THE NEW INRIM PRIMARY STANDARD OF WATER FLOW RATE

Carlo Marinari
INRIM – Italy
Strada delle Cacce, 91 – 10135 Torino (Italy)
c.marinari@inrim.it

Abstract

In 2011, INRIM opened a noteworthy upgrading work to plane an extensive renovation of the national water flow rate primary standard, to get better its structural features and to increasing its metrological performance.
The paper presents the main activity of revamping of the INRIM liquid flow calibration rig in order improve its flow rate range and, mainly, to update its ancillary instrumentation towards a more modern approach to signal conditioning, by introducing automatic and user-friendly control of the measurement-taking process.

1- Introduction

The INRIN water flow rate primary standard is a flow calibration rig based on the static weighing gravimetric system with flying start-and-finish, as established by standard EN-ISO 24185
It was designed and built in the 80's and it still represents a high accuracy water flow calibration facility, but it showed, of course, a deep gap on the side of the efficiency and the reliability of process controls, signals acquisition and computer interface.
The task of refurbishing the national standard of water flow rate requires to overhaul all the component parts contributing to measurement accuracy : gravimetric references, flow diverter, density and temperature measuring devices, time measure, correction factors, in order to maintain or improve the uncertainty requirement of a primary standard. (Fig. 1).

Fig. 1- Overview of the new INRIM flow rate measurement laboratory

During the calibration facility's measurement the main process quantities (water flow rate, pressure and temperature), are monitored and measured, with several other relevant process parameters like fluid density, diverter actuation, balance readout and ambient-air conditions. This is an essential prerequisite to provide reproducible conditions that are necessary to achieve a high degree of reproducibility in the measurement and calibration processes.
Major improvements concerned the updating of the measurement rig and its ancillary instrumentation in order to implement a modern approach to signals conditioning. As a result, the measurements process is now automatic and user-friendly, thanks to the innovative choices of a more efficient human-machine interface and the presentation of the test results to meet the goal of measurement uncertainty minimization. (Fig. 2).

2- General plant setup

The flow rate of INRIM primary standard rate ranges from 0,01 kg/s to 10 kg/s; the plant is equipped with four different measurement lines (pipes bore from 25 mm to 50 mm), a 150 kg balance and a high speed flow diverter. The temperature of tests can vary from 18 °C up to 80 °C.

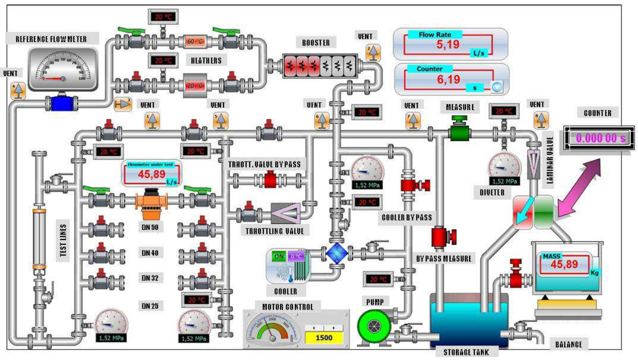

Fig. 2- Layout of scheme of the INRIM water flowrate primary standard.

The plant includes the devices required to generate and maintain constant flow rate, pressure and temperature. The ratio of the accumulated water mass to the time interval of water collection provides the value of the mass flow:

$$q_m = k\frac{m+c}{\tau} \qquad (1)$$

where *m* is the mass of fluid indicated by the balance, corrected by the term *C* accounting for the balance calibration and thermal effects during the measurement;

τ is the time interval during which water was collected, and k a correction factor for the buoyancy exerted on the fluid and for losses due to evaporation and splashing during filling of the reservoir.

Consequently the flow rate in volume is:

$$q_v = \frac{q_m}{\rho} \qquad (2)$$

where ρ is, of course, the density of the fluid at the measurement temperature, expressed in kg/m^3.

