Assessment of airflow measurement uncertainty at terminal devices

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ABSTRACT

Existing protocols for the inspection of mechanical residential systems poorly address both the assessment of uncertainties and recommendations or specifications for measurement methods and devices to be used to guarantee low measurement uncertainties. This paper gives the major elements of a new protocol developed within the Promevent project to overcome this problem. We have analyzed results from 180 airflow measurements performed in laboratory conditions in accordance with this protocol. The methodology developed to analyze uncertainties addresses errors due to repeatability, reproducibility and measurement method consistently with standard error propagation methods. Our analyses of laboratory results show that the measurement method often dominates the overall uncertainty. To contain the overall uncertainty within certain limits, several tables give the Maximum Permissible Error (MPE) of the measurement device as a function of the measurement technique and the geometry of the air terminal devices. These results show that in 6 out of 15 tested configurations, the measurement uncertainty cannot be contained within 15%. For the other tested configurations, the MPE must stay below 9-13% to contain the overall uncertainty below 15%.

KEYWORDS

Ventilation, airflow rate, measurement, uncertainty

1 INTRODUCTION

One major challenge of the ventilation industry is to develop systems that both provide good indoor air quality and ensure high energy performance. However, several field studies in different countries have shown many important issues regarding the quality of the residential ventilation systems (Janssens et al., 2013). For instance, the analysis of regulatory compliance checks on 1,287 dwellings in France has shown that over one new dwelling out of two has a ventilation system that does not meet regulatory requirements (Jobert & Guyot, 2013), 46% and 33% of the problems being due to poor installation and poor design, respectively. Several field studies in Estonia, Austria, and The Netherlands report frequently malfunctioning mechanical systems in these countries (Carrié, 2016).
Requiring functional and performance checks at commissioning appears to be one effective means to overcome these problems. In France, the effinergie+ label (Effinergie, 2015) requires that the ductwork airtightness complies with airtightness class A (the levels are defined in EN

12237 or EN 1507) and that the ventilation system is commissioned with a protocol specified by Effinergie (Effinergie, 2014).
While the Effinergie protocol requires a visual check of the system and gives recommendations for the measurements of airflow rates, it did not require the measurement of airflow rates until the recent publication of the results of the Promevent project. This is due to the lack of knowledge on the uncertainties obtained when measuring airflow rates at air terminal devices when the label was developed. Different technologies exist for measuring airflow rates at terminal devices, and some studies from Walker and collaborators (Walker et al., 2001), (Walker et al., 2003) and (Wray, 2002) have pointed out that the uncertainties of those measurements vary a lot from one device to another. Moreover, Caillou (Caillou, 2014) has shown that the type of air terminal device has a significant impact on those uncertainties. Depending on on-site conditions, Caré (Caré, 2013) has shown measurement uncertainties ranging from 10% to over 50%.
The objective of the Promevent project (Bailly & Lentillon, 2014) was to propose a protocol to assess the quality of the residential ventilation system including specifications for the measurement of airflow rates at air terminal device with acceptable uncertainties. This paper proposes a methodology to evaluate those uncertainties for measuring devices and air terminal devices commonly used in mechanical residential ventilation systems in France.

2 UNCERTAINTY CALCULATION METHOD

The proposed uncertainty analysis, in accordance with JCGM 100 (BIPM, 2008), also known as GUM, considers four main uncertainty sources, for which the following standard uncertainties have been identified:

- $u_{Q,1}$ pertaining to the contribution of the instrument, as a result of its characteristics;
- $u_{Q,2}$ pertaining to the contribution of the method, which is in our case a combination between the measurement principle of the instrument (array of hot wire anemometry, vane anemometer, (un)powered flow hood with Pitot tube, etc.), its use, including centering, airtightness, and (if applicable) alignment of the thermal anemometer, and the flow pattern generated by the air terminal device;
- $u_{Q,3}$ pertaining to the repeatability of the measurements;
- $u_{Q,4}$ pertaining to reproducibility of the measurements.

Assuming these components are uncorrelated, the combined expanded uncertainty, U_c, is calculated as shown in Equation 1:

$$U_c = 2 * u_c = 2\sqrt{u^2{}_{Q,1} + u^2{}_{Q,2} + u^2{}_{Q,3} + u^2{}_{Q,4}} \quad (1)$$

where
u_c is the combined standard uncertainty;
U_c is the expanded uncertainty with a 95% confidence level;
$u_{Q,i}$ are the standard uncertainties defined above.

