000	1162.2 (m_1) 1162.0 (m_3) 1162.8 (m_5) 574.6 (m_7)	958.4 (m_2) 960.0 (m_4) 958.2 (m_6)	6938.2 ($m_1+m_2+m_3+m_4+$ $m_5+m_6+m_7$)	630	29.5	996.18	0.011067	39841.11	39586.4	-0.639
8.	8000	1160.6 (m_1) 1162.8 (m_3) 1162.6 (m_5) 1160.8 (m_7)	958.6 (m_2) 960.8 (m_4) 962.2 (m_6) 668.4 (m_8)	8196.8 ($m_1+m_2+m_3+m_4+$ $m_5+m_6+m_7+m_8$)	720	29.5	996.18	0.01144	41184.81	40988.3	-0.477
9.	9000	1164.8 (m_1) 1161.8 (m_3) 1160.8 (m_5) 1163.8 (m_7) 764.4 (m_9)	959.8 (m_2) 960.8 (m_4) 961.0 (m_6) 959.8 (m_8)	9257.0 ($m_1+m_2+m_3+m_4+ m_5$ $+m_6+m_7+m_8+m_9$)	810	29.7	996.11	0.011485	41346.92	41056.1	-0.703
10.	10000	1161.6 (m_1) 1164.2 (m_3) 1164.0 (m_5) 1161.4 (m_7) 1162.2 (m_9)	958.0 (m_2) 960.8 (m_4) 957.4 (m_6) 959.8 (m_8) 638.4 (m_{10})	10287.8 ($m_1+m_2+m_3+m_4+ m_5$ $+m_6+m_7+m_8+m_9+m_{10}$)	900	29.7	996.11	0.011488	41355.94	40987.1	-0.892

Table 4.8. Flowmeter error and uncertainty in single weighing and multiple weighing where diverter error is uncorrected and proximity switch is not adjusted.

S. No.	Type (single/ multiple weighing)	Collected Mass		Collection Time		Water Density		Flowmeter Error %	*Expanded uncertainty at k=2 U (flow)
		Estimate (M) kg	Standard uncertainty (u_M) %	Estimate (t) s	Standard uncertainty (u_t) %	Estimate (ρ) kg/m^3	Standard uncertainty (u_ρ) %		
1.	Single weighing	1000	0.02	90	0.1811	996	0.005	0.521	0.363
2.	Multiple weighing	2000	0.02	180	0.0906	996	0.005	-0.713	0.183
3.		3000	0.02	270	0.0604	996	0.005	-0.540	0.129
4.		4000	0.02	360	0.0453	996	0.005	-0.575	0.093
5.		5000	0.02	450	0.0362	996	0.005	-0.773	0.076
6.		6000	0.02	540	0.0302	996	0.005	-0.751	0.064
7.		7000	0.02	630	0.0259	996	0.005	-0.639	0.056
8.		8000	0.02	720	0.0226	996	0.005	-0.477	0.051
9.		9000	0.02	810	0.0201	996	0.005	-0.703	0.046
10.		10000	0.02	900	0.0181	996	0.005	-0.892	0.043

Fig. 4.7 shows the plot of flowmeter error and uncertainty in graphical form. It is clearly evident from the plot that measurement uncertainty improves considerably in case of multiple weighing. As collection time increases, the contribution of diverter error decreases. As explained in ***Section 4.3***, *installation effects* was detected in measurements which created distorted flow velocity profile. So, the difference between single and multiple weighing results is mostly due to installation effects. Also the differences between multiple weighing results are observed which is due to poor repeatability. However, it shows that in case of multiple weighing, the effect of distorted flow velocity profile generated from installation effects is partially compensated due to longer collection time resulting from larger collected mass.

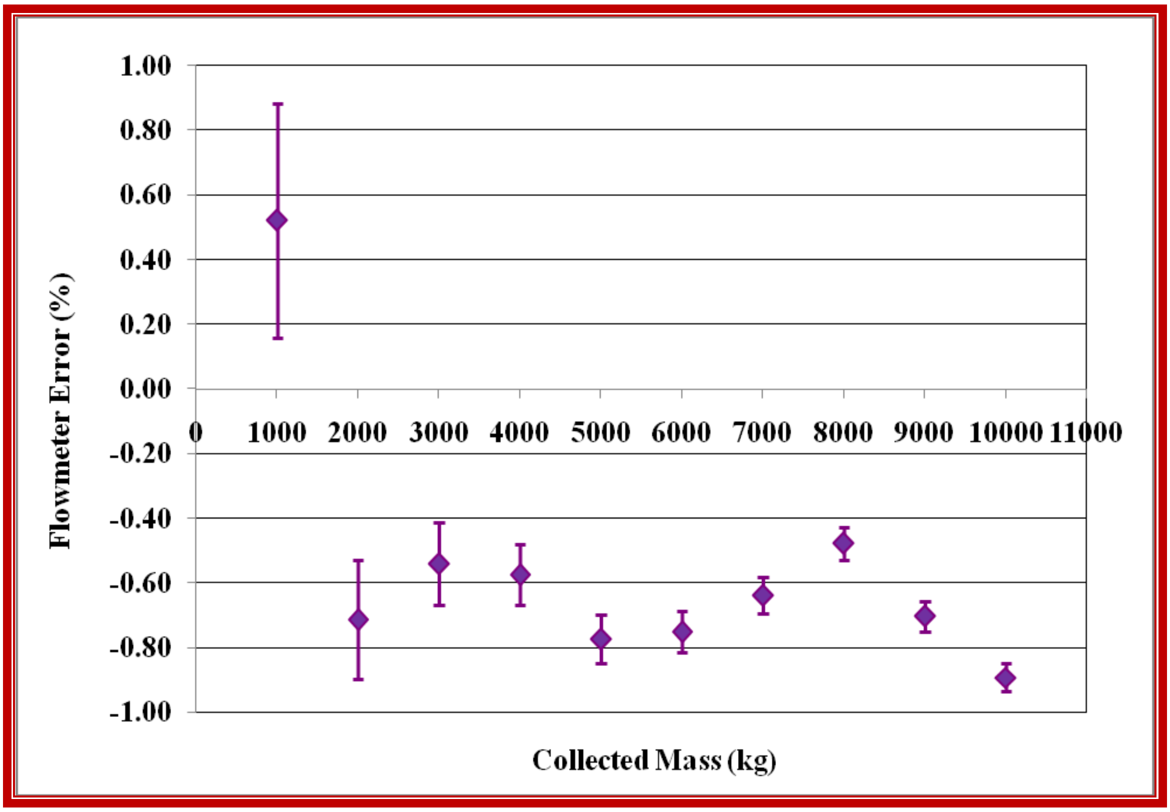


Figure 4.7: Plot of Flowmeter error and uncertainty in single and multiple weighing.

