The Concept of a New Primary Standard for Liquid Flow Measurement at PTB Braunschweig

Walter Pöschel and Rainer Engel

Physikalisch-Technische Bundesanstalt Braunschweig, Germany

Abstract -- **Presently, at Physikalisch-Technische Bundesanstalt Braunschweig (Germany) a new water flow test rig is under construction that is destined to serve as the national primary standard for liquid flow measurement. The test rig will comprise a gravimetric reference and a volumetric part with a claimed expanded uncertainty of 0.02 %.**

The paper describes the test rig and, in particular, the measures how to attain the high accuracy goal.

I. INTRODUCTION

Presently, at Physikalisch-Technische Bundesanstalt Braunschweig (Germany) a new water flow test rig is under construction. This test rig is intended to establish the national primary standard for the field of liquid flow measurement.

One of it's main tasks is to calibrate secondary flow standards and to prove by intercomparison the accuracy of calibration facilities in accredited test laboratories. Nowadays for test facilities in this laboratories expanded measurement uncertainties of 0.1 % or even 0.05 % are claimed. Therefore the aim for the new primary standard was set to achieve a total expanded uncertainty (2σ value) of 0.02 %. That means - in terms of the ISO-Guide [1] - a total standard uncertainty (1σ value) of 0.01 %, including all components type A and B. These uncertainties refer to the mass or volume of liquid passed through the meter under test or to the average flow rate during a certain time period.

This paper describes the test rig and in particular the measures how to attain the high accuracy goal and how to prove, that it is realistic with respect to the conditions of the dynamic measurement process.

II. GENERAL DESCRIPTION OF THE TEST RIG

Fig. 1 shows a simplified diagram and Table 1 gives the specification of PTB's high accuracy water flow standard facility that is under construction now. In principle it is a combined gravimetric-volumetric test rig, comprising diverter-weighing systems and a pipe prover, which can be used separately or together for comparison purposes.

For generating and stabilising flow rates from 0.3 m^3/h to 2100 m^3/h the supply system has a 200 m^3 storage tank, a set of eight pumps (all frequency controlled), a constant head tank (30 m^3, at a height of 30 m) and two measuring sections (lane A for nominal diameters from DN 200 to DN 400 mm and lane B for DN 20 to DN 150 mm). For each diameter an upstream straight pipe length more than 50D and downstream 20D is available. All pipe work and valves consist of stainless steel. The pressure in the measuring section will be between 1.5 and 3 bars when using the constant head tank, whereas the pressure is adjustable up to 5 bars

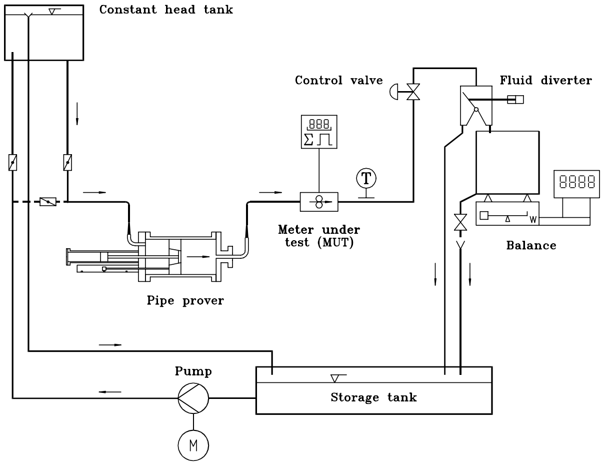

Figure 1. High accuracy flow calibration facility with combined gravimetric and volumetric reference standards

Table 1. Claimed specification of the water flow calibration facility

Feature	Provision(s)	Parameters or Options
Operation modes:	- Fluid flow via constant head tank - Fluid flow directly fed by pump to the measuring section	constant pressure operation adjustable pressure operation
Calibration methods:	- Gravimetric method - Volumetric method	30-t , 3-t and 300-kg balances Pipe prover (250 litres)
Methods of measurement:	- Flying start-and-finish method - Standing start-and-finish method	
Flow ranges:	- Measuring lane(s) **A** / **B**	0.3 m^3/h ... 2100 m^3/h
Pipe sizes:		DN 20 ... DN 400
Pressure	up to 5 bars	at max. flow rate
Extented total uncertainty:	±0.02 %	operation via constant head tank
Standard deviation: (repeatability)	0.004 %	operation via constant head tank

