EXPERIENCES FROM A ROUND ROBIN TEST FOR FLUE GAS TEMPERATURE, VOLUME AND FLOW MEASUREMENTS

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ABSTRACT

In Flanders, laboratories, recognised for emission measurements in the framework of the environmental legislation (Vlarem II), have to implement a quality system that meets the requirements of EN 45001 and are forced to participate in external quality controls organised by AMINAL, the Flemish Administration for environment and/or the reference laboratory for air measurements, e.g. Vito (Vlarem, Art. 1.3.3.1.).
In September 2000 a first test for physical parameters was arranged including the determination of flue gas temperature, volume and flow. The aim of these tests is a comparison of the results of the individual participants with the reference value and with each other.
Different gas temperatures were generated in a fluidised sand bath.
For volume control tests, an Automated Gas Flow Calibration System, the Bell Prover, with a total volume of about 600 l was used.
Gas flow measurements were performed in a wind tunnel with a total length of 6 m and an internal diameter of 50 cm. A constant flow was generated by a frequency regulated fan. Homogeneity over the total diameter was ensured by a grid placed just in front of the fan.
The equipment was proved to fulfil the demands of accuracy, reproducibility and traceability.
From the results of the 23 participating laboratories it was concluded that 4, respectively 3 participants show a deviation of more than 1% versus the low and high temperature. Only 5 laboratories had a deviation of more than 10 % compared to the reference volume. The gas velocity results of 18 respectively 20 participants were at least 95% of the reference low and high flow rate.
From the experiences with this ring test it was also concluded that the usefulness of the results could be improved by limiting the allowed equipment, e.g. 1 type of Pitot tube, use of operational field equipment only…

INTRODUCTION

On 6 September 2000 a round robin test was organised for laboratories, recognised for emission measurements in the framework of the environmental legislation in Flanders. The parameters temperature, volume and flue gas velocity were tested. The aim of the test was to compare the results of the individual participants with the reference value, to obtain an estimate of the overall uncertainty of the measurements and to reveal eventual large systematic errors.
23 participants subscribed. They were explicitly asked to use operational field equipment.
The test equipment as well as the results of the round robin test are presented in the next paragraphs. The results were reported anonymous. Each participating laboratory is given a complete report but only knows his own participant number.

DESCRIPTION OF THE TEST EQUIPMENT

Temperature

“Low” and “high” temperatures were generated in a fluidised sand bath with a diameter of 22,8 cm and a useful depth of 14 cm. This bath was filled with 16 kg of alundum. The adjustable temperature range is from 50°C ± 1°C to 600° ± 3°C. The homogeneity is guaranteed by blowing dry air through the sand. The temperature is regulated with a Techne type TC-8D temperature controller, equipped with a chromium alumel type K thermocouple and controlled with a Ametek Digital Temperature Indicator 100 (DTI) from Jofra Instruments, designed for rapid and traceable calibration. The validation of the system was focused on trueness, homogeneity and stability in function of time.
Trueness is guaranteed by a BKO certified reference thermometer.
Homogeneity was tested at five different locations, equally divided over the surface of the sand bath, and at a depth of 6 cm and 13 cm respectively (figure 1).

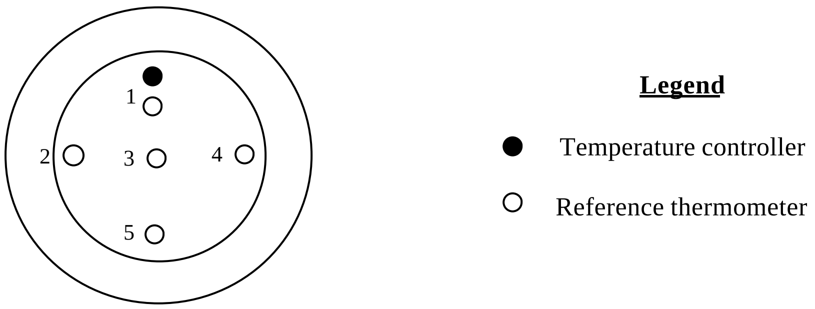


Figure 1: Positions of the measuring points during homogeneity tests

The results, represented in table 1, indicate that the measured temperatures, expressed as 10 minute averages are comparable with the reference value within 1% and this in all 5 measuring points and at both depths.