4.4 Performance Evaluation of the New System

The performance of any flow measurement system is normally carried out through an interlaboratory comparison (ILC) using an appropriate artifact for this purpose. In this comparison, the measurements on artifact are first performed by the laboratory "A" and its error/ calibration factor (X_A) along with uncertainty (U_A) is determined. Then the measurements on the same artifact are performed by the laboratory "B" and its error/ calibration factor (X_B) along with uncertainty (U_B) is determined. One of the laboratory's values is considered reference values, the laboratory "B" in the present case. Then the normalized error (E_n) is determined through eq. (4.1),

$$E_n = \frac{(X_A - X_B)}{\sqrt{U_A^2 + U_B^2}} \tag{4.1}$$

The absolute value of E_n i.e. $|E_n| \leq 1$ indicates the satisfactory performance of the system. The $|E_n| > 1$ indicates the unsatisfactory performance of the system and requires root cause analysis followed by corrective action [60-63].

For performance evaluation of the developed system, an interlaboratory comparison was carried out with Fluid Control Research Institute (FCRI), Kerala, India as a reference laboratory. An electromagnetic flowmeter of DN80 size, model IFC 100, make Krohne was used as the artifact. Fig. 4.8 shows the photograph of installation of this flowmeter at NPLI WFMS set-up.

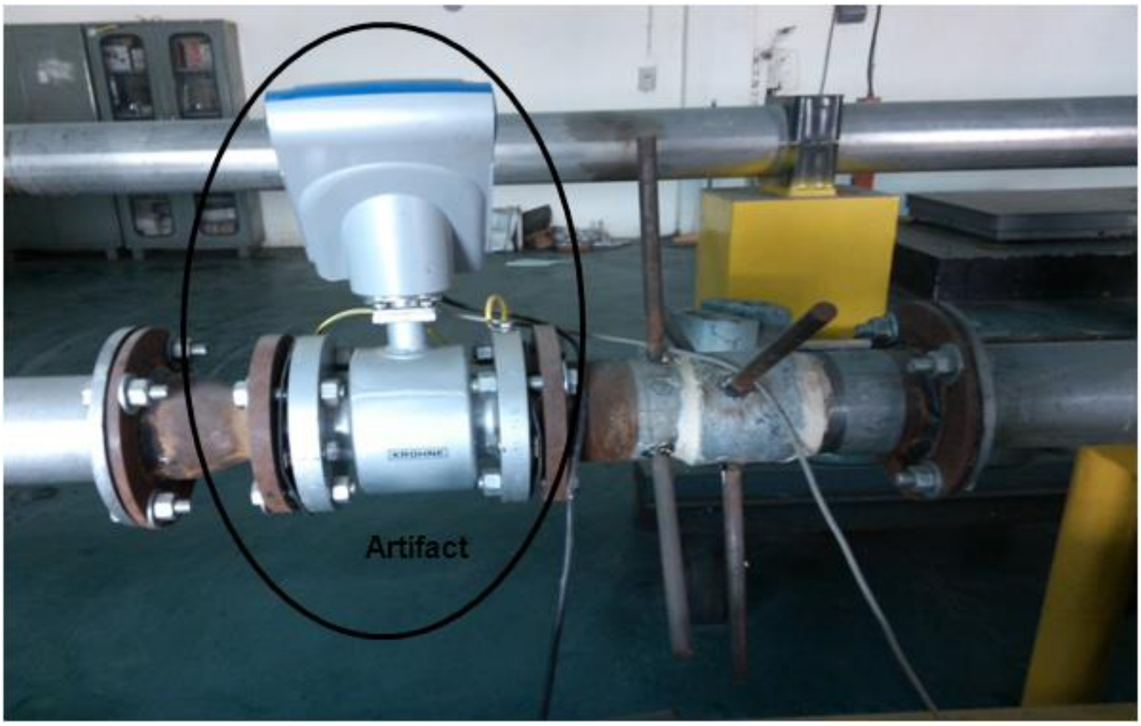


Figure 4.8: Photograph of installation of electromagnetic flowmeter at NPLI.

From the Fig. 4.8, it is clear that NPLI did not have adequate facility for the minimum installation requirement (5D upstream and 2D downstream minimum straight length requirement recommended by the flowmeter manufacturer). Therefore, reducer and expander were installed too close to the flowmeter. Also, there was no provision of adjustable dismantling joint for creating gap in the flow line for flowmeter installation. This flowmeter was calibrated in our developed WFMS in the flow range (10-90) m^3/h. The measurement data thus obtained is shown in Table 4.9. Thereafter, the artifact was sent to FCRI for measurement.

Table 4.9. NPLI data of electromagnetic flowmeter calibration without meeting installation requirement of flowmeter.

S. No.	Nominal flow rate Q_N m^3/h	Initial mass W_1 kg	Final mass W_2 kg	Collected mass m kg	Collection time t s	Water temp. T ºC	Water density ρ kg/m^3	Standard volume flow rate Q_S LPH	MUT volume flow rate Q_M LPH	Error %	Average Error %	Type A unc. (±) %	Expand. unc. (at k=2) (±) %
1.	10	0.4	1004.0	1003.6	335.903	28.3	996.55	10805.60	10814.6	0.083	-0.176	0.106	0.306
2.		0.4	1005.0	1004.6	335.458	28.2	996.55	10833.49	10841.0	0.069			
3.		0.4	1004.2	1003.8	332.239	28.1	996.62	10927.45	10880.6	-0.429			
4.		0.6	1004.8	1004.2	329.507	28.2	996.55	11025.43	10993.4	-0.290			
5.		0.8	1004.4	1003.6	328.933	28.2	996.55	11037.71	11003.3	-0.312			
6.		0.6	1009.0	1008.4	126.672	28.9	996.33	28766.37	28684.0	-0.286	-0.028	0.032	0.134
7.		0.8	1010.6	1009.8	119.516	28.6	996.48	30524.68	30517.3	-0.024			
8.		1.0	1009.4	1008.4	119.312	28.6	996.48	30557.14	30482.3	-0.245			
9.		1.0	1012.2	1011.2	121.141	28.5	996.48	30159.27	30168.3	0.030			
10.		1.0	1010.0	1009.0	118.922	28.4	996.48	30648.47	30640.1	-0.027			
11.	50	1.2	1522.0	1520.8	108.776	28.4	996.48	50556.51	50399.5	-0.311	-0.185	0.082	0.310
12.		1.2	1520.2	1519.0	110.217	28.4	996.48	49836.37	49729.6	-0.214			
13.		1.2	1518.0	1516.8	109.337	28.4	996.48	50164.83	50135.9	-0.058			
14.		1.2	1519.4	1518.2	109.414	28.4	996.48	50175.81	50202.4	0.053			
15.		1.2	1521.6	1520.4	109.570	28.5	996.48	50177.10	49977.4	-0.398			
16.	70	0.8	1536.6	1535.8	77.6250	28.8	996.40	71434.27	71281.3	-0.214	-0.450	0.065	0.190
17.		1.0	1527.0	1526.0	79.3594	28.7	996.40	69429.59	69098.8	-0.476			
18.		1.2	1533.4	1532.2	79.5937	28.6	996.48	69501.52	69196.2	-0.439			
19.		1.2	1532.8	1531.6	79.7344	28.6	996.48	69351.90	68992.8	-0.518			
20.		0.6	1533.8	1533.2	78.0469	29.0	996.33	70933.63	70506.8	-0.602			
21.	90	1.2	1538.0	1536.8	61.1719	28.7	996.48	90660.77	90372.2	-0.318	-0.580	0.153	0.449
22.		1.2	1539.2	1538.0	61.8437	29.0	996.33	89761.10	88930.4	-0.926			
23.		1.2	1551.6	1550.4	62.4687	29.0	996.33	89581.39	88940.5	-0.715			
24.		1.2	1545.6	1544.4	62.1875	29.1	996.33	89637.36	88909.5	-0.812			
25.		1.0	1541.2	1540.2	62.3125	29.1	996.33	89214.60	89101.9	-0.126			

The flowmeter was installed in FCRI WFMS set-up which has all the facilities for installation (5D upstream and 2D downstream minimum straight length requirement recommended by the flowmeter manufacturer) as shown in Fig. 4.9. The straight length provided is several times more than the minimum installation requirement of the flowmeter.