2.1- Flow control

The flow rate stabilization is guaranteed by a variable-speed multi stadium centrifugal pump driven by a control loop for flow rate regulation. Four measurement lines, with different bores (DN20, DN36, DN42, DN50), provide an adequate pipe section at different flow rates. An accurate control of the circulated water pressure is managed by a throttling valve. A final laminar valve gives the water flow a rectangular section in order to improve the flow deviation. Thus, an accurate and stable flow rate is guaranteed over the whole range. (Fig. 3)

Fig. 3 – Laminar valve

2.2 Temperature control

The INRIM standard flow rate is designed to work in a temperature range from 18 °C to 80 °C The desired temperature is obtained by two integrated control loops systems:

- a cooling circuit, to reduce down the water temperature to 18 °C or hampering the temperature increasing due to the thermal dissipation during tests **(**fig. 4). It is made up by a water cooling system that can reach temperatures as low as 4 °C coupled to the measurement rig by means of a heat exchanger;
- a three-stage heating circuit including a set of electrical resistances that dissipate a power precisely programmable by an automatic loop control.

Fig. 4- Flow rate standard heating section

These two control systems are managed by nine temperature sensors (PT100), allocate along the measurement circuit.

Real-time, adaptive parameter adjustment of the temperature controller is provided, via fieldbus communication, by a sophisticated control loop implemented on a dedicated computer.

The temperature value is continuously controlled by the main supervising program that drives the cooling or heating systems. Time stability and homogeneity of the temperature are both within 0.1 °C.

2.3 Pressure control

Pressure is controlled by a throttling valve, operating in the range from 0.5 bar to 6 bar. (fig. 4).

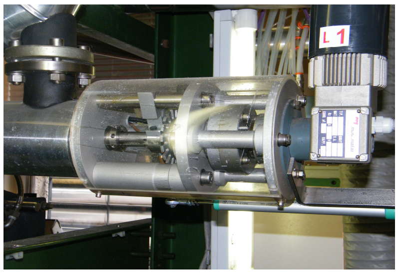

Fig. 5 - Throttling valve

Four different pressure transducers are connected at the output of the pump, at the beginning and the ending of the measurement lines and just before the diverter.

They allow to control and to record the value of pressure along the measurement lines.

3 - Flow diversion and monitoring

This is an essential part of the flying start-and-finish calibration method, as it realizes the liquid collection in the weighing tank. It allows directing the liquid flow into the weighing tank on start and redirecting the flow back to the bypass circulation once the collection is completed. In order to correctly measure the collection time, the diverter also provides timer actuation when changing position.

The diverter's design is optimized that it combines a good repeatability with an elevated transient symmetry as in figure 6.

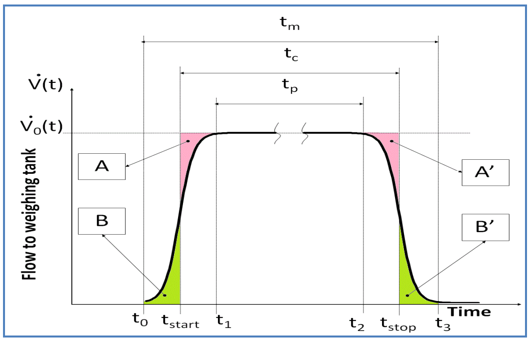

Fig 6: Principle of flow diversion

Furthermore, in order to contribute to minimize the flow diversion errors a system to reduce the transition time down to 4 ms was designed:

1. an AC motor, supplied for 100 ms, rotates about 45° and launches a flywheel with a hitting tooth;
2. during its rotating strikes a catch fixed on the rotating system which is stopped by two shock absorbers;
3. the diverter is integral to the system of rotation, and is switched from the recovery position of the flow to the measurement position and vice versa;
4. when the diverter crosses the verticality. an optoelectronic signal switches on or off the counter, to start or finish the measurement time respectively.

