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Ductwork airtightness - A review

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1 Introduction

There are a number of studies demonstrating a significant impact of ductwork leakage on fan energy use [1], [2], [3], [4], [5], [6], [7], [8], [9].

However, a recent survey performed in the framework of the Tightvent Airtightness Association Committee (TAAC) working group showed that awareness in Europe regarding ductwork airtightness is very low [10]. In addition, recent measurements performed in France in the context of the Effinergie + label [11] have shown that almost 50% of the ductwork systems in the tested houses have a ductwork airtightness of 2.5*class A or worse. This stresses the need to change construction habits because ductwork, in most of the tested buildings, was designed to achieve at least class A (required by the Effinergie + label) but missed the target.

This paper aims to complement Ventilation Information Paper (VIP)°1 "Airtightness of ventilation ducts" [12]. It provides a literature review of the work performed since 2003 in the field of ductwork airtightness. Its objectives are to provide information on:

- the impact of ductwork airtightness;
- regulations and standards;
- measurements methods; and
- the implementation of ductwork airtightness.

2 Ductwork airtightness classes

The air-tightness classes ranging from A to D determine the level of airtightness in ductwork. Table 1 gives the maximum air leakage flow rate for each class according to CEN standards (EN 12237 & EN 1507). In order to increase the air-tightness class, a ventilation system must become three times tighter. Class C or D correspond to very tight ductwork, while class A or poorer (classified as 3A, 9A, 27A) correspond to low-airtightness systems.

Table 1: Airtightness classes of ductwork according to CEN standards

Air tightness class	Air leakage limit (L/s.m²)
A	$0.027\ p_{test}^{0.65}$
B	$0.009\ p_{test}^{0.65}$
C	$0.003\ p_{test}^{0.65}$
D	$0.001\ p_{test}^{0.65}$

3 How do duct leaks change energy use?

3.1 Fan energy use and/or indoor air quality impact

When a ductwork is leaky, part of the flowrate generated by the fan comes from (for extract ductwork) or goes through (for supply ductwork) leakages instead of air terminal devices (ATDs). Therefore, the fan needs to move more air to compensate for the extra flowrate and the extra pressure losses due to leakages. If air flows are not increased to compensate for leakage, then the required flowrates are not met at ATDs which may lead to a poor indoor air quality (IAQ). This has been illustrated in a field study [13] in a bunker (no outside opening) relying only on a HVAC system to ensure a good air quality: when the airtightness of the ductwork system and the HVAC system improved (from 1.5*class A to class C) the average concentration of CO_2 dropped from 1400 ppm to 650 ppm.

On the other hand, if the fan compensates for leakage (with either higher fan power or a longer operating time) this will lead to an increase in fan energy use. One example study found that fan energy doubled when adjusted to have the desired air delivery rate [3].

The fan may only partly compensate for leakages and therefore induce both an increase of energy use and a decrease of the indoor air quality. This is summed up in Figure 1 and explained in more detail in [14].

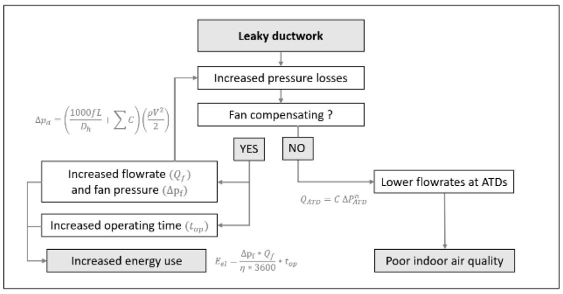

Figure 1: Impact of leaky ductwork on energy consumption and/or poor IAQ

Fan energy use

The fan power consumption depends upon the flowrate produced by the fan and the pressure difference on either side of the fan.

$$P_{el} = \frac{\Delta p_f * Q_f}{\eta_f * 3600} \quad (1)$$

P_{el}	W	Electrical power of the fan
Δp_f	Pa	Pressure difference at fan
Q_f	m^3/h	Flowrate at fan
η_f		Efficiency of the fan (may depend on the pressure difference and flow rate)

The higher the pressure drop (resistance) in the ductwork, the higher the pressure difference the fan needs to produce to overcome this resistance and achieve the hygienic flow rate.

So, leakages can be compensated by a higher fan power or by a longer operating time to achieve the same average indoor contaminant level. Both will increase energy use.

Pressure losses

Pressure profiles along a simple extract ductwork are presented in Figure 2 for three cases:

1) without leakages;
2) with leakages not compensated by the fan: the pressure drop is reduced at the ATD, inducing a lower airflow rate (poor indoor air quality);
3) with leakages compensated by the fan: same pressure drop as 1) at the ATD to meet a hygienic airflow rate which requires an increased fan pressure (increased energy use).

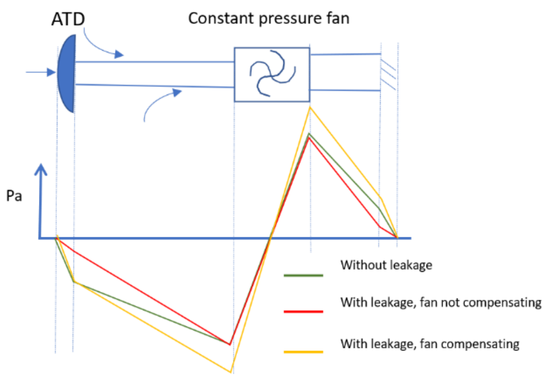

Figure 2: Pressure profile within the extract system with and without leakages according to the pressure created by the fan

Calculation models

Theoretically, as the pressure loss in the ductwork scales with the flowrate at power two, the fan power shall scale with the flowrate at power three. Nevertheless, the efficiency of the fan also depends on the flowrate and the resistance in the ductwork. This relationship between the efficiency and the flowrate and pressure depends on the kind of fan used (axial or centrifugal and synchronous or DC). Therefore, Modera [15] has estimated that the fan power increases when the fan flow is raised according to a power law with exponent between 2 and 3 [15].