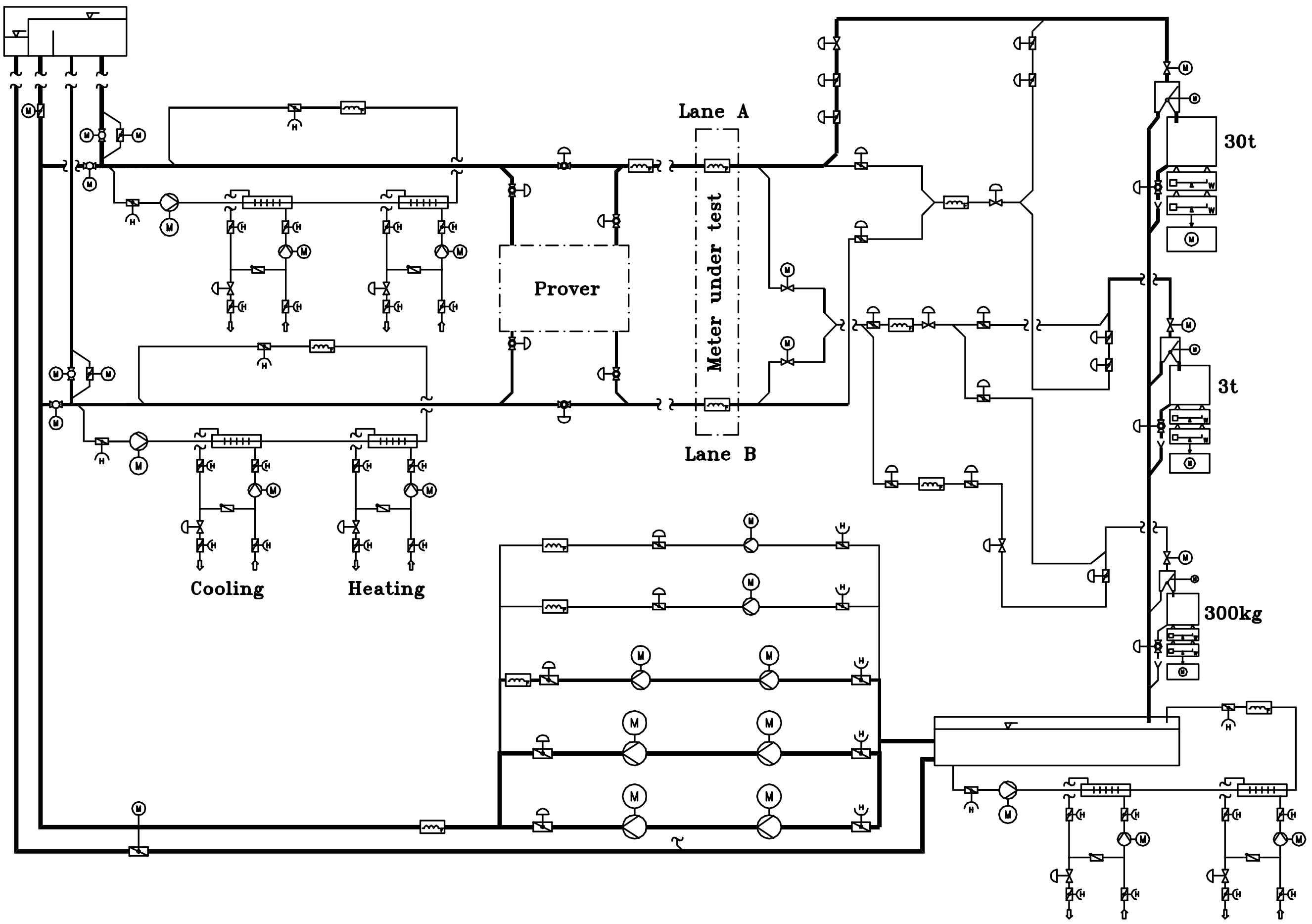

Figure 2. Piping and instrumentation scheme

when feeding the water directly by pump into the measuring section. For stabilising the liquid temperature a cooling-heating system will exist. Both flow rate/pressure and temperature control will be performed by computer (Paragraph III.B.5). Fig. 2 shows the scheme and Fig. 3 the cut-away view of the test rig.