Table 1: Results of the homogeneity tests for temperature (10 minute averages)

	Reference temperature: 69°C		Reference temperature: 209°C	
Measuring point	**Depth = 13 cm**	**Depth = 6 cm**	**Depth = 13 cm**	**Depth = 6 cm**
1	68,5	68,3	207,4	207,2
2	68,4	68,5	207,2	207,5
3	68,5	68,3	207,2	207,3
4	69,0	68,8	207,7	207,6
5	68,8	68,6	20,80	208,3

The stability of temperature in function of time was tested during 13 hours for a reference value of 69°C and during 20 hours for a value of 209°C. The results are illustrated in figure 2 and 3.

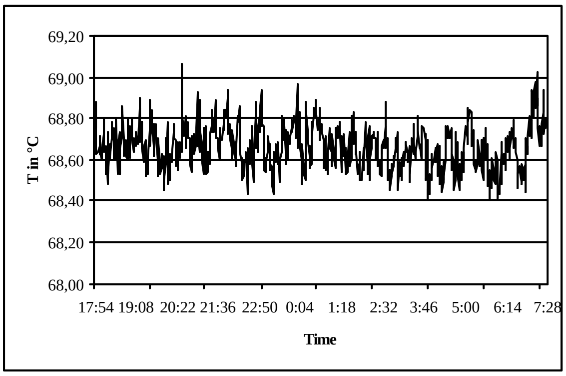


Figure 2: Stability of the reference temperature at 69°C

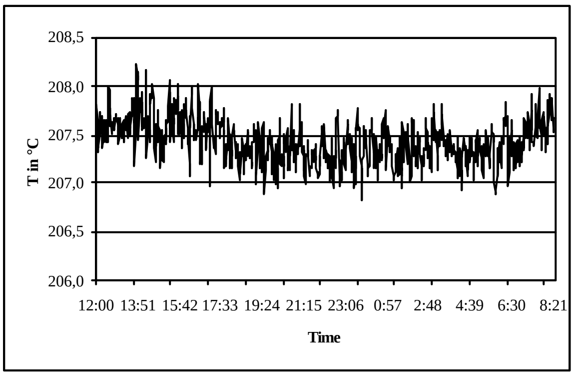


Figure 3: Stability of the reference temperature at 209°C

The average temperature for the 13 hours measuring period was 68,7 °C with a maximum value of 69,1 °C and a minimum of 68,4 °C. For the high temperature range a 20 hours average of 207,4°C was measured with 206,8 °C and 208,2 °C as minimum and maximum respectively.

Volume

Volume tests were performed using a Cal-Bench Automated Gas Flow Calibration System with a total volume of about 600 l. Constructed of stainless steel the prover is fitted with inlet and outlet valving, two counter weights, an optical encoder, and automated inputs of temperature and back pressure measurements. A stainless steel bell of known and consistent volume is suspended in a low vapor pressure oil-filled chamber. As gas flows through the device under test the bell is displaced. The bell is counter balanced throughout its travel by two counter

weights suspended on chains. Thus, as the bell rises, additional segments of chain pass over the pulleys, achieving neutral buoyancy in al positions.
A small gauge wire is connected to the top of the bell and connects to a linear encoder system, which measures the bell's location as it is displaced by the gas flowing into or out of the chamber. Cal-bench collects this information, as well as the temperature and pressure measurements and calculates the mass flow of the gas entering or leaving the prover. The result in an instantaneous reading of gas mass flow.
The methodology is based on primary measurements of length and time.
The cylinder volume was calibrated by the manufacturer with the stratting method: each five cm the outer diameter was taped with certified pi-tape, while the wall thickness was determined with a deep throat micrometer. The mean internal diameter was calculated as the difference between the outer diameter and two times the wall thickness.
The encoder was calibrated with a certified measuring tape.
Temperature measurements were validated between 0°C and room temperature. Pressure was controlled with a certified pressure sensor.
The analogue output signals of displacement, pressure and temperature were continuously registered as 10 s averages with a datalogger coupled to a PC.