To estimate the additional energy used to overcome ductwork leakage, the calculation model based on EN 16798-5-1 [16] and developed by Leprince & Carrié [9] can be used. The study emphasizes that air tightening the ductwork may not always induce energy savings (if the fan was not compensating for leakages before air tightening) but will always either reduce fan energy use or improve indoor air quality or both.

For VAV (variable air volume) systems, Wray & Sherman [17] have developed a duct leakage model for Energy Plus to assess the impact of ductwork leakage on fan energy use. The model applies to large buildings with VAV systems as it considers the share of leakage on each side of the VAV system (high and low pressure).

Calculation and measurements performed in various studies are summarized in Table 2. It shows that improving ductwork airtightness may reduce the fan energy use between 30% to 75%.

3.2 *Losses of preconditioned air*

In the US, air is often the carrier of the thermal distribution. A study from 2005 indicated that 10%–30% of the conditioned air in an average central air conditioning system escapes from the ducts [18]. Therefore, the main concern in the US, regarding ductwork leakages, is the loss of preconditioned air.

Indeed, leakages also induce an increase of heating and cooling loads as:

- when leakages occur in a conditioned space this may lead to over-ventilation;
- when the air is pre-conditioned and leakages of the supply ductwork occur outside the conditioned space, the pre-conditioned air is not fully used for the building (lost heated or cooled air);
- when there is a heat exchanger, leakages of the extract ductwork in an unconditioned space decrease the energy recovery;
- when the air is pre-cooled, a secondary impact of the increased fan power is an increase in the cooling load associated with the heat generated from the increased fan power [15].

It can also induce comfort issues as leaky thermal distribution ducts can prevent air from reaching the intended rooms, leading to rooms that are too hot or too cold.

Calculation models

It is possible to calculate the impact of ductwork leakages on fan energy use using only the fan and ductwork characteristics. However, when it comes to heating and cooling loads, the calculation becomes complex as it depends also on the building characteristics and climate. Therefore, calculating the impact of leakages on the heating and cooling load may require a full dynamic energy calculation for the whole building or to perform measurements on-site.

The new EPBD standard EN 16798-5-1 [16], now includes equations to take into account ductwork leakages on heating and cooling loads in the EP-calculation. It is also done in the French EP-regulation (RT 2012).

To estimate the impact of ductwork leakage and heat conduction losses in steady state conditions, Carrié & Leprince [19] have developed a simple model based on EN 15241 (now EN 16798-5-1) that is now implemented in the French EP-regulation. As an example of application, for a balanced ventilation system with heat recovery and a ductwork of 3*class A with 20m² outside the conditioned space, the efficiency of the heat exchanger is almost reduced by half.

Measuring the impact of ductwork leakages on heating and cooling loads is also complex as leakages mingle with conductions losses.

As both calculation and measurements are challenging, few studies estimate the impact of ductwork leakages on heating and cooling loads (summarized in Table 2). The impact of leakages on heating loads is estimated between 5% and 18% and between 10% and 29% for cooling loads. The highest impact seems to be on the cooling design power that can be increased by 48% if leakages are considered.

Table 2: - Case studies on the impact of ductwork leakages presented in the literature

Authors	Year	M/C*	Description	Leakage	Impact
Carrié et al. (Save-duct)	[7]	M C	Field measurement in France and Belgium and calculation (42 duct systems)	Cumulative energy savings in Europe due to the installation of airtight ductwork in new and rehabilitated dwellings: about 10 TWh in 10 years	
			Residential and commercial buildings	The cooling capacity of air delivered through supply registers decreased by 10–40% due to air leakage, conduction and convection losses	
Modera	[15]	C	Calculations according to standard 152-2004 with ductwork located in ceiling plenum space (light commercial buildings). For 3 US climates and 3 types of insulation.	From 35% to 6% of the balanced flowrate	+5 up to +18% on Heating loads +10 up to+29% on Cooling loads Up to +48% on cooling design power
Wray et al.	[17]	C	Simulations	From 2.5% to 10%	+30% of supply fan power (leakages upstream the VAV have a larger impact)
Guyot et al. (ASIEPI)	[20]	C	Calculations with the French EP calculation tool	Global efficiency of a heat recovery system reduced from 85% (nominal value) to less than 60% due to duct leakages (equivalent to approximately 5 kWh/m^2/year of space heating)	
Dyer	[4]	C	Simulation on a large pharmaceutical plant	5 times SMACCNA standards	+ $1,000,000 over the system's life (heating and cooling loads)
Soenens & Pattijn	[1]	C	3 simulation cases: a hospital wing, a rest home and an office building	The total energy use related to ventilation can be reduced by over 30% by achieving an airtight ventilation system	
Bailly et al.	[5]	C	Calculation on 3 test houses	Class 2.5A; leakages inside conditioned space inducing over-ventilation	+13% of heating energy use
Berthault et al. Leprince & Carrié	[3] [9]	M C	Laboratory replication of residential ductwork	From 1.5 class A to class C	Almost -50% of fan energy use
Krishnamoorthy & Modera	[8]	C	Central heating and cooling of outdoor air in commercial buildings with VAV systems	From 19% to 2%	$1.72 to $2.8 per m² annually (including fan power, fan heat removal and conditioning of excess outdoor air)
Zhivov & Lohse	[21]	C	In the United States, HVAC system air leakage, which is ranked as the primary source of energy inefficiencies in commercial buildings, wasted an estimated $2.9 billion in 2005		
Richieri et al.	[13]	M	Refurbishment of a bunker's ventilation system	From 30% to 5%	About -75% of fan power

* M: measurements
C: calculations

Fan energy use — Heating and/or cooling loads — Cumulated losses

3.3 *Case studies*

Case studies illustrating the impact of ductwork leakages are listed in Table 2. Most of them focus on the impact on fan energy use or on heating/cooling load detailed in the previous sections. Some studies estimate the cumulated loss of energy and/or the corresponding energy cost and allow to compare this cost with the additional cost induced by the implementation of airtight ductwork. According to Soenens & Pattijn [1], the additional investments to achieve a good air tightness of the ventilation system in new buildings are low compared to the avoided energy losses.