We performed a series of experiments to:

1. evaluate the minimum instrument uncertainty component available instruments can meet;
2. evaluate the standard uncertainties $u_{Q,2}$, $u_{Q,3}$ and $u_{Q,4}$ for different types of measuring instrument used to measure the flow rate at the level of different types of terminal device;
3. evaluate, for different values of the overall uncertainty, the maximum permissible instrument uncertainty;
4. define requirements for the maximum permissible instrument uncertainty depending on the overall uncertainty target.

2.1 Instrument uncertainty component ($u_{Q,1}$)

For each measuring device, the instrument standard uncertainty $u_{Q,1}$ can be calculated according to JCGM 100, after evaluation of the several components. This procedure needs certain knowledge of uncertainty calculation and should be applied separately to all the used instruments.
A simpler method, also in accordance with JCGM 100, is to check after each calibration that the error of the instrument used (the difference between the value the instrument gives and the value the standard measurement gives) is lower than a target value named Maximum Permissible Error, MPE. Equation 2 gives the instrument standard uncertainty:

$$u_{Q,1} = \frac{MPE}{\sqrt{3}} \qquad (2)$$

where MPE is the Maximum Permissible Error of the measuring device.

Combining Equation 1 and 2 leads to Equation 3:

$$MPE = \sqrt{3 * \left[\left(\frac{U_c}{2}\right)^2 - \left(u_{Q,2}{}^2 + u_{Q,3}{}^2 + u_{Q,4}{}^2\right)\right]} \qquad (3)$$

Therefore, we need to assess the other uncertainty components ($u_{Q,2}$, $u_{Q,3}$ and $u_{Q,4}$) to obtain the MPE to remain within a given expanded combined uncertainty U_c found reasonable for the protocol.

2.2 Measurement method uncertainty ($u_{Q,2}$)

The aim of this study is to evaluate the uncertainties of the measurements performed according to the Promevent protocol. We thus consider that the instrument is correctly placed. Then, the measurement method standard uncertainty, $u_{Q,2}$, linked to the use of a measuring device on an air terminal device, can be determined according to **Error! Reference source not found.**.

$$u_{Q,2} = u_{Q,p} \qquad (4)$$

where:
$u_{Q,p}$ is the standard uncertainty due to the interaction of the instrument and the terminal device.

2.3 Repeatability measurement uncertainty ($u_{Q,3}$)

According to the JCGM 200 (BIPM, 2012), also known as VIM, the measurement repeatability is the “measurement precision under a set of repeatability conditions of measurement”. This set of conditions “includes the same measurement procedure, same operators, same measuring system, same operating conditions and same location, and replicate measurements on the same or similar objects over a short period of time”. This uncertainty component is estimated from results of measurements performed in repeatability conditions as defined here.

2.4 Reproducibility measurement uncertainty ($u_{Q,4}$)

According to the JCGM 200, the measurement reproducibility is the “measurement precision under reproducibility conditions of measurement”. These conditions are “out of a set of conditions that includes different locations, operators, measuring systems, and replicate measurements on the same or similar objects”. In our case, the condition which has been considered is the operator and the uncertainty component is estimated from results of several measurements performed with the same measuring instrument, on the same terminal device but by different operators.

3 EXPERIMENTAL SETUP

To evaluate the different standard uncertainties ($u_{Q,2}$, $u_{Q,3}$ and $u_{Q,4}$), we performed about 180 airflow measurements in laboratory conditions reflecting the following key requirements of the Promevent protocol:

- the air terminal device is connected to an airtight plenum;
- the measuring instrument is placed around the air terminal device in such a way that:
  - there is no leakage between the measurement device and the wall or the ceiling,
  - it is centered relative to the aperture,
  - the measurement is performed during stable conditions: when for 30 seconds, the flow rate does not vary by more than 10%. The result is the average of the airflows measured during that time;
- The measured airflow is corrected for:
  - the error of the used instrument,
  - on-site temperature and pressure conditions, according to the recommendations of the manufacturer.

3.1 Description of the facility

The measurements are performed in a lab with a facility shown in figure 1 below.