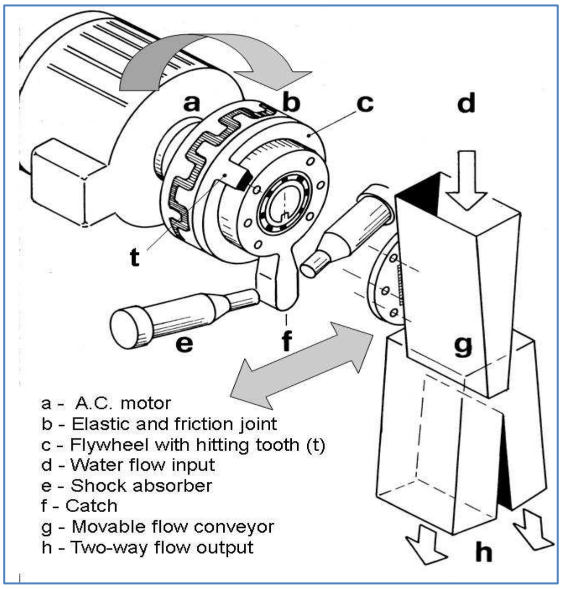

Fig 7: Scheme of INRIM diverter

In order to verify the water flow behavior during diversion a continuous recording is carried out, a high speed camera (1200 frame/s) supervises the diverter commutation to detect any anomalous behavior that could lead to systematic and hidden errors.
The movie analysis can detect a asymmetrical features in flow diversion and enabled detection of a spurious reflux of fluid that could slightly alter the final mass value. (Fig. 8)

3- Measurement procedures and data acquisition and processing

Special attention was dedicated to the human-machine interface and data presentation, in order to obtain a friendly use of the flow rate standard and a close control on errors of connection, circuit default or random reading errors.

3.1 Human-machine interface and data presentation.

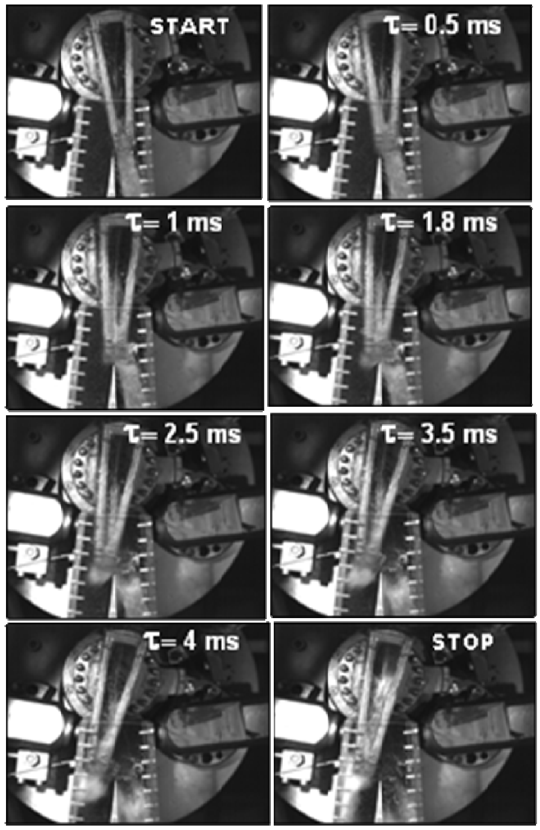

Fig. 8- Diversion run by high speed camera recording

The calibration of the DUT runs in a fully automated way, thanks to a *"Supervisory Control and Data Acquisition for Human Machine Interface"* system (SCADA/HMI) being utilized for automatic process control and operator interaction.