Figure 4.9: Photograph showing NPLI electromagnetic flowmeter installed at FCRI WFMS.

During physical inspection of artifact at FCRI before installation, it was observed that one of the electrodes of flowmeter having some deposits. Both the electrodes were then cleaned properly. Thereafter, the artifact was calibrated at FCRI using static weighing based WFMS. The measurement data is shown in Table 4.10. The comparison data thus obtained at NPLI and FCRI is given in Table 4.11 and its graphical representation is shown in Fig. 4.10.

Table 4.10. FCRI data of electromagnetic flowmeter calibration meeting the installation requirement of flowmeter.

S. No.	Nominal flow rate Q_N m³/h	Initial mass W_1 kg	Final mass W_2 kg	Collected mass m kg	Collection time t s	Water temp. T ºC	Water density ρ kg/m³	Standard volume flow rate Q_S LPH	MUT volume flow rate Q_M LPH	Error %	Average Error %	Type A unc. (±) %	Expand. unc. (at k=2) (±) %
1.	10	135.15	1074.55	939.40	343.568195	31.72	995.00	9903.24	9828.2	-0.757	-0.745	0.007	0.080
2.		87.30	986.85	899.55	328.919174	31.72	994.99	9905.58	9833.9	-0.724			
3.		85.70	794.00	708.30	259.018823	31.75	994.99	9904.44	9831.8	-0.734			
4.		794.00	1528.40	734.40	268.507304	31.75	994.99	9906.50	9831.3	-0.759			
5.		163.55	913.15	749.60	274.214114	31.85	994.95	9901.50	9827.3	-0.749			
6.	30	96.30	1230.85	1134.55	134.245813	31.60	995.04	30608.71	30337.7	-0.885	-0.880	0.010	0.080
7.		169.15	1056.75	887.60	105.029990	31.60	995.04	30607.37	30330.8	-0.903			
8.		242.90	1131.15	888.25	105.103781	31.62	995.03	30608.59	30348.4	-0.850			
9.		139.70	1425.30	1285.60	152.136837	31.62	995.03	30605.39	30330.5	-0.898			
10.		138.15	1417.05	1278.90	151.359546	31.68	995.00	30603.16	30339.7	-0.861			
11.	50	135.30	1527.35	1229.45	72.001407	31.86	994.95	50717.85	50236.5	-0.949	-0.952	0.010	0.080
12.		239.60	1519.90	1365.80	66.230942	31.88	994.94	50712.85	50233.3	-0.946			
13.		209.85	1450.35	1443.60	64.156480	31.90	994.94	50714.28	50217.6	-0.979			
14.		99.00	1534.50	1593.35	74.254117	31.90	994.94	50711.14	50221.0	-0.967			
15.		94.50	1446.55	1144.55	69.935597	31.92	994.94	50713.84	50246.3	-0.922			
16.	70	191.85	1730.05	1392.05	61.720971	31.94	994.93	70029.97	69381.3	-0.926	-0.873	0.014	0.080
17.		182.05	1625.85	1280.30	57.950911	31.94	994.93	70019.80	69423.6	-0.852			
18.		154.15	1601.95	1240.50	58.114431	31.95	994.92	70037.51	69442.8	-0.849			
19.		169.60	1731.75	1435.50	62.704569	31.95	994.92	70025.64	69418.0	-0.868			
20.		146.00	1725.35	1352.05	63.382930	31.97	994.91	70028.25	69417.9	-0.872			
21.	90	135.30	1527.35	1538.20	72.001407	31.97	994.91	90273.21	89378.1	-0.992	-0.966	0.009	0.080
22.		239.60	1519.90	1443.80	66.230942	31.97	994.91	90245.51	89378.8	-0.960			
23.		209.85	1450.35	1447.80	64.156480	32.00	994.90	90241.80	89384.1	-0.950			
24.		99.00	1534.50	1562.15	74.254117	32.00	994.90	90241.59	89355.8	-0.982			
25.		94.50	1446.55	1579.35	69.935597	32.00	994.90	90258.74	89402.9	-0.948			

Table 4.11. Comparison of NPLI and FCRI measurement results.

Sr. No.	Nominal Flow Rate (m^3/h)	NPLI assigned value			FCRI assigned value			E_n values
		Average Error (%)	Type A Uncertainty (%)	Expanded Uncertainty (%)	Average Error (%)	Type A Uncertainty (%)	Expanded Uncertainty (%)	
1.	10	-0.176	0.106	±0.306	-0.880	±0.010	±0.080	2.23
2.	30	-0.028	±0.031	±0.138	-0.745	±0.007	±0.080	4.49
3.	50	-0.185	±0.082	±0.236	-0.952	±0.010	±0.080	3.08
4.	70	-0.450	±0.065	±0.183	-0.873	±0.014	±0.080	2.12
5.	90	-0.580	±0.153	±0.450	-0.966	±0.009	±0.080	0.84