Other effects of ductwork leakages are also reported, such as changes in noise that tends to increase with increasing duct flows. In [13], when the ductwork airtightness and the air handling unit (AHU) improved, people within the bunker acknowledged a reduction of noise.

Leakages can have 3 noise related effects that need further investigation:

1. Increasing fan flowrate and pressure needed will increase the noise produced by the fan
2. Leaks can also increase the transmission of fan sound pressure
3. Leaks can create their own "whistling" noise

Leakage downstream of filters but before the fan can bypass the filter, leading to poor indoor air quality issues. It is also believed that leakages can increase dust accumulation in filters [4], heat exchangers and ducts, as there is more flowrate going through.

Moreover, ductwork leakages lead to uncontrolled airflows that may induce depressurization causing backdrafting of combustion equipment or pressurisation causing moisture damage in walls [15]. This unbalance may also weaken contamination protection of sensitive areas (operating theatres, clean rooms, etc.)

4 Where are we?

According to a survey performed in the TAAC working group [22] awareness on ductwork airtightness has increased moderately in Europe. However, there is a broader awareness regarding the efficiency of ventilation systems which could lead to improvements in ductwork airtightness. This section sums up the information on national regulations and ductwork airtightness levels per country published in the literature.

4.1 *Regulations*

Table 3 shows national regulations and ductwork airtightness levels in Portugal, UK, France, Sweden, Norway, Finland

4.2 *Impact on Energy Performance (EP)-calculation*

A questionnaire on ductwork airtightness in regulation has been sent to TAAC members [10]. Only 4 country members filled in the questionnaire (Belgium, France, Latvia and Germany), while the Czech and Polish respondents answered that ductwork airtightness was not really considered in their country.

Among the countries only France (RT2012) and Belgium EPB consider ductwork airtightness as an input in the EP-regulation but there are no minimum requirements.

In France, ductwork airtightness class is an input for the Energy-calculation and so is the part of leakages inside the conditioned space. These data are used to:

- Calculate the thermal losses of the air in both extract and supply ductwork
- Calculate over-ventilation due to leakages inside the conditioned space

However, the fan power is an input of the EP-calculation and is not corrected according to leakages within the EP-calculation. The default value in France is 2.5 class A.

In Belgium, the ductwork leakage flow (according to EN 14134) is an input for the EP-calculation only for residential buildings. By default (without measurement) it is assumed that the leakage represents 18% of the required flowrate. Leakages induce over ventilation in the conditioned space and therefore thermal losses in winter. As in France, the impact on fan energy use is not directly calculated in the EP-calculation but should be measured at commissioning and therefore taken into account.

Table 3: Regulation on ductwork airtightness for 6 countries

Country	Regulation	Application
Portugal	Since 2006: mandatory tests for new HVAC systems in buildings larger than 1000m² included in the regulation. Ductwork leakage may not exceed 1.5 L/s.m² under 400 Pa[1]	Rarely applied. A survey on the 15 biggest contractors (11 answers) in the market showed that 64% of them perform only 1 to 10 tests/year (only 4 own the test equipment)[2]
UK	Mandatory tests for high-pressure ductwork systems (non-domestic ventilation) in accordance with BESA DW/143[3], Class C shall be reached.	The ductwork designer chooses the section to be tested and may ask for additional tests. The test is usually performed by the contractor.
France	Justification required for using a better value than the default one in the EP-calculation (test performed by a qualified tester or by certified quality approach). The French programmes Effinergie + and Effinergie BEPOS require a justified class A for ductwork airtightness[1]	More than 100 qualified testers in 2020 (Qualibat 8721) Specific guideline for testing: FD E 51-767, 2014 Awareness regarding ductwork airtightness increased between 2002&2005 [1]
Sweden	Ductwork requirements started from the AMA of 1966 and have been increasing since then[4]. In version 2007: every ductwork shall meet class C. 10% of the total round duct systems and 20% for rectangular ducts must be verified.	It is expensive for contractors to install inferior duct systems: they must pay for both remedial work and additional tests. This motivates contractors to ensure that the work is done properly in the first place[5]
Norway	The building regulations only states that “Ducts and air-handling units shall be satisfactorily airtight” (no quantitative requirements)[3]	Building owners usually specified for a class B, and over 90% of installed ductwork is round with gasket[3]
Finland	Building regulations require minimum Class B for the whole system and recommend ducts and components of Class C or better.[5]	If the system deserves more than one room, measurements are performed to check compliance with the regulations. Sampling is possible if Class C or D ductworks are installed

[1] Leprince et al [10] [2] Lisboa [23] [3] BESA [24] [4] Andersson [25] [5] Schild & Railio [26]

Table 4: In-use factors for mechanical ventilation system (Table 4h from SAP 2012)

In-use factors are applied to the data for mechanical ventilation systems in all cases

Type of mechanical ventilation	Approved installation scheme	In-use factor for Specific fan power			In-use factor for Efficiency	
		Flexible duct	Rigid duct	No duct	Uninsulated ducts	Insulated ducts [d)]
Mechanical extract ventilation, centralised [a)]	No	1.70	1.40	-	-	-
	Yes	1.60	1.30	-	-	-
Mechanical extract ventilation or positive input ventilation from outside, decentralised [a)]	No	1.45	1.30	1.15	-	-
	Yes	1.45	1.30	1.15	-	-
Balanced whole house mechanical ventilation, without heat recovery [a)]	No	1.70	1.40 [c)]	-	-	-
	Yes	1.60	1.25 [c)]	-	-	-
Balanced whole house mechanical ventilation, with heat recovery [a)]	No	1.70	1.40 [c)]	-	0.70	0.85
	Yes	1.60	1.25 [c)]	-	0.70	0.85
Default data from Table 4g (all types) [b)]		2.5			0.70	

[a)] Use these values for data from the database or from data sheets obtained from www.ncm-pcdb.org.uk/sap.
[b)] Use these values for data from Table 4g.
[c)] The values for rigid ducts also apply to semi-rigid ducts provided that the semi-rigid ducts are listed in the database.
[d)] This column applies when all ductwork is within the insulated envelope of the building even though ductwork is not itself insulated.

