

# Bell Prover – Calibration and Monitoring of Time Stability

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**Abstract:** This paper is focused on the calibration and measuring of the geometric parameters of a bell prover, that served as a standard of volume of gas flow. It also includes methods for monitoring of time stability of the bell prover: intra- and inter-laboratory comparison measurements, Shewhart analysis and planned evaluation of recalibration intervals.

**Keyword:** Bell prover, Uncertainty analysis, Time stability, Inter-laboratory comparison, Recalibration interval

## 1. Introduction

The primary standard of gas flow rate – the bell prover - was established by Slovak Institute of Metrology (SMU) during 1999 to 2002. The flow range of this standard is (from 2 to 65) m<sup>3</sup>/h, the expanded uncertainty of measurements is 0,12 %<sup>[1,2]</sup>. This standard is listed in CMC tables BIPM (SK 13)<sup>[3]</sup>.

## 2. Mathematic model of a bell prover

The volumetric flow rate realized by a primary standard - bell prover is evaluated as follows<sup>[4]</sup>:

$$Q_{VZ} = \frac{h_c \cdot S_c}{\Delta t} + \frac{\Delta r_a \cdot V_a}{r_c \cdot \Delta t} + Q_{Vn} = \frac{\sum_{j=1}^n K_j \cdot I_j}{\Delta t} + \frac{\Delta r_a \cdot V_a}{r_c \cdot \Delta t} + Q_{Vn} \quad [\text{m}^3 \cdot \text{h}^{-1}] \quad (1)$$

where:

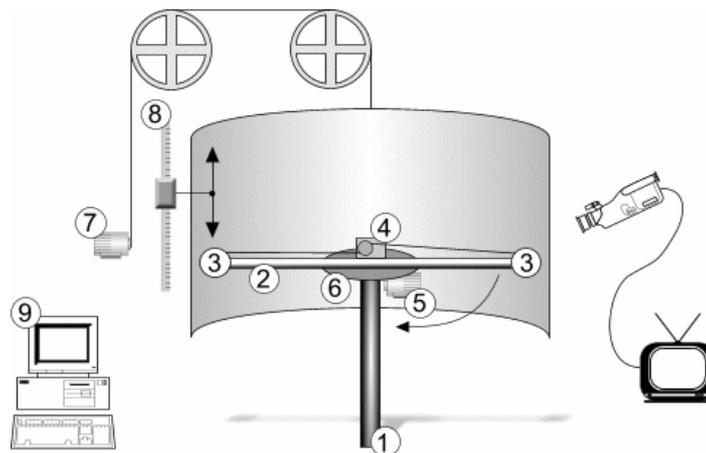
$h_c$	length of the vertical displacement of the bell [m]
$S_c$	cross-sectional area of the bell [m <sup>2</sup> ]
$V_a$	residual volume of air in the system [m <sup>3</sup> ]
$\Delta \tau$	time interval of measuring cycle [h]
$\rho_c$	density of discharged air [kg. m <sup>-3</sup> ]
$\Delta \rho_a$	change in air density during the measuring cycle [kg. m <sup>-3</sup> ]
$Q_{Vn}$	volumetric flow rate through leaks [m <sup>3</sup> . h <sup>-1</sup> ]
$K_j$	pulse coefficient [m <sup>3</sup> . imp <sup>-1</sup> ]
$I_j$	number of pulses [imp]

## 3. Calibration of the bell prover

Calibration includes the bell prover inside part geometric dimensions in 110 horizontal levels. Furthermore instruments installed in the primary standard were calibrated including associated uncertainties so they are included in the uncertainty budget of the equation (1).

### 3.1 Determination of geometrical parameters of the bell

A special structure for centering of the measuring device placed inside the primary standard frame and for attaching the measuring arm was manufactured prior the measurement (Fig. 1, position 1). The platform of this structure (pos. 6), where the arm was clamped, was equipped with the step motor (pos. 5) for 180° horizontal displacement.