Gas flow measurements

The gas flow measurements are performed in a wind tunnel, built by Vito. This stainless steel tunnel has a total length of 6 m and an internal diameter of 50 cm. A constant gas flow is generated by a frequency regulated fan and continuously measured with a standard Pitot tube. The results are recorded on a computer. To obtain a sufficient homogeneous velocity and to limit swirl, a flow straightening grid is placed just in front of the fan. The wind tunnel is equipped with 6 measuring holes: three of them could be used by the participants, the other three were intended for the reference standard Pitot tube, a thermocouple and a probe for relative humidity.
The equipment is represented schematically in figure 4.

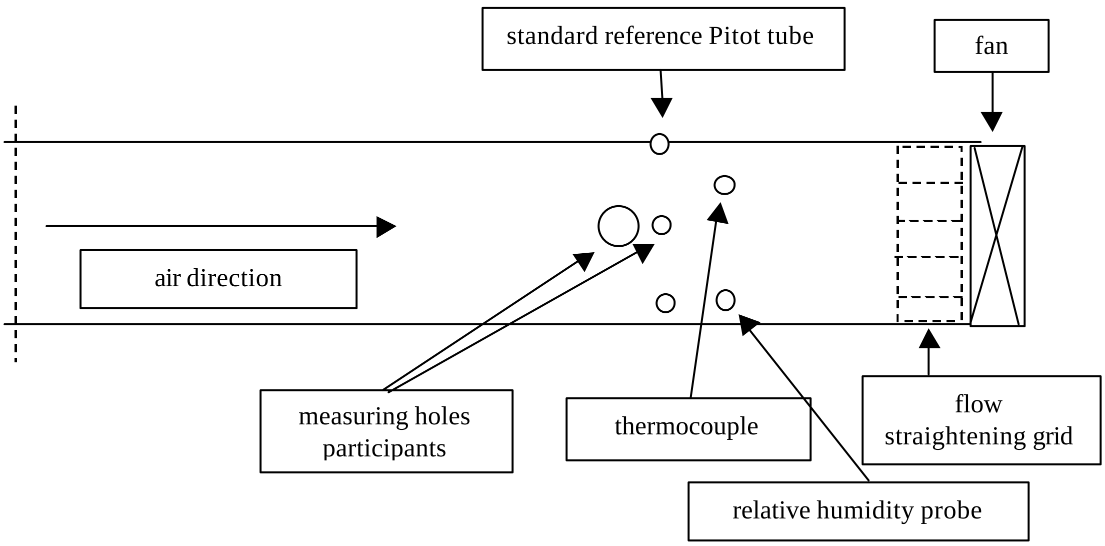


Figure 4: Schematic representation of the equipment for flue gas velocity measurements

Before the round robin tests started, a validation was performed for the comparability between the measuring and the reference point, the homogeneity of the measuring section, the stability of the velocity in function of time and the repeatability.
For comparability control, two standard Pitot tubes were positioned, one vertically at a depth of 25 cm (reference Pitot) and a second horizontally at a depth of 20 cm. The fan was adjusted to generate a gas velocity of 15 m/s. The 1 minute averages of both Pitot tubes were compared over a 2 periods of 14 and 12 minutes each. The ratio v_1/v_2 averaged over the whole period amounted to 0,9968 ± 0,012.
In order to check whether a significant systematic error was present the mean difference $\bar{z}$ was calculated using the formula

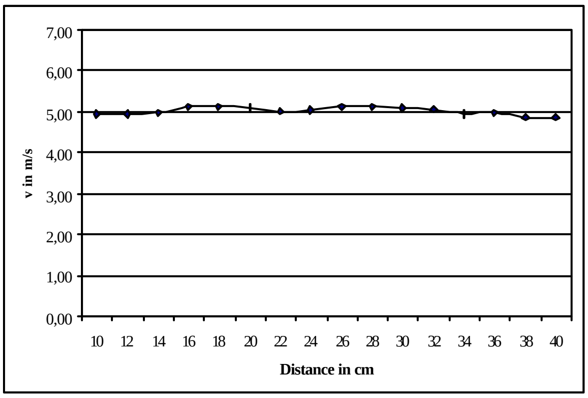
$$|\bar{z}| \geq 2\frac{s_D}{\sqrt{n}} \quad [1]$$

with $\bar{z} = \frac{1}{n}\sum_{i=1}^{n}(x_i - y_i)$ [2]

$$s_D = \sqrt{\frac{1}{n-1}\left[\sum_{i=1}^{n} z_i^2 - \frac{1}{n}\left(\sum_{i=1}^{n} z_i\right)^2\right]} \quad [3]$$

s_D is calculated from the differences of the pairs of measured values according to the equation for standard deviation
$z_i = x_i - y_i$ is the difference in the pairs of measured values
n is the number of comparative measurements
The results indicated that there is no significant difference between the points.