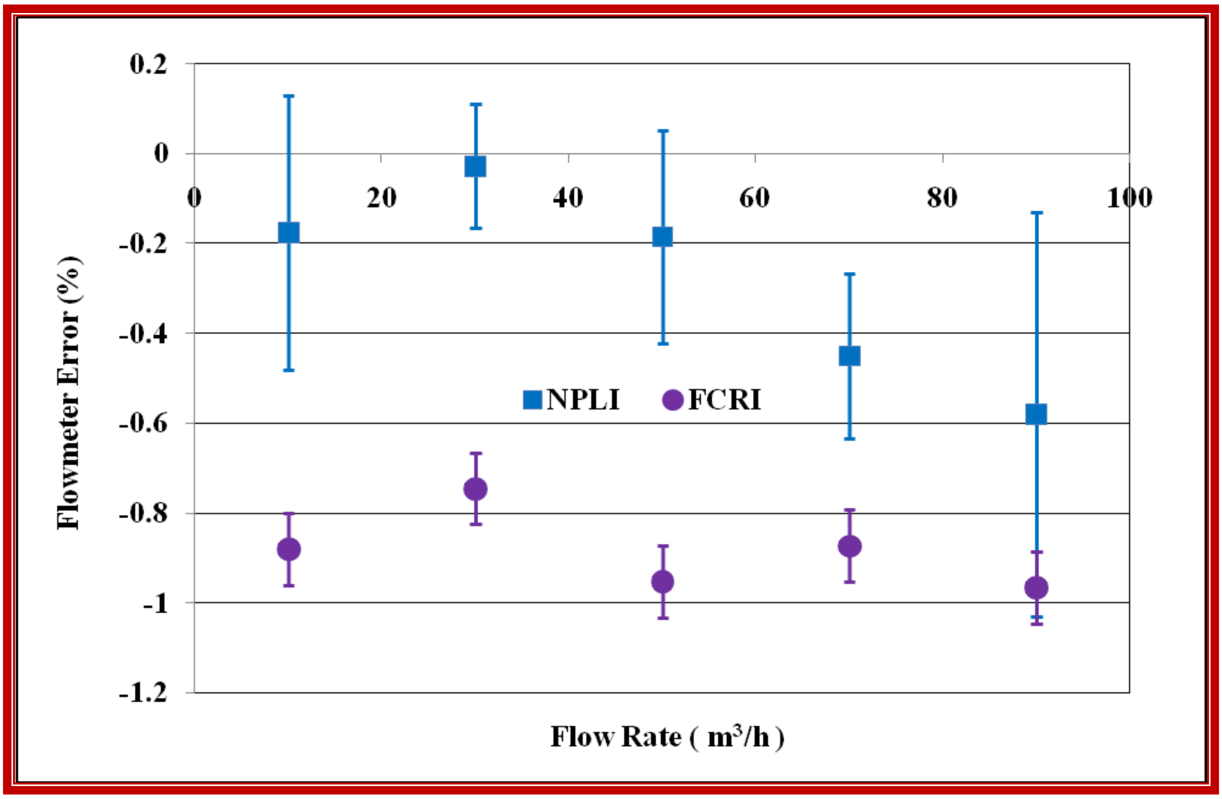


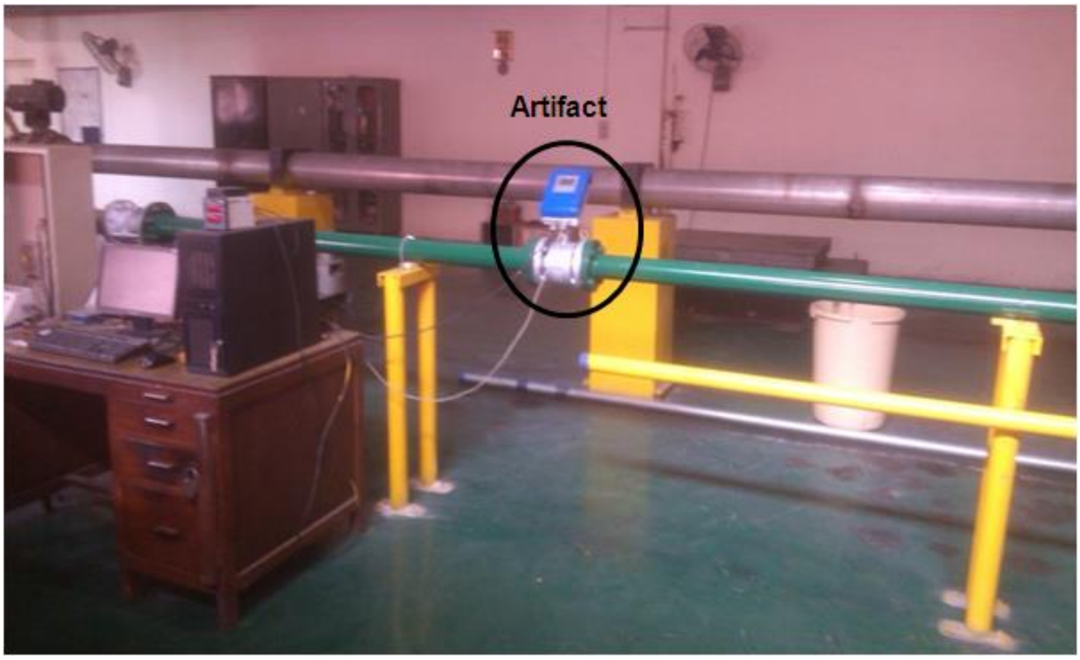
Figure 4.10: Comparison of NPLI and FCRI measurement results.

It is clearly evident from Table 4.11 and Fig. 4.10, the normalized error values (E_n) of NPLI are >1 at all measurement points except one point, which are not acceptable. The reasons for such discrepancies are offset error and higher estimated Type A uncertainty. Although, the measurement at flow rate of 90 m^3/h is having, E_n ratio < 1, indicating satisfactory result, but this is also basically due to higher estimated measurement uncertainty. Such results are not acceptable specially for the Primary WFMS. The root cause of this unsatisfactory result was analyzed and it was found as the ***installation effects*** of the flowmeters which is a very dominant factor in flow metrology [5].

In order to improve the results as per root cause analysis, specialized job works were carried out. The adaptors of (15-100) mm sizes were fabricated from MS seamless pipe for the flowmeters as per the installation requirement (Fig. 4.11). The seamless pipe provides uniform flow profile. These adaptors were prepared of such a long straight length that any type of flowmeter of sizes (15-100) mm can be calibrated. The gate valves were replaced by ball valves (Figs. 3.8 and 3.16). The adjustable dismantling joints were installed to create gap in flow line to install the flowmeter without any problem (Fig. 3.16). The components in the flow line were adjusted. Some mechanical works were also done on diverter system for strengthening its support to reduce any vibration. The proximity switch was properly (firmly) mounted on the angles suspended from the beam of the roof for rigidity and also provided sufficient slot length for proximity switch adjustment to reduce diverter error (Fig. 3.14).

Figure 4.11: Adaptors of (15-100) mm sizes fabricated from seamless MS pipe.

After the fabrication of special adopters, the 80 mm electromagnetic flowmeter (i.e. artifact standard) was installed in the flow line fulfilling the minimum upstream and downstream straight lengths requirement recommended by the flowmeter manufacturer (Fig. 4.12).



(a)

(b)

Figure 4.12: Photographs showing installed electromagnetic flowmeter with proper upstream and downstream straight length at NPLI WFMS set-up.

The straight lengths are now several times more than the minimum requirement. The proximity switch was adjusted to improve the diverter error. The collection time was measured by the Agilent universal frequency counter for diverter error evaluation. The flowmeter was calibrated again in the flow range (10-90) m^3/h. The collection time and flowmeter current output were measured using Agilent 53131A model universal frequency counter and Fluke 8846A model digital multimeter, respectively. The water temperature has been measured using Fluke 1523 model digital thermometer. Since temperature deviation of the flowing water is very less (<0.2 ºC), therefore the water density value at 24 ºC has been used for the whole measurement. The small variation in density values due to temperature deviation is within the uncertainty limit (0.01%) of water density measurement. The water density has been measured using high precision analytical weighing balance. Table 4.12 shows the measurement results of the flowmeter performed at NPLI. The new comparison of the measurement results of NPLI and FCRI after meeting installation requirement is given in Table 4.13 and Fig. 4.13. From Table 4.13 and Fig. 4.13, it is observed that the measurement results are now considerably improved. The normalized error value, E_n, is found < ±1, which is a pre-requisite for the satisfactory performance of the system. Thus, all the results at each measurement point is acceptable. Fig. 14 shows the plot of E_n ratio before and after fulfilling the installation requirements of the flowmeters.

Table 4.12. NPLI data of electromagnetic flowmeter calibration after meeting installation requirement of flowmeter.

