

NEW TEST FACILITY FOR LARGE WATER FLOWRATES UP TO 1000 m³/h IN A TEMPERATURE RANGE BETWEEN 3 °C AND 90 °C AT PTB - BERLIN

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Abstract

PTB's Thermal Energy Measurement Section built up a new gravimetric test facility, serving as the national primary standard for volume flowrates of water from 3 m³/h to 1000 m³/h and temperatures between 3 °C and 90 °C. The maximum Reynold's number achieves a value of $5.5 \cdot 10^6$. The test facility can be operated in four different modes to generate the water flow and comprises two independent weighing procedures, to obtain highly-valuable measurement results with an expanded combined uncertainty of 0.04%.

This paper describes the test facility with particular consideration of the technical methods to achieve this high accuracy level.

Introduction

As shown in fig. 1, the new test facility extends the calibration and measurement capabilities of PTB's Thermal Energy Measurement Section. We are now able to provide traceability in the whole technical relevant flow rate range from 10 l/h up to 1000 m³/h typically in a temperature range from 20 °C to 80 °C and/or 90 °C, respectively. The new test facility additionally covers temperatures down to 3 °C and makes therefore accessible the emerging market for comfort-cooling meters. The test device will be used for pattern approval tests of both industrial heat meters as well as comfort-cooling meters. Furthermore the unique measurement facility will be offered to research and development work within the framework of industrial cooperations, e. g. for the development of transfer standards for volume flow / flow rate with sufficiently small uncertainties.

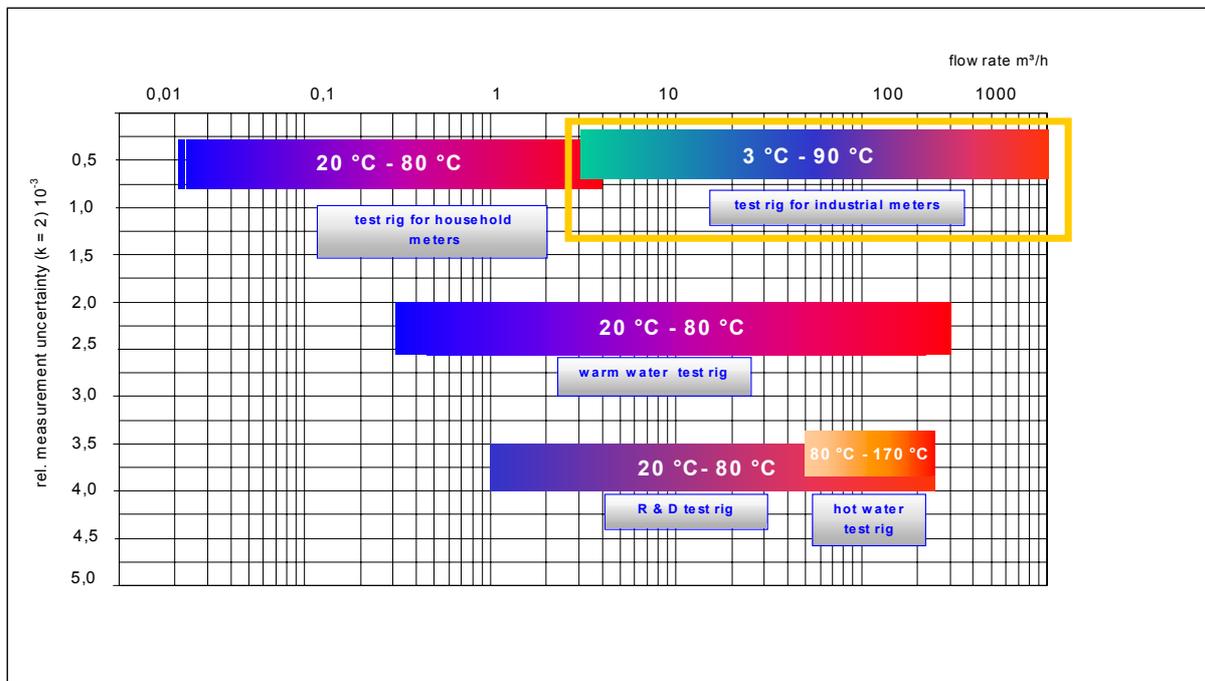


Figure 1: The measurement and calibration capabilities for volume flow of PTB's Thermal Energy Measurement Section. The temperature ranges of the different test facilities are indicated by corresponding colours.