The same experiment was performed at a rate of 6,4 m/s with two periods of 14 minutes. The ratio v_1/v_2 was 0,9999 ± 0,012 and no significant difference between the points could be detected.
Homogeneity of the duct was tested with an S Pitot tube in the horizontal section: the tube was successively positioned at two cm intervals in the duct. To avoid wall effects the first and last 10 cm were neglected. The 'low' velocity was averaged as 5,02 m/s ± 0,09 m/s, with 4,85 m/s and 5,13 m/s as lowest and highest value. In the high region an average of 14,47 m/s ± 0,13 m/s was calculated with 14,14 m/s and 14,64 m/s as extremes. The results are visualised in figures 5 and 6.



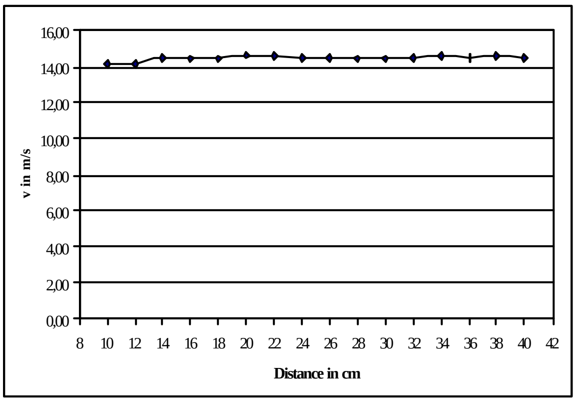


Figure 5: Scan results at 'low' velocity

Figure 6: Scan results at 'high' velocity

Repeatability and stability of the velocity in function of time were tested in a number of successive half hourly experiments. The fan was adjusted, the resulting flue gas velocities were measured in the reference and in the measuring point simultaneously and averaged every 20 seconds. The results are summarised in table 2 for the 'low' and in table 3 for the 'high' velocities.

Table 2: Results of the 'low' flue gas velocity measurements during stability and repeatability tests

	Reference point (vertical axis, 25 cm)			Measuring point (horizontal axis, 20 cm)		
Experiment	**$v_{average}$ in m/s**	**v_{min} in m/s**	**v_{max} in m/s**	**$v_{average}$ in m/s**	**v_{min} in m/s**	**v_{max} in m/s**
1	6,23 ± 0,12	6,07	6,37	6,09 ± 0,11	5,98	6,28
2	6,17 ± 0,12	6,06	6,30	6,12 ± 0,13	5,98	6,29
3	6,07 ± 0,10	5,98	6,14	6,03 ± 0,12	5,96	6,17
4	6,02 ± 0,10	5,92	6,10	6,03 ± 0,12	5,92	6,18
5	5,98 ± 0,11	5,84	6,09	6,01 ± 0,14	5,90	6,20
6	5,94 ± 0,13	5,88	6,10	5,92 ± 0,13	5,77	6,05

Table 3: Results of the 'high' flue gas velocity measurements during stability and repeatability tests

	Reference point (vertical axis, 25 cm)			Measuring point (horizontal axis, 20 cm)		
Experiment	$v_{average}$ in m/s	v_{min} in m/s	v_{max} in m/s	$v_{average}$ in m/s	v_{min} in m/s	v_{max} in m/s
1	14,9 ± 0,3	14,6	15,3	14,9 ± 0,3	14,7	15,2
2	15,1 ± 0,3	14,7	15,3	15,1 ± 0,3	14,9	15,4
3	15,0 ± 0,3	14,7	15,2	15,1 ± 0,3	14,7	15,3
4	15,0 ± 0,3	14,7	15,3	14,9 ± 0,3	14,7	15,3
5	15,1 ± 0,3	14,8	15,3	15,1 ± 0,3	14,9	15,3
6	15,0 ± 0,3	14,7	15,3	15,0 ± 0,3	14,7	15,3

RESULTS OF THE ROUND ROBIN TEST

Temperature

The temperature measurements were performed two times: first a low temperature of 68,5°C was generated. In a second round an elevation to 208°C was realised. The results of both tests are visualised in figure 7 and 8.