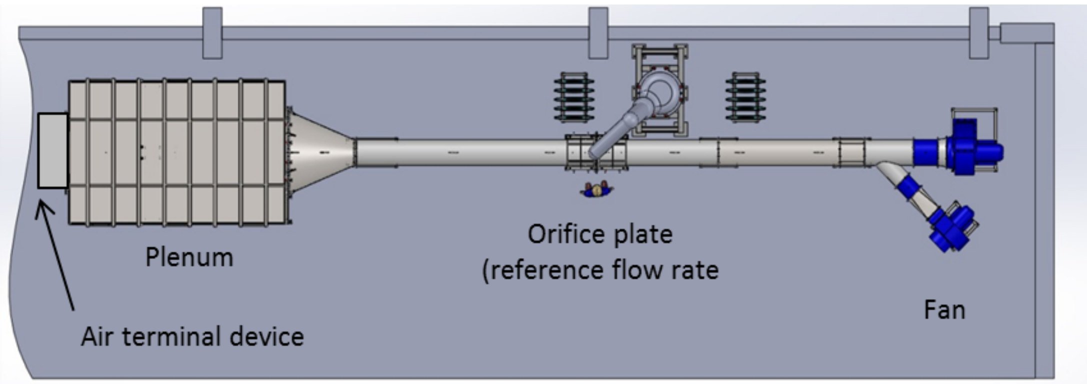


Figure 1: Facility used for the tests performed in lab

The flow rate is generated by changing the rotation frequency of a fan. The mass flow rate is then calculated by measuring the differential pressure at an orifice plate. Pressure and temperature sensors at the level of the terminal device are used to convert it to volume flow rate.

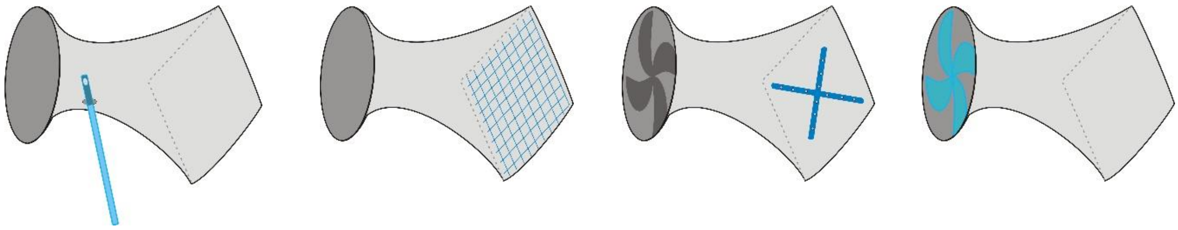
The flow range of the test rig is:

- in exhaust mode, from 5 to 17000 m^3/h;
- in supply mode, from 5 to 5000 m^3/h.

3.2 Description of the tests

The measurements were performed in supply mode, considering that the measurement method uncertainty is higher than in exhaust mode because of the impact of the distorted flow pattern on the measuring instrument (Mélois & Berthault, 2016).

Measurements were performed by 4 operators, with 4 measuring devices (4 different technologies commonly used in France, see Figure 2).

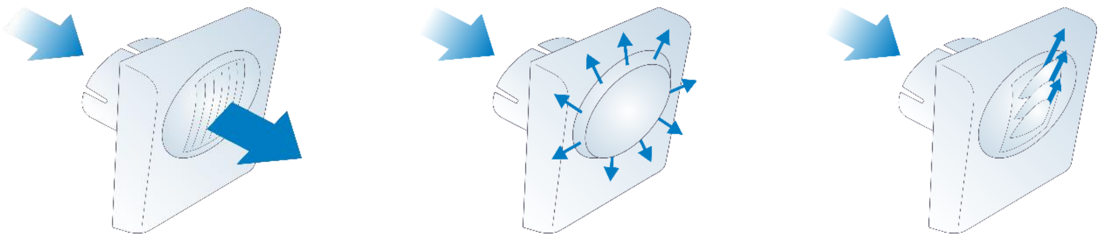


Measuring device 1: One-point thermal anemometer + hood | Measuring device 2: Checkered thermal anemometer + cone | Measuring device 3: Pitot tube + powered flow hood | Measuring device 4: Propeller anemometer + hood

Figure 2: Measuring instruments used

In the cases of devices 1 and 4, an anemometer at the smallest section of a hood measures the air speed which is converted into volume flow rate. In the case of device 2, an array of small hot wires in a cross-section of the hood gives the flow rate. In device 3, the flow rate measurement is based on an array Pitot tubes. Moreover, the device 3 includes a fan which compensates the pressure drop induced by the positioning of the device on the terminal device.

Generally, the range of airflow rates at residential supply terminal devices in France is around 30 $m^3.h^{-1}$. We thus performed all laboratory tests at 30 $m^3.h^{-1}$. The measurements were performed at the facility for 3 supply air terminal devices representing 3 of the different geometries most used in France (**Error! Reference source not found.**3).



