Reliability of ductwork airtightness measurement: impact of pressure drop and leakage repartition on the test result

Sylvain Berthault[1*], Valérie Leprince[2]

1 Cerema Centre-Est, Laboratoire d'Autun
Bd Giberstein, BP 141
71405 Autun Cedex, France
*sylvain.berthautl@cerema.fr

2 PLEIAQ
84 C Av de la Libération
69330 Meyzieu, France

ABSTRACT

Building airtightness requirements are becoming more and more common in Europe (Leprince, Carrié, & Kapsalaki, 2017). However, airtight buildings require an efficient ventilation system to ensure good indoor air quality. In France, the inspection of ventilation system (Jobert, 2012) has revealed many noncompliance. They are mainly due to bad conception, poor implementation, and lack of maintenance. This often leads to reduced ventilation flowrates and poor indoor air quality. Leaky ductwork is one of the reasons for this noncompliance.

Therefore, in France, a ductwork airtightness test is now mandatory for new building applying to an Effinergie label, and the ductwork shall reach at least the class A.

Since the test is mandatory and a minimum level required, it raises the question of the reliability of the test.

Inside a ductwork a flowrate undergoes pressure drop due to friction and dynamic losses. It is relevant to wonder whether these losses have an impact on the result of the ductwork airtightness test.

Before the Promevent project, an experiment was conducted to estimate the impact of these losses on the result of the airtightness test. Results were briefly presented at the AIVC 2014 conference (Berthault, Boithias, & Leprince, 2014) and stated that:

- the position of the measuring device seemed to have no impact on the result of the airtightness test for various distribution of leakages
- only very high dynamic losses (almost completely closed damper) had an impact on the result.

The objectives of this paper are:

- to present the experimental set-up and detail the tests carried out
- to present the developed numerical model to estimate the impact on the result of the airtightness test of friction and dynamic losses according to the level of airtightness.
- to compare the results obtained with the numerical model and the experimental set-up.

It has been shown that, for airtight ductwork (class C) the impact of pressure losses on the measured flowrate is expected to be very small.

Nevertheless for very leaky ductwork it would be good practice to define a maximal length to be tested (distance between the measuring device and the farthest end of the ductwork) or to check in various location the homogeneity of the pressure.

KEYWORDS

Ductwork, Airtightness, Measurement, Pressure drop, Ventilation.

1 INTRODUCTION

Building airtightness requirements are becoming more and more common in Europe (Leprince, Carrié, Kapsalaki, 2017). However, airtight buildings require an efficient ventilation system to ensure good indoor air quality. In France, the inspection of ventilation system (Jobert, 2012) has revealed many noncompliance. They are mainly due to bad conception, poor implementation, and lack of maintenance. This often leads to a reduced ventilation flowrates and poor indoor air quality. Leaky ductwork is one of the reasons for this noncompliance.

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- only very high dynamic losses (almost completely closed damper) had an impact on the result.

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- to compare the results obtained with the numerical model and the experimental set-up.

2 METHOD

As for a building airtightness test, a ductwork airtightness test assumes that the pressure difference between inside and outside the ductwork is homogeneous along the measured section.

However, the pressure drop due to friction and dynamic losses in the ductwork may induce a variation of this pressure difference. The following numerical model aims at estimating the maximum pressure variation in the ductwork due to these losses during an airtightness test. The experimental set-up has been used to compare this theoretical variation to the measured one.

2.1 Numerical model

Pressure drop in ductwork systems is due to the irreversible transformation of mechanical energy into heat (ASHRAE, 2013). There are two types of losses:

- friction losses (occurring along the ductwork)
- and dynamic losses (occurring at bends and junctions)

Total pressure loss in a duct section with a constant flow speed is calculated by combining friction and dynamic losses (equation 1).

$$\Delta p = \left(\frac{1000f}{D_h} + \sum C\right)\left(\frac{\rho V^2}{2}\right) \tag{1}$$

$$\Delta p = \zeta\left(\frac{\rho V^2}{2}\right) \tag{2}$$

C	-	Total loss coefficient
Δp	Pa	Total pressure loss
V	m/s	velocity
ρ	kg/m^3	air density
f	-	Friction factor

L	m	duct length
D_h	m	hydraulic diameter
ζ	-	Total pressure drop coefficient

Therefore, the pressure loss in the ductwork system is proportional to the square of the flowrate and the higher the flowrate (the more leakage during the test) the higher resistance in the ductwork (equation 2).
Friction and dynamic losses coefficients can be calculated from tabulated data such as those given in (ASHRAE, 2013).

The objective of the numerical model, developed in this paper, is to estimate the maximum pressure variation in the ductwork due to these losses during an airtightness test, that is to say the variation in the "worst" case that corresponds to a unique leak at one end of the ductwork and the measuring device at the opposite end (see Figure 1).
In this case, it is possible to make the hypothesis of constant flowrate along the ductwork (coming from the unique leak).