Survey of the new test facility

As shown in fig. 2 the test facility extends over 2 floors, with two measuring sections of 25 m length each and a height of 11 m of the constant level tank. From a service area in the basement comprising collection tank ($V = 40 \text{ m}^3$) and storage tank ($V = 65 \text{ m}^3$), the test facility is supplied with water flow in four different operation modes

- by means of frequency controlled circulation pumps up to a volume flow rate of $1000 \text{ m}^3/\text{h}$,
- using a constant level tank for small volume flow rates up to $80 \text{ m}^3/\text{h}$, for pulsation-free water flow at a constant static pressure,
- using the pressure-based "single" mode for flow rates up to $200 \text{ m}^3/\text{h}$, where the water of the storage tank is expelled pulsation-free by compressed air at pressures up to 5.5 bar,
- using the pressure-based "continuous" mode for flow rates up to $1000 \text{ m}^3/\text{h}$ at pressures between 1.5 bar and 5.5 bar, where the expelled water of the storage tank is refilled continuously using frequency controlled pumps between the collection and the storage tank.

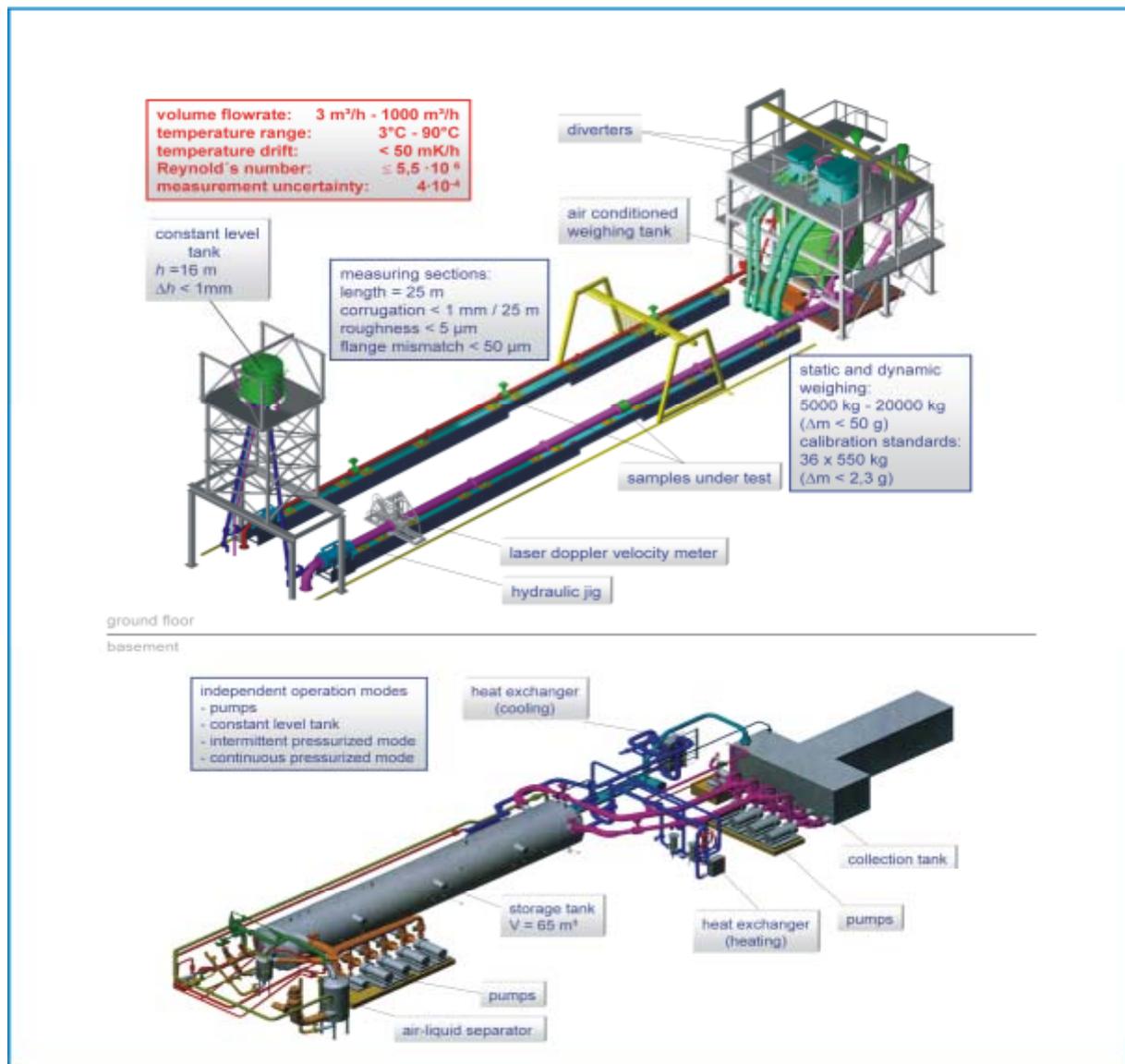


Figure.2: View of the new gravimetric test facility for large water flow rates of PTB

The temperature of the water entering into one of the two measuring sections in the ground floor varies less than 100 mK during 2h. Additionally the density and the conductivity of the water is measured.