*Fig. 1 Scheme of geometrical parameters bell measuring equipment*

The contact method was selected after preliminary tests and the digital micrometers with communication interface (pos. 3) having the measuring range of 12 mm, with a resolution of 1  $\mu\text{m}$  and the possibility of remote transmission of measured data were used. Non equal distance of measuring points was specified based on the final bell manufacturing. The points at 50 mm distance were designated on the circumference of the inner casing and 10 mm distance around the weld. Because of 1100 mm working stroke it was decided that the measurements would be performed in the horizontal plane and in the 110 planes, it means that the vertical displacement of measurements would be 10 mm. A vertical displacement was performed by bell displacement, which was driven using a step motor for the vertical ruler movement (pos. 7). Location of the bell was taken using an optical ruler (pos. 8). Angle rotation of the arm, respectively shifting in the vertical direction was carried out when the micrometer tips were out of contact with the bell (protection of tips against abrasion). It was ensured by assembly mechanism (pos. 4), that detached tips from the bell after the reading. The process of determining geometrical parameters run fully automatically and was controlled from the control centre by a computer program designed specifically for these measurements (pos. 9). The measurement was performed in the air-conditioned enclosure ( $22 \pm 0,1$ ) °C. Video camera system was monitored the measurement inside the bell and was recorded in the control center. The measurements were performed in fifty diameters in the horizontal plane. Based on measurements in 110 planes the cycle of measurements included 5 500 measurement points. The time interval of one cycle of measurements was approximately 12 hours. Every cycle was repeated three times and data were recorded in the database files<sup>[4]</sup>.



Fig. 2 Measurement of geometrical parameters of the bell

The diameter was calculated according to the following:

$$d_{j,i} = 1099,99 + 12,0 - a_{1,j,i} - a_{2,j,i} \quad [\text{mm}] \quad (2)$$

where:

$d_{j,j}$  measured internal diameter of the bell at an angle  $\alpha_{j,j}$  on the height  $h_j$  [mm]

$a_{1,j,i}$  value given by the sensor No.1 [mm]

$a_{2,j,i}$  value given by the sensor No. 2 [mm]

value 1099,99 is statement from the calibration certificate of the measuring arm [mm]

value 12,0 is the sum of half-strokes of both micrometers, on which micrometers by calibration of measuring arm were set [mm].

These measured data of the inner diameters of the bell were then transferred to the computer program where the area for each plane was calculated using the following equation:

$$s_j = \sum_i (p_{1,j,i} + p_{2,j,i}) \quad [\text{mm}^2] \quad (3)$$

where:

$s_j$  a surface of the bell in the plane j

$p_{1,j,i}$  a surface of the bell in the plane j, in the segment i, for the angle  $(\alpha_{j,i+1} - \alpha_{j,i})$ , for the sensor No. 1 [mm<sup>2</sup>]

$p_{2,j,i}$  a surface of the bell in the plane j, in the segment i, for the angle  $(\alpha_{j,i+1} - \alpha_{j,i})$ , for the sensor No. 2 [mm<sup>2</sup>].

Area of the segment  $p_{1,j,i}$  is expressed in the following equation:

$$p_{1,j,i} = \frac{a_{j,i+1} - a_{j,i}}{6} \cdot (r_{1,j,i+1}^2 + r_{1,j,i+1}r_{1,j,i} + r_{1,j,i}^2) \quad [\text{mm}^2] \quad (4)$$

where:

$$r_{1,j,i} = \frac{1099,99}{2} + 6 - a_{1,j,i} \quad [\text{mm}] \quad (5)$$

is an radius determined by the sensor No. 1 in the plane j by measurement i.

Similarly area of the segment  $p_{2j,i}$  is expressed in the following equation:

$$p_{2j,i} = \frac{a_{j,i+1} - a_{j,i}}{6} \cdot (r_{2,j,i+1}^2 + r_{2,j,i+1}r_{2,j,i} + r_{2,j,i}^2) \quad [\text{mm}^2] \quad (6)$$

where:

$$r_{2,j,i} = \frac{1099,99}{2} + 6 - a_{2,j,i} \quad [\text{mm}] \quad (7)$$

given radius determined by the sensor No. 2 in the plane j by measurement i.