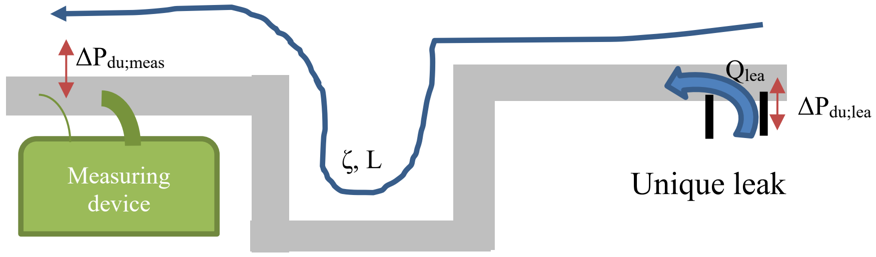


Figure 1: Case of a unique leak located on the opposite side of the ductwork compared to the measuring device

In this case

$$|\Delta P_{du;meas}| - |\Delta P_{du;leak}| = \frac{\zeta\rho}{2} * V^2 \tag{3}$$

With

$\Delta P_{du;meas}$	Pa	Pressure difference at measuring device
$\Delta P_{du;lea}$	Pa	Pressure difference at the leakage

If it is assumed that the section of the ductwork is constant (main diameter or average of all sections)

$$|\Delta P_{du;meas}| - |\Delta P_{du;leak}| = \frac{\zeta\rho}{2} * \left(\frac{4Q}{\pi D^2}\right)^2 \tag{4}$$

With

D	m	Diameter of the ductwork
Q	m^3/s	Leakage flowrate

And with the air leakage coefficient of the ductwork (K)

$$Q = K\Delta P_{du;leak}{}^{\frac{2}{3}}S \tag{5}$$

With

K	$m^3/s/Pa^{2/3}/m^2$	Air leakage coefficient of the ductwork
S	m^2	Ductwork area

$$|\Delta P_{du;meas}| - |\Delta P_{du;leak}| = \frac{\zeta\rho}{2} * \left(\frac{4K|\Delta P_{du;leak}|^{\frac{2}{3}} * L\pi D}{\pi D^2}\right)^2 \tag{6}$$

$$\left|\Delta P_{du;meas}\right| - \left|\Delta P_{du;leak}\right| = \frac{8\zeta\rho K^2 L^2}{D^2} * \left|\Delta P_{du;leak}\right|^{\frac{4}{3}} \qquad (7)$$

Solving this equation requires to apply an iterative method since:

- $\Delta P_{du;leak}$ depends on the pressure drop in the ductwork,
- this pressure drop is proportional to the square of the leakage flowrate,
- the leakage flowrate depends on $\Delta P_{du;leak}$.

During the test the objective was to have a small pressure drop compared to the pressure difference between inside and outside. As an alternative, it was therefore decided to use the pressure difference at the measuring device to maximise the variation of pressure within the ductwork due to pressure losses:

$$\left|\Delta P_{du;leak}\right| \leq \left|\Delta P_{du;meas}\right| \qquad (8)$$

As a result:

$$\frac{\left|\Delta P_{du;meas}\right| - \left|\Delta P_{du;leak}\right|}{\left|\Delta P_{du;meas}\right|} \leq \frac{8\zeta\rho K^2 L^2}{D^2} * \left|\Delta P_{du;meas}\right|^{\frac{1}{3}} \qquad (9)$$

The variation of the measured flowrate is described with equations 10 to 13:

$$\frac{\left|Q_{\Delta P_{du;meas}}\right| - \left|Q_{\Delta P_{du;lea}}\right|}{\left|Q_{\Delta P_{du;meas}}\right|} = \frac{K\left|\Delta P_{du;meas}\right|^{\frac{2}{3}} - K\left|\Delta P_{du;leak}\right|^{\frac{2}{3}}}{K\left|\Delta P_{du;meas}\right|^{\frac{2}{3}}} \qquad (10)$$

$$\frac{\left|Q_{\Delta P_{du;meas}}\right| - \left|Q_{\Delta P_{du;lea}}\right|}{\left|Q_{\Delta P_{du;meas}}\right|} = 1 - \left(\frac{\left|\Delta P_{du;leak}\right|}{\left|\Delta P_{du;meas}\right|}\right)^{\frac{2}{3}} \qquad (11)$$

$$\frac{\left|Q_{\Delta P_{du;meas}}\right| - \left|Q_{\Delta P_{du;lea}}\right|}{\left|Q_{\Delta P_{du;meas}}\right|} = 1 - \left(1 - \frac{\left|\Delta P_{du;meas}\right| - \left|\Delta P_{du;leak}\right|}{\left|\Delta P_{du;meas}\right|}\right)^{\frac{2}{3}} \qquad (12)$$

$$\frac{\left|Q_{\Delta P_{du;meas}}\right| - \left|Q_{\Delta P_{du;lea}}\right|}{\left|Q_{\Delta P_{du;meas}}\right|} \leq 1 - \left(1 - \frac{8\zeta\rho K^2 L^2}{D^2} * \left|\Delta P_{du;meas}\right|^{\frac{1}{3}}\right)^{\frac{2}{3}} \qquad (13)$$

Therefore, to ensure a variation of the flowrate of less than -3% (for example) it is necessary to check (see equations 14 and 15):

$$1 - \left(1 - \frac{8\zeta\rho K^2 L^2}{D^2} * \left|\Delta P_{du;meas}\right|^{\frac{1}{3}}\right)^{\frac{2}{3}} \leq 0.03 \qquad (14)$$

So

$$\frac{8\zeta\rho K^2 L^2}{D^2} * \left|\Delta P_{du;meas}\right|^{\frac{1}{3}} \leq 1 - 0.97^{\frac{3}{2}} = 4.5\% \qquad (15)$$

2.2 The experimental set-up

The experimental set-up was a laboratory replication of a multi-family dwelling's ductwork (Figure 2). The ductwork was made of two main columns that were both connected to two dwellings. Each dwelling had a kitchen and a bathroom. Therefore, each column had four air terminal connected devices.