The UK's Building Regulations' 'Approved Documents' and associated compliance guides make little reference to ductwork airtightness in domestic mechanical ventilation systems. However, SAP 2012 (the software used to calculate the energy performance of new domestic buildings) features a range of 'in-use factors' to estimate the installed performance of mechanical ventilation systems more accurately (see Table 4). They have been developed to reflect the impact of typical installation and operation practices of flexible, semi-rigid and rigid ductwork systems. If the installation is set under an "approved installation scheme" the in-use factor is smaller. The fan power is proportional to the in-use factor.

4.3 Ductwork airtightness level

There are two ductwork airtightness databases that are often discussed in literature, the French database from CEREMA and the US database from Lawrence Berkeley National Laboratory (ResDB). The data gathered in the context of the SAVE-DUCT project are still being used as reference.

In addition to comparing the performance between countries as it was done between France, Belgium and Sweden in the SAVE-DUCT project and presented in VIP °1 [12], these databases give the opportunity to:

- observe the evolution of ductwork airtightness;
- point out the relation between ductwork airtightness level and building characteristics;
- estimate the percentage of flowrate due to leakages.

4.3.1 Evolution of ductwork airtightness

Results from the SAVE-DUCT project showed that in 1998, 83% of the ductwork tested were 3*Class A or worse. They can be compared to the new French database, created in 2016 and gathering around 1300 measurements performed by qualified testers [11]. As half of the measurements were performed in buildings applying for the Effinergie + label (which requires class A) they cannot be generalized to all new buildings in France. However, results show that the French residential buildings tested are now mostly class A or better while non-residential buildings are Class B or better (see Figure 3 & Figure 4). So, in 20 years' time, ductwork leakages seem to have been divided by a factor of 3 to 9.

In the U.S., measurements are gathered in the LBNL database (ResDB). Contributions are made voluntarily by energy auditors, building contractors, energy efficiency programme managers, and researchers. Through the analysis of the data it has been estimated that between 2000 and 2010 ductwork airtightness in residential houses has been been improved by 50% to reach 3.7 cfm25 per 100 ft² of conditioned floor (0.19 L/s/m² at 25 Pa) [27].

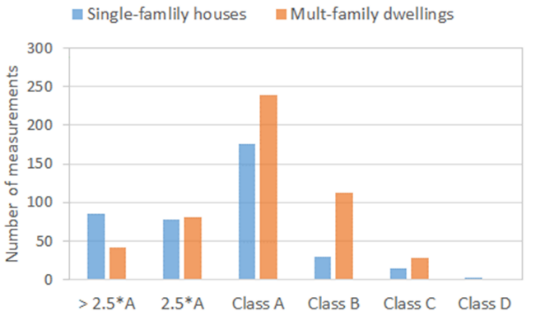

Figure 3: Distribution of ductwork airtightness measured classes in residential buildings [11]

Figure 4: Distribution of ductwork airtightness measured classes in non-residential buildings [11]

4.3.2 Relation between ductwork airtightness level and building characteristics

The analysis of the French database by Moujalled, Leprince & Mélois [11] has shown that ductwork airtightness levels seem to relate to:

- the use of the building(see Figure 3 & Figure 4);
- the ventilation system;
- and the type of ducts (flexible/rigid).

Class A is the most frequent result for residential buildings mainly equipped with single-exhaust ventilation systems. In single dwellings where flexible ducts are mostly used, 55% of measurements achieved Class A or better, against 77% in multi-family buildings with a large part of rigid metallic ducts. In non-residential buildings mainly equipped with a balanced ventilation system and rigid metallic ducts, class B is the most frequent result, and 90% of measurements achieved Class A or better.

4.3.3 Percentage of flowrate due to leakage

Carrié, Andersson & Wouters [28] found that in France and in Belgium, the ratio between the ductwork leakage airflow rates and the minimum airflow rate, measured in 9 multi-family buildings, was an average of 13% at 50 Pa. For commercial and institutional buildings, the ratio between the leakage airflow rate and the design airflow rate was 21% at 100 Pa.

Those findings are consistent with measurements in the US; in 10 large buildings the ductwork leakage was significant, averaging 28% of fan flow [29].

5 How to measure?

5.1 *Testing methods*

5.1.1 Classical method

The classical method to measure ductwork airtightness is described in various publications as for example §6.2 of the SAVE-DUCT project (chapter 6).

As illustrated in Figure 5, the ductwork under test is "isolated" from the rest of the ductwork, extremities of the tested ductwork are sealed and so are the ATDs.

The measurement device consists of:

- a fan maintaining a constant pressure in the tested ductwork;
- an airflow rate gauge, measuring the flowrate needed to maintain the constant given pressure; and
- a pressure gauge, checking the constancy of the pressure.