Air terminal device A: Fix grille | Air terminal device B: Circular diffuser | Air terminal device C: Dirigible air jet with pivoting vane

Figure 3: Supply air terminal devices tested

The airflow pattern generated by each of these air terminal devices has specificities:

- the fix grille (A) is perpendicular to the wall, so the direction of the airflow is consistent with the axis of the measurement device;
- the airflow induced by the circular diffuser (B) is omnidirectional: very close to the terminal device, there is no airflow along the axis of the measurement device (perpendicular to the wall);
- the airflow induced by the dirigible air jet with pivoting vane (C) follows a direction governed by the movable vanes, which can significantly deviate from the axis of the measurement device. This terminal device has been used with the vanes in the closed position which generates the most distorted flow.

We conducted analyses for each pair of measuring device/terminal device. **Error! Reference source not found.** gives the matrix of our experiments.

Table 1: Number of measurements performed by each operator depending on the measuring instrument and the air terminal device

	Number of measurements											
Air terminal device	Fix grille				Circular diffuser				dirigible air jet with pivoting vane			
Operator	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
Punctual thermal anemometer + cone	3	3	3	3	3	3	3	3	3	3	3	3
Checkered thermal anemometer + cone	3	3	3	3	3	3	3	3	3	3	3	3
Pitot tube + cone with compensation	3	3	3	3	3	3	3	3	3	3	3	3
Propeller anemometer + cone (without extension)	3	3	3	3	3	3	3	3	3	3	3	3
Propeller anemometer + cone (with extension)	3	3	3	3	3	3	3	3	3	3	3	3

3.3 Preliminary tests

Before measuring flow rates at the air terminal devices, we performed a first test to estimate the measurement error of the instruments. We placed the instruments on the plenum with no terminal device and a reference flow rate of 30 m^3/h was generated. Figure 4 represents this preliminary measurement.

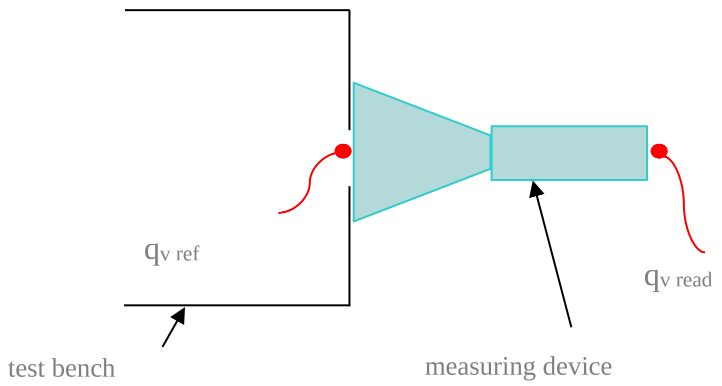


Figure 4: Measurement method in laboratory

The observed difference between the reading of the meter and the reference flow rate was used during experiments to correct the measurement of the meter from the instrument error. This preliminary experiment allowed to know the measurement error of each instrument to correct it in the following tests using Equation 5:

$$q_{v\,read,corrected} = q_{v\,read} + C_{calibration} \quad (5)$$

The relative errors between the "read, corrected" airflow $q_{v\ read,\ corrected}$ and the design rate $q_{v\ ref}$ have been considered in the analyses. This method allowed us to calculate the uncertainties considering the actual airflow rate generated by the test bench.

We defined $q_{v\,ref,ij}$ the result of the measurement number with:

- i the number of the measurement performed by on operator (i=1 for the first measurement, i=2 for the second and i=3 for the last one);
- j is the identification of the operator (from j=1 for the first operator to j=4 for the fourth operator).

4 RESULTS OF LABORATORY MEASUREMENTS

4.1 Evaluation of the measurement method uncertainty $u_{Q,2}$

For each pair of measuring device and terminal device, 3 measurements were performed by each of the 4 operators, therefore, 12 measurements in total. Assuming the errors follow a rectangular distribution, we assessed the uncertainty due to the method using Equation 6:

$$u_{Q,p} = \frac{average_{j=\{1;4\}} average(\frac{q_{v\,ref,ij} - q_{v\,\text{read,corrected},ij}}{q_{v\,ref,ij}})_{i=\{1;3\}}}{\sqrt{3}} \quad (6)$$

Table 1: Measurement method uncertainty results for 3 air terminal devices and 4 technologies of measuring devices