The gravimetric measurement part consists of three branches (each is accessible from one of the two measuring sections) with diverter and balance, thermometer and density meter:

1. Diverter DN 400 for 24 .. 2100 m³/h with weighing system 3,000 .. 30,000 kg, resolution 10 g,
2. Diverter DN 150 for 3 .. 320 m³/h with weighing system 300 .. 3,000 kg, resolution 1 g,
3. Diverter DN 50 for 0.3 .. 30 m³/h with weighing system 30 .. 300 kg, resolution 0.1 g.

A calibration using the gravimetric system is started by diverting the flow into the weighing tank and starting the registration of the output of the meter under test and the time measurement. During the filling time of the weighing tank the water temperature and density is recorded continuously. By switching back the diverter recording of meter output and time is stopped. Using all necessary corrections (see formula 1), the reference volume is calculated and the calibration factor of the meter under test.

The volumetric part is a small volume pipe prover (Fig. 6) with a measuring volume of about 250 l. The maximum flow rate is planned to be 550 m³/h or higher.

To enlarge the limited volume and flow rate range a set of parallel transfer turbine meters is installed in series to the prover. Carrying out a calibration of a large meter the output of the meter under test is compared with the output of one or up to 4 transfer meters in parallel while at the same time the actual calibration factors of the transfer meters are determined successive by comparison with the prover.

The automatic control of measurement process, data collection and calculation will be carried out by computer.

III. ACCURACY REQUIREMENTS AND MEASURES TO MEET THEM

A. Model of Measurement Process

To derive accuracy requirements on different parts of the test rig and on the measurement process a theoretical error analysis was carried out [2] considering all possible error sources [3]. The analysis is based on the mathematical model according to formula (1).

With slight modifications, this formula can also be applied for the measurement of mass and volume flow rate.

In Table 2 limits for the standard uncertainties of the main error influences are given which must not exceed when the total standard uncertainty of 0.01 % shall be achieved.

$$V_M = \frac{m_W + C_W}{\rho_{dest}\left(\vartheta_{LM}\right) + C_{\rho L}} C_B\left[1 + C_\vartheta + C_C + C_{Div}\right] + C_P + C_{ev} + C_G + \delta\, V_M \qquad (1)$$

V_M	*Volume passed through the meter under test*
m_W	*balance indication*
C_W	*correction of balance indication*
ϑ_{LM}	*temperature at the meter under test*
$\rho_{dest}(\vartheta_{LM})$	*density of distilled water at* ϑ_{LM}
$C_{\rho L}$	*density deviation from distilled water*
C_B	*Buoyancy correction*
C_ϑ	*correction for deviations of the thermometer indication from the real average water temperature*
C_C	*compressibility of water*
C_{Div}	*correction for diverter errors*
C_P	*correction for thermal expansion of the pipe between meter under test and diverter*
C_{ev}	*correction for volume loss by evaporation and splashing (neglected)*
C_G	*correction for gas within the water (neglected)*
δV_M	*repeatability of* V_M

Table 2. Uncertainty contributions

Factor of influence	*Standard uncertainty*
Balance readout	0.005 %
Balance calibration	0.002 %
Water temperature and density	0.004 %
Buoyancy factor	0.003 %
Fluid diverter	0.004 %
Repeatability	0.004 %
others (evaporation, gas content, compressibility)	0.003 %
Total standard uncertainty	0.01 %

To meet these requirements we follow a double strategy:

1. Improving and refining the main parts of the test rig.
2. Creating possibilities for investigating single errors and different components of the total uncertainty by internal comparison measurements between two independent methods, the gravimetric and the volumetric one.

Details are described in the next paragraphs.