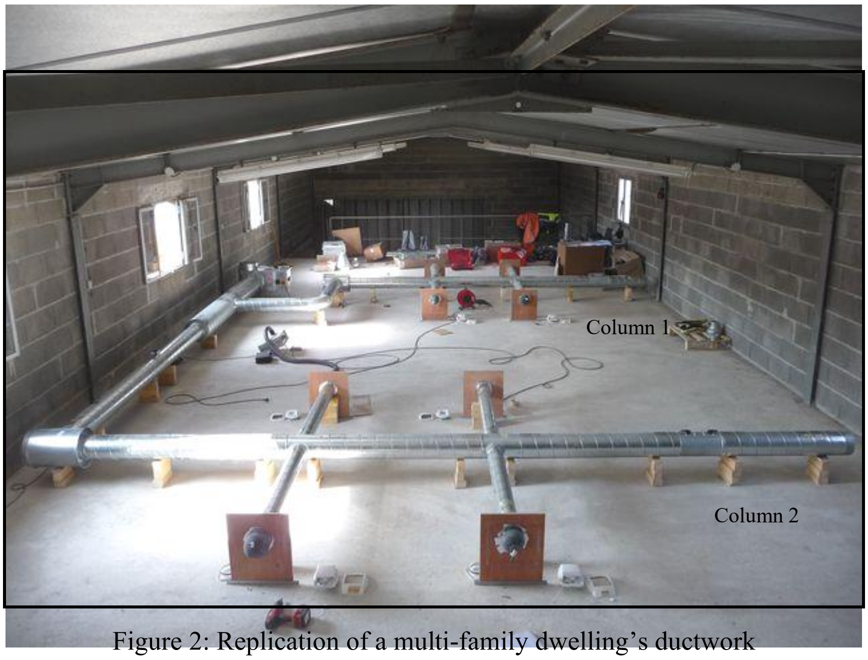


Figure 2: Replication of a multi-family dwelling's ductwork

The main technical characteristics are shown in Figure 3 and Table 1.

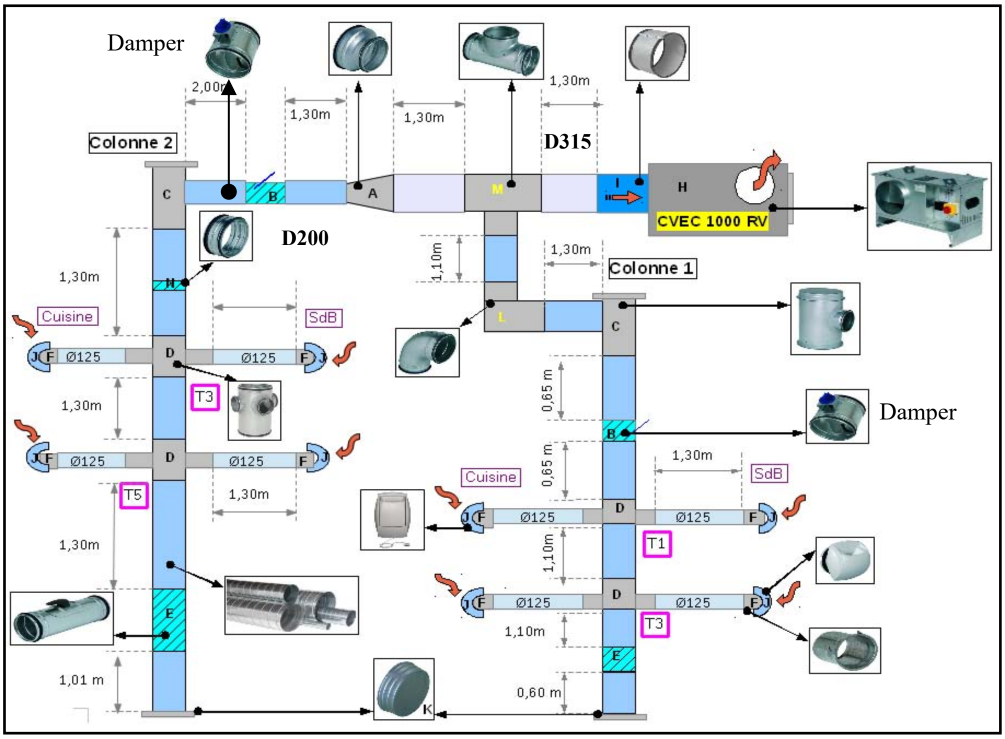


Figure 3: Ductwork with accessories

Kitchen air terminal devices provided two different flowrates. For the column 1: the maximum air flowrate was 225 m^3/h and the minimum air flowrate 110 m^3/h. For the column 2, the maximum air flowrate was 300 m^3/h and the minimum air flowrate 150 m^3/h.

Table 1: Length circular GALVA ducts and total flow ductwork available

Circular GALVA duct Diameter (mm)	Length (m)	Maximum total flow fan (m^3/h)	Minimum total flow fan (m^3/h)
315	2.60	525	260
200	15.08		
125	10.4		

First the ductwork was built airtight (class C) then the ductwork was drilled to reach 1.5*class A.