S. No.	Nominal flow rate Q_N m^3/h	Initial mass W_1 kg	Final mass W_2 kg	Collected mass m kg	Collection time t s	Water temp. T ºC	Water density ρ kg/m^3	Standard volume flow rate Q_S LPH	MUT volume flow rate Q_M LPH	Error %	Average Error %	Type A unc. %	Expand. unc. (at k=2) %
1.	10	0.0	1004.6	1004.6	344.359125	23.97	995.91	10556.65	10470.2	-0.819	-0.792	0.029	0.088
2.		0.0	1004.6	1004.6	350.391018	23.90	995.91	10374.91	10285.2	-0.865			
3.		0.0	1004.6	1004.6	348.859253	23.89	995.91	10420.47	10335.5	-0.815			
4.		0.0	1005.0	1005.0	347.562491	23.89	995.91	10463.53	10391.2	-0.691			
5.		0.0	1005.4	1005.4	345.703957	23.88	995.91	10523.98	10443.1	-0.769			
6.	30	0.2	1010.4	1010.2	116.500192	24.03	995.91	31378.03	31093.6	-0.906	-0.865	0.033	0.098
7.		0.2	1011.2	1011	116.500837	24.05	995.91	31402.88	31112.0	-0.926			
8.		0.2	1012.6	1012.4	117.609354	24.05	995.91	31149.84	30867.9	-0.905			
9.		0.2	1011.8	1011.6	118.703856	24.02	995.91	30838.37	30579.0	-0.841			
10.		0.2	1013.6	1013.4	117.953479	24.07	995.91	31089.67	30857.6	-0.746			
11.	50	0.0	1519.6	1519.6	110.891235	23.93	995.91	49581.55	49062.77	-1.046	-1.012	0.025	0.079
12.		0.2	1523.6	1523.4	110.687564	23.95	995.91	49797.16	49321.79	-0.955			
13.		0.2	1521.8	1521.6	110.703289	23.96	995.91	49731.12	49192.82	-1.082			
14.		0.2	1523.0	1522.8	110.734876	23.97	995.91	49756.42	49249.17	-1.019			
15.		0.2	1518.4	1518.2	110.078023	23.99	995.91	49901.72	49424.64	-0.956			
16.	70	0.2	1528.4	1528.2	78.093759	23.84	995.91	70802.99	70238.2	-0.798	-0.783	0.027	0.081
17.		0.2	1527.8	1527.6	78.281247	23.85	995.91	70605.67	70112.6	-0.698			
18.		0.2	1528.8	1528.6	78.437542	23.86	995.91	70511.11	69942.8	-0.806			
19.		0.0	1527	1527	77.843710	23.91	995.91	70974.6	70439.5	-0.754			
20.		0.0	1527.8	1527.8	78.046939	23.90	995.91	70826.9	70217.9	-0.860			
21.	90	0.2	1532.6	1532.4	61.296928	23.81	995.91	90452.63	89651.3	-0.886	-0.891	0.031	0.092
22.		0	1532.4	1532.4	61.218772	23.78	995.91	90568.17	89814.7	-0.832			
23.		0	1535.6	1535.6	61.203165	23.77	995.91	90780.46	89881.8	-0.990			
24.		0	1537.4	1537.4	61.343701	23.78	995.91	90678.57	89933.5	-0.822			
25.		0	1530.2	1530.2	60.890627	23.78	995.91	90925.44	90083.3	-0.926			

Table 4.13. Comparison of NPLI and FCRI measurement results after fulfilment of the installation requirement of the flowmeter.

Sr. No.	Nominal Flow Rate (m^3/h)	NPLI assigned value			FCRI assigned value			E_n value
		Average Error (%)	Type A Uncertainty (%)	Expanded Uncertainty (%)	Average Error (%)	Type A Uncertainty (%)	Expanded Uncertainty (%)	
1.	10	-0.792	0.029	0.088	-0.880	0.010	0.080	0.74
2.	30	-0.865	0.033	0.098	-0.745	0.007	0.080	-0.95
3.	50	-1.012	0.025	0.079	-0.952	0.010	0.080	-0.53
4.	70	-0.783	0.027	0.081	-0.873	0.014	0.080	0.79
5.	90	-0.891	0.031	0.092	-0.966	0.009	0.080	0.62

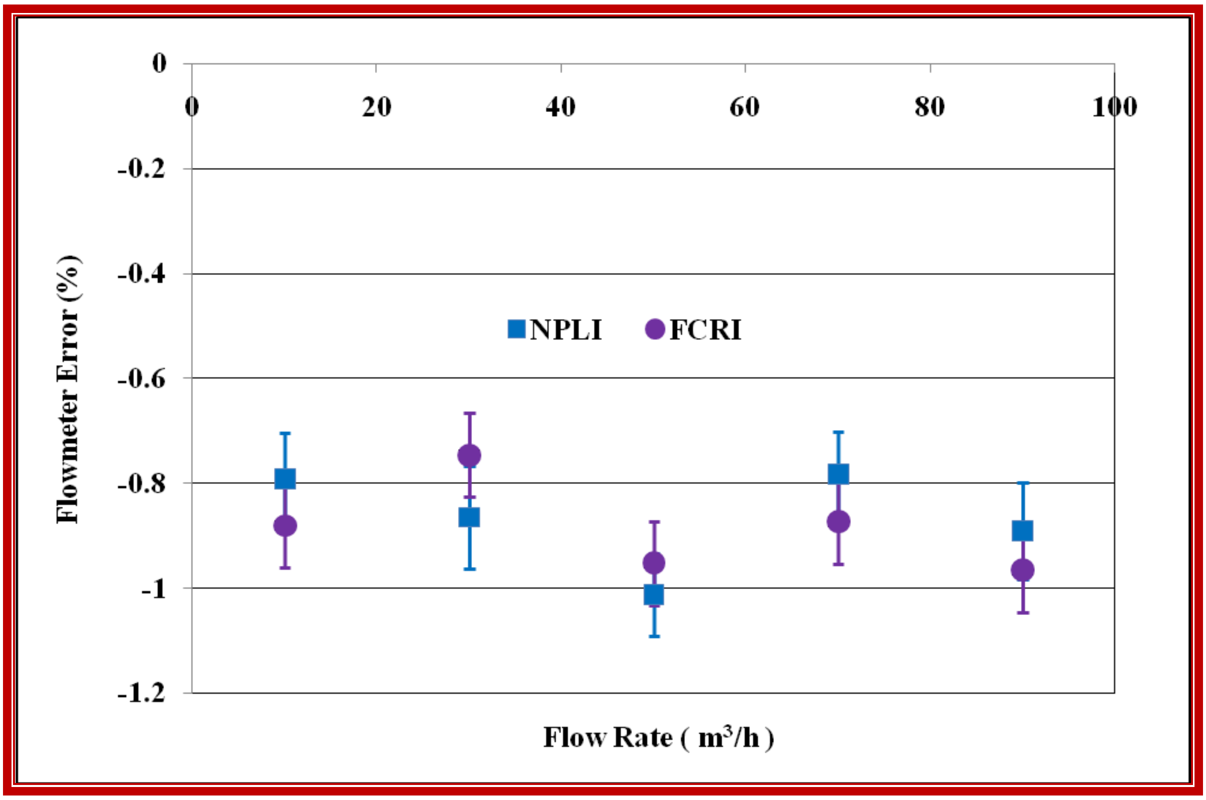


Figure 4.13: Comparison of NPLI and FCRI measurement results where the installation requirement of flowmeter was fulfilled by both NPLI and FCRI.