Type of measuring device \ Type of terminal device	Fix grille	Circular diffuser	Dirigible air jet with pivoting vane
Punctual thermal anemometer + cone	3%	9%	14%
Checkered thermal anemometer + cone	7%	32%	29%
Pitot tube + cone with compensation	2%	5%	2%
Propeller anemometer + cone (without extension)	0%	1%	15%

Table 1 gives results of the association air terminal device together with a measuring instrument.
They support that the uncertainty due to the method significantly depends on the type of air terminal device (up to 25% from one measuring device to another with the checkered thermal anemometer + cone) and on the type of measuring device (up to 32% for the circular diffuser). These results confirm the need to conduct an error analysis for each pair of measuring device/terminal device.

4.2 Evaluation of the repeatability uncertainty $u_{Q,3}$

For each pair of measuring device and air terminal device, we first analyzed the distribution of the results of the 3 measurements performed by the same operator. We obtained an evaluation of the repeatability for each operator. Then, we have evaluated the repeatability uncertainty component for each pair of measuring device/terminal device regardless of operators, according to the Equation 7.

$$u_{Q,3} = average_{j=\{1;4\}}\left(\sigma_j\left(\frac{q_{v\,ref,ij} - q_{v\,\text{read,corrected},ij}}{q_{v\,ref,ij}}\right)_{i=\{1;3\}}\right) \quad (7)$$

where σ_j is the standard deviation between the 3 measurements performed by the operator j.

Table 2 presents the uncertainties due to repeatability for each tested case. Most values of repeatability uncertainties lie between 1% and 3%, which is good. They are higher for few particular cases, especially for the movable vanes grilles (the grilles were half opened during the whole series of measurements). The geometry of such air terminal devices induces difficulties to repeat the measurement.

Table 2: Repeatability uncertainties results for 3 air terminal devices and 4 technologies of measuring devices

Type of measuring device \ Type of terminal device	Fix grille	Circular diffuser	Dirigible air jet with pivoting vane
Punctual thermal anemometer + cone	2%	2%	9%
Checkered thermal anemometer + cone	6%	3%	6%
Pitot tube + cone with compensation	1%	2%	1%
Propeller anemometer + cone (without extension)	0%	1%	5 %

4.3 Reproducibility measurement uncertainty

For each pair of measuring device and terminal device, the objective was to evaluate the impact of the operator. We thus characterized the operator results with his average error for each pair of measuring device/terminal device. Then, we analyzed the distribution of those average errors in order to compare the 4 operator results. We defined the reproducibility uncertainty component according to the **Error! Reference source not found.**8.

$$u_{Q,4} = \sigma_{\ j=\{1;4\}}(average_{i=\{1;3\}}\left(\frac{q_{v\,ref,ij} - q_{v\,\text{read,corrected},ij}}{q_{v\,ref,ij}}\right)) \quad (8)$$

where σ is the standard deviation between the 4 average results, one average is calculated for each of the 4 operators, from his 3 measurement results.

Table 3: Reproducibility uncertainties results for 3 air terminal devices and 4 technologies of measuring devices

Type of measuring device \ Type of terminal device	Fix grille	Circular diffuser	Dirigible air jet with pivoting vane
Punctual thermal anemometer + cone	3%	3%	11%
Checkered thermal anemometer + cone	4%	5%	10%
Pitot tube + cone with compensation	1%	1%	1%
Propeller anemometer + cone (without extension)	0%	2%	7%

Table 3 presents the uncertainties due to repeatability for each tested case. The results of the reproducibility tests are similar to those for repeatability. Few values are higher than 3%, due to the geometry of the air terminal device

4.4 Comparison of the three uncertainties: method, repeatability, and reproducibility

Figure 1 shows that, in the case of a dirigible air jet with pivoting vane, the uncertainty due to the method ($u_{Q,2}$) is higher that uncertainties due to repeatability ($u_{Q,3}$) and reproducibility ($u_{Q,4}$). We observed the same tendency for the fix grille and the circular diffuser.

The range of uncertainties (from nearly 0% up to 32%) is very large and depends significantly both on the type of measuring device and the type of terminal device. This conclusion confirms the need to formulate different conclusions depending on each combination.