Evaluation of the impact of the measuring device location according to leakage distribution

The aim was to quantify the impact of leakage distribution and location of the measuring device on the result of the airtightness test. Four different leakage distributions inducing approximately the same airtightness level were tested (leakages were created by drilling):

1. Leaks gathered close to the fan (Figure 4)
2. Leaks gathered at the bottom of columns 1 and 2 (Figure 6)
3. Leaks gathered at the bottom of column 2 (Figure 5)
4. Equally distributed leaks all along the ductwork (Figure 7)

Tests were carried out by placing the measuring device at three different locations (as seen in green on Figure 4, Figure 5, Figure 6 and Figure 7):

1. By the fan
2. On column 1
3. On column 2

▲ Leakage (drilled)
🟩 Measuring device
◆ Sealing

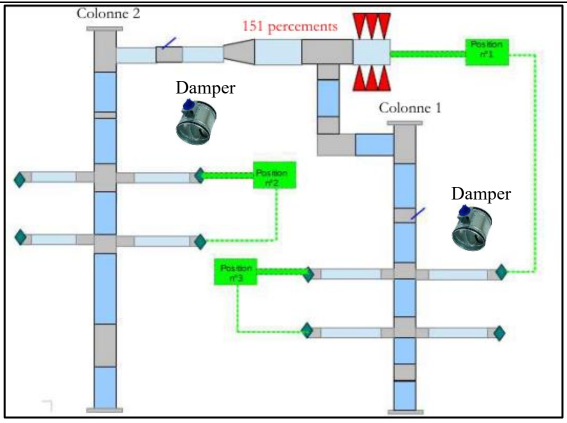


Figure 4: Measuring device position and leakage located at the fan

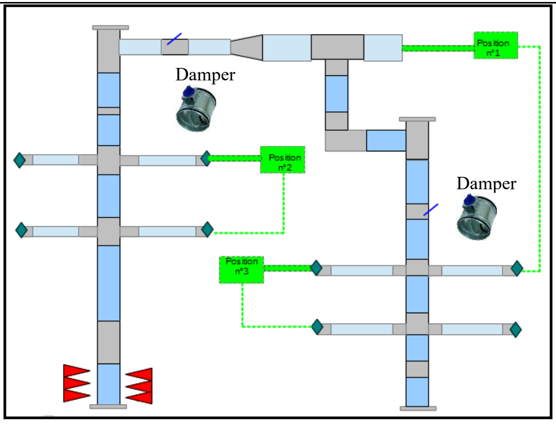


Figure 5: Measuring device position and leakage located at the bottom of column 2

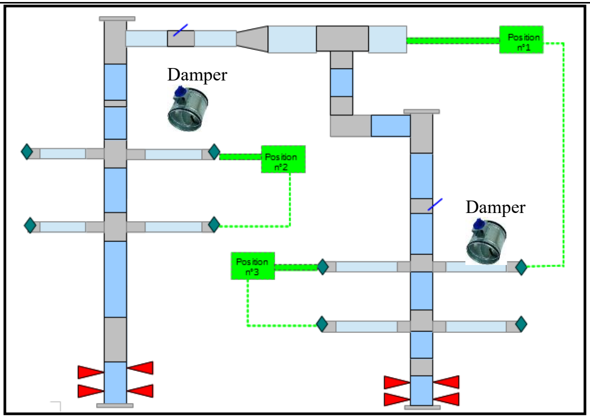


Figure 6: Measuring device position and leakage located at the bottom of columns 1 and 2

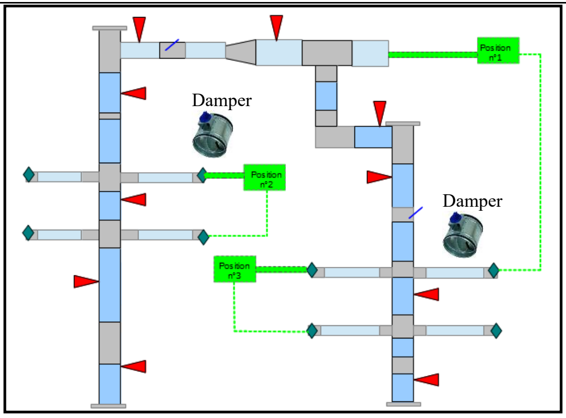
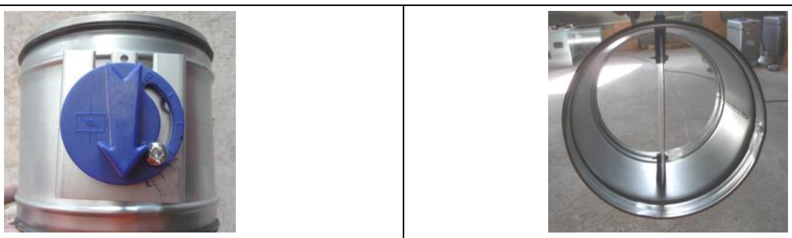


Figure 7: Measuring device position and leakage distributed along the ductwork

Evaluation of the impact of the pressure drop on the result of the airtightness test.

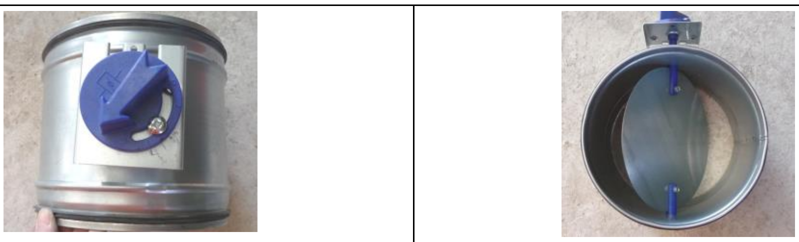
As the ductwork was rather small compared to the ductwork of a large building, the pressure drop in the ductwork was quite small. Therefore, to induce larger pressure drop dampers were included at the top of column 1 and of column 2.
The objective was to estimate the impact of large pressure drop on the result of the airtightness test. Each damper had 7 positions from "0" open (Figure 8) to "6-F" closed (Figure 10).



Top view of the damper control in position 0

Interior view of the shutter position

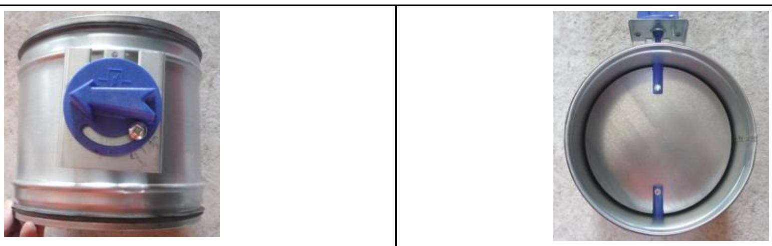
Figure 8: Open damper (position 0)



Top view of the damper control in position 3

Interior view of the shutter position

Figure 9: Open damper half (position 3)



Top view of the damper control in position F

Interior view of the shutter position

Figure 10: Closed damper (position F)

The position of the 2 dampers were modified simultaneously from open to closed through the 7 positions and an airtightness test performed for each position at three different pressure (90 Pa, 120 Pa et 160 Pa).

This was done for two levels of ductwork airtightness:

- An airtight ductwork / Class C
- A leaky ductwork / 1.5*class A with distributed leakage (Figure 11).

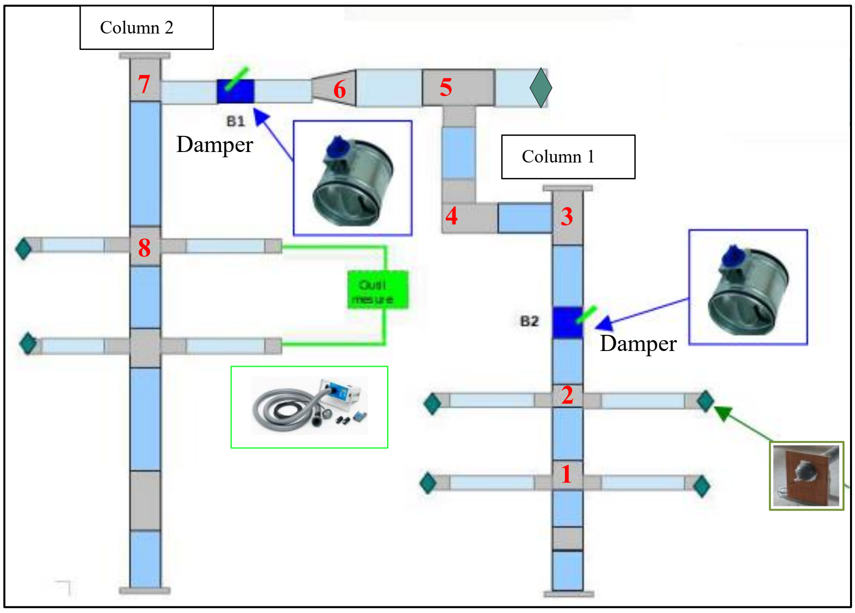


Figure 11: Impact of pressure drop (7 positions of damper) in the ductwork on the test result (3 different pressure, 2 level of airtightness for the ductwork)

In order to calculate the pressure loss coefficient of the damper according to its positions:

- the fan was switched on to maintain a pressure of 90 Pa, 120 Pa and 160 Pa,
- and the pressure after the damper was measured for the class C ductwork with the minimum flowrate (110 m^3/h in column 1 and 150 m^3/h in column 2).

3 RESULTS

3.1 Impact of the leakage distribution and measuring device location

Theoretical impact

In order to estimate the theoretical maximal impact of the leakage distribution and the position of the measuring devices, the worst case was to assume that there was only one large leakage at the bottom of column 1 and that the measuring device was at the bottom of column 2.

According to the calculations carried out with the French standard DTU 68.3 linear pressure drop (friction losses) are negligible considering the ductwork diameter, their material (metallic) and the flow speed during an airtightness test.
Average pressure losses coefficient (ζ) due to dynamic losses implied by accessories is given in the Table 2. It was estimated with DTU 68.3.

Table 2: Average pressure losses coefficient (ζ) for accessories along the ductwork (see Figure 11 for the number of each accessories)

Accessories	1 T-linear flow	2 T-linear flow	3 Roof collector	4 Bend	5 T-lateral	6 Narrowing	7 Roof collector	8 T-lateral	Total
ζ	0.15	0.15	2	0.5	0.5	1.1	2	0.5	6.9

As the length of the ductwork is 28 m, the average diameter 0.2 m, when the measurement is performed at 120Pa the error on the measured flowrate is below 3% if (cf. §2.1):

$$\frac{|\Delta P_{du;meas}| - |\Delta P_{du;leak}|}{|\Delta P_{du;meas}|} \leq \frac{8\zeta\rho K^2 L^2}{D^2} * |\Delta P_{du;meas}|^{\frac{1}{3}} \leq 0.045 \qquad (16)$$

$$K \leq \sqrt{\frac{0.045 D^2}{8\zeta\rho L^2 |\Delta P_{du;meas}|^{\frac{1}{3}}}} \qquad (17)$$

$$K \leq 0.00008 \approx 3 * Class\ A \qquad (18)$$

Therefore, we should not observe any variation of the ductwork airtightness test result when changing the measuring device location, regardless of the location of leakages, if the ductwork is at most 1.5*class A.

Experimental impact

According to the previous calculation the variation of the measured flowrate was expected to remain below 3%. This was confirmed by the measurements performed that showed no impact of the position of the measuring devices according to the leakage repartition. The small-observed variation (below 2%) is in the range of the measurement uncertainty.

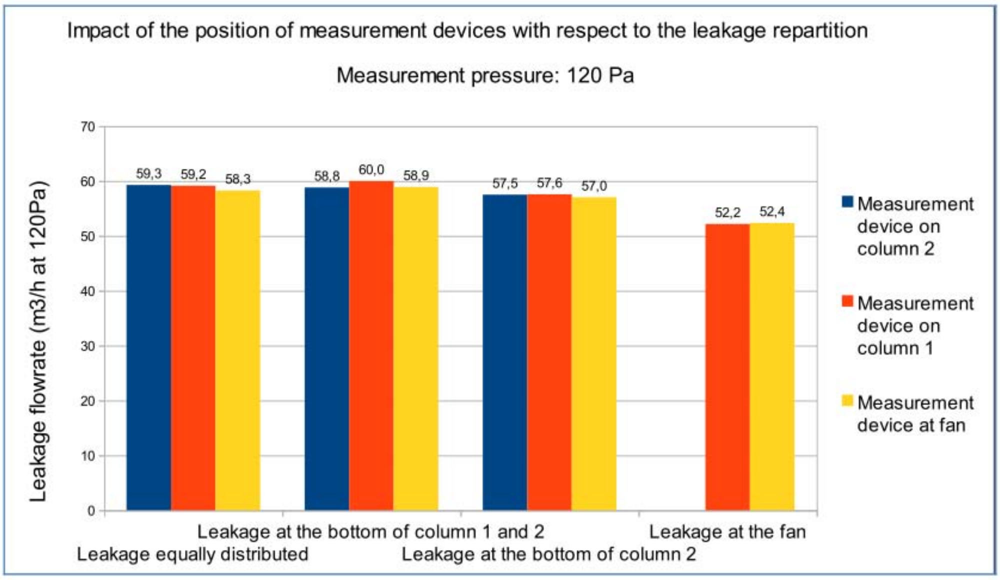


Figure 12: Leakage flowrate as a function of leakage distribution and location of the measuring device at 1.5*class A

3.2 Impact of the pressure drop

Pressure drop due to the damper

The pressure drop due to the dampers was measured (see Figure 13) and the associated pressure loss coefficient was calculated using the following formula:

$$\zeta = \frac{2\Delta P}{\rho v^2} \qquad (19)$$

Table 3: pressure drop calculated

Damper position	0	1	2	3	4	5	F
Pressure drop due to damper in column 1 (Pa)	0	1	1.5	5.5	9	49.2	73
Dzeta (ζ) damper 1	0.0	1.8	2.6	9.7	15.9	86.7	128.6
Pressure drop due to damper in column 2 (Pa)	0	0	1	1	42	73.5	85.5
Dzeta (ζ) damper 2	0.0	0.0	0.9	0.9	39.8	69.6	81.0

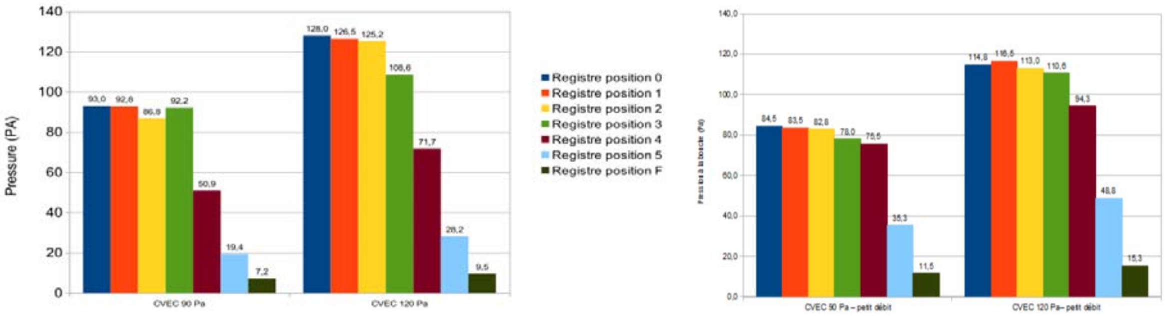


Figure 13: Pressure at the air terminal devices (left: top of column 2, right: top of column 1) according to the damper position

Theoretical impact

In Table 4, the maximal variation of the measured leakage flowrate due to the pressure drop was estimated using equations developed in §2.1. It was assumed that all leakages were located at one end of the ductwork and the measuring device at the other end.

In order to calculate the total pressure drop in the ductwork, the calculated pressure drop coefficients of dampers (Table 3) were added to the pressure drop coefficient (ζ) of the rest of the ductwork: 6.9 Pa (Table 2).

Table 4: Maximal variation of measured flowrates at 90 Pa, 120 Pa and 160 Pa according to the damper positions

	Dampers position	Open	1	2	3	4	5	Closed
	Total pressure drop (Pa)	6.9	8.7	10.5	17.5	62.6	163.2	216.5
1.5* class A	K (1.5*Class A)	3.88E-05						
	Max. variation at 90 Pa	1%	1%	1%	1%	5%	14%	19%
	Max. variation at 120 Pa	1%	1%	1%	2%	6%	16%	21%
	Max. variation at 160 Pa	1%	1%	1%	2%	7%	18%	24%
class C	K (class C)	2.12E-06						
	Maxi. variation at 90 Pa	0.00%	0.0_0%	0.00%	0.01%	0.02%	0.06%	0.08%
	Max.variation at 120 Pa	0.00%	0.00%	0.00%	0.01%	0.03%	0.07%	0.09%
	Max. variation at 160 Pa	0.00%	0.00%	0.00%	0.01%	0.03%	0.08%	0.10%

The variation is negligible for Class C but may be quite important for 1.5*class A when the damper is in position 5 or closed.

However, as leakages are distributed along the ductwork, assuming that there is a unique leak at the end of the ductwork is a strong hypothesis. According to the distribution of leakages (Figure 14) less than 80% of leakages undergo pressure drop due to the two dampers. When only 80% of leakages are considered, the variation of the measured flowrate is shown in Table 5.

Table 5: Variation of the measured flowrate when only 80% of the leakages are taken into account

Dampers position	Open	1	2	3	4	5	Closed
Variation at 90 Pa	0%	0%	0%	1%	3%	9%	12%
Variation at 120 Pa	0%	0%	1%	1%	4%	10%	13%
Variation at 160 Pa	0%	0%	1%	1%	4%	11%	15%

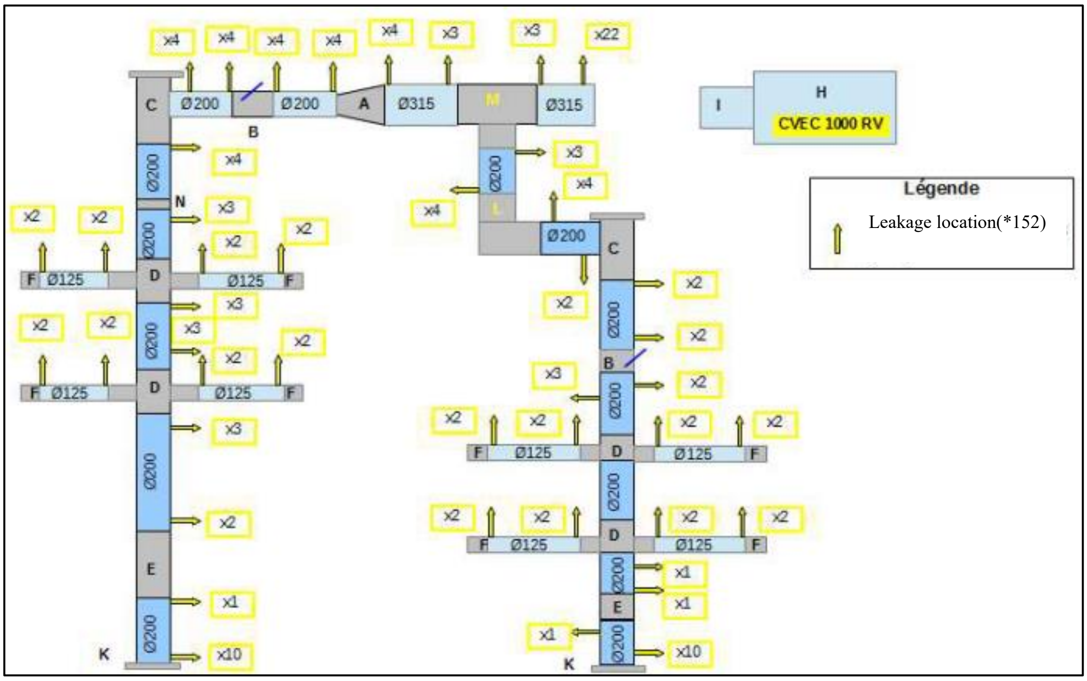


Figure 14: Repartition of leakages (drill) when the ductwork is 1.5*Class A

Experimental impact

Figure 15 and Figure 16 give the measured leakage flowrate of the ductwork according to the positions of the two dampers for a leaky ductwork and an airtight ductwork.

As predicted with the theoretical approach, the position of the damper has no impact on the measured flowrate for an airtight ductwork (Class C).

However, when the ductwork is leaky the measured flowrate decreases slightly from position 4. Table 6 gives the variation of the measured flowrate according to the position of the damper. The measured variation is close to the estimated maximum variation when taking into account only 80 % of leakages (see Table 5).

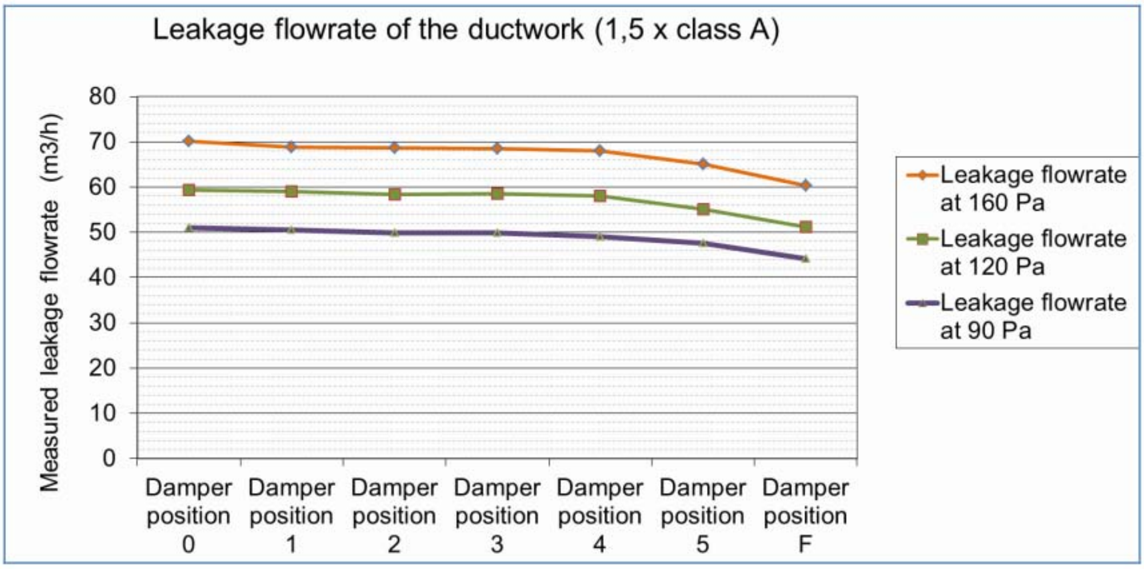


Figure 15: Leakage flowrate of the ductwork as a function of the damper's position at 1.5*class A (position 0 open; position F: closed)

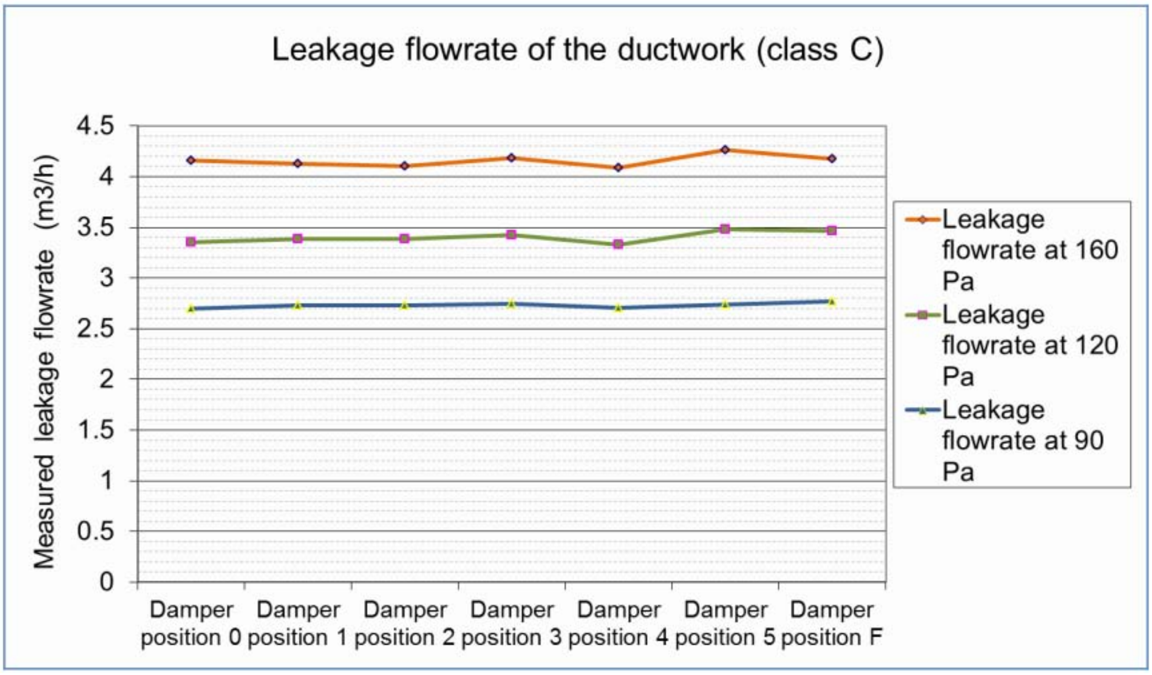


Figure 16: Leakage flowrate of the ductwork as a function of the damper's position at class C (position 0: open; position F: closed)

Table 6: Variation of the measured flowrate on the experimental set-up

Position dampers	Open	1	2	3	4	5	Closed
Variation at 90	0.0%	0.9%	2.1%	2.2%	3.8%	6.5%	13.4%
Variation at 120	0.0%	0.6%	1.7%	1.5%	2.3%	7.0%	13.7%
Variation at 160	0.0%	1.9%	2.0%	2.2%	3.1%	7.1%	13.9%

4 DISCUSSION

The equation developed in this paper allowed to calculate the maximum variation of the measured leakage flowrate according to the length and shape of the ductwork and the foreseen airtightness.
If we assume an accessory (bend, convergence, etc.) every 2 m inducing an average pressure loss coefficient of 0.5, the maximum length to be tested (*L*) can be estimated according to the airtightness class objective and to the maximum error (*E*) using the equations 18 and 19:

$$\frac{\left|Q_{\Delta P_{du;meas}}\right| - \left|Q_{\Delta P_{du;lea}}\right|}{\left|Q_{\Delta P_{du;meas}}\right|} \leq 1 - \left(1 - \frac{8\rho K^2 L^3}{D^2} * \left|\Delta P_{du;meas}\right|^{\frac{1}{3}}\right)^{\frac{2}{3}} \leq E \quad (20)$$

$$L \leq \left(\frac{D^2}{8\rho K^2 \left|\Delta P_{du;meas}\right|^{\frac{1}{3}}} \left((E-1)^{\frac{3}{2}} + 1\right) \right)^{\frac{1}{3}} \quad (21)$$

Test cases showed that the impact of pressure losses is expected to be very small for airtight ductwork. However, in case of large and leaky ductworks, it is better to put the measuring device in the middle of the measured section and to check the maximum length. It is also important to notice that the higher the test pressure, the higher the flowrate and therefore the higher the pressure drop and the greater the impact on the final result.

5 CONCLUSIONS

A mathematical model was developed to estimate the maximal error on the measured flowrate according to:

- the airtightness of the ductwork,
- the ductwork configuration (friction and dynamic loss coefficient).

The relevance of this mathematical model was checked through measurements on an experimental set-up.
It was shown that the impact of pressure losses on the measured flowrate is expected to be very small for airtight ductwork (class C).
Nevertheless, for very leaky ductworks it would be advisable to define a maximal length to be tested (distance between the measuring device and the farthest end of the ductwork) or to check the homogeneity of the pressure at various locations.

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