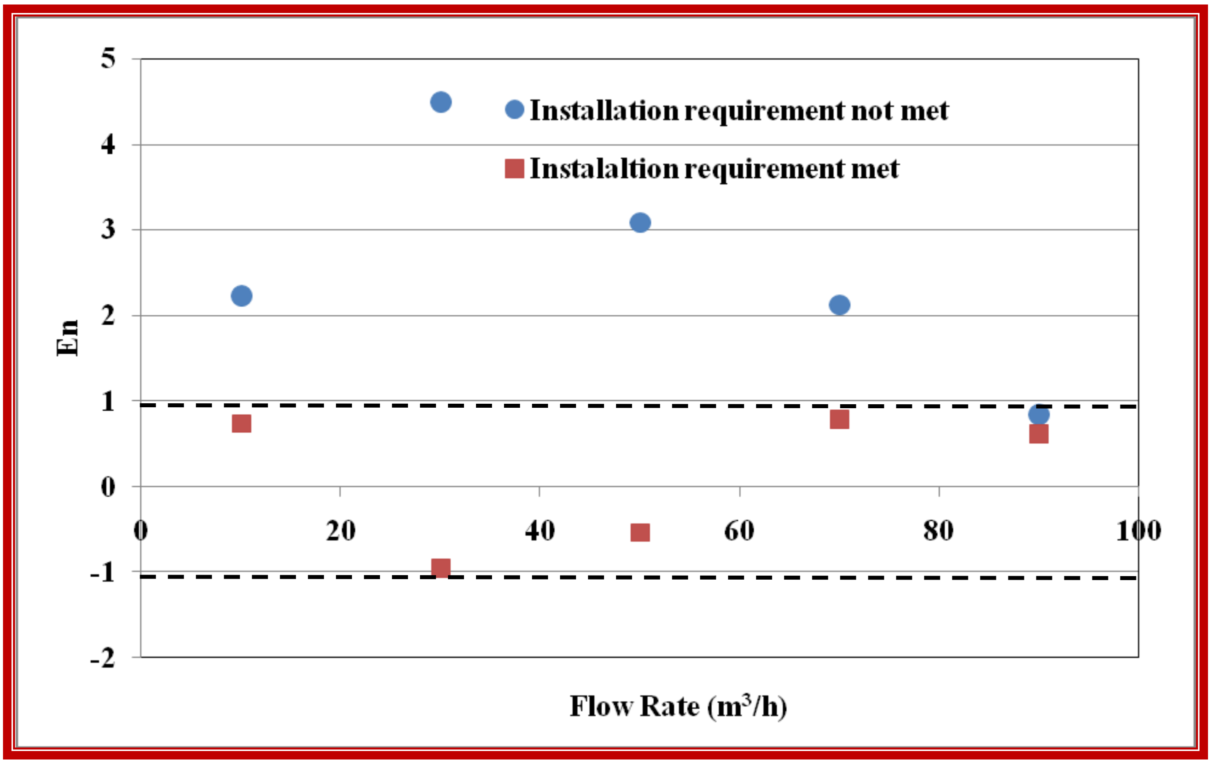


Figure 4.14: Plot of E_n values verses flow rates. Error band shown between two dotted lines is the acceptable limit.

After performance verification of WFMS, the single and multiple weighing experiments were again performed using PC counter where diverter error is not corrected. The data and results of these experiments are shown in Tables 4.14 and 4.15. After removal of installation effects, the repeatability of the flowmeter and system has improved and it is about ±0.03% at *k*=1. Therefore, for uncertainty estimation shown in the Table 4.15, Type A uncertainty of ±0.03% at *k*=1 has been considered for expanded uncertainty estimation.

Table 4.14. Data of electromagnetic flowmeter calibration in multiple weighing mode at flow rate of 40 m^3/h.

S. No.	Collected mass target kg	Tank1 collected mass m_{tank1} kg	Tank 2 collected mass m_{tank2} kg	Collected mass $= m_{tank1} + m_{tank2} + \ldots$ kg	Collection time (PC counter) t seconds	Water temp. T ºC	Water density ρ kg/m^3	Standard volume flow rate Q_S m^3/s	Standard volume flow rate Q_S LPH	MUT volume flow rate Q_M LPH	Flowmeter Error %
1.	1000	1008.6 (m_1)	-	1008.6 (m_1)	90	30.2	994.21	0.011284	40622.09	40278.8	-0.845
2.	2000	1163.6 (m_1)	841.8(m_2)	2005.4 (m_1+m_2)	180	30.3	994.17	0.011218	40386.13	40040.3	-0.856
3.	3000	1162.8 (m_1) 882.0 (m_3)	962.6 (m_2)	3007.4 (m_1+m_2+m_3)	270	30.2	994.21	0.011215	40375.23	40026.5	-0.864
4.	4000	1161.4 (m_1) 1160.8 (m_3)	962.6 (m_2) 752.4 (m_4)	4037.2 (m_1+m_2+m_3+m_4)	360	30.2	994.21	0.011292	40650.44	40301.5	-0.858
5.	5000	1161.4 (m_1) 1163 (m_3) 789.2 (m_5)	961 (m_2) 961 (m_4)	5035.6 (m_1+m_2+m_3+m_4+m_5)	450	30.2	994.21	0.011267	40562.64	40211.1	-0.867
6.	6000	1163 (m_1) 1161.8 (m_3) 1163 (m_5)	965.2 (m_2) 962.2 (m_4) 638.2 (m_6)	6053.4 (m_1+m_2+m_3+m_4+m_5+ m_6)	540	30.2	994.21	0.011353	40869.28	40518.1	-0.859
7.	7000	1164.4 (m_1) 1160.8 (m_3) 1162.2 (m_5) 713.2 (m_7)	964.4 (m_2) 961.2 (m_4) 963.0 (m_6)	7089.2 (m_1+m_2+m_3+m_4+ m_5+m_6+m_7)	630	30.2	994.21	0.01133	40789.11	40426.9	-0.888
8.	8000	1165.8 (m_1) 1160.2 (m_3) 1162.2 (m_5) 1163.8 (m_7)	961.2 (m_2) 964.2 (m_4) 958.2 (m_6) 649.4 (m_8)	8185.0 (m_1+m_2+m_3+m_4+ m_5+m_6+m_7+m_8)	720	30.3	994.17	0.011447	41208.79	40824.2	-0.933
9.	9000	1164.0 (m_1) 1163.2 (m_3) 1163.6 (m_5) 1163.4 (m_7) 677.8 (m_9)	960.6 (m_2) 963.2 (m_4) 963.2 (m_6) 960.4 (m_8)	9177.8 (m_1+m_2+m_3+m_4+ m_5 +m_6+m_7+m_8+m_9)	810	30.2	994.21	0.011409	41071.55	40677	-0.961
10.	10000	1161.4 (m_1) 1163.6 (m_3) 1163.2 (m_5) 1162.4 (m_7) 1162.6 (m_9)	958.6 (m_2) 959.8 (m_4) 960.8 (m_6) 963.2 (m_8) 478.2 (m_{10})	10133.8 (m_1+m_2+m_3+m_4+ m_5 +m_6+m_7+m_8+m_9+m_{10})	900	30.2	994.21	0.011337	40814.77	40412.5	-0.986

Table 4.15. Flowmeter error and uncertainty in single weighing and multiple weighing after meeting the installation requirement of the flowmeter.