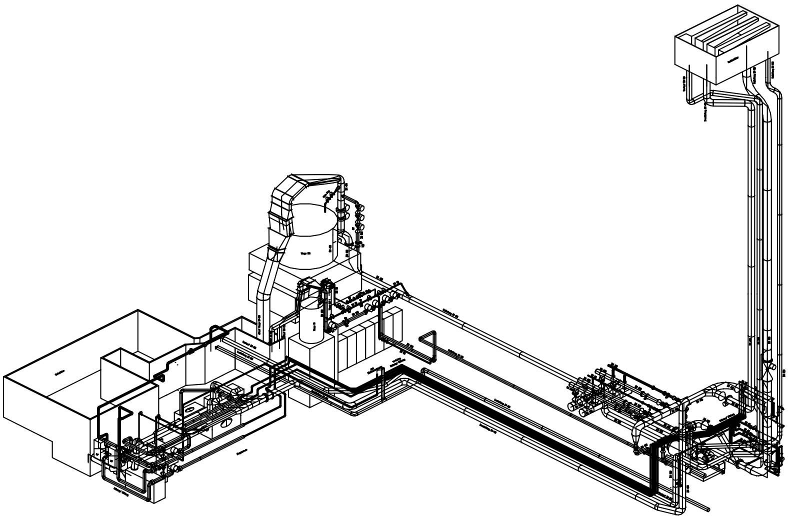

Figure 3. Cut-away view of PTB's water flow calibration plant
(Courtesy of Dröge, Kelemen and Partners, Consulting Engineers, Salzgitter/Germany)

B. Measures to attain the claimed accuracy

1) Weighing systems

Each of the three balances consists of a complex system, comprising two different mass metering devices (3 precision strain gauge load cells in addition to a platform weighing machine with an electrodynamic force compensation system) and an automatic calibration system with standard weights for the whole measuring range (Fig. 4). The high resolution readout (up to 10^6 incremental steps) will be processed by computer to get stable mean values as a result. Care is taken that the centre of gravity is provable on the same position when weighing water and when using the standard weights and also that the loading process is similar in both cases.

This weighing system allows to determine the actual balance correction factor at any time and to detect additional error influences (e.g. dynamic ones) by comparison the indications of the two mass metering devices. The relative standard deviation (repeatability) is expected to be smaller than 0.002 %, the allowed instability between two calibrations (normally during one day) is 0.004 % and the standard uncertainty (including unknown systematic errors) shall be not grater than 0.005 %.

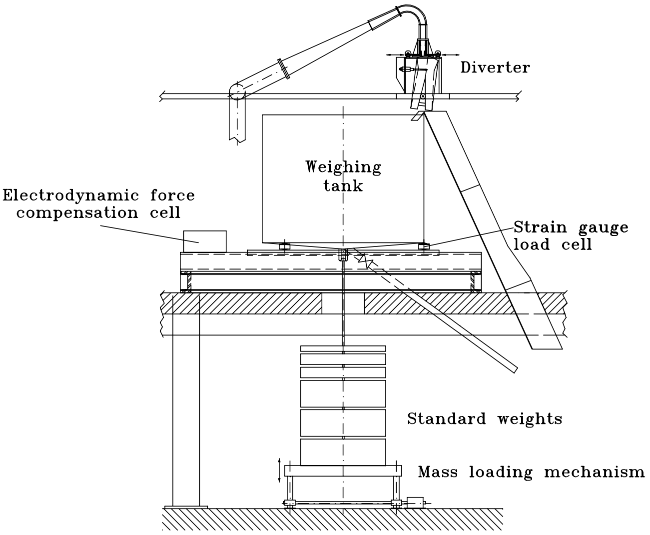

Figure 4. Dual balance weighing system with reference weights

2) Flow diverter

Besides the weighing system, the flow diverter is an essential part of the test rig. Our specially designed diverter has a rectangular nozzle with variable cross section (Fig. 5). This ensures over a wide flow rate range of about 1:100 a full and smooth jet without splashing. The pipe work upstream of the diverter has a special design to attain a nearly symmetrical velocity profile at the outlet of the nozzle. The relative difference of the half flow rates left and right from the symmetry line is smaller than 2 %.

A high precision electrical actuator ensures a constant transition speed during the transition time and in both directions. The transition time through the jet is 8 .. 150 ms (large diverter) resp. 3 .. 50 ms (other diverters) depending on the chosen width of the nozzle. The standard deviation of transition time is 0.2 ms. The start and stop signal will be justified at the symmetry line with a maximum deviation of ± 1 mm.