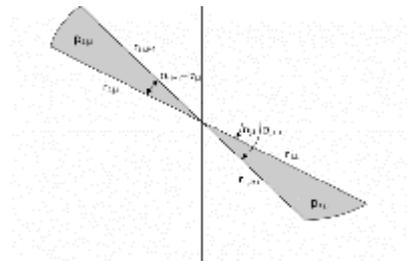


Fig. 3 Graphical representation of measurement of the area of the bell

Areas of the bell in the single cross sections were calculated from the measured values and the calculation entered into the database of evaluation program of the bell prover. The set of calculated values of the inner diameter of the bell in different horizontal planes in time is presented in figure 4.

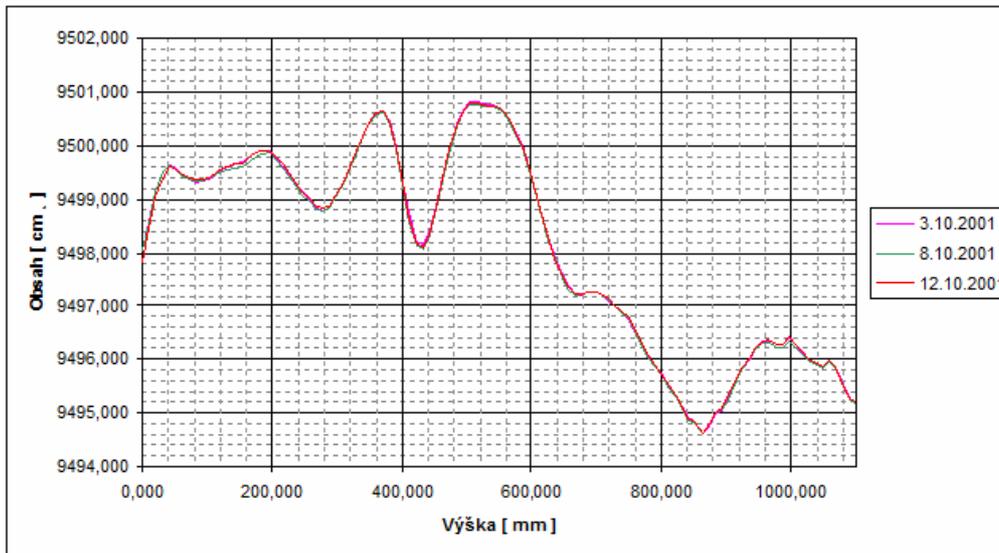


Fig. 4 Charts of the inner bell diameter the areas of in the individual horizontal planes

### 3.2 Sources of uncertainty of measurement of the bell prover

Source of uncertainty	Relative standard uncertainty [%]
<b>Collection volume</b>	<b>0,015</b>
Bell area	0,007
Collection length	0,008
Oil film adherence	0,010
<b>Air density</b>	<b>0,030</b>
Temperature	0,020
Pressure	0,010
Compressibility	0,020
<b>Collection time</b>	<b>0,040</b>
Timer calibration	0,001
Timing error	0,040
<b>Residual volume</b>	<b>0,010</b>
<b>Leakages</b>	<b>0,010</b>
<b>Relative standard uncertainty of flowrate</b>	<b>0,058</b>
<b>Relative expanded uncertainty of flowrate</b>	<b>0,116</b>

*Table 1 Uncertainty budget of the bell prover*

## 4. Interlaboratory Comparisons

The primary standard was bilaterally compared with the primary standard of PTB Braunschweig, Germany in 2002-2005<sup>[5]</sup>. The bell prover was declared in 2007 as a national standard of gas flowrate in the Slovak Republic<sup>[6]</sup>.

The Euramet and Key comparison of national (primary) standards of gas flowrate were initiated by the Slovak Institute of Metrology and they were prepared with the co-operation with PTB for 2010-2011. The results of these comparisons will be used by SMU for independent checking the bell prover main uncertainty contributions<sup>[7]</sup>.

## 5. Time Stability Monitoring

Further it was necessary to have reliable information about state of standard equipment in the period between international comparisons. Therefore the Centre of Flow of Slovak Institute of Metrology developed the method for regular monitoring the bell prover measuring system time stability. The method is based on a data set required using different for monitoring (intra-laboratory comparisons, set of control charts and planned evaluation of recalibration intervals). Fixed points of flow - the critical nozzles – were used as a witness standard for the measuring range of flow rate, too.