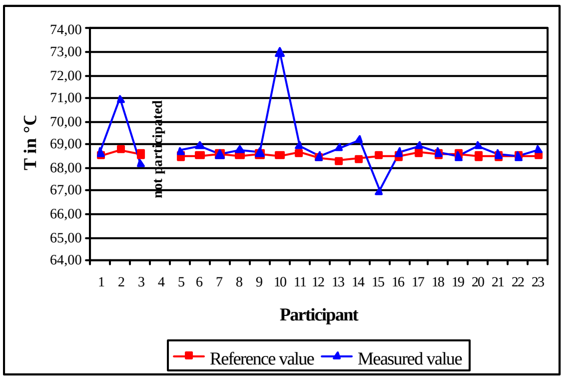


Figure 7: Results of the 'low' T measurements

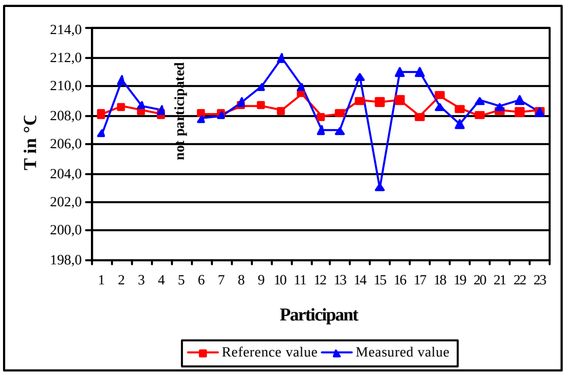


Figure 8: Results of the 'high' T measurements

The deviations of the measured values are rather small compared to the reference value. Only 4 participants obtained a difference of more than 1% in the low and 3 of them in the high range. In both cases 22 of the 23 candidates were participating.

Volume measurements

Each laboratory was asked to sample a volume of about 100 l with an operational flue gas sampling train consisting of a two water filled impingers, a pump and a gas counter. The available time was about 20 minutes. The results are shown in figure 9.

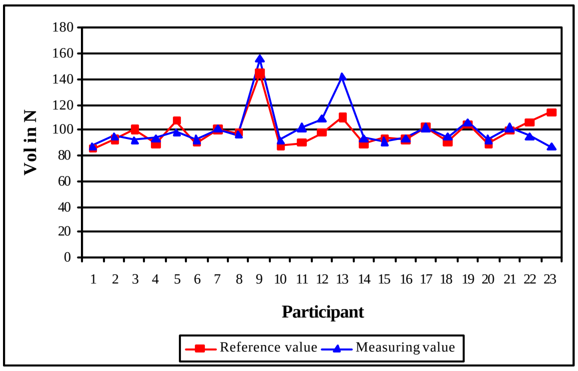


Figure 9: Results of the volume measurements

The results demonstrate relative errors in a range from – 24% (lab 23) to +29,6% (lab 13).
18 participants have a difference less than 10% with 15 of them less than 5%.
3 laboratories show deviations between 10% and 20% and 2 more than 20%.

Flue gas velocity

As for temperature also two velocity measurements had to be performed in the range of 6,0 m/s and 15,0 m/s respectively. Figure 10 and 11 show the results.