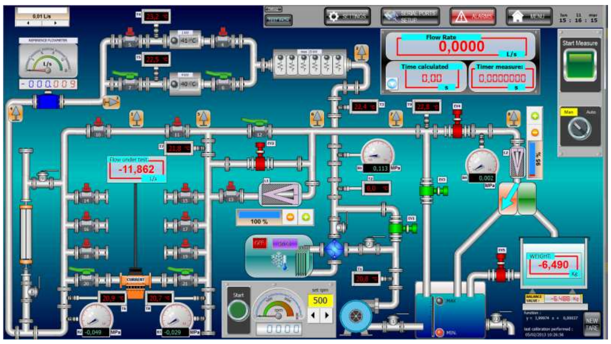

Fig. 9- Monitor 1 with the graphic plant representation

The SCADA/HMI platform Movicon 11.2 (by PROGEA) is a realistic interface with efficiency and performances based on emergent and multiplatform technologies, with graphic symbols completely customizable, using VBA scripts as well, and symbols with Power Template technology.
The operator has full access to all process variables of the calibration plant directly interacting with the two monitors: monitor 1 for process control (fig.9) and monitor 2 for readout measurement and testing condition, in fig. 10.

Fig. 10- Monitor 2 with the complete read outs screen

The graphic layout represents realistically the flow rate standard plant, and all the graphic symbols are active keys to sensing and actuating devices, their status and the actual measurement values. Virtual on-screen buttons are the "active points" to control, by mouse, valves, heaters, cooler, diverter, balance ect., and to check, in real time, all the measurement readout: flow, pressure, temperature, time.
Further windows are available concerning balance calibration, programming of the input/output digital ports and the definition of the testing procedure.

4- Correction of measurement data.

4.1 Weighing system

The gravimetric-reference system comprises a 150 kg balance by Toledo Mettler, with resolution of 0.1 g and nominal expanded uncertainty of 1 g.
Also the weighing system is controlled by the SCADA/HIM, that sets up a readout delay in order to avoid the influence of the water oscillation into the balance tank on the final weight value.
The formula /1/ can also be written as:

$$q_m = \frac{W}{\tau} \qquad (1_{bis})$$

Where W is the weight of water indicates by the balance and corrected as in formula**:**

$$W = A \cdot E \cdot (B + F + G + H) \qquad (3)$$

where A, E, F, and G are corrections for buoyancy, losses due to evaporation and splashing, balance calibration and thermal effects, respectively, and H is a supplementary water buoyancy factor at high temperature

4.2 Time and diversion

The flow diverter represents a critical part of a flow calibrator as it has a direct impact on measurement uncertainty. Thus the supervision of the diverter's reproducible operation and the weighing time are of essential importance.

The flow rate which is directed into the weigh tank is, of course, a function of time. It is zero while the water is flowing through the by-pass into the storage tank and increases up to the value in the test rig during the transition time T_{jet} between the actuation of the diverter and the completion of its trajectory through the jet.
This rise depends mainly on the speed of the diverting edge, the shape of the jet's cross section, the velocity profiles across the jet width and the start/stop time switch.
The process of switching back can be described by analogue considerations.

Fig. 11- Rectangular shape of water flow jet.

The diverter design is optimized in order to balance the shortest diversion time with good repeatability. A rectangular shape of the jet is ensured by the laminar valve, as shown in fig 11.

4..31 In-process density metering

In a gravimetric-reference system, when the subject of calibration is a volumetric flow meter, is evident that the measurement of the exact value of water density at the measurement temperature, during a calibration run, has to be performed.
All the different formula to calculate the water density value are reported in terms of

- the temperature scale in use (ITS-90), covering a determined range of temperature [2].
- Density results are corrected to the density of V-SMOW .
- Results are based on de-aerated water at standard atmospheric pressure (101 325 Pa).