The pipe diameters range from DN 80 to DN 400. The carefully designed double wall pipes are characterised by smoothed inner surfaces and a reduced mismatch of flanges of less than 50 µm. This allows the water flow to form an undisturbed, fully developed turbulent flow profile. Its velocity distribution can be measured via specially designed window-chambers using a Laser-Doppler-Velocimeter with a measuring volume of less than 100 µm in maximum dimension. The gravimetric system comprises the weighing tank ($V = 20 \text{ m}^3$) mounted on four weighing platforms. Before a weighing process, the balance can be calibrated within less than 60 sec. by an automated loading and unloading procedure, where a combination of 36 mass standards (560 kg each) is used to determine the calibration curve of the balance. For the static measurement the mass of the water in the weighing tank is determined within 50 grams. The inlet of the weighing tank consists of a steel plate with 250 drain pipes, in order to ensure low and defined momentum transfer from the water flowing into the weighing tank. On top of the weighing tank two closed diverters of different sizes are mounted. The diverter systems (see fig. 3) are carefully designed to avoid evaporation losses during the filling time as an influence quantity and to allow the deflection of large volume flow rates with a minimum of momentum transfer in shortest times. The switching process for the water either filling the weighing tank or moving directly into the collection tank takes approximately 1 s, repeatability of the switching process is better than 13 ms. Another influence quantity is reduced by providing the weighing tank at the beginning of the measuring procedure with air of well defined temperature and humidity. During the filling process, the humidity and the temperature of the expelled air from the weighing tank is controlled. Besides the common static weighing procedure, the weighing system can be used in a dynamic procedure, where the use of the diverter is avoided and the weight of chosen mass standards is replaced by the same amount of water during the measuring time. For this purpose the readout frequency of the weighing cells is increased up to 40 Hz, whereas each readout of each cell is time-stamped within an uncertainty of less than 0,7 ms. To avoid influences from thermally driven air flow and air draught in the measurement hall during the dynamic weighing procedure, it is planned to build up a temperature stabilised containment for the whole weighing system.

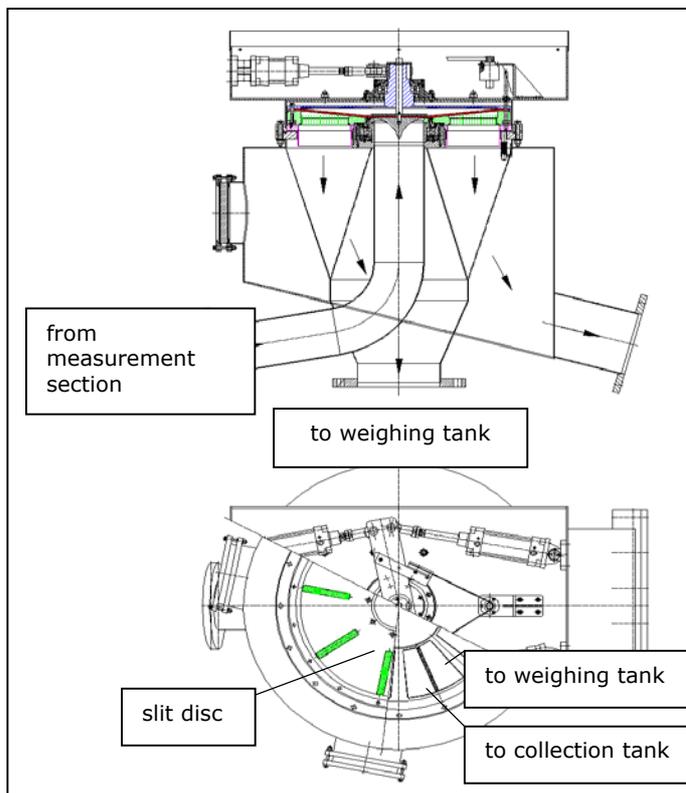


Figure 3: functional principle of the diverters:

The water flow is divided symmetrically in 8 portions flowing against a diaphragm, which covers a radial symmetric slit disc. Dependent of the position of the slit disc the flowing water enters the weighing tank or is led directly into the collection tank.