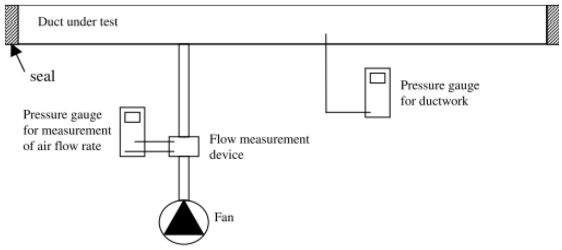

Figure 5: Fan pressurization measurement principle and equipment [28]

Usually in Europe, the test consists of a one-point measurement of the leakage flowrate. The test pressure may either be the working pressure of the ductwork or defined in the regulation or standard. For example:

- In the US, ductwork airtightness in residential buildings is commonly tested at 25 Pa [30]. Standard test methods ASTM E1554 [31], RESNET 380 [32] as well as in ASHRAE Standard 152 [33] also use this reference pressure. Commercial systems are tested at much higher pressures stated in SMACNA test procedures [34] (from 125 to 2500 Pa).
- In France, testing values are defined in FD 51-767:
  - 80 Pa for single houses
  - 160 Pa for multi-family buildings
  - 250 Pa for non-residential buildings

  However, if the default pressure is very different from the actual working pressure the test shall be done at working pressure.

The measured flowrate, pressure and ductwork area give a leakage coefficient per square meter of ductwork area. This leakage coefficient is compared to the airtightness class as defined in Chapter 2.

$$\frac{Q}{A} = f_{ref} = K\Delta p_{ref}^{0.65}$$

Q	m^3/s	Measured flowrate
A	m^2	Tested duct surface area
f_{ref}	$m^3/s.m^2$	Leakage factor
Δp_{ref}	Pa	Test pressure
K	$m^3/s.m^2.Pa^{0.65}$	Loss coefficient (dynamic losses)

The output value can be the equivalent leakage area [35] calculated for a given "n" (usually 0.65)

$$\text{ELA} = Q\sqrt{\frac{\rho}{2}}\left[\frac{\Delta P_{\text{ref}}^{(n-0.5)}}{\Delta P^{n}}\right]$$

5.1.2 Pressurisation leakage to outside

Another method exists to estimate only ductwork leakages to the outside. In this case both the ductwork and building are pressurized at the same pressure and at the same time, using a Blowerdoor for the building [36], [31] [32].

5.1.3 The Delta Q method

The classical method pressurizes the whole ductwork at the same pressure (test pressure). However, in operation, every leakage does not have the same impact on fan energy use and heating and cooling losses as they are not under a homogeneous pressure. Therefore, leaks close to the fan are more critical than those close to ATDs.

Another testing method called DeltaQ method, has been developed in the US to estimate the real leakage flowrate under operating conditions. DeltaQ testing uses a blower door mounted in a door connecting the inside to the outside. Four tests are conducted combining depressurization, pressurization and with the HVAC system blower off and on. A computer is used to analyse the data and calculate the duct leakage to the outside under operating conditions. ASTM E1554 describes how to perform this method [30]. Theoretically, this method is more sensitive to wind conditions as it includes building airtightness tests. However, repeatability tests performed by Walker et al. [36] have shown no big difference with other methods.

5.2 *Uncertainty of ductwork airtightness tests*

According to Walker et al. [37] field work shows that the *pressurization leakage to outside* test method is the most repeatable with a standard deviation of only 1% of the lower flow; the other 2 methods have a standard deviation of approximately 6%. The tighter the duct system the better the repeatability (standard deviation from 0.3% to 3%).

Berthault, Boithias & Leprince [3] have tested the impact of the pressure drop, the leakage repartition and the location of the measurement device on the result of a classical test. Their study showed that:

- the position of the measurement device seems to have no impact on the results of the airtightness test for various leakage distributions;
- only very high dynamic losses (almost completely closed damper) had an impact on the result when the ductwork was leaky.

5.3 *Existing standards and guidelines*

5.3.1 European and American standards

Regarding ductwork airtightness tests, in the US the standards ASTM E1554 [31], RESNET 380 [32] and ASHRAE Standard 152 [33] describe the methodology to perform the test.

In Europe, there is not just one standard describing ductwork airtightness tests but as many standards as ductwork types.

Existing standards regarding ductwork airtightness test are listed in Table 5.

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The variety of standards can cause a confusion between the test of the airtightness of products themselves (in laboratory, non-implemented) and the test of ductwork implemented off site. Even if airtight products are needed to build an airtight ductwork, they are not enough to guarantee an airtight implemented ductwork. Bad implementation can lead to a leaky ductwork.

5.3.2 National initiatives

As there is no European standard covering multiple types of ductwork, national protocols have been developed in countries where ductwork airtightness tests are performed. Some of them are presented in Table 6.

5.4 *Qualification for testers*

A qualification framework for ductwork airtightness exists in France as described in [38]. Since 2012, Effinergie has introduced a training scheme for testers within the creation of the Effinergie+ label. Then, the government created a qualification for ductwork airtightness testers including training, in-situ examination and expertise checking.

A certification of ventilation installers that includes testing also exists in Sweden.

6 How to build airtight ductwork?

6.1 *Implementing airtight ductwork*

The first VIP on ductwork airtightness (1) was already providing information on how to build ductwork airtightness. One can also refer to the “Source book for efficient air duct systems in Europe” [39] and to the chapter 4 of the SAVE-DUCT project [28].

A key point to improve ductwork airtightness is to implement ducts with factory-fitted airtight gasket joints. The market share of these products is increasing in countries where ductwork airtightness is promoted. According to Schild & Railio [40], approximately 90-95% of ductwork in Scandinavia is now circular steel ductwork with factory-fitted airtight gasket joints (certified with airtightness class C or better).

Examples of double lipped gaskets for spiral ducts are given in [21] and shown in Figure 6

To improve the airtightness of existing ductwork, a technique consisting of sealing duct leakages through aerosol injections was developed in the beginning of the years 2000 in the US and is now being implemented in Europe (since 2015). This technique allows to seal 66–86% of the leakage in the duct system once the ductwork is installed [43].