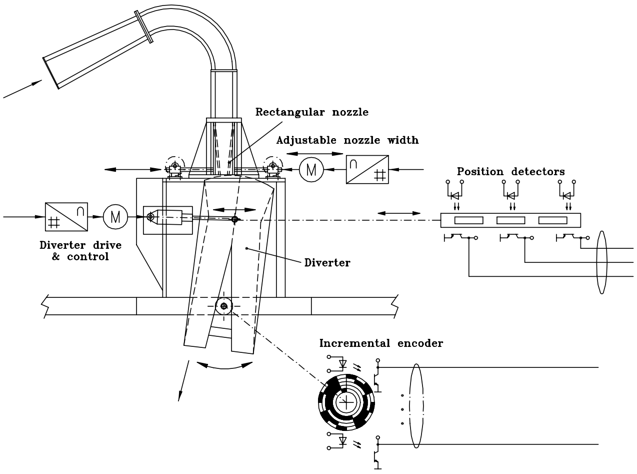

Figure 5. Flow diverter

Under these suppositions for measuring times not smaller than 50 s the contribution of the flow diverter to the total standard uncertainty is expected to be smaller or equal to 0.004 %. Results of investigations (using methods given in [4]) on a diverter of similar design at PTB showed, that this is a realistic value.

3) Determination of liquid density

The water density will be determined in two ways:

- By measuring the water temperature in the measuring section and calculation the density using an appropriate formula for the distilled water density together with an experimentally determined constant factor. The uncertainty of the measured water temperature must be smaller than 0.1 °C and the expected standard uncertainty of the calculated density is 0.004 %.
- By continuous density measurement in a particular by pass upstream the measuring section. Comparing the results of both methods it can be checked, if there are additional error influences (e.g. impurities or gas within the liquid).

4) Pipe prover

For direct volumetric measurements a small volume pipe prover with continuous measurement of the piston position is used (Fig. 6). The calibration will be carried out both geometrically (by measuring the inner diameters) and volumetrically (by water draw method). The expected standard uncertainty of the calibration is 0.005 %.

Besides it's work as an independent standard for effective flowmeter calibration, the pipe prover can be used for internal comparison measurements against the gravimetric test rig to investigate the measurement uncertainty experimentally (see subparagraph C). By using a set of parallel turbine meters in series to the prover, it's flow rate can be enlarged up to the maximum flow rate of the gravimetric test rig.

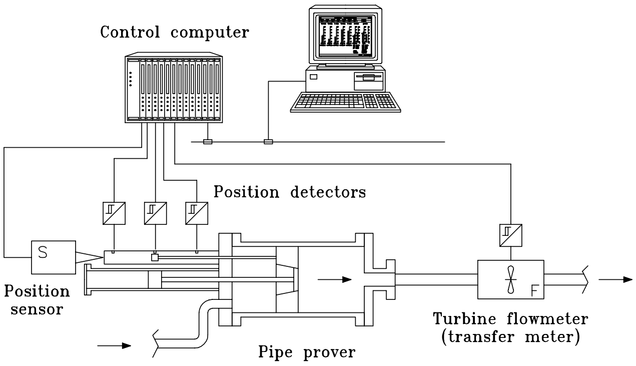

Figure 6. Pipe prover with transfer meter

5) Automatic control facilities

In order to achieve a high accuracy in flow calibration, it is necessary to stabilise the process variables flow rate, temperature and pressure very accurately. Special means and facilities are provided to fulfil these tasks in the new PTB water calibration rig:

- Pressure and flow stabilisation basing on a 30-m³ constant head tank
- Supplementary level, pump speed, and flow rate control loops
- Dual fine and coarse temperature control loops

In the first order, the pressure or the flow rate, respectively, is stabilised due to the weir in the constant head tank. To ensure that there is a stable overflow with a constant level above the weir and a smooth surface, level sensing and controlling devices are provided (Fig. 7).The signal output of this controller and the actual flow rate in the test section act as a variable set point to the pump speed controller of the test rig. In this way a constant level, i.e. a constant pressure and flow rate in the test section, is realised.