### 5.1 Intra-laboratory Comparisons

Eight intra-laboratory measurement comparisons was performed during years 2005 to 2009 between the bell prover and the standard with the equivalent amount of liquid. The standard with the equivalent amount of liquid<sup>[2]</sup> is a part of the national standard of gas flow.

Results of intra-laboratory comparisons are given in the figure 5. Values of standardized deviation  $E_n$  did not exceed the value of  $|0,4|$ .

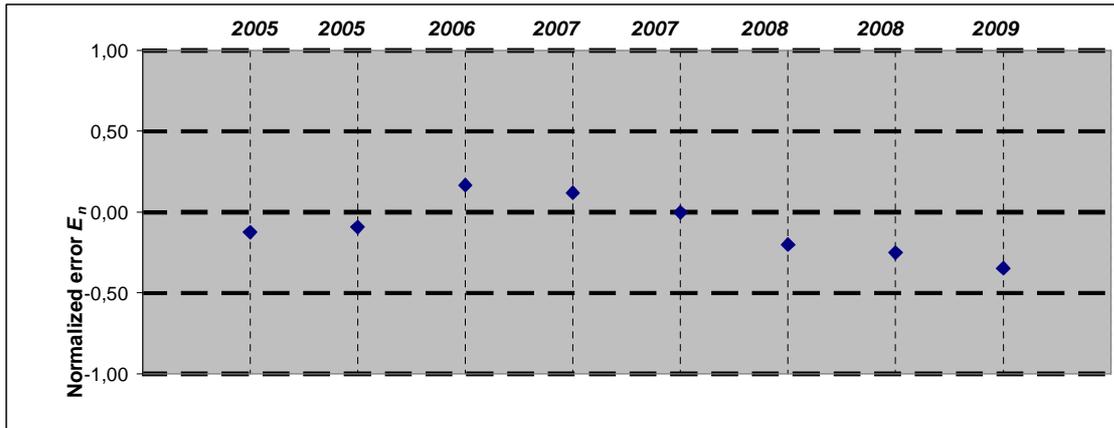


Fig. 5 Normalized errors of intra-laboratory comparisons from 2005 to 2009 between the bell prover and the standard with the equivalent volume of liquid

### 5.2 Shewhart Analysis

The Shewhart regulatory diagrams [8] were chosen as a second tool for the bell prover time stability monitoring. These diagrams are used for identification of determinable causation of variability in the measurement process in the production. The Centre of Flow applied that diagrams to determining of time stability of metrological parameters of the bell prover. The measurements were provided by connection of the critical nozzles (witness standards) with the bell prover.

The diagrams shows the central line representing arithmetic mean of flow rate of the bell prover. Other parallel lines to the central line are warning limits ( $2s$ ) and control limits ( $3s$ ), where  $s$  is the standard deviation of measurement of critical nozzle. All points measured in 2005 – 2009 lie within warning limits and then the time stability of the bell prover is found to be statistically stabile.