S. No.	Type (single/ multiple weighing)	Collected Mass		Collection Time		Water Density		Flowmeter Error %	*Expanded uncertainty at k=2 U (flow)
		Estimate (M) kg	Standard uncertainty (u_M) %	Estimate (t) s	Standard uncertainty (u_t) %	Estimate (ρ) kg/m^3	Standard uncertainty (u_ρ) %		
1.	Single weighing	1000	0.02	90	0.0951	994	0.005	-0.845	0.205
2.	Multiple weighing	2000	0.02	180	0.0476	996	0.005	-0.856	0.121
3.		3000	0.02	270	0.0317	996	0.005	-0.864	0.099
4.		4000	0.02	360	0.0238	996	0.005	-0.858	0.089
5.		5000	0.02	450	0.0190	996	0.005	-0.867	0.085
6.		6000	0.02	540	0.0159	996	0.005	-0.859	0.082
7.		7000	0.02	630	0.0136	996	0.005	-0.888	0.080
8.		8000	0.02	720	0.0119	996	0.005	-0.933	0.079
9.		9000	0.02	810	0.0106	996	0.005	-0.961	0.078
10.		10000	0.02	900	0.0095	996	0.005	-0.986	0.078

Figs. 4.15 and 4.16 show the plot of flowmeter error and uncertainty in graphical form. The flowmeter was calibrated in single weighing mode using universal frequency counter and its error was determined as -0.937 % with expanded uncertainty of ±0.104 % at *k*=2. From the Figs. 4.15 and 4.16, it is evident that the flowmeter error and uncertainty have improved due to longer collection time resulting from larger collected mass. It is also evident from the Figs 4.15 and 4.16 that flowmeter's error is going in negative direction. Admittedly, the reasons for this negative direction of flowmeter's error are not clearly known and explored. However, in order to optimize and to ensure consistency in the results, the weighing system, universal frequency counter, PC counter and diverter system were properly calibrated for their specific related parameters and all the calibration results were found within acceptable limits. For further improvement in measurement results, the recommendations have been given in the next chapter.

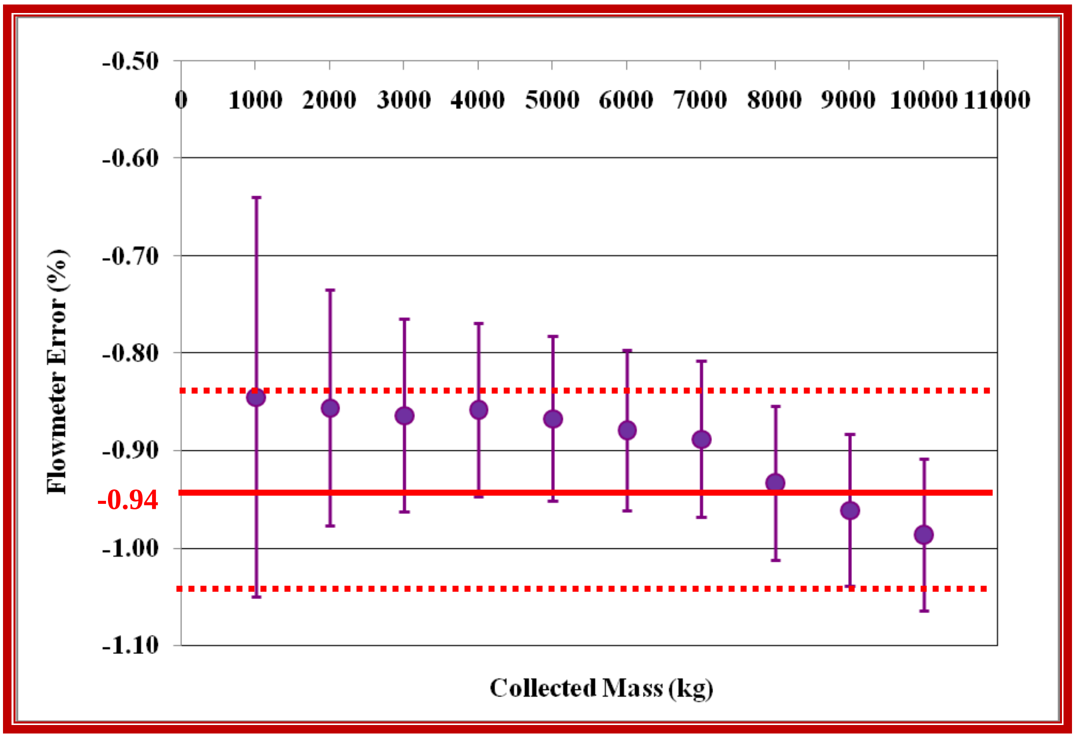


Figure 4.15: Plot of flowmeter error verses collected mass in single and multiple weighing. The result in the red colour is for flowmeter calibration in single weighing mode using universal frequency counter and those in the violet colour are for single and multiple weighing methods using PC counter.