A second significant controlling facility are the temperature metering and regulating devices. The thermal energy, induced by the pumps, causes an increase in water temperature. This effect and its dynamics are influenced by the actual pump speed, the total water contents of the system and the thermal dissipation to the environment.

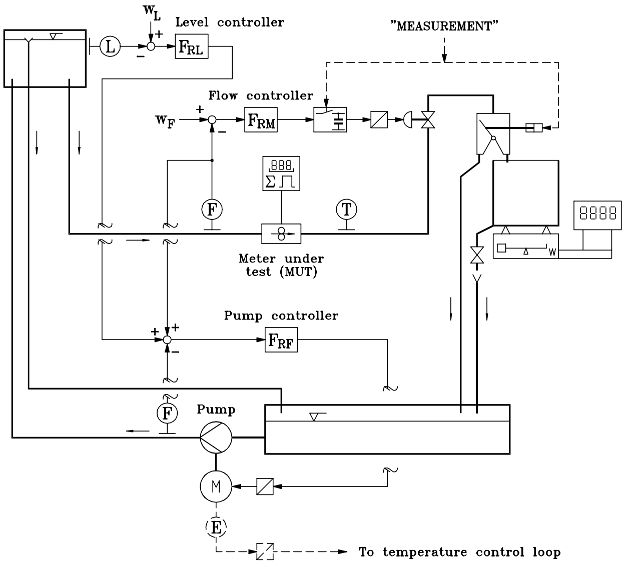

Figure 7. Fluid flow calibration facility: flow control loops

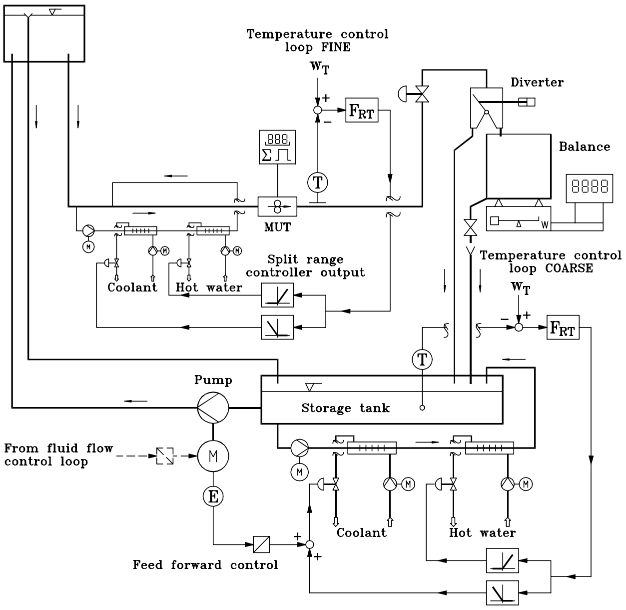

Figure 8. Temperature control loops

Fig. 8 shows in a schematic diagram the items of the temperature regulating facilities. The aim of the temperature control is to stabilise the fluid temperature in the test section. Owing to the fact that at any flow rate the total water contents in the pipe work is incorporated in the circulation, time delay constants of the system's temperature response due to change in pump speed or environmental temperature will vary over tremendously wide range. Under this point of view the task of temperature stabilisation was dedicated to two separate control loops: coarse and fine control.

The first acts as a temperature stabilising control loop in the storage tank and the latter upstream the measuring section(s). In both cases, a part of the test fluid is fed to a by-pass pipe system via two heat exchangers to heat or to cool this by pass stream. Returned to the storage tank or the measuring section, respectively, this by-stream controls the water temperature in the whole pipe system. In order to improve the dynamic behaviour , i.e. to reduce the response time on flow rate changes, the measured actual pump power is fed to the temperature control loop as a feed-forward signal (see Fig. 8).

All these analog control functions will be implemented in a computer-based process control system that serves to automate all the functions of the whole test rig:

- Analog and binary signal process data acquisition
- Analog and logic control
- Process visualisation and graphical operator interface
- Sequential control (system start-up, measurement procedures, system shutdown)
- Fail-safe control function (supervision of critical process variables, e.g. water level in weighing tanks).

6) Further error influencing factors

The *buoyancy factor* will be corrected considering the air density within the weighing tank. Therefor the temperature in the weighing tank is measured. A possible changing of this temperature during the measurement is also taken into account because a deviation of 2 °C together with a slightly filled weighing tank can cause an error of 0.01 %.