Measurement uncertainty

As already pointed out, the test facility will be operated as a national primary standard to provide traceability for the volume flow / flow rate of water up to 1000 m³/h in the temperature range between 3 °C and 90 °C. The extended combined uncertainty of this test facility is assessed to be 0.04 % in the whole parameter range.

This value is deduced for the commonly used static weighing procedure, where in a two-stage process the scale of the balance is transferred to a master-meter (a magnetic-inductive flow meter, in our case), to which the flow meter under test is compared.

According to the Guide to the expression of Uncertainty in Measurement (GUM) [1] the measurement deviation of a meter under test is given as

$$D_{\text{mut}} = \frac{V_{\text{act}} - V_{\text{nom}}}{V_{\text{nom}}} \quad (1)$$

where V_{act} and V_{nom} are the actual and nominal values for the volume of water passed through the flow meter under test. The corresponding variance is given as

$$s_{D,\text{mut}}^2 = \left(\frac{1}{V_{\text{nom}}} \right)^2 s_{V,\text{act}}^2 + \left(\frac{V_{\text{act}}}{V_{\text{nom}}^2} \right)^2 s_{V,\text{nom}}^2 \quad (2)$$

Neglecting $s_{V,\text{act}}^2$ and assuming $V_{\text{nom}} \approx V_{\text{act}}$ [2],

$$s_{D,\text{mut}}^2 = \left(\frac{1}{V_{\text{nom}}} \right)^2 s_{V,\text{nom}}^2 \quad (3)$$

follows from Eq. (2).

The nominal value of the volume of water passed through the meter under test is given as:

$$V_{\text{nom}} = V_{\text{M}} + \Delta V_{\text{T}} + \Delta V_{\text{P}} + \Delta V_{\text{A}} \quad (4)$$

- with
- V_{M} volume of the water passes through the master-meter,
 - ΔV_{T} difference of volume of water passed through the meter under test and the master-meter due to changes of the temperature of the water,
 - ΔV_{P} difference of volume of water passed through the meter under test and the master-meter due to temperature caused changes in the dimensions of the pipes and
 - ΔV_{A} difference of volume of water passed through the meter under test and the master-meter due to temperature caused changes of the volume of air in the water.

V_{M} is given as

$$V_{\text{M}} = \frac{M_{\text{M}}}{\rho_{\text{M}}} + \Delta V_{\text{D}} \quad (5)$$

- with
- M_{M} mass of the water passed through the master-meter,
 - ρ_{M} corresponding density and
 - ΔV_{D} difference of water volume collected in the weighing tank caused by systematic measurement deviations during the diverter switching process.

The mass M_M of the water passed through the master meter is determined by a static weighing process. Taking into account the influences of buoyancy and the effects of humidity, M_M holds Eq. (6):

$$M_M = \frac{\Delta G \left[\left(1 - \frac{\rho_A}{\rho_N} \right) - V_0 (\rho_{A2} - \rho_{A1}) \right]}{\left(1 - \frac{\rho_{A2}}{\rho_{W2}} \right)} \left(1 - \frac{h_2}{\rho_{W2}} \right) + V_0 (h_2 - h_1) + M_A \quad (6)$$

with:	M_M	mass of the water passed through the master-meter	in kg
	ΔG	difference in weight of the filled and the empty weighing tank, corrected with the actual calibration curve of the balance	in kg
	ρ_A	density of the ambient air	in kg/m ³
	ρ_N	density of the calibration weights	in kg/m ³
	V_0	volume of the weighing tank	in m ³
	ρ_{A1}	density of the air inside the weighing tank before the filling process	in kg/m ³
	ρ_{A2}	density of the air inside the weighing tank after the filling process	in kg/m ³
	ρ_{W2}	density of the water inside the weighing tank after the filling process	in kg/m ³
	h_1	humidity of the air inside the weighing tank before the filling process	in kg/m ³
	h_2	humidity of the air inside the weighing tank after the filling process	in kg/m ³
	W_A	mass of the water in the expelled air	in kg

In the case of PTB's new test facility, the weighing tank is filled with well-defined, saturated air at the same temperature of the water passing through the master-meter.