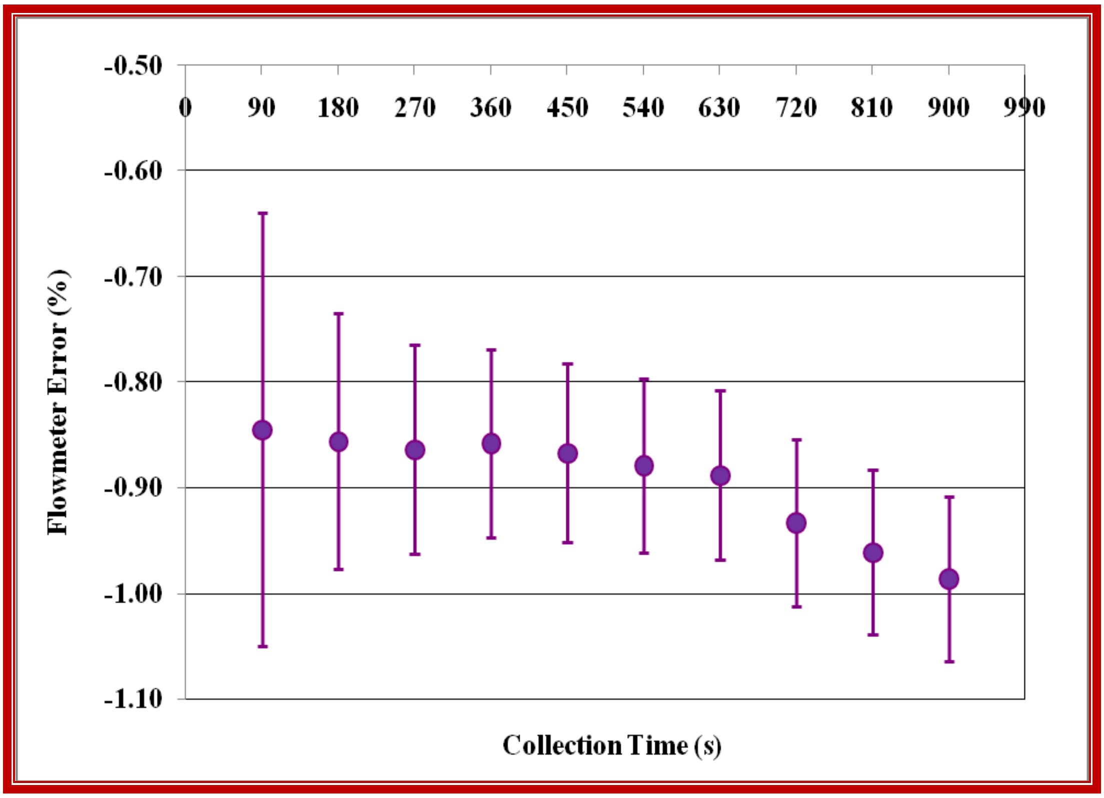


Figure 4.16: Plot of flowmeter error verses collection time in single and multiple weighing. The results in the violet colour are for single and multiple weighing methods using PC counter.

In the present chapter, establishment of metrological traceability of the developed water flow measurement system has been described. The metrological traceability has been achieved through the results obtained during various experiments carried out related to installation effects, evaluation of diverter error, measurement uncertainty in single weighing and multiple weighing methods and performance evaluation through inter laboratory comparison. The measurement uncertainty associated with multiple weighing has been found much improved in comparison to single weighing.

5

CONCLUSIONS AND FUTURE RECOMMENDATIONS

5.1 Conclusions

In the present study, a new water flow measurement system of 100 mm size (DN100) has been developed for calibration of high accuracy flowmeters such as coriolis, electromagnetic, ultrasonic, differential pressure type *etc*. The expanded measurement uncertainty associated with flow measurements using this system is 0.081% to 0.055% for (500-2000) kg collected mass. However, the repeatability / Type A uncertainty associated with measurement using MUT is not included. The flow range of the system is up to 100 m^3/h. The main conclusions drawn from the studies are as follows;

- The system has been developed indigenously as a low-cost solution for industrial calibrations and measurements.

- In a traditional WFMS, there exists one weighing tank and one bypass line. In the new design, the bypass line has been replaced by second weighing tank. Initially, one of the tanks is used as bypass line and subsequently for weighing to increase collection time by cyclic weighing method, also called multiple weighing. The error and uncertainty in flow measurement is improved considerably when multiple weighing method is used for collecting larger water mass. Also, the diverter error evaluation and correction can be avoided, which is time consuming and cumbersome process. In case of use of diverter error correction, the accuracy of the flow measurement is further increased.

- The present system is simpler and easy to operate. The maintenance cost of the operations is also comparatively on lower side.

- The system automation has been optimized for easy operation and maintenance. One of the significant advantages is its software and hardware over earlier WFMS of

NPLI. The earlier system utilized complex electronics, controls and fully automatic operations, thus requiring highly skilled manpower and financial resources to maintain.

- For collection time measurement, single proximity switch has been used for easy adjustment and also for non-automated collection time measurement. In the earlier system, there were three proximity switches requiring automation for collection time measurement. Also, the adjustment of these proximity switches was difficult. All these problems are amicably addressed in this newly developed simpler system.

- In the earlier system, the flow control valve was the integral part of the fishtail and nozzle assembly which was very difficult to repair and maintain. In the present design, the fishtail and nozzle are kept apart from the flow control valve which makes its operation and maintenance simpler.

- The weighing process of calibration of tanks in the earlier system was very difficult and time consuming, involving a lot of physical manpower. In this process, the total mass of 10000 kg (using 20 weights of 500 kg each) or 1000 kg (using 20 weights of 50 kg each) were used to be placed on a plate inside the weighing tank. This plate was meant for distributing the load uniformly on the tank. For this purpose, mechanical cranes with auto operations were used for loading and unloading individual weight inside the tank. This was achieved through a person going inside the tank for adjusting the placement of weight in the tank.

  In the new system, a 6 mm thick MS plate has been suspended beneath weighing tank (2000 kg capacity) mounted with four support arms. This arrangement enables us to place 20 weights of 50 kg each, manually on the plate easily. As the height of plate position is not more than 1 m, two persons holding weights through lever arm arrangement can easily place on the plate. Also, the requirement of manpower going inside the tank for loading and unloading of weights through crane is avoided. This makes system operation much simpler, easy and also saves a lot of human power and electricity.

5.2. Significance of Present Work and Future Recommendations

5.2.1 Significance

The newly developed method of multiple weighing is a unique method for improving the diverter error in flow measurements. The studies reveal that the diverter error and overall uncertainty improves considerably while using multiple weighing. Using this system, the user can now perform flow measurements in a simpler way, with not much worried about complicated electronics, instrumentation and diverter error and overall with lesser cost. This system is now available for dedicated national service for measurements and calibrations of high accuracy flowmeters like electromagnetic, ultrasonic, coriolis, differential pressure type *etc.*

5.2.2 Future Recommendations

The presently developed system has the potential to develop further a low-cost reference standard for users, industries specially water flowmeters manufacturers and accredited laboratories. This would help them to improve the quality of their products, services and in establishing their traceability chain. Following are the recommendations for researchers, students and metrologists to utilize present findings to their future research and developmental works;

- At present, the system has been developed in the flow range up to 100 m^3/h which can be further increased up to 200 m^3/h using same system and also with some minor design modifications having increased capacity of drain line to handle such a large flow rate.

- In the present system, a cheaper weighing system based on load cell has been used. This weighing system can be replaced by electromagnetic force compensation type. This would enhance the stability, linearity and resolution manifold and finally overall accuracy. Similarly, the improved densitometer can be used for density measurement in place of analytical weighing system used with present system. Although, admittedly this will increase the cost of the system, however, expecting the much improved measurement uncertainty, one can compromise with increased cost. At NMIs level, such improved system can be developed approximately within Rs. 80 Lakhs. However, the import cost of such a precise system is not expected less than Rs. 2 Crores. Therefore, this system can be developed indigenously in less than half cost.

- If a calibrated preset (fixed) timer with associated instrumentation for switching / triggering is used in place of PC counter in the present system, the accuracy of the collection time and the collection volume can be improved. This will improve the diverter error and uncertainty of the system as a whole. This system can be developed for improved collection time measurement.

- The stability of the flow can be improved by using flow conditioner in the flow line. There are different types of flow conditioner used, for example, to reduce straight length, to increase flow stability by removing swirl in the flow etc. and also using flow control loops in the line. This will also improve the repeatability of the flow measurement and diverter error.

- The flowmeter was calibrated in current output mode using digital multimeter in the present study. In future, the flowmeter can be calibrated in pulse (frequency) output mode. Since frequency counters have better accuracy than digital multimeter, so this will also improve the accuracy of the flow measurement.

In this chapter, the conclusions drawn from the studies, significance, suggestions and recommendations for future research work have been highlighted.

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