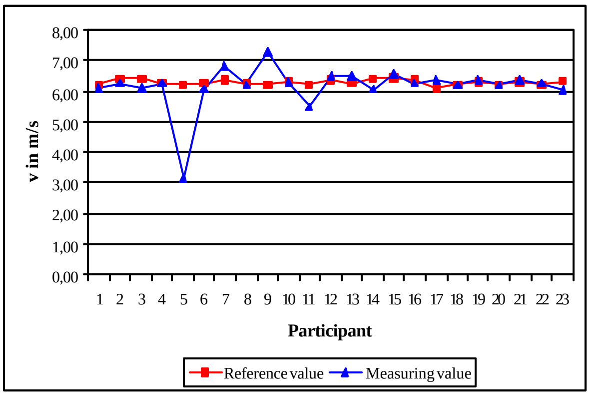


Figure 10: 'Low' velocity measurements

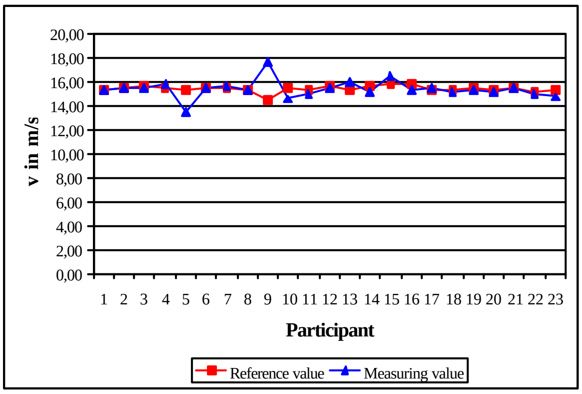


Figure 11: 'High' velocity measurements

All 23 laboratories participated at the velocity measurements.
Comparing the 'low' range tests one can conclude that 18 candidates measured a value better than 95% of the reference value, 2 show a deviation between 5 and 10 %, 2 between 10 and 20% and 1 almost 50%.
In the high velocity region 20 participants had a difference less than 5%, 1 became a deviation of 5,5%, the last 2 deviate more than 10% and 20% respectively.

CONCLUSIONS AND ACTIONS

In total 23 labs subscribed the round robin test. 22 of them participated in the three disciplines, temperature, volume and gas flow measurements. The remaining one only took part in the volume and flow tests.

The reference values of the generated 'low' temperature varied in the range from 68,4°C to 68,8°C

- 18 laboratories show a deviation less than 1%. To estimate their overall measurement uncertainty a coverage factor of 2 is applied to s_D [3]. This results in an uncertainty of 0,53°C at a temperature of 68,5°C or 0,8%.
- the 4 remaining lab's had differences between 1 and 6,5%. The last one already announced they took the temperature probe out of use. The 3 others were considered as outliers with unacceptable systematic errors. They were asked to make an action plan with corrective measures.

The reference 'high' temperature had a value between 207,9°C and 209,5°C.

- for the 19 best participants the calculated uncertainty $2s_D$ equals 2,1°C or 1% of the average reference temperature
- only 3 candidates had to take action attributed to differences of more than 1%.

For the volume test, each participant decided the size of the sampled volume in the order of magnitude of 100 Nl. The real values were situated between 85 and 144 Nl with the subsequent results:

- 18 participants with deviations less than 10% were considered to have no unacceptable systematic error. The overall uncertainty of this group was 9,0 Nl.
- 3 results were located between 80% and 90% of the reference value, 2 values were beneath 80%

The last five laboratories, with aberrations of more than 10%, were asked to make an action plan.

The results of the ‘low’ flow measurements demonstrate that

- the reference velocities ranged from 6,11 tot 6,46 m/s.
- the 19 best lab's, with differences less than 7%, produce an overall uncertainty of 0,34 m/s or 5,5% of the reference value.
- the deviation of 1 of the 4 remaining laboratories rose to about 50%.
- only 4 participants were asked to take corrective measures.

The ‘high’ flow measurements allowed to conclude that

- 21 'good' participants showed a measurement uncertainty of 0,7 m/s or 4,5% of the average reference value.
- 2 candidates had a difference of 10% and 20% respectively and had to take corrective actions.

For all tests which took place under optimal ring test conditions 10 to 20% of the results show gross deviations from the reference value. These results can be considered as erroneous and require corrective measures.
The achievable accuracy for each parameter can be derived from the combined results of the other participants.
We estimate that in real field conditions both the occurrence of faulty measurements and measurement uncertainty will be higher.

During the round robin test it was observed that some of the participants were using calibration tools instead of their operational field equipment in contrast with the written instructions they had received. In some cases also more 'specialised' performers were dealing with the round robin experiments. Also different measuring principles were used especially with respect to the flow test., e.g. standard and S Pitot tubes and anemometers.
For these reasons it was concluded that the usefulness of the results as a quality control could be improved by limiting the allowed equipment and performers in the future.

About the author

Maria Wevers is working at Vito since 1988. She is active in the field of environmental measurements and project leader of emission measurements. She is involved in the recognition procedure for candidate laboratories for emission measurements in the framework of the environmental legislation and takes part in the organisation of round robin tests.