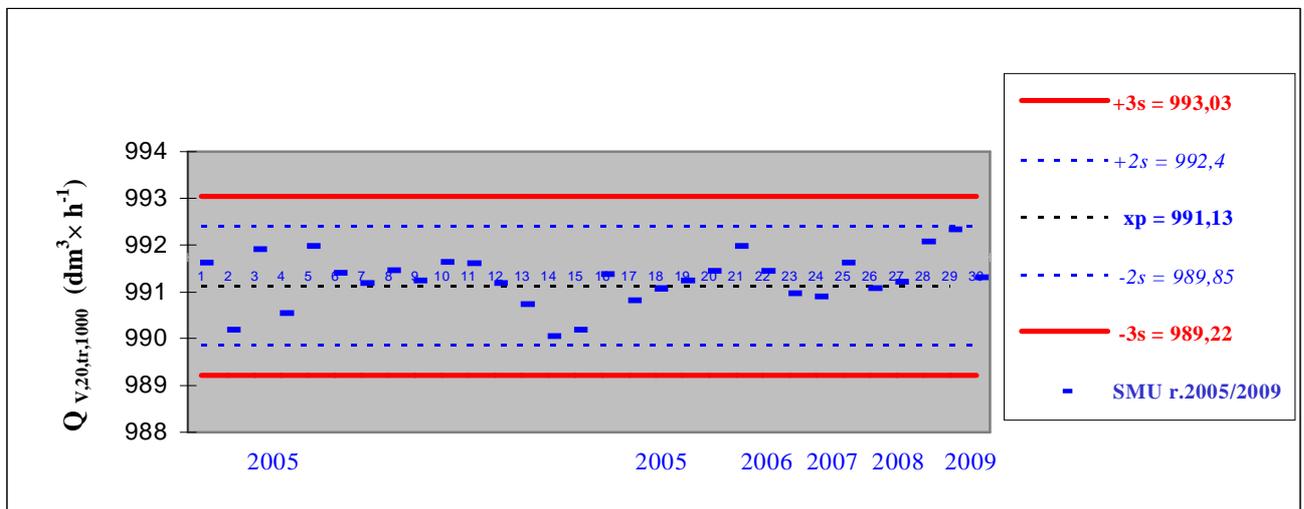


Fig. 6 Regulatory diagram with critical nozzle JT 01-1000-99 in the lower flow range ( $1 \text{ m}^3/\text{h}$ ) - from year 2005 to 2009

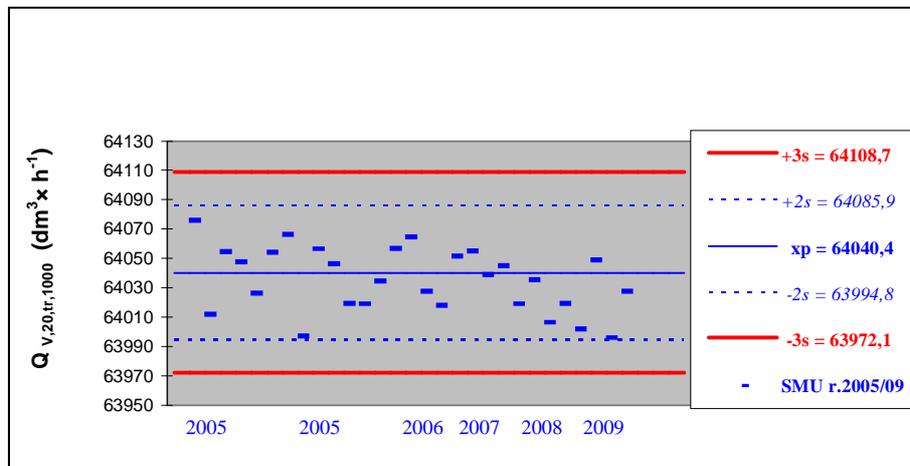


Fig. 7 Regulatory diagram with critical nozzle 02-64000-99 in the upper range of flow ( $64 \text{ m}^3/\text{h}$ ) – from year 2005 to 2009

### 5.3 Planned Project of Recalibration Intervals Evaluation

The Centre of Flow has launched a project for recalibration interval determination for flow standards.

Special attention is paid to the gas flow national standard, which the bell was measured in 2001. Monitoring the time stability of the bell prover will continue. However, analysis and design of the recalibration interval exhibit what time it will be necessary for next measurement of the geometrical parameters of the bell. The project is based on the document OIML and NASA Guide<sup>[9,10]</sup>.

## 6. Results

Monitoring tool	Criteria	Fulfil of criteria	Note
Intra-laboratory comparison	$ E_n  < 1$	$-0,4 < E_n < 0,2$	-
Shewhart analysis	$x_p - 3s < Q < x_p + 3s$	$x_p - 2s < Q < x_p + 2s$	-
Recalibration intervals	planned	-	project in year 2010

Table 3 Review of monitoring tools

## 7. Conclusion

Previous periodic monitoring in 2005-2009 exhibited that the standard maintained stability within specified limits. The methods described in sections 4.1 and 4.2 consistently confirm the time stability of bell prover.

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