In our application the *M. Tanaka et alii.* formula was chosen /4/.
It applies to various properties for water including the impact on the density due to the air saturation of water and compressibility, across the temperature range 0 °C to 40 °C.

$$\rho = \left\{ a_5 \cdot \left[1 - \frac{(a_1 + t)^2 \cdot (a_2 + t)}{a_3 \cdot (a_4 + t)} \right] + C_{is} \right\} \cdot C_{com} \qquad (4)$$

where: t is temperature in °C; a_5 = 999.974950 kg/m^3 ± 0.00084; a_1 =-3.983035 °C^{-1} ± 0.00067 ; a_2 = 301.797 °C^{-1}; a_3 = 522528.9 °C^{-2}; a_4 = 69.34881 °C^{-1}.

Most users of water as a density standard rely on tap water, therefore further corrections due the isotopic abundance by using $a_5' = 999.972$ kg/m^3 instead a_5, C_{is}, for the different in density between air-free and air saturated water, and the water compressibility C_{com} must be considered.

The correction for thermal expansion of pure water having natural isotopic abundance by the dilatometric method in a temperature range from 0 to 85 °C and under a pressure of 101 325 Pa, was determined by M Takenaka and R Masui [2].
The following equation was obtained:

$$\rho(t)/\rho_{max} = 1 - [(t - 3{,}98152)^2 \cdot (t + 396{,}18534) \cdot (t + 32{,}28853)] / [609\,628{,}6(t + 83{,}12333) \cdot (t + 30{,}24455)] \quad (5)$$

where $\rho(t)$ is the density of water at temperature t, which is expressed in terms of the ITS-90, and ρ_{max} the maximum density. The density ratio which the above equation gives is estimated to have an uncertainty of approximately 1×10^{-6} [2].

<u>4.4 Buoyancy correction</u>

For the wide temperature range in which the INRIM flow rate standard can work, a careful assessment of the temperature influence on the water density and buoyancy is required.
The water buoyancy correction factor (see in formula 3) is expressed as:

$$A = \frac{1 - \frac{\rho_{at}}{8000}}{1 - \frac{\rho_{at}}{\rho_{wt}}} \quad (6)$$

Where ρ_{at} is the air density and ρ_{wt} is the water density, at different temperatures.

According to EN 24185 the air density to be taken in the calculation should be that of the ambient. This rule does not consider the case of measurements of liquids at a temperature significantly different from that of the environment.
Therefore, in the case of the INRIM plant, which is equipped with a tank weighing insulated and tightly closed by a cover (although not hermetically) the density value to be considered is that of the air inside the tank.
For water temperatures higher than 30°C the value of the coefficient A is calculated according to the water and the air temperature inside the tank, so measured, and based on the value of the ambient atmospheric pressure. Relative humidity Hr is given the constant value: Hr = 90%.

However, a further effect should be taken into account. The weighing tank has an internal volume of 144 l and is covered by a metal cover fitted with gaskets. This means that, during the weighing, the volume of the air V_a into the tank (that varies in inversely to the quantity of water which it intends to accumulate) is never in equilibrium with the environment; the mixing between the two environments being severely hampered.
If the air inside appears to have constant density over time, we do not have an impact on weight. But if there is a variation during the weighing cycle (for example with a higher temperature in the measurement phase of the gross mass) the mass measurement of the accumulated water will be affected by an error.
It is therefore necessary to measure, during the test, the thermodynamic temperatures T_1 and T_2, the air inside the tank (before and after the weight of the accumulated water) and to determine the relative change of thermodynamic temperature $(T_2 - T_1) / T_1$. It is assumed that it corresponds to a relative change in air density $(\Delta\rho_a / \rho_a)$ of equal value and opposite sign (thereby neglecting the influence of moisture). The difference in mass of the air (m_a) contained in the volume should be in the two conditions is then given by:

$$\Delta m_a = -\rho_{a1} \cdot V_a \cdot \frac{(T_2 - T_1)}{T_1} \quad (7)$$

In accordance with /3/ this supplementary water buoyancy factors can be expressed as:

$$H = \Delta m_a \quad (8)$$

<u>4.5 Avoid the presence of air in calibration lines</u>

An important source of error is the presence of air (bubbles or solved air) in the calibration line. To avoid this abnormal plant operation, air-eliminating facilities were installed at several locations of the pipe system. The setup of such a air eliminators comprises inlet and outlet pneumatic valves connected to a dummy line for air-bubble removal. Also in this case the pneumatic valves are triggered by the active graphic symbols on the screen control.