Table 5: Measurement and inspection European standards for ductwork airtightness tests

Standard	**Ductwork type**	**Purpose**	**Contents**
EN 12237 [41]	Circular; Metallic	Test protocol	Includes definitions, sampling rules, testing pressure, equations to correct the flowrate, basic content of test report
EN 1507 [42]	Rectangular; Metallic		Similar to EN 12237. Includes the measurement of the deflection
EN 13403 (2003)	Non-metallic		Includes a test procedure that can be used either on site or in laboratory
EN 15727 (2010)	Components		Classifies components and provides a test method that can be performed either on-site or in laboratory
EN 14239 (2004)	Any	Surface area measurement	Ductwork airtightness test protocols all refer to this standard for the measurement of the surface area of the ductwork
EN 12599 (2012)	Non-residential buildings	Inspection method	Includes references to the measurement standards above (EN 1507 and EN 12237). Under revision (2019). Its next version shall include more information regarding ductwork airtightness tests. Gives default test pressure of 200-400-1000Pa for supply 200, 400, 750 for extraction ductwork. The closest of the working pressure should be chosen

Table 6: National initiatives for ductwork airtightness tests

Country	**National guidelines**	**Contents**
France	FD 51-767	Completes existing standard with information to: - Deal with various kinds of ductwork in a system - Do sampling according to the kind of building: the tested section shall be representative of all shapes, sizes, materials used in the ductwork (requirements according to the length of junction and the area of the ductwork) - Take into account specific devices: plenum, climate box and flexible sleeve shall be included in the measured section, if not the penalty applied on the flowrate can reach 50%. - Choose the test pressure - Apply corrections according to the pressure and temperature - Define the minimum number of Air Handling Units tested Imposes a calibration of the measurement device every 2 years with requirements on the accuracy.
	label Effinergie +	Provides technical rules that allow to estimate the ductwork area with a flat rate according to the maximum flowrate (only if the ductwork is fully tested, no sampling)
Sweden	AMA VVS&KYL 19 (HVAC and Plumbing)	Gives requirements to perform ductwork airtightness tests on: - The test pressure: working pressure (> 200 Pa), otherwise the default value is 400 Pa - The sampling (only if a third-party certified tester does the test): at least 10% of circular ductwork; 20% of rectangular ductwork; default area: 25 m² (at least 10 m² required)
Belgium	« Cahier des charges type 105 » by « Régie des Bâtiments », 2017 (Article E5 part 5)	Gives requirements to perform ductwork airtightness tests on: - Area that shall be tested: at least 10m² and 30% of the ductwork area - The pressure test for insufflation: 400 Pa, 1000 Pa and 2000 Pa respectively for low, medium and high-pressure ductwork - The pressure test for extraction: 500 Pa for Class B; 750 Pa for Class C and D - The maximum uncertainty of the measurement - Test protocol, length and frequency of measurement - Measure corrections according to the actual pressure and temperature.
UK	DW143	Gives practical recommendations to perform ductwork airtightness tests as well as to build airtight ductwork (in UK tests are mostly performed by installers).

		- The part of the ductwork to be tested and the test pressure shall be agreed with the client or the system designer. - The test shall be performed before insulation and installation of ATDs. - The test is always done under positive pressure, even for extract ductwork, to be able to track the leakage path (specific to UK) - Only the test of high-pressure ductwork is required (above 1000 Pa), without sampling (100% of the ductwork tested) - It is recommended to test at least 10% of medium pressure ductwork.

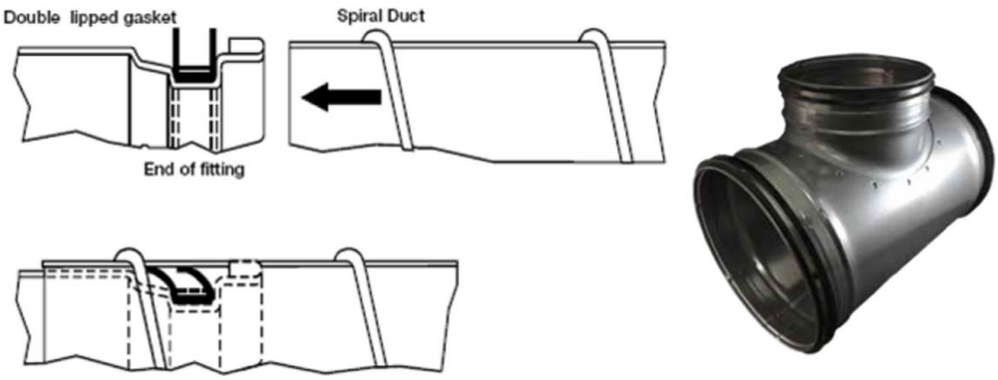

Figure 6: Example of double lipped gaskets (Linx Industries)

6.2 *Existing certification*

Eurovent Certita Certification has settled a new certification programme for Ventilation Ductwork Systems. It was presented in [44]. The objective was to ensure that the airtightness class claimed by the manufacturer can be achieved on site if the system is properly installed. Unlike the initiatives presented in Table 6, this is a product certification and not a building certification. Requirements for the DUCT programme rely on:

- testing typical setup of the ventilation ductwork system; and
- production sites auditing.

The scope of the programme covers rigid and semi-rigid ventilation ductwork systems.

6.3 *The durability of ductwork airtightness*

A protocol to estimate the durability of ductwork sealant materials has been set up by Sherman & Walker [45]. The tests involved the aging of common “core-to-collar joints” of flexible duct to sheet metal collars, and sheet metal “collar-to-plenum joints”. Periodic air leakage tests and visual inspection were done to document changes in sealant performances. Following this study an ASTM standard (E2342-03) has been developed to standardize test procedures and increase reliability of testing that has been used to rate sealant materials.