The *compressibility of water* is corrected, also a possible thermal expansion of the *pipe volume* between the meter under test and the diverter.

Evaporation errors can be considered as negligible when temperature variations within the weighing tank during the measurement are smaller than 3 .. 6 °C (depending on the filling grade). *Gas content* in the measuring water must be avoided and will be checked by continuous density measurement and comparison measurements with the pipe prover.

C. Proving the uncertainty by internal comparison measurements

It's a recognised fact, that a theoretical error analysis together with static tests of the main elements of a test rig is not sufficient for the realistic evaluation of total uncertainty - a completion by intercomparison programs is absolutely needed [5],[6].

Because of insufficient long-term stability of the available flow transfer standards, for high accuracy standard devices in [7] a new concept was presented: the total error analysis by internal comparison measurements between two metrologically independent standard devices. Using this method, it is possible to determine experimentally different parts of total uncertainty, e.g. the short-term component (repeatability), a medium-term (day-to-day or week-to-week) uncertainty and a long-term component.

This concept for investigation and verification the total uncertainty will be realised by comparing the gravimetric part (balance and diverter) and the volumetric part (pipe prover) of the test rig. The obtained standard deviations will comprise contributions of both measuring devices, which can be separated however by using a special method [8]. As an example, for a gravimetric test facility in a test installation a short-term standard deviation of 0.0037 % and a medium-term standard deviation over two weeks of 0.005 % were obtained [7].

Internal comparison measurements can also be used for investigating single error sources and correlation effects (examples are described in [7,8]).

IV. CONCLUSION

The concept of a new primary standard for liquid flow measurement at PTB Braunschweig has been presented. To attain the claimed total standard uncertainty of 0.01 % much effort is needed to reduce the influence of different error sources but also a new approach in proving and verifying the total uncertainty in an objective way. This will be done by internal comparison measurements between two metrological independent flow standard devices.

As a national standard the new test rig will be the basis to prove and confirm the claimed total uncertainties of water flow calibration facilities in accredited laboratories in Germany. Together with flow standards of similar accuacy level in other countries it would be possible to establish an international standard as a group standard linked by intercomparisons. Flow measurement laboratories having traceability to such an international standard could offer a much better comparability and a higher credibility of their calibration results in a global market.

[1] ISO International Standard Organisation: *"Guide to the expression of uncertainty in measurement"*, 1992

[2] PTB report (unpublished): *"Hydrodynamisches Prüffeld" (Hydrodynamic test facility*, Chapter 4: Uncertainty budget and requirements to attain the claimed measurement uncertainty) , PTB, 1998, Braunschweig (Germany)

[3] W. Pöschel, *"Methoden zur realistischen Bewertung der Meßunsicherheit von Normalmeßeinrichtungen zur Mengen- und Durchflußmessung von Flüssigkeiten (Methods for a realistic evaluation of the uncertainty of liquid flow standards)"*, Thesis, College of Advanced Technology at Leuna- Merseburg (Germany) 1986

[4] ISO International Standardisation Organisation, *"Measurement of liquid flow in closed conduits - Weighing method"*, ISO 4185, 1980.

[5] G. E. Mattingly, *"Dynamic Traceability of Flow Measurements"*, FLOMEKO 1979, Tokyo (Japan), Proceedings pp. 401-411.

[6] E. A. Spencer, *"Improving the Transfer of Flow Measurement Technology to Industry"*, FLOMEKO 1993, Seoul (Korea), Proceedings pp. 3-9.

[7] W. Pöschel, *"Investigation and Verification of the Measurement Uncertainty of High Accuracy Flowmeter Calibration Devices by Internal Comparing Measurements"*, Report of the 5th International IMEKO-Conference, Duesseldorf,Oct. 1989 (VDI-Berichte No 768, p. 247-256, VDI-Verlag, Duesseldorf, Germany, 1989).

[8] W. Pöschel, *"Testing the Repeatability of flow Meter Calibration Devices"*, 2nd Brazilian Symposium on Flow Measurement, 1995, Sao Paulo (Brazil), Proceedings pp. 171-181.