5- The measurement uncertainty model

The overview of quantities that exert an influence on measurement uncertainty in liquid flow meter calibration is summarized by the following equation:

$$\Delta Q_{Meas} = m_{REF} / \rho_{Water} + \Delta\tau + \Delta Q_{Line} + \Delta Q_{DUT} \quad (9)$$

where:

- m_{REF} is the deviation due to the gravimetric system (mass of water, balance calibration, buoyancy, water density, diverter operation, evaporation of collected water, …).
- ρ_{Water} fluid density (density and temperature measurement, …).
- $\Delta\tau$ indicates the possible errors due to the counter in use and to the diverter timing.
- ΔQ_{Line} influence of temperature and pressure change during calibration run, leakage flow, compressibility of water.
- ΔQ_{DUT} points out the flow meter under test reading (function of water density, measurement time,

temperature change, compressibility of water, change of flow rate, pressure stability, velocity profile in the DUT…).

The estimation of the measurement uncertainty budget of the water flow calibration facility can summarized as follow:

$$u^2_q = u^2_{mass} + u^2_{time\ diversion} + u^2_{diverter\ time\ error} + u^2_{temp.\ of\ fluid} + u^2_{fluid\ density} + u^2_{buoyancy} + u^2_{DUT} \quad (10)$$

Any previous sources of uncertainty are associated to further standard uncertainty contribution.

Mass	Calibration of standard weights	$u^2_{c.s.w.}$
	Resolution of balance	$u^2_{d.b.}$
	Repeatability of balance	$u^2_{r.b.}$
	Drift of balance	$u^2_{b.d.}$
	Losses for evaporation and splashing	$u^2_{loss.}$
Time	Calibration of Timer	$u^2_{c.t.}$
	Discrimination of Timer display	$u^2_{ris.\ d.t.}$
	Discrimination of Diverter Time	$u^2_{ris.\ d.t.}$
Diverter timing error	Diverter timing error	$u^2_{d.r.}$
	Flow rate	$u^2_{f.r.}$
	Diversion error volume	$u^2_{d.e\ v.}$
Temperature of fluid	Resolution of temperature measurement	$u^2_{ris.\ temp.m}$
	Sensor calibration	$u^2_{s.cal.}$
	Temp. gradient in water	$u^2_{w.t.\ grad.}$
Density of fluid	Temp. measure	$u^2_{t.m.}$
	Density measure	$u^2_{d.m.}$
	Temp. downstream of DUT	$U^2_{t.d.DUT.}$
	Numeric approx. Error	$u^2_{n.a.e}$
Buoyancy	Ambient air density	$u^2_{air\ d.}$
	Water density	$u^2_{water\ d.}$
	Density of calibration weights	$u^2_{std.w.d.}$
Device meter under test (DUT)	Accuracy	$u^2_{acc.}$
	Repeatability	$u^2_{repea.}$
	Reproducibility	$u^2_{repr.}$
	Resolution	$u^2_{ris.}$

6- Conclusions

The main refurbishment of a primary standard for liquid flow measurement at INRIM has been presented.
The renovation and automation of the plant has allowed a greater reliability in monitoring and measuring the parameters that in this field of measurement.
The ability to have a real-time control of the plan setup makes it possible to obtain a more reliable measurement and to reduce random errors.

The monitoring of the flow diversion, by using of a see-through flow conveyor and a high speed camera, allows a continuous control of the flow jet and the detection of any anomalous behavior that could lead to systematic and hidden errors.
An efficient human-machine interface is realized in order to have a full automated DUT calibration and a more user-friendly and strict control on all measurement process

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