7 Conclusion: what do we need?

In USA, due to construction habits, work on the subject has been done for more than 20 years as ductwork airtightness has a major impact on heating and cooling loads. In European countries, in the last ten years a lot of work has been performed to promote ductwork airtightness and the awareness on this issue is growing slowly.

However, there is still a lack of knowledge regarding the impact of ductwork airtightness on the energy use of buildings. In respect to heating and cooling loads as well as fan energy use, equations are known to perform the calculations but there is a need:

- For field measurements in various buildings with different climates, ventilation systems, etc. to convince stakeholders of the impact of ductwork airtightness.
- To improve EP-calculation to ensure that the impact of ductwork leakages is properly taken into account. Without a

correct EP-calculation, designers do not see the point of improving ductwork airtightness.

Research is also needed to quantify the impact of ductwork leakages on other aspects such as noise, dust accumulation, indoor air quality, etc.

Improving ductwork airtightness also stresses the need to improve the measurement protocol. Moreover, as regards building airtightness, it is important to:

- enhance the knowledge on the uncertainty of the test and decrease it;
- have a unique and homogeneous international protocol (not split in various standards).

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9 References

[1] Feasibility study of ventilation system airtightness. Soenens, Jeroen and Pattijn, Pedro. Brussels, Belgium: AIVC, 2011. Proceedings of the 32nd AIVC & 1st TightVent Conference, 12-13 October. pp. 51-54.

[2] Class C air-tightness: proven ROI in black and white. Stroo, Peter. Brussels, Belgium: AIVC, 2011. Proceedings of the 32nd AIVC & 1st TightVent Conference, 12-13 October. pp. 96-97.

[3] Ductwork airtightness: reliability of measurements and impact on ventilation flowrate and fan energy consumption. Berthault, Sylvain, Boithias, Florent and Leprince, Valérie. Poznan: AIVC, 2014. Proceedings of the 35th AIVC-4th TightVent-2nd venticool Conference, 24-25 September. pp. 478-487.

[4] Case study: Effect of excessive duct leakage in a large pharmaceutical plant. Dyer, David F. Brussels, Belgium: AIVC, 2011. Proceedings of the 32nd AIVC & 1st TightVent Conference, 12-13 October. pp. 55-56.

[5] Impact of a poor quality of ventilation systems on the energy efficiency for energy-efficient houses. Bailly, Adeline, Duboscq, Franck and Jobert, Romuald. Poznan, Poland: AIVC, 2014. Proceedings of the 35th AIVC-4th TightVent-2nd venticool Conference, 24-25 September. pp. 108-118.

[6] Effects of airflow infiltration on the thermal performance of internally insulated ducts. Levinson, Brennen, et al. 2000, Energy and Buildings 32(3), pp. 345-354.

[7] Duct leakage in European buildings: status and perspectives. Carrié, François Rémi, et al. 2000, Energy and Buildings, Vol. 32, pp. 235–243.

[8] Impacts of duct leakage on central outdoor-air conditioning for commercial-building VAV systems. Krishnamoorthy, Sreenidhi and Modera, Mark. 2016, Energy and Buildings, Vol. 119, pp. 340–351.

[9] Impact of ductwork airtightness on fan energy use: Calculation model and test case. Leprince, Valérie and Carrié, François Rémi. 2018, Energy & Buildings, Vol. 176, pp. 287–295.

[10] Building and ductwork airtightness requirements in Europe – Comparison of 10 European countries. Leprince, Valérie, Carrié, François Rémi and Kapsalaki, Maria. Nottingham : AIVC, 2017. Proceedings of the 38th AIVC Conference "Ventilating healthy low-energy buildings", Nottingham, UK, 13-14 September 2017. pp. 192-201.

[11] Statistical analysis of about 1,300 ductwork airtightness measurements in new French buildings: impacts of the type of ducts and ventilation systems. Moujalled, Bassam, Leprince, Valerie and Mélois, Adeline. Juan-Les-Pins, France: AIVC, 2018. Proceedings of the 39th AIVC-7th TightVent-5th venticool Conference, 18-19 September. pp. 222-229.

[12] Airtightness of ventilation ducts. Delmotte, Christophe. 2003, Ventilation Information Paper n°1 - AIVC.

[13] Ductwork design flaws and poor airtightness: a case study about a ventilation system reconditioning in a sealed building. Richieri, Fabrice, et al. Juan-Les-Pins, France: AIVC, 2018. Proceedings of the 39th AIVC-7th TightVent-5th venticool Conference, 18-19 September. pp. 442-451.

[14] Impact of ductwork leakage on the fan energy use and sound production of central mechanical ventilation units in houses. Leprince, Valérie, Lightfoot, Marcus and de Jong, Jelmer. Ghent: 2019. 40th AIVC conference.

[15] Fixing duct leaks in commercial buildings. Modera, Mark. 2005, ASHRAE journal, pp. 22-28.

[16] Energy performance of buildings - Ventilation of buildings - Part 5-1: Calculation methods for energy requirements of ventilation and air conditioning systems. CEN. EN 16798-5-1:2016. 2016.

[17] Duct Leakage Modeling in EnergyPlus and Analysis of Energy Savings from Implementing SAV with InCITe. Wray, Craig P. and Sherman, Max H. Lawrence Berkeley National Laboratory, 2010.

[18] Measurement of air leakage in air-handling units and air conditioning ducts. Srinivasan, K. 2005, Energy and Buildings, Vol. 37, pp. 273–277.

[19] Impact of ductwork airtightness and conduction losses on heat recovery efficiency. Carrié, F.R. and Leprince, V. Berlin-Adlershof, Germany: euz, 2011. Proceedings of the 6th International BUILDAIR-Symposium.

[20] Stimulation of good building and ductwork airtightness through EPBD. Guyot, Gaëlle and Carrié, Rémi. ASIEPI, 2010.

[21] A Guide to Achieving Significant Energy Use Reduction with Major Renovation Projects (IEA EBC Annex 61, Subtask A). Zhivov, Alexander and Lohse, Rüdiger. New Buildings Institute (NBI), 2017.

[22] OVERVIEW | Right and Tight: What's New in Ductwork and Building Airtightness?. Leprince, Valérie, Kapsalaki, Maria and Carrié, François Rémi. BUILD UP. [Online] 2 October 2017. http://www.buildup.eu/en/news/overview-right-and-tight-whats-new-ductwork-and-building-airtightness-1.

[23] Duct leakage testing in Portugal, a consulting engineer view and experience. Lisboa, Carlos. Juan-Les-Pins, France: AIVC, 2018. Proceedings of the 39th AIVC-7th TightVent-5th venticool Conference, 18-19 September. pp. 216-217.

[24] BESA. DW/143: Ductwork air leakage testing. London: Building Engineering Services Association, 2013.

[25]. Can we learn from the Swedish quality approach to ductwork airtightness and the regular inspection of ventilation systems? Andersson, Johnny. Brussels, Belgium: AIVC, 2012. Proceedings of the International workshop: Achieving relevant and durable airtightness levels: status, options and progress needed, 28-29 March 2012. pp. 95-101.

[26] Duct system air leakage – How Scandinavia tackled the problem. Schild, P.G. and Railio, J. BUILD UP. [Online] 1 September 2009. http://www.buildup.eu/sites/default/files/content/P187_Duct_System_Air_Leakage_ASIEPI_WP5.pdf.

[27] Building Envelope and Duct Airtightness of New US Dwellings. Chan, Wanyu R. and Sherman, Max H. ASHRAE, 2013. Thermal Performance of the Exterior Envelopes of Whole Buildings XII International Conference.

[28] Improving Ductwork - A Time for Tighter Air Distribution Systems, Report. Carrié, F.R., Andersson, J. and Wouters, P.,. [ed.]. ISBN 1902177104. Brussels: EU Project SAVE-DUCT, 1999.

[29] Field experience with sealing large building duct leakage with an aerosol based sealing process. Modera, Mark. Washington: AIVC, 2013. Proceedings of the Workshop on Building and Ductwork Airtightness Design, Implementation, Control and Durability: Feedback from Practice and Perspectives, 18-19 April.

[30] Duct leakage repeatability testing. Walker, Iain and Sherman, Max. Lawrence Berkeley National Lab, 2014.

[31] ASTM E1554. ASTM E1554 / E1554M-13, Standard Test Methods for Determining Air Leakage of Air Distribution Systems by Fan Pressurization. Washington DC: ASTM International, 2018.

[32] RESNET 380. ANSI/RESNET/ICC 380. Standard for Testing Airtightness of Building, Dwelling Unit, and Sleeping Unit Enclosures; Airtightness of Heating and Cooling Air Distribution Systems; and Airflow of Mechanical Ventilation Systems. ICC & RESNET, 2019.

[33] ANSI/ASHRAE Standard 152. ANSI/ASHRAE Standard 152. Method of Test for Determining the Design and Seasonal Efficiencies of Residential Thermal Distribution Systems. Atlanta, GA: ASHRAE, 2014.

[34] SMACNA. HVAC AIR DUCT LEAKAGE TEST MANUAL. Chantilly: Sheet Metal and Air Conditioning Contractors National Association Inc. , 1985.

[35] Duct systems in large commercial buildings: physical characterization, air leakage, and heat conduction gains. Fisk , William J. , et al. 2000, Energy and Buildings, Vol. 32, pp. 109–119.

[36] Improving Building Envelope and Duct Airtightness of US Dwellings - the Current State of Energy Retrofits. Chan, Wanyu R and Sherman, Max H. Washington: AIVC, 2013. Proceedings of the Workshop on Building and Ductwork Airtightness Design, Implementation, Control and Durability: Feedback from Practice and Perspectives, 18-19 April.

[37] Duct Leakage Repeatability Testing. Walker, I. S., Sherman, M. H. and Francisco, P. F. Clearwater Beach: ASHRAE/DOE/BTECC, 2016. Thermal Performance of the Exterior Envelopes of Whole Buildings XIII.

[38] About 1,000 ductwork airtightness measurements performed in new French buildings: database creation and first analyses. Bailly Mélois, Adeline and Moujalled, Bassam. Nottingham, UK: AIVC, 2017. Proceedings of the 38th AIVC-6th TightVent-4th venticool Conference, 13-14 September. pp. 310-318.

[39] Source book for efficient air duct systems in Europe. Malmstrom, T, et al. AIRWAYS project, 2002.

[40] Airtight ductwork - The Scandinavian success story. Schild, Peter G. and Railio, Jorma. REHVA. [Online] 2011. https://www.rehva.eu/publications-and-resources/rehva-journal/2011/022011/airtight-ductwork-the-scandinavian-success-story.html

[41] CEN. European Standard EN 12237:2003. Ventilation for buildings - Ductwork - Strength and leakage of circular sheet metal ducts. CEN, 2003.

[42] EN 1507:2006 Ventilation for buildings - Sheet metal air ducts with rectangular section Requirements for strength and leakage. CEN, 2006.

[43] Sealing ducts in large commercial buildings with aerosolized sealant particles. Modera, M, et al. 2002, Energy and Buildings 34, pp. 705–714.

[44] Ventilation Ductwork Systems Certification for a Better Air Tightness. Briffaud, Marie-Clémence. Juan-Les-Pins, France: AIVC, 2018. Proceedings of the 39th AIVC-7th TightVent-5th venticool Conference, 18-19 September. pp. 230-236.

[45] Duct Tape Durability Testing. Sherman, M.H and Walker, I.S. Lawrence Berkeley National Laboratory, 2004.

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