Therefore Eq. (6) simplifies to

$$M_M = \frac{\Delta G \left(1 - \frac{\rho_A}{\rho_N} \right)}{(\rho_{W2} - \rho_{A2})} \quad (7)$$

and together with Eq. (5) the nominal volume of the water passed through the meter under test is given as

$$V_{\text{nom}} = \frac{\Delta G \left(1 - \frac{\rho_A}{\rho_N} \right)}{(\rho_{W2} - \rho_{A2})} + \Delta V_D + \Delta V_T + \Delta V_P + \Delta V_A \quad (8)$$

The corresponding variance holds Eq. (9)

$$s_{V,\text{nom}}^2 = \left(\frac{\partial V_{\text{nom}}}{\partial \Delta G} \right)^2 s_{\Delta G}^2 + \left(\frac{\partial V_{\text{nom}}}{\partial \rho_A} \right)^2 s_{\rho_A}^2 + \left(\frac{\partial V_{\text{nom}}}{\partial \rho_{W2}} \right)^2 s_{\rho_{W2}}^2 + \left(\frac{\partial V_{\text{nom}}}{\partial \rho_{A2}} \right)^2 s_{\rho_{A2}}^2 + \left(\frac{\partial V_{\text{nom}}}{\partial \rho_N} \right)^2 s_{\rho_N}^2 + \left(\frac{\partial V_{\text{nom}}}{\partial \Delta V_D} \right)^2 s_{V,D}^2 + \left(\frac{\partial V_{\text{nom}}}{\partial \Delta V_T} \right)^2 s_{V,T}^2 + \left(\frac{\partial V_{\text{nom}}}{\partial \Delta V_P} \right)^2 s_{V,P}^2 + \left(\frac{\partial V_{\text{nom}}}{\partial \Delta V_A} \right)^2 s_{V,A}^2 \quad (9)$$

The sensitivity coefficients are calculated for a complete filling of the weighing tank ($\Delta G = 20\,000$ kg) at the maximum flow rate (1000 m³/h) with a water density of 1000 kg/m³ and the air density of 1.15 kg/m³ and a maximum temperature drift of 100 mK within 2h.

Together with the measurement uncertainties described in the section above the total measurement uncertainty can be assessed as:

Table 1:

input parameter	uncertainty ¹ of the input quantities	sensitivity coefficient	contribution to the measurement uncertainty
ΔG	$2.89 \cdot 10^{-2}$ kg	$1.0 \cdot 10^{-3}$ m ³ /kg	$2.89 \cdot 10^{-5}$ m ³
ρ_{Lu}	$2.89 \cdot 10^{-3}$ kg/m ³	$2.5 \cdot 10^{-3}$ (m ³) ² /kg	$7.23 \cdot 10^{-6}$ m ³
ρ_N	$1.73 \cdot 10^{-1}$ kg/m ³	$3.4 \cdot 10^{-7}$ (m ³) ² /kg	$5.88 \cdot 10^{-8}$ m ³
ρ_{W2}	$5.77 \cdot 10^{-2}$ kg/m ³	$2.0 \cdot 10^{-2}$ (m ³) ² /kg	$1.15 \cdot 10^{-3}$ m³
ρ_{L2}	$1.44 \cdot 10^{-2}$ kg/m ³	$2.0 \cdot 10^{-2}$ (m ³) ² /kg	$2.88 \cdot 10^{-4}$ m ³
ΔV_U	$3.61 \cdot 10^{-3}$ m ³	1	$3.61 \cdot 10^{-3}$ m³
ΔV_R	$1.08 \cdot 10^{-4}$ m ³	1	$1.08 \cdot 10^{-4}$ m ³
ΔV_T	$1.18 \cdot 10^{-4}$ m ³	1	$1.18 \cdot 10^{-4}$ m ³
ΔV_L	$2.13 \cdot 10^{-5}$ m ³	1	$2.13 \cdot 10^{-5}$ m ³

¹ normal distributed

absolute combined measurement uncertainty (k=1) $4.0 \cdot 10^{-3}$ m³
relative expanded measurement uncertainty (k=2) **0.04 %**

As can be seen from table 1 the uncertainty of the water density as well as the uncertainty due to the diverter switching process constitute the main contributions to the combined measurement uncertainty.

Conclusion

PTB's new gravimetric test facility will serve as the national primary standard for volume / volume flow rates of water from 3 m³/h to 1000 m³/h and temperatures between 3 °C and 90 °C. Measurement results will be obtained within an expanded combined uncertainty of 0.04% using the static weighing procedure.

Two main future challenges will be

- the investigation of the measurement performance and corresponding uncertainty for the dynamic weighing procedure and
- the use of this unique measurement equipment for the development of improved transfer standards for volume flow / flow rate with reduced relative uncertainties of about 0,05 % or less, necessary for the upcoming intercomparisons of test facilities in Europe and/or world-wide.

References

- [1] ISO International Standard Organisation: "Guide to the expression of uncertainties in Measurement", 1992
- [2] PTB report: "Messanlagen für Volumenmessteile von Wärmezählern – derzeitiger Stand und Entwicklungen, Verlag NW 1995, ISBN 3-89429-911-8