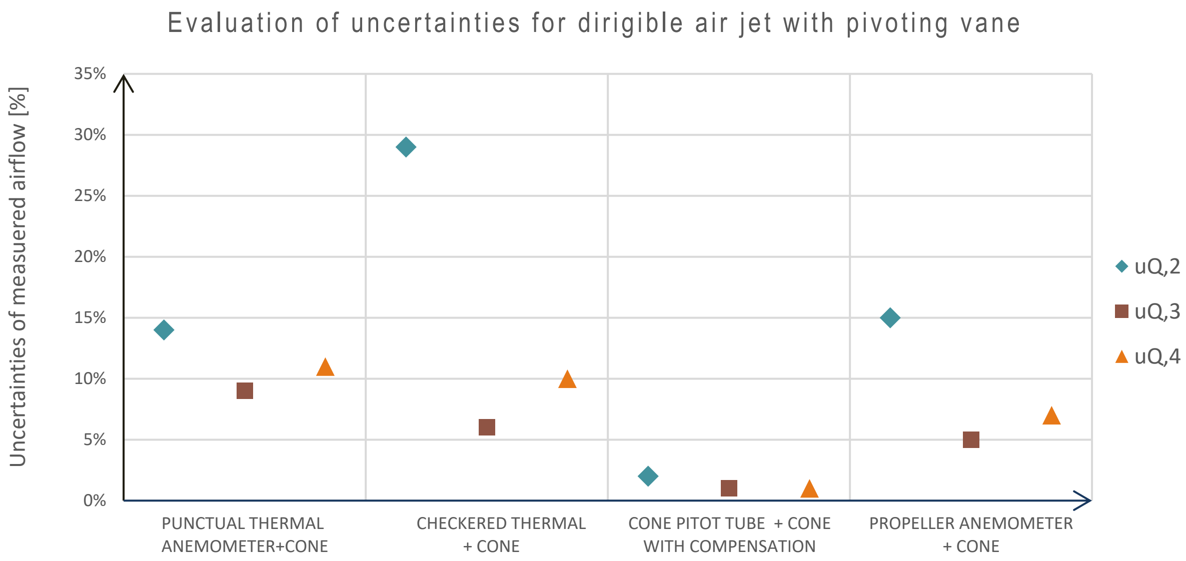


Figure 1: Evaluation of uncertainties from measurements performed on the test bench with a dirigible air jet with pivoting vane

5 CONCLUSION: DISCUSSION AND APPLICATION TO LARGE-SCALE FIELD MEASUREMENTS

The first result of this study is that the airflow measurement uncertainty depends very significantly on both the type of terminal device and measuring device. Therefore, the operator has to choose his measuring device to contain the uncertainty within acceptable limits.

The second result is the determination of Maximum Permissible Errors to respect an overall measurement uncertainty. We calculated MPEs to comply with several overall measurement uncertainties. Table 5 gives MPEs for a 15% overall measurement uncertainty. Cells with an "X" represent the incompatibility between the couple air terminal device/measuring device. In those cases, the combined uncertainties $u_{Q,2}$, $u_{Q,3}$ and $u_{Q,4}$ are already higher than the acceptable limit. That means that there is no possibility of MPE which can allow making the measurement within the acceptable limit.

Table 5: MPEmax for a 15% overall uncertainty

Type of measuring device \ Type of terminal device	Fix grille	Circular diffuser	Dirigible air jet with pivoting vane
Punctual thermal anemometer + cone	11	X	X
Checkered thermal anemometer + cone	X	X	X
Pitot tube + cone with compensation	13	9	12
Propeller anemometer + cone	13	12	X

**An "X" means that the 15% limit cannot be met given the other uncertainty components (measurement method, repeatability, and reproducibility)*

With a 15% limit, the measurement can be performed in 6 cases out of 12, yet with reasonable MPEs. Setting the limit up to 20% or even 25% does not help: some cases remain impossible given other uncertainty components or the resulting MPE is too low. Therefore, 15% appeared to be a reasonable target for the overall combined expanded uncertainty. In this case, the MPEs of the eligible measuring devices have to be lower than 9% to 13% depending on the type of measuring device and air terminal device.

For practical large-scale applications, however, we preferred defining a unique MPE applicable to all types of the eligible measuring device. We chose to set 10% as the limit for the MPE, which is close to the most stringent requirement that can be inferred from table 5.

These requirements are now part of the Promevent protocol which has been discussed with stakeholders at French level. The protocol requires ensuring a combined expanded measurement uncertainty below 15% and states that a calibration certificate proving that the measuring device has an MPE lower than or equal to 10% is sufficient to meet this requirement provided that the measurement device is used on a compatible terminal device, as shown in table 6.

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