*Energy Conservation in Buildings*
*and Community Systems Programme*

# Improving ductwork

## A time for tighter air distribution systems

### A status report on ductwork airtightness in various countries with recommendations for future designs and regulations

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**J Andersson**
**P Wouters**
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**European Commission**
**Directorate General XVII for Energy**

*International Energy Agency*
**Air Infiltration and Ventilation Centre**

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**Front page picture:** Bend with separate outlet for cleaning (courtesy Lindab Ventilation AB). A double sealing gasket of EPDM rubber provides a tight reliable joint.

# Contents

# Foreword

A large number of modern European buildings are equipped with ducted air distribution systems. Because they represent a key parameter for achieving a good indoor climate, increased attention has been given to their performance during the past fifty years. One aspect that is particularly developed in this handbook concerns the airtightness of the ductwork, which has been identified as a major source of inadequate functioning and energy wastage of HVAC systems.

These investigations were carried out within the framework of the DUCT project (1997 -1998) whose objectives may be summarised as follows:

1. Quantify duct leakage impacts;
2. Identify and analyse ductwork deficiencies;
3. Propose and quantify improvements;
4. Propose modifications to existing standards.

DUCT was funded in part by the SAVE II ("Specific Action on Vigorou s Energy Efficiency") programme of the Commission of the European Communities - Directorate-General for Energy (DG XVII). It involved five teams representing three different countries:

- Ecole Nationale des Travaux Publics de l'Etat, Lyon, France;
- Belgian Building Research Institute, Brussels, Belgium;
- ALDES Aéraulique, Lyon, France;
- SCANDIACONSULT, Stockholm, Sweden;
- Centre d'Etudes Techniques de l'Equipement, Lyon, France.

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***Target audience***

This handbook is aimed primarily at policy makers, HVAC manufacturers and installers, maintenance contractors, architects, building managers, and building services engineers interested in ductwork performance. It focuses on sheet metal ducts that are mostly used in Europe although most of the information also applies to other types of ductwork systems (plastic-and-wire composite, fibreglass board, concrete, etc.). It includes expert knowledge derived from research and industry, as well as practical information based on surveys and field work. Calculation details are condensed to put the emphasis on end results and qualitative information.

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| Chapter 2 : Quality requirements for ductwork systems | F.R. Carrié, J. Andersson |
| Chapter 3 : Review of codes and standards | D. Ducarme, A. Bossaer, P. Wouters |
| Chapter 4 : Ductwork airtightness: state-of-the-art review of construction and installation technologies | F.R. Carrié, A. Bossaer, J. Andersson |
| Chapter 5 : Traditions in the design and installation of duct systems | O. Faure |
| Chapter 6 : Field measurements | A. Bossaer, F.R. Carrié, J. Andersson, P. Wouters, M. Kilberger |
| Chapter 7 : Air distribution system leakage versus energy, indoor air quality and costs | F.R. Carrié, O. Faure, J. Andersson |
| Chapter 8 : Potential energy impacts of a tight air duct policy at the European level | P. Wouters, A. Bossaer |
| Chapter 9 : Outcome of the international DUCT seminar in Brussels, June 1998 | P. Wouters, A. Bossaer |
| Chapter 10: Recommendations for future technical and governmental measures | F.R. Carrié, P. Wouters, J. Andersson |
| Chapter 11: Conclusions | F.R. Carrié |

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Chapter 3 has been reviewed by members of Working Group 3 of CEN Technical Committee 156 “Ventilation for Buildings”.

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- Aeroseal Inc., USA, Figure 21;
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- Lawrence Berkeley National Laboratory, Figure 38, Figure 39;
- Lindab Ventilation AB, Sweden, Figure 3, Figure 4, Figure 6, Figure 16;
- Swedish Council for Building Research, Figure 17, Figure 18, Figure 19.

# Chapter 1 Introduction

The primary function of a building is to provide occupants with an environment that is suitable for their activities and well being. In fulfilling this role, outdoor perturbations and internal loads must be processed to achieve a good indoor climate. However, because there are a number of underlying issues, space conditioning in buildings has been given increased attention over the past few years. In fact, it is estimated that it represents about a fourth of the final energy demand in the EU. In addition, climate control is strongly related to public health and productivity concerns and recent studies[1] suggest that it has an effect on measures of productivity such as absence from work or health costs. These usually lie between 5 % and 15 %.

In this context, the efficiency of air distribution systems is a very active field of investigation. These systems are often used in modern European buildings as a strategy to control thermal conditions and indoor air quality. Many problems have been reported in relation to energy use and peak power demand, clean air supply, flow balancing and airtightness etc. The purpose of this handbook is to give an overview of these aspects with a special focus on duct leakage and its consequences.

Although this topic of study has been visited in the late fifties in Sweden, leading to the first ductwork airtightness requirements in the Swedish AMA guideline in 1960, this concern seems rarely present today in most other European countries. In the context of energy conservation, sustainable development, and harmonisation of standards and regulations in Europe, this issue needs to be re-addressed to evaluate the implications of a tight air duct policy at the European level.

The contents of this handbook are briefly described below:

- Chapter 2 gives an overview of quality requirements of ductwork;
- Chapter 3 summarises ductwork airtightness related standards in Europe and some other non European countries;
- Chapter 4 looks at today's ductwork technology. It includes a review of ductwork construction, installation and rehabilitation techniques that may be used to limit duct leakage;
- Chapter 5 is concerned with traditions in the design and installation of duct systems;
- Chapter 6 deals with duct leakage field measurements in European countries. Little information is available on this subject, however, field data from the SAVE -DUCT project suggest that the ductwork airtightness is in general very poor;
- Chapter 7 discusses the energy, indoor air quality and cost issues associated with duct leakage. Sample calculations are performed based on realistic data;
- Chapter 8 is dedicated to a macroscopic approach to the energy implications of a tight air duct policy at the European level;

[1] See for instance Wyon, D. P. Healthy Buildings and their impact on productivity. In Indoor Air 93. Vol. 6, Proceedings of Indoor Air. 1993. pp. 3-13.

- Chapter 9 consists of a synthesis of issues brought to light by practitioners , manufacturers, and policy makers in the international seminar on ductwork airtightness held in Brussels June 10-11, 1998;
- Chapter 10 is more particularly geared towards the implementation of a tight air duct policy, with recommendations for technical and governmental measures.

These investigations were carried out within the framework of the DUCT project (1997 -1998; Cf. appendix) funded in part by the SAVE programme of Commission of the European Communities - Directorate-General for Energy (DG XVII).

# Chapter 2 Quality requirements for ductwork systems

| | |
|---|---|
| **Airtightness** | **Fire protection** |
| **Thermal insulation** | **Corrosion** |
| **Pressure drop** | **Installation** |
| **Clean air supply** | **Life Cycle Cost** |
| **Strength** | **Design issues** |
| **Noise** | **Commissioning and maintenance** |

The key role of an air distribution system is to provide clean air (sometimes at required specific thermodynamic conditions) to rooms so as to dilute or extract pollutants and / or to condition spaces. In achieving this goal, many other issues have to be examined to comply with the essential requirements of the Construction Products Directive (EU) and to obtain an acceptable indoor climate at a minimum cost. The purpose of the chapter is not to give a comprehensive list of those issues but rather to focus on a few aspects that are closely linked to the ductwork.

It is important to have a properly designed ductwork, i.e.:

1. It shall be tight and secure the air transport through the system (§ 2.1);
2. It shall have such a heat resistance that energy losses are restricted (§ 2.2);
3. The system shall have a low resistance to the flow to minimise the fan power demand and energy use (§ 2.3);
4. Components shall be laid so that they are accessible for cleaning and shall, if necessary, be supplied with cleaning facilities (§ 2.4);
5. They have to be able to withstand normal handling and installation stresses as well as the positive or negative operating pressure of the system in which they will be integrated (§ 2.5);
6. Noise should be prevented from getting through to the occupied spaces (§ 2.6);
7. Duct systems shall not contribute to the spread of fire, smoke or gases (§ 2.7);
8. The materials should be chosen according to the aggressiveness of the environment to limit corrosion damages (§ 2.8);
9. The ductwork shall be safe and easy to install (§ 2.9);
10. It should preferably use standard sizes, facilitating prefabrication of ducts and components, thus allowing for shorter delivery times and possibly lower costs.

Along with Life Cycle Cost issues (§ 2.10), all of these design requirements need to be integrated at the design stage as it may influence the building design. An interesting illustration lies in the choice of round rather than rectangular ducts (§ 2.11).
In general, a compromise must be found between these issues, the cost of the plant and the building as a whole. As a simple example, a larger duct will have a lower pressure drop; however, the additional space required may not be compatible with the budget and the building design.

Finally, evidence suggests that commissioning and maintenance plays a major role in sec uring optimum system performance. Special care should be given to these aspects (§ 2.12).

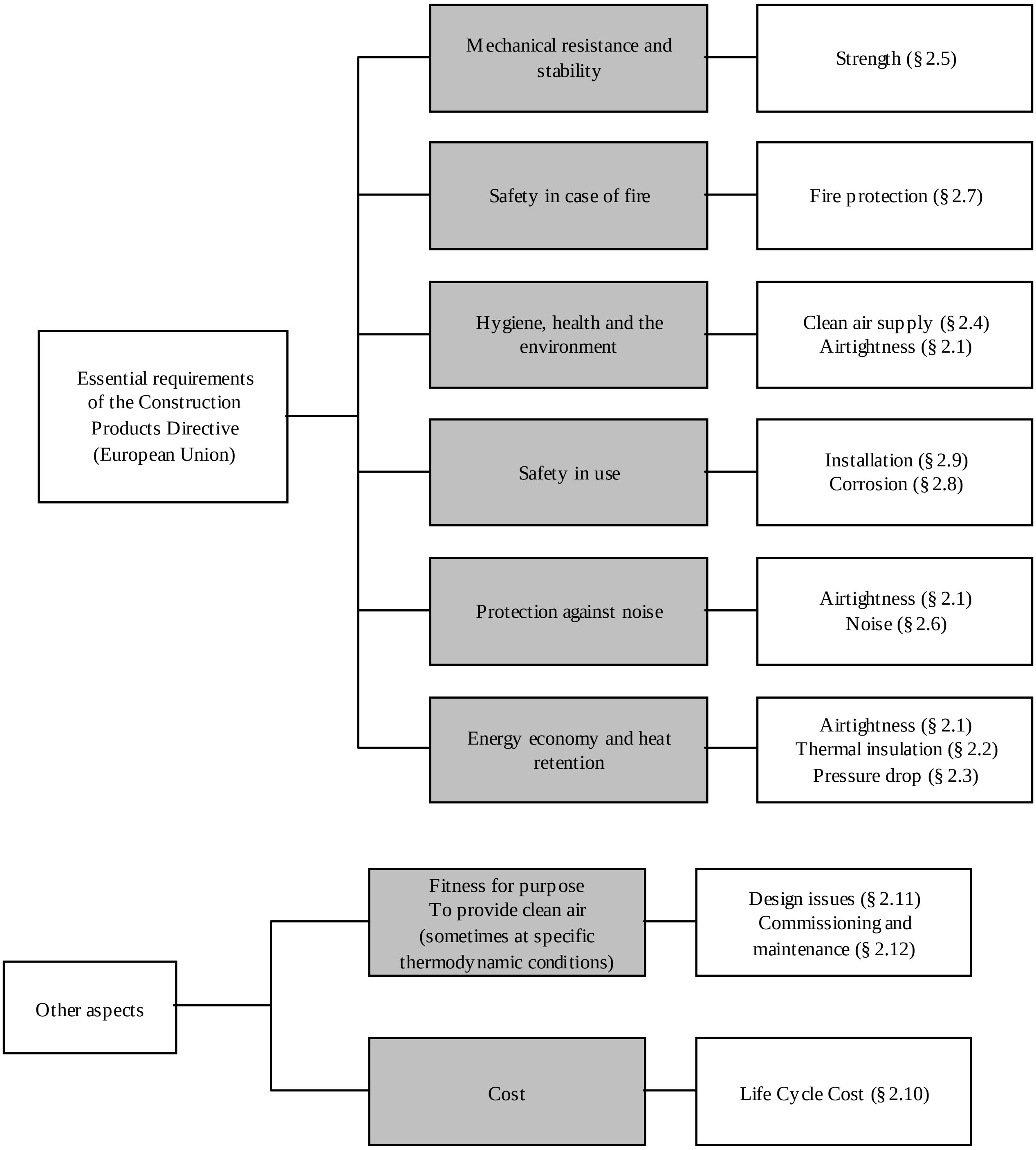


*Figure 1: Ductwork requirements.*

## *2.1 Airtightness*

In most of the member states, it is commonly accepted that the ductwork airtightness is not a key issue to efficiently distribute the air within the building and thus leakage tests are viewed as an unnecessary expense. However, as stated in EUROVENT Guidelines 2/2, a ductwork airtightness limit may be required to minimise the cost and the energy penalty due to an over-sized or inefficient plant, and/or to ease the flow balancing process, and/or to have control over the leakage noise. Other impacts such as the entry or release of pollutants through leaks or the in/ex filtration to unconditioned spaces can be foreseen, with potentially large effects on energy use, power demand, indoor air quality, and comfort-effectiveness. To provide a general (however simplified) picture, we have represented, schematically, duct leakage implications in Figure 2. To avoid these problems, the use of quality commercially available products should be considered and particular attention should be paid to the installation process.

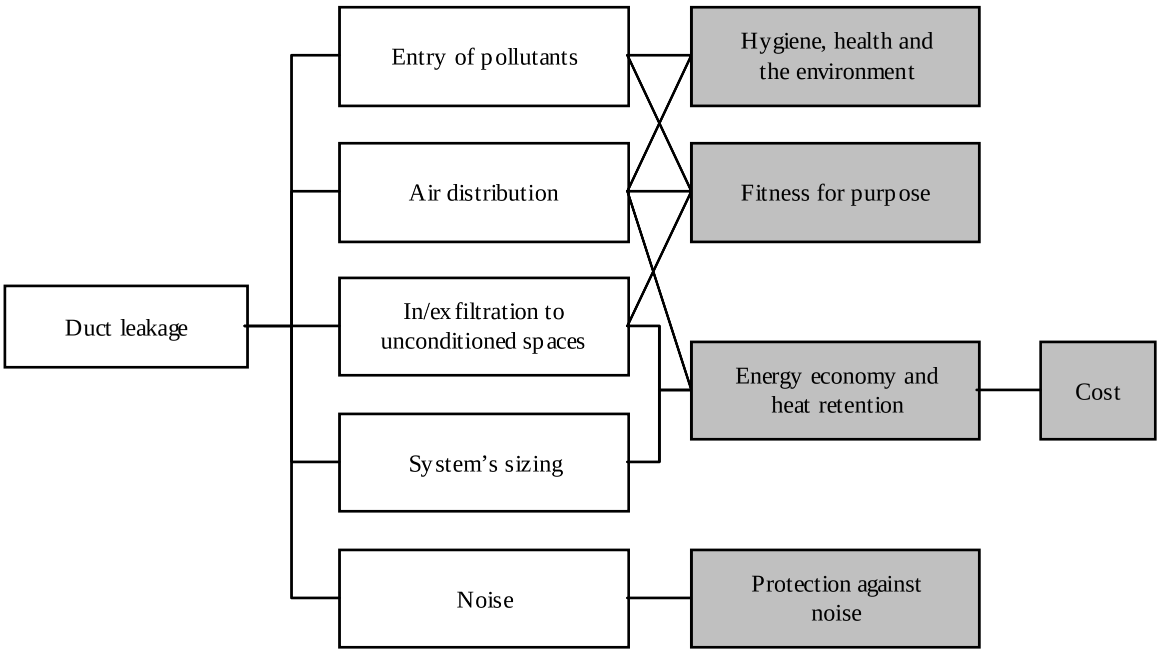


*Figure 2: Flow chart of duct leakage implications.*

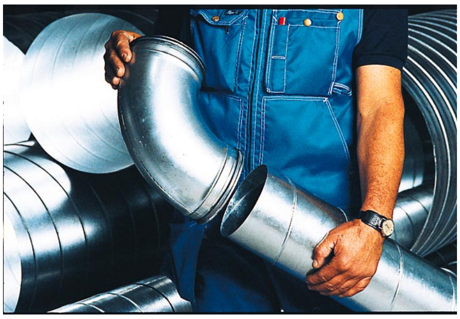

*Figure 3:* Lindab*Safe® sealing system (courtesy Lindab Ventilation AB). A double sealing gasket of EPDM rubber provides a tight reliable joint.*

### *2.2 Thermal insulation*

Air distribution systems may be used for heat recovery, or for heating, or air conditioning. The air in the extract ducts may be used to pre-condition the incoming outdoor air that is transported through the supply ducts. In such cases, the ductwork should be insulated to limit conduction losses (i.e. thermal losses through the duct shell). The use of thermal insulation, in combination with a vapour barrier, should also be considered when water condensation on duct surfaces is expected.

### *2.3 Pressure drop*

In a ductwork system, pressure can be viewed as energy created by the fan that can be reversibly converted into kinetic energy (airflow), or irreversibly dissipated by wall friction or turbulence effects (e.g. in a bend or a sudden expansion). These losses, commonly called pressure drops or flow resistances, must be overcome by the fan to meet the desired flow rates at the registers. Also, pressure drops are expensive in that they are directly linked to the fan energy use. These two points imply that calculations taking into account the resistance of every component (including filters) should be carried out at the design stage. This task can become quite complicated in the case of a complex system. However, some HVAC manufacturers provide their customers with computerised tools enabling them to compare the performance of different designs. The calculation is of course simpler and more accurate if it is based on the use of prefabricated duct components that have been laboratory tested.

### *2.4 Clean supply air*

During operation of an air distribution system, dust and other contaminants (e.g. condensed water) may deposit onto surfaces such as ducts, fan blades, or coils. This may lead to microbial growth on the surfaces, especially on air intake ducts with internal thermal insulation, and to the entry of polluted air within the occupied spaces. Such contamination becomes a health hazard to the occupants. In some cases, especially for smaller dimension ductwork carrying moist air, e.g. from bathrooms, a considerable decline of the delivered airflow rates may be expected (Luoma et al., 1993; Wallin, 1994). The building manager and occupants generally ignore these issues. To minimise these effects the system needs to be inspected and, if needed, cleaned periodically. This implies that maintenance or inspection schemes be accounted for at the design stage to ensure a good accessibility of such components as fans, filters, and air ducts. Also, the materials shall neither emi t pollutants nor enhance the growth of microorganisms that could be transported to the living-areas. They shall be able to withstand standard cleaning procedures (e.g. brushing, vacuum cleaning, chemical disinfection) that are expected to be necessary during the course of operation.

*Figure 4: Bend with separate outlet for cleaning (courtesy Lindab Ventilation AB).*

### *2.5 Strength*

The ductwork can incur physical damage during shipping and handling, as well as during later work or inspection on or near the system. It is important that the ductwork be resistant to stresses commonly applied during these operations. The ductwork also needs to be able to withstand the positive or negative operating pressure of the system in which it will be integrated. This information is usually readily available from the manufacturers. Hangers and support systems shall be constructed so as to ensure a secure installation and operation. Distance between and size of the hangers shall withstand spot loads in addition to the dead weight of the duct. A spot load of 1 kN (about the weight of a person) is used in VVS AMA 98 (1998). The reason for this Swedish requirement lies in the occurrence of fatal accidents to people who have been wrongly using rectangular ducts as working platforms instead of scaffolds or ladders. Exposure to temperature extremes, earthquakes, sudden stoppage of airflow or any other conditions specific to the installation should be considered where necessary.

### *2.6 Noise*

Noise can either be generated in or transmitted through the ductwork. It is a major source of complaints. Aerodynamic noise (due to the airflow) can be limited with good design:

- Low air velocity in the ductwork;
- Use of round ducts;
- Use of bends with large internal radii;
- Smooth transitions and changes in flow direction;

- Use of low-noise control valves;
- Low air leakage.

As for noise propagation through the ductwork, the integration of silencers should be considered.

*Figure 5: Cylindrical type silencer combining passive sound attenuation by rock wool with reactive attenuation (neutralisation of noise by the addition of opposite sound). The Noise Negator is used as a component in the HVAC systems of commercial buildings or domestic dwellings (courtesy ALDES Aéraulique).*

*Figure 6: Silencer bend for use in ventilation systems where space considerations or other circumstances prevent the use of straight silencers (courtesy Lindab Ventilation AB).*

### *2.7 Fire protection*

The main rule in all countries is that a building installation - a ventilation duct, a pipe or a cable - passing through a fire partition must not decrease the fire protection properties of the structure, i.e. the wall with the passing duct shall be as safe as a combination as the original wall itself without the passing duct. The fire protection quality of the construction is often classified in three ways that can be used solely or in combination:

- ***Integrity***, i.e. the possibility of the construction to be tight to flames and smoke - normally designated with the letter **E**;

- ***Insulation***, i.e. the possibility of the construction to withstand heat on the fire side of the construction without having the other side heat up to a temperature where a new fire will start on that side of the construction - normally designated with the letter **I;**
- ***Resistance to mechanical strain*** caused by the fire - normally designated with the letter **R**.

As an illustration, fire walls classified as **EI 60** are able to withstand the standard fire during 60 minutes and still be tight to fire and flames without risk of starting a fire on the other side of the wall. There are mainly two ways to obtain a wall of equal fire resistance with and without a passing duct:

- Insulating the duct so as to prevent the fire from breaking through the duct wall and spread to the other side;
- Using a fire damper, at the wall, that closes when a fire is detected (Figure 7).

*Figure 7: Fire damper to be used at a fire cut-off partition (courtesy ALDES Aéraulique).*

### *2.8 Corrosion protection - Environmental class*

Corrosion damage on ductwork installed in aggressive environments often leads to leaking and unsafe installations with drastically reduced lifetime. It is thus important to choose the ductwork quality according to the aggressiveness of the environment. Helpful advice to the designer and contractor is given in VVS AMA 98 (1998) where the corrosion impact on ductwork is stated for six different "environment classes", from "M0" ("in dry indoor air, e.g. in heated spaces") with "no aggressiveness" through to"M4B" (e.g. for "indoor and outdoor in industrial areas with high level of aggressive air contaminants, e.g. some chemical industries such as pulp mills, refineries or fertiliser industries") with "very high aggressiveness". The recommendations given in VVS AMA 98 should normally result in an expected lifetime of the installation of 20 years or more. Thus, choosing the right corrosion-proof material combination will normally result in lower life cycle costs even though the first installation cost might be higher. There is also a more generic environmental advantage with higher quality material - longer life span of the installation and thus less need for replacement reduces waste and material use.

### *2.9 Installation*

Field studies indicate that the installation process plays a major role in the performance of the system. Added to this fact is that, in general, installation represents a significant fraction of the cost of an air distribution system. It is therefore essential that the ductwork is quick and easy to install, and is adapted to the workers' skills. For this reason, the right choice of the products is an important factor. These issues should also be considered at the design stage (e.g. to take into account the accessibility of the ducts for sealing).

### *2.10 Life cycle cost*

The choice between different ventilation products is often based on the initial cost (i.e. on the cost of the equipment and the installation). Today's concern about energy efficiency and quality assurance brought to light the need to evaluate ventilation systems on a Life Cycle Cost (LCC) basis since it includes both operating costs and the costs for writing off the investment over a given period of time, normally fifteen or twenty years. The LCC of an installation should ideally incorporate all of the criteria that imply a cost. However, decision criteria that cannot be reliably referenced to a cost (e.g. indoor air quality, ease of use) should be considered separately.

### *2.11 Design issue example : round versus rectangular ducts*

Early in the design phase, it is often possible to choose between different design alternatives. For ventilation design, one early decision is whether to use round or rectangular ductwork - or more often to use a suitable combination between the two. What then are the main differences between the two? The advantages with the round system include:

- Connecting two circular spiral wound ducts only requires one fitting, whereas rectangular ducts are connected by use of a c ompletely separate flanging system. The round ducts can have any length between the connections, a duct length of 3 m is standard but 6 m is also frequently used. On the other hand, the length of a rectangular duct is limited by the size of the steel sheet usually to less than 2 m and therefore requires many more connections;
- Round ducts are tighter. Larger duct systems ($\geq$ 50 m² duct surface area) are, according to VVS AMA 83 (1984), required to be three times tighter than a rectangular duct system;
- The installation cost is normally lower, at least in countries where round ducts have been in use for a longer period of time. The overall cost of a duct system built with circular ducts is distinctly lower than one with rectangular ducts;
- The installation is simpler to carry out and the installation time for a circular duct system is normally shorter, sometimes only a third of that for a similar rectangular system;
- The pressure drop in circular duct system is often lower than in a rectangular duct at the same air velocity due to industrially manufactured and more aerodynamically designed duct components such as elbows and branches;
- The noise generated in straight ducts is normally of no significance while the noise generated e.g. in elbows might cause problems at higher air velocities. Circular duct components have normally known properties while 'tailor-made' parts in rectangular ducts are less well known;
- The circular duct wall is stiffer than the rectangular one and thus will allow less sound transmission through the duct wall. Whether this is an advantage or not must be considered case by case;
- The weight of the round system is lower. Thus, the amount of steel needed is smaller, which, on a larger scale, has environmental benefits.

Fire insulation of a duct to a specified fire safety class might be possible to obtain with a thinner insulation layer on a round duct (the weak points on a rectangular duct, in this case, are the corners where the insulation material is compressed to a thinner, thickness than on the rest of the duct perimeter. The round duct does not have any corners!).

- Ductwork is measured and tailor-made for each installation. Using round ductwork with standard sizes (the diameters of the ducts increase by 25 % upwards: 80, 100, 125, 250 mm, etc.) normally decreases the waste when the ducts do not fit. The round duct or component does not have to be scrapped, it can be used somewhere else in the building, there are probably plenty of ducts of the same diameter.

The main advantage with a rectangular duct is that, for the same free cross area, it can be flattened, i.e. be made wider but lower. In buildings with restricted room heights it could thus be easier to cross underneath beams and other space restrictions. On the other hand, if considered early in the design phase, it might be possible to use parallel round ducts instead of a flat rectangular one. Normally, the best solution is a compromise between round and rectangular. For example, rectangular ducts might be used at the start of the system (ne ar the fan), where the airflow ducts are large. Further on, with the airflow being distributed to smaller ducts, the ducts should be round.

### *2.12 Commissioning and maintenance*

Ductwork systems should be commissioned and properly documented as recommended in the Nordic guidelines "Indoor climate – Air quality" (NKB, 1991). The Swedish VVS AMA 83 (1984), on which practically all building contracts are based in Sweden, requires that, before a building or a part of a building is put into use, an inspection of the duct systems and fire protection installations be performed to demonstrate that it is clean, ready for operation, and correctly documented. For this, fixed sockets for measuring instruments shall be provided in the main ducts for measuring the total airflow of the plant both for commissioning and for future monitoring of plant performance. VVS AMA 83 furthermore requires that all airflows be measured and adjusted to correct values, that the ductwork be leak tested and recorded, and details should be included in the manuals for operation and maintenance. Detailed drawings of the ductwork installations, specifications for the materials and devices as well as for the maintenance schedule shall be available to the building manager to ease maintenance and retrofit.

### *2.13 References*

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# Chapter 3 Standards review

**EUROVENT Guidelines 2/2**

**National standards and building regulations**

**European Committee for Standardisation (CEN)**

### *3.1 Introduction and summary*

This chapter gives an overview of standards and building regulations related to the airtightness of air distribution systems in Europe. It looks at existing standards as well as those currently under preparation at the European level. Some non-European countries are also included. First, EUROVENT Guidelines 2/2 are described, as the leakage classes defined in this document are essentially similar to those that are adopted in many national standards in the member states. We then review the existing standards or pre-standards at the national level, as well as existing building regulations or guidelines/recommendations. Finally, the work carried out at European level, in the European Committee for Standardisation (CEN) is presented.

### *3.2 EUROVENT Guidelines 2/2 "Air leakage rate in sheet metal air distribution systems"*

#### 3.2.1 Introduction

EUROVENT is the European Committee of Air Handling and Air Conditioning Equipment Manufacturers. It was created in 1959 and the following countries are members of this committee: Belgium, Finland, France, Germany, Great Britain, Italy, Netherlands, Norway, Sweden, Turkey.

The foreword of the EUROVENT guidelines mentions:

"*EUROVENT has the aim, at the European level, to facilitate closer ties between the companies of the profession, to promote all desirable and possible exchanges between European manufacturers and to contribute to an improvement of the profession. EUROVENT represents the profession in relation with the European authorities and the International Organisations.*"

In 1996 EUROVENT merged with CECOMAF, the committee of refrigeration equipment industries. Most of the standards or guidelines in member states as well as the CEN pre-standards (in preparation) rely on a ductwork airtightness classification that is essentially similar to the EUROVENT Guidelines 2/2 "Air leakage rate in sheet metal distribution systems".

This document applies to laboratory and field tests of the ductwork between the air handling unit and the air terminal devices.

### 3.2.2 The leakage factor

The leakage factor is the leakage flow rate at a known static pressure per $m^2$ of duct surface area:

$$f_{ref} = \frac{q_{vl}}{A}$$ *Equation 1*

where:

$f_{ref}$ is the leakage factor at a reference pressure $\Delta p_{ref}$ ($m^3\ s^{-1}\ m^{-2}$);
$q_{vl}$ is the leakage volume flow rate ($m^3\ s^{-1}$);
$A$ is the duct surface area ($m^2$).

The leakage factor depends on the pressure $\Delta p_{ref}$ at which the leakage airflow rate is measured. According to this document, it shall be set to the arithmetical mean value of maximum and minimum values of static pressure difference across the ductwork (Pa).

### 3.2.3 Leakage classes

This document defines three classes of airtightness (A, B and C) for normal ventilating and air-conditioning installations. The classification is based on the quantity:

$$K = \frac{f_{ref}}{\Delta p_{ref}^{0.65}}$$ *Equation 2*

where:

$K$ is the leakage coefficient per $m^2$ of duct surface area ($m^3\ s^{-1}\ m^{-2}\ Pa^{-0.65}$).

This quantity gives a measure of the ductwork leakage which should be independent of the static test pressure in the ductwork[2]. The next table gives the upper limits of this quantity for the three different classes.

| | | | |
|---|---|---|---|
| Class A | $K_A$ = | $0.027 \cdot 10^{-3}$ | $m^3\ s^{-1}\ m^{-2}\ Pa^{-0.65}$ |
| Class B | $K_B$ = | $0.009 \cdot 10^{-3}$ | $m^3\ s^{-1}\ m^{-2}\ Pa^{-0.65}$ |
| Class C | $K_C$ = | $0.003 \cdot 10^{-3}$ | $m^3\ s^{-1}\ m^{-2}\ Pa^{-0.65}$ |

*Table 1: Airtightness classes defined in the EUROVENT Guidelines 2/2. Note that for laboratory duct testing, these values are divided by 2.*

[2] Assuming a flow exponent of 0.65 and low measurement errors (see chapter 6).

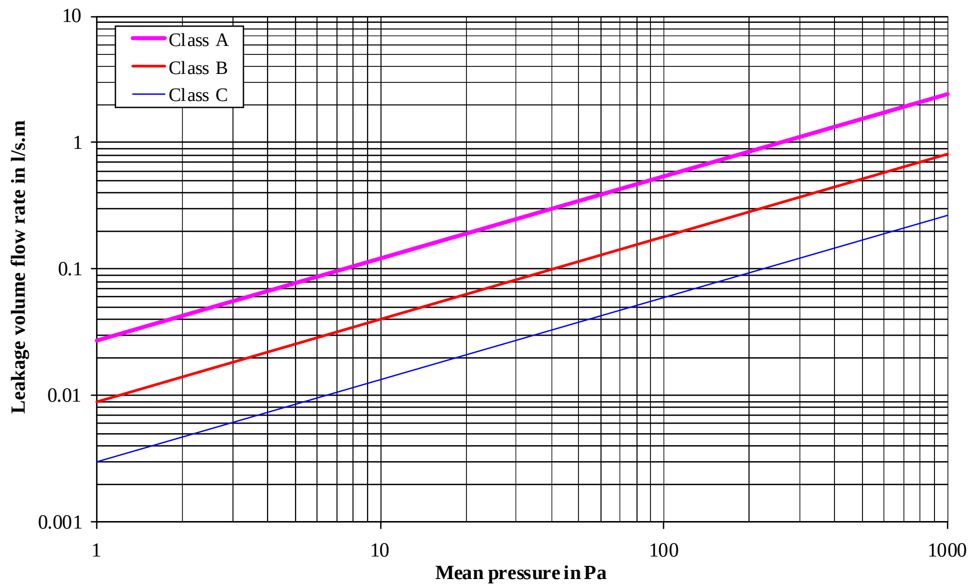


*Figure 8: Leakage volume flow rate per m² duct area as a function of the mean static pressure.*

Also, a graph included in this document enables the test operator to calculate:

- The leakage airflow as a function of the mean pressure and the duct area;
- The leakage airflow as a percentage of system airflow rate.

### 3.2.4 Testing

#### ➤Fan pressurisation method

The ends of the test section are sealed. Then, the leakage factor is determined by artificially creating a (or a series of) pressure differential(s) in the test section and by measuring the leakage flow rate (fan pressurisation method).

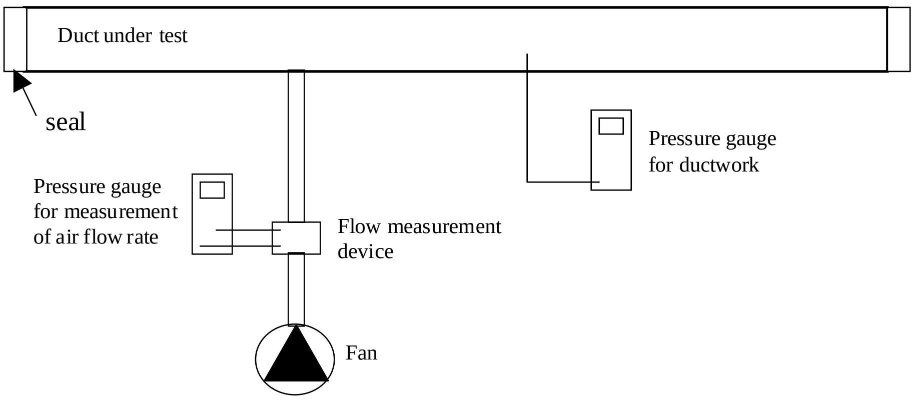


*Figure 9: Ductwork leakage testing with fan pressurisation technique.*

#### ➤Test pressure

The test pressure for Class A and B ductwork should not exceed 1000 Pa or the maximum design static gauge duct pressure, whichever the smaller. For Class C ductwork, the pressure can be increased to 2000 Pa. The test pressure shall not be less than the design operating pressure.

The next table gives the upper limits of the leakage volume flow rate for the 3 classes at typical test pressures.

| Class | Maximum leakage factor ($m^3 . s^{-1} . m^{-2}$.) | Test static pressure difference (Pa) | | | |
|---|---|---|---|---|---|
| | | 2000 Pa | 1000 Pa | 400 Pa | 200 Pa |
| A | $f_A$ | - | $2.4 \cdot 10^{-3}$ | $1.32 \cdot 10^{-3}$ | $0.84 \cdot 10^{-3}$ |
| B | $f_B$ | - | $0.8 \cdot 10^{-3}$ | $0.44 \cdot 10^{-3}$ | $0.28 \cdot 10^{-3}$ |
| C | $f_C$ | $0.42 \cdot 10^{-3}$ | $0.28 \cdot 10^{-3}$ | $0.15 \cdot 10^{-3}$ | - |

*Table 2: Maximum leakage factor for the 3 classes and for typical test pressures.*

### ➤Test procedure

For circular ducts at least 10 % of the total surface shall be tested, and for rectangular ducts at least 20 % shall be tested. In either case the area to be tested shall normally be at least 10 $m^2$.
It is noteworthy that there is no specific information on the duct surface area measurement.
If the air leakage rate does not comply with the Class requirement, the test shall be extended to include an additional equal percentage of the total surface area. If the system is still too leaky, the total surface area shall be tested.

## *3.3 National standards and building regulations*

### 3.3.1 Overview

This chapter gives an overview of the standards, building regulations and/or guidelines that exist in different countries. Due to the current European standardisation process, development of new national standards is not expected in the member states.

Table 3 gives a non-exhaustive list of pre-standards, standards, guidelines, and building regulations in some European countries, Australia and the United States.

| Country | Document | Type | Application | Description |
|---|---|---|---|---|
| Australia | AS 4254-1995 | Standard | All | Ductwork for air-handling systems in buildings |
| Austria | ÖNORM M 7615 | Standard | All | Lüftungstechnishe Anlagen – Leckverlust in Luftleitungen |
| Denmark | DS 447 | Standard | All | Code of Practice for Ventilation Installations |
| Denmark | DS 1122.1 | Standard | Sheet metal | Strength and airtightness – testing |
| Denmark | DS 1122.2 | Standard | Sheet metal | Strength and airtightness – requirements |
| Europe | PrEN 13403 | Pre-standard | Insulation ductboard | Ductwork made of insulation ductboards |
| Europe | PrEN 1507 | Pre-standard | Rectangular sheet metal | Rectangular sheet metal air ducts. Strength and leakage. |
| Europe | PrEN 12237 | Pre-standard | Circular sheet metal | Circular sheet metal air ducts. Strength and leakage. |
| Europe | prEN 13180 | Pre-standard | Flexible | Dimensions and mechanical requirements for flexible ducts |
| France | NF X 10-236 | Standard | Sheet metal | Degré d'étanchéité dans les réseaux de distribution d'air en tôle |
| Germany | DIN V 24194 | Pre-standard | Sheet metal | Dichtheitsklassen von Luftkanalsystemen |
| Sweden | AMA 98 | Specification guideline | Sheet metal | General requirements for Material and Workmanship |
| Switzerland | VSHL 63123 | Standard | Sheet metal | Leckverluste in Luftverteilanlagen aus blech |
| The Netherlands | NEN-EN 1507 | Pre-standard | Rectangular sheet metal | Rechthoekige dunwandige metalen luchtleidingen. Sterkte en lekkage. |
| The Netherlands | NEN-EN 12237 | Pre-standard | Circular sheet metal | Ronde dunwandige metalen luchtleidingen. Sterkte en lekkage. |
| United kingdom | DW/144 | Standard | Sheet metal | Specification for sheet metal ductwork |
| United States | ASHRAE 152 P | Pre-standard | All | Method of test for determining the design and seasonal efficiencies of residential thermal distribution systems |

*Table 3: Non-exhaustive list of pre-standards, standards, guidelines, and building regulations in some European countries, Australia and the United States.*

### 3.3.2 European countries

#### ➤Sweden

| Specification Guideline | Standard | Regulation |
|---|---|---|
| ☑ | ☐ | ☐ |

Nearly all buildings and their installations are performed according to the AMA specification guidelines (AMA 83, 1984; Allmän Material- och Arbetsbeskrivning, i.e. General Requirements for Material and Workmanship). The AMA requirements are made valid when they are referred to in the contract between the owner and the contractor. AMA refers to relevant national Swedish standards and European norms. The 1983 version of AMA which had been used for 15 years has recently been reissued as AMA 98. The airtightness classes are similar to those defined in EUROVENT 2/2.

The need for tight systems has been identified in this country since the early sixties. The requirements have evolved over time in conjunction with technology progress:

- AMA version 1966:

Two “tightness norms” A and B, to be spot checked by the contractor; minimum tested surface is 10 m²;

- AMA version 1972:

Requirements transformed into two “tightness classes” A and B (same as EUROVENT classes). Class A was the requirement for the **complete duct system** in the air handling installation (i.e. including dampers, filters, humidifiers and heat exchangers). It was advised to meet Class B when:

  - The system operates for more than 8 hours/day;
  - The air is treated (cooling, humidification, high class filters etc.);

- AMA version 1983:

In this version of AMA tightness Class C is added. The following requirements are given:

  - Class C for round ductwork larger than 50 m²;
  - Class B for round duct systems with a surface smaller than 50 m² and also for rectangular ductwork;
  - Class A for visible supply and exhaust ducts within the ventilated room;

- AMA version 1998:

In this version of AMA, a tightness Class D has been added (3 times tighter than Class C). It will be an optional requirement for larger circular duct systems.

Besides specifying classes which have to be met, AMA also requires commissioning of all ventilation and air conditioning systems:

- Measurement and adjustment of all extracted and supplied airflows in the building; the result should be within ± 15 % (including the measurement error);
- Measurement of the duct system leakage:
  - Done by the contractor as part of the contract;
  - Parts to be checked chosen by the owner’s consultant;
  - Round duct systems 10 % of the duct surface; rectangular duct systems 20 % of the duct surface.

If part of the system is found to be leakier than required the tested part shall be tightened and another equally sized part of the sys tem shall be tested. If the second tested part is also found to be too leaky, the complete installation has to be tested and tightened until the requirements are fulfilled. The cost for these additional tasks is covered by the contractor.

### ➤Denmark

| Specification Guideline | Standard | Regulation |
|---|---|---|
| ☑ | ☑ | ☑ |

Guidelines specify Class A for systems with only exhaust or in case the ventilation runs less than 8 hours a day. For more than 8 hours a day, a Class B ductwork is recommended. Airtightness of ductwork is often checked by visual inspection at commissioning. In general, it is measured only if required in the technical prescription, in case of large projects, or in case of problems. Standard DS 447 describes a code of practice for ventilation installations. The building code requires that the ductwork airtightness be specified in the technical prescriptions of projects.

### ➤United Kingdom

| Specification Guideline | Standard | Regulation |
|---|---|---|
| ☐ | ☑ | ☐ |

DW/144[3] "Specification for Sheet Metal Ductwork" gives a classification of ductwork airtightness according to the CEN documents prEN 12237 and prEN 1507. The requirements for the airtightness of the ductwork mentioned in DW/144 depend on the operating pressure:

| Duct pressure class | Static pressure difference limit | | Maximum air velocity (m/s) | Air leakage limit (l/s per m²) |
|---|---|---|---|---|
| | Positive (Pa) | Negative (Pa) | | |
| Class A – low pressure | 500 | 500 | 10 | $0.027 \cdot \Delta p^{0.65}$ |
| Class B – medium pressure | 1000 | 750 | 20 | $0.009 \cdot \Delta p^{0.65}$ |
| Class C – high pressure | 2000 | 750 | 40 | $0.003 \cdot \Delta p^{0.65}$ |

*Table 4: Air leakage limits for different pressure classes.*

According to DW/144, testing of the ductwork is only mandatory for the high pressure classes. In the case of low and medium pressure, testing is not part of the ductwork contract unless it is required in the job specification. The testing should be performed according to DW/143 – "A practical guide to ductwork leakage testing".

The following duct areas to be tested during an air leakage measurement are recommended:

- High pressure ducts: whole area tested;
- Medium pressure ducts: 10 % of the ductwork randomly selected and tested;
- Low pressure ducts: untested.

[3] Note that DW/142, which was the reference document until 1998, has been reissued as DW/144.

If an air leakage measurement on a randomly selected part (10 %) of a medium pressure ductwork reveals that the requirements are not fulfilled, the test has to be performed again on two other randomly selected duct sections. In the case of successive failures, there shall be a right to require the contractor to apply remedial measures to the complete ductwork system. Items of inline plant, such as air han dling devices, sound attenuators, heat exchangers etc. will normally not be included in an air leakage test.

Recommended test pressures and the corresponding leakage rates are given in Table 5.

| Static pressure difference (Pa) | Maximum leakage of ductwork (l/s.m²) | | |
|---|---|---|---|
| | Class A | Class B | Class C |
| 200 | 0.84 | 0.28 | |
| 400 | 1.32 | 0.44 | |
| 800 | | 0.69 | 0.23 |
| 1200 | | | 0.30 |
| 1500 | | | 0.35 |
| 2000 | | | 0.42 |

*Table 5: Recommended test pressures and corresponding air leakage rate according to DW/144.*

DW/144 describes also in detail the requirements for seams, cross joints, fastenings, etc. for different types of ductwork, for example regarding the presence of sealant.

### ➤Belgium

| Specification Guideline | Standard | Regulation |
|---|---|---|
| ☑ | ☐ | ☑ |

At present there is no standard in Belgium regarding ductwork airtightness.

There is no building regulation applicable for private projects. However, for public buildings, general technical prescriptions (Typebestek 105, article C14, luchtleidingen) require that the ductwork class (A or B) be specified in the specific technical prescriptions. By default, Class A is required. However, if:

- the nominal airflow rate of the network is above 3 m³/s;
- the air is cooled or humidified;
- if the daily on-time is more than 12 hours;

Class B is required. The prescriptions do not give requirements for the testing of ductwork. The prescriptions require the leakage airflow rate be added to the nominal airflow rate for the determination of the airflow rate of the fan. If the leakage airflow rate does not meet the requirements, the following has to be done:

- Tighten the tested part;

- Perform a test on a part of the system that has to include the first one and be twice as large;
- If the leakage airflow rate is still too large the same procedure should be repeated once more. If the result is still not good enough, the ductwork should be tested as a whole. The airtightness should be improved until the requirements are fulfilled.

### ➤Switzerland

| Specification Guideline | Standard | Regulation |
|---|---|---|
| ☐ | ☑ | ☐ |

There is a Swiss standard based on the EUROVENT Guidelines 2/2. Although there is no regulation in Switzerland, a ductwork class is often required in technical prescriptions for large projects. At commissioning, one or several sections of the ductwork are generally tested.

### ➤The Netherlands

| Specification Guideline | Standard | Regulation |
|---|---|---|
| ☑ | ☐ | ☐ |

There are no official standards on ductwork in the Netherlands. The European pre-standards prEN 1507 and prEN 12237 (see § 3.4) are used as pre-standards: NEN 1507 and NEN 12237. Although there are no official building regulations, ductwork manufacturers follow the national LUKA specifications, which make a classification according to EUROVENT: class A, B and C. LUKA is the association of Dutch manufacturers of ductwork. The goal of LUKA is the determination of quality standards for the production and installation of ductwork, the organisation of quality control of ductwork from members, the organisation of training courses for installers, the distribution of quality certificates etc. A quality handbook was edited by LUKA in which the different requirements are described in detail.

As regards the airtightness, the installations made by the LUKA-members are supposed to comply with the class B requirement. The following additional aspects are mentioned in the LUKA specifications:

- the tested part should be mounted, but not yet insulated;
- the tested part should have an area of at least 10 m² and should not exceed 30 m²;
- in a laboratory test, the leakage airflow should not exceed 50 % of the required value.

### ➤France

| Specification Guideline | Standard | Regulation |
|---|---|---|
| ☐ | ☑ | ☐ |

Standard NF X 10-236 *“Degré d’étanchéité à l’air dans les reseaux de distribution d’air en tôle”* is similar to the EUROVENT 2/2 document.

Two other standards deal with the duct leakage:

- NF XP P 50-410: *"Installation de ventilation mécanique contrôlée – Règles de conception et de dimensionnement"*

This standard states that leaks are supposed to be localised at the registers and correspond to an arbitrary value of 10 % of the nominal maximal airflow rate of the register;

- NF P 50-411: *"Exécution des installations de ventilation mécanique"*

This standard states that the installation must be so that the airtightness is compatible with the good functioning of the system and specifies also (vaguely) the types of materials which have to be used to ensure a good airtightness.

### ➤Germany

| Specification Guideline | Standard | Regulation |
|---|---|---|
| ☐ | ☑ | ☐ |

The pre-standard DIN V 24194 "Ducting for ventilation equipment; air leakage classification of sheet metal duct systems" classifies the ductwork airtightness similarly to EUROVENT 2/2. However, the standard does not describe any test method.

### ➤Finland

| Specification Guideline | Standard | Regulation |
|---|---|---|
| ☑ | ☐ | ☑ |

The national building code of Finland *"Indoor Climate and Ventilation in Buildings – Regulations and Guidelines"* specifies three leakage classes A, B and C (identical to those of EUROVENT 2/2). An extra class K is defined for enclosed air conditioners, equipment rooms and chambers for fans and other assemblies.

### ➤Austria

| Specification Guideline | Standard | Regulation |
|---|---|---|
| ☐ | ☑ | ☐ |

ÖNORM M 7615 defines three tightness classes (A, B, and C) based on the leakage factor concept similarly to EUROVENT 2/2. This norm concerns all ventilation ducts installed in buildings except for ducts in hospitals and ducts containing toxic gases. This document recommends tightness classes depending on the operating pressure (< 630 Pa or ≥ 630 Pa) and the airflow rate (return: lower or greater than 3 $m^3/s$; supply: lower or greater than 2 $m^3/s$). In addition, the norm describes the calculation of leakage and testing procedure. Although not mandatory, this "ÖNORM" is specified in nearly every public or private tender.

### 3.3.3 Non-European countries

**➤Australia**

Standard AS 4254, *"Ductwork for air-handling systems in buildings"* (version 1995) deals with the requirements for air-handling systems in buildings. A part of the standard is dedicated to the airtightness of ductwork. The requirements in AS 4254 are based on a static pressure classification, which is given in Table 6.

| Pressure class | Operating pressure range, Pa |
|---|---|
| 125 | ≤ 125 |
| 250 | 126 to 250 |
| 500 | 251 to 500 |
| 750 | 501 to 750 |
| 1000 | 751 to 1000 |
| 1500 | 1001 to 1500 |
| 2500 | 1501 to 2500 |

*Table 6: Pressure classes in AS 4254.*

Depending on the pressure class, the standard gives requirements for the duct sealing. These requirements are not values, but only prescriptions about the parts that have to be sealed. This is shown in Table 7.

| Static pressure classification, Pa | Seal class | Sealing required |
|---|---|---|
| ≥ 1000 | A | All transverse joints, longitudinal seams[4] and duct wall penetrations |
| 750 | B | All transverse joints and longitudinal seams |
| 500 | C | Transverse joints |
| < 500 | --- | Ductwork to be sealed only where required by the designer |

*Table 7: Sealing requirements in AS 4254.*

For unsealed, low pressure ducts the standard gives leakage airflow rates to apply for design purposes. These are given in Table 8.

| Duct pressure (Pa) | Leakage airflow (l/s per m²) | Leakage airflow EUROVENT Class A (l/s per m²) |
|---|---|---|
| 25 | 0.52 | 0.22 |
| 60 | 0.94 | 0.39 |
| 125 | 1.46 | 0.62 |
| 250 | 2.27 | 0.98 |

*Table 8: Leakage rate in unsealed low pressure ducts.*

The sealing of ductwork can be done by means of mastics, liquids, gaskets or tapes. Each of these sealing techniques are described briefly in the standard.

[4] A seam is defined as the joining of two longitudinally oriented edges of duct surface material occurring between two joints.

Special requirements are given for kitchen exhaust ductwork sealing.

### ➤United States

ASHRAE standard 152P (draft of 97/3) describes in a detailed way the test method for determining the design and seasonal efficiencies of residential thermal distribution systems. It applies to single-family detached and attached residences, with independent thermal systems. The standard describes a method to determine the leakage airflow rate of the duct system **to outside**. Briefly, the method consists of the following steps:

- Measurement of the leakage airflow rate of exhaust and supply ductwork to outside, for a pressure of 25 Pa (positive or negative). Therefore the building is first pressurised with a blower door and then the pressure between the building and the ductwork is brought to zero by regulating the speed of the fan for the duct pressurisation. The measured flow through the fan connected to the duct is the duct leakage to outside;
- Determination of the operating pressure as the average of the pressures at the different registers;
- Conversion of the measured duct leakage airflow to the leakage airflow at operating pressure.

### *3.4 European Committee for Standardisation (CEN)*

#### 3.4.1 Introduction

CEN is the European organisation responsible for the planning, drafting and adoption of standards. When the need for the development of a new standard has been clearly established and when it does not appear possible to use an existing reference document or one under development in a different forum (e.g. ISO), a team of experts is set up in the framework of a Technical Committee (TC). When consensus is reached on a draft in the TC, a thorough procedure, designed to ensure the general acceptability of the proposed standard, is then started. This procedure includes a public enquiry and adoption of the standard through a formal vote by each National CEN member; several majority criteria must be met for the standard to be ratified. The use of these standards is always the result of voluntary action by trade, industry and social and economic partners.

Within CEN, standards in the field of ventilation are being prepared by Technical Committee (TC) 156: “Ventilation for Buildings”. TC 156 consists of 9 Working Groups (WG). The following table gives an overview of these different Working Groups. As it can be seen, WG 3 deals with the standards about ductwork.

| Working group | Description |
|---|---|
| WG 1 | Terminology |
| WG 2 | Residential ventilation |
| WG 3 | Ductwork |
| WG 4 | Terminal devices |
| WG 5 | Air handling units |
| WG 6 | Indoor climate |
| WG 7 | System performance |
| WG 8 | Installation |
| WG 9 | Fire protection of air distribution systems |

*Table 9: Overview of the different working groups within CEN TC 156.*

The following figure shows the position of standards related to ductwork airtightness in the field of standards related to mechanical building services within CEN TC156.

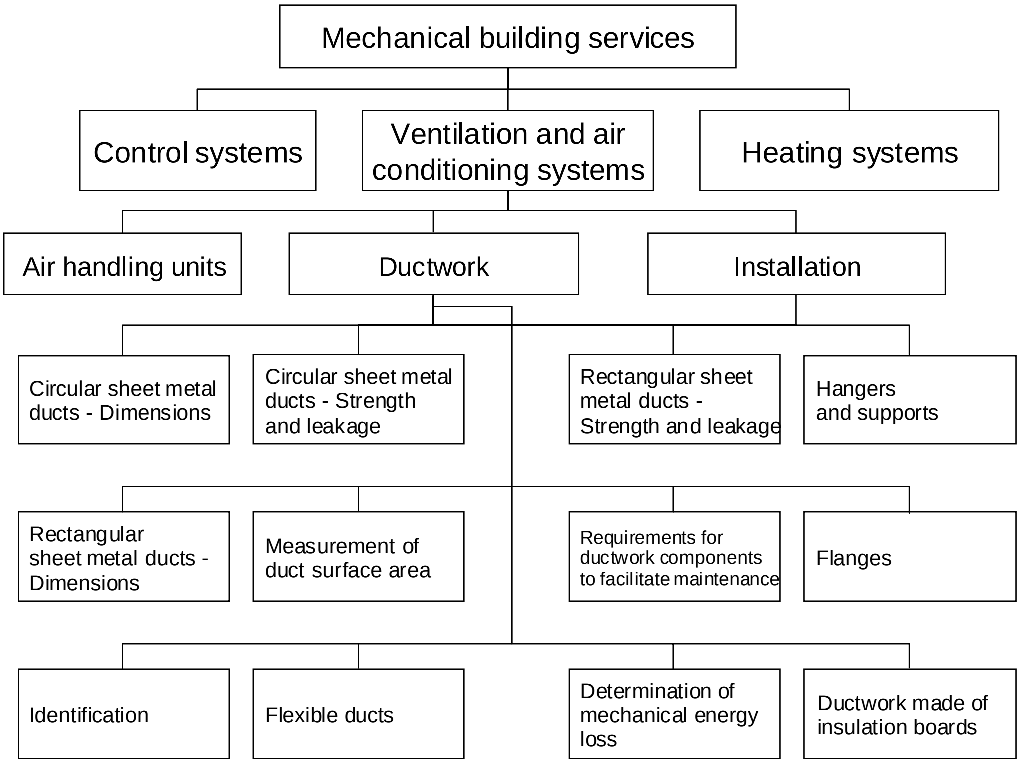


*Figure 10: Ductwork airtightness related standards within CEN TC 156.*

### 3.4.2 Circular sheet metal ducts: Strength and leakage – prEN 12237 (version of October 1998)

#### ➤General

This standard specifies requirements and **laboratory** test methods for the strength and air leakage testing of **circular** ducts. It is applicable to circular ducts used in ventilation and air conditioning systems in buildings for human occupancy. Primarily, it refers to ducts made from steel, but it is also applicable for other metallic ductwork (e.g. aluminium and copper).
The following characteristics are tested or inspected:

- Deflection of the installed duct;
- The air leakage of the duct.

#### ➤Definition of leakage classes and requirements

The definition of the tightness classes has been adopted from the EUROVENT guidelines 2/2 (Table 1). The requirement is that the leakage factor shall not exceed 90 % of maximum leakage rate for the applicable tightness class.

#### ➤Test equipment

The standard describes the test equipment to be used:

Fan with variable airflow rate, with an airflow capacity sufficient to maintain the required pressure level (Table 10).

- Airflow meter, with a maximum error of less than 4 % or 0.1 l/s (whichever is the greater value);

- Pressure gauge meter, with an accuracy of 10 Pa or 2 % (whichever is the greater value).

#### ➤Test procedure to determine the leakage

For the test of the air leakage the ductwork shall be submitted to:

- A certain load, calculated from the mass of the duct ($m_d$):

$$m_{test} = m_d + 1.5 \cdot m_d$$

where $1.5 \cdot m_d$ is the external loading

This load is foreseen to cover loadings caused by insulation and to give some safety against transport damages.

- A certain pressure, as specified in the following table:

| Class | Test static gauge pressure[1] | | | |
|---|---|---|---|---|
| | 1000 Pa | | 400 Pa | |
| | + | - | + | - |
| A | | | X | X |
| B | X | X | | |
| C | X | X | | |

[1] *For design pressures exceeding 1000 Pa, the test shall be carried out at that pressure.*

*Table 10: Test pressures.*

The test pressure has to be maintained until steady-state is reached. Then the leakage flow is recorded. The air leakage has to be given as the leakage factor, i.e. the airflow rate divided by the duct surface area. The leakage factor has to be determined with and without load.

#### ➤Test report

A test report has to be made, including the following information:

- Manufacturer, number of tested ducts, duct material, design of joints;
- Cross sectional and longitudinal dimensions of the duct and sketch of test arrangement;
- Mass of insulation (if applicable);
- Test load;
- Distance between supports;
- Deflection; } *Strength aspects* (distance between supports, deflection, ovality)
- Ovality;
- Test pressure and leakage factor with and without load;
- Tightness class;
- Time, place and signature.

### 3.4.3 Rectangular sheet metal air ducts: Strength and leakage – prEN 1507 (version of October 1998)

This standard specifies requirements and test methods for the strength and air leakage testing of **rectangular** ducts, including joints. As regards duct leakage testing, this standard is very similar to prEN 12237.

### 3.4.4 Ductwork made of insulation ductboards – prEN 13403

This European Standard contains the basic requirements and characteristics for ductwork made of insulation ductboards, used in ventilation and air conditioning systems of buildings, subject to human occupancy. Ductboard is defined as a rigid board composed of insulation material body with one or both sides faced; ductboards are fabricated into rectangular or multisided duct sections; the outer facing is a duct vapour barrier and is supposed to make the duct airtight. The standard gives requirements regarding maximum air speed, resistance against pressure, airtightness, bulging and/or caving, supports and hangers, facilities for cleaning and requirements for materials (board stiffness, water vapour resistance, dimensional tolerances, acoustical absorption etc.). Regarding airtightness, the same requirements apply as in prEN 1507 and prEN 12237.

#### 3.4.5 Handing over installed ventilation and air conditioning systems – prEN 12599 (Final draft, version 10/97)

This pre-standard details test procedures and measuring methods for handing over installed ventilation and air conditioning systems designed for the maintenance of comfort conditions (note that prEN 1507 and prEN 12237 apply to laboratory tests). It includes special measurements that shall be carried out only when required and especially agreed. Air leakage is among these special measurements that are detailed in the informative annex F. It refers to prEN 1507 and prEN 12237 but states that the test pressure should be adjusted to 200, 400 or 1000 Pa, whichever is closest to the mean operating pressure of the system.

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# Chapter 4 Ductwork airtightness: state-of-the-art review of construction and installation technologies

**Ductwork construction**

**Ductwork installation**

**Field test with aerosol-based duct sealant**

### *4.1 Summary*

The construction and installation of duct systems are two key aspects that have a major impact on ductwork airtightness. This chapter looks at today's technologies that may be used to limit duct leakage. It includes a short review of manufacturing processes. Also, installation issues are discussed as well as site sealing techniques. The last paragraph focuses on a field test of an aerosol-based internal-access technology in a European building.

### *4.2 Construction*

Seams and joints should be suitably selected for the type of ductwork and leakage requirements. They should be compatible with the maintenance work (e.g. cleaning) to be performed on the system as well as the installers' skills and the time granted for site work. At the construction stage, the airtightness of individual components depends on the design (rectangular versus round, pressed versus segmented bends, flexible ducts, etc.) and assembly (seam type and welding quality). DW/144 (HVCA, 1998) gives a list of requirements to seal seams, laps, cross-joints and duct penetrations of different type. Also, DW/143 (HVCA, 1983) states that it is important "to make components with a good fit, and to use only enough sealant to make a satisfactory joint. A poor fit cannot be remedied by the use of more sealant – it will not work".

Factory-fitted sealing devices (e.g. gaskets, clips) are available on the market. They appear to be efficient at reducing the installation time and give very satisfactory results in terms of airtightness. Some manufacturers include in their brochures informa tion about the airtightness of individual components or the air distribution system between air handling unit and the terminal devices. As for air handling units and terminal devices themselves, very little information is available from the manufacturers although experience shows that they can represent a significant source of leakage. Special care should be given to the fitting and sealing of maintenance panels and paths for electric wires, fluid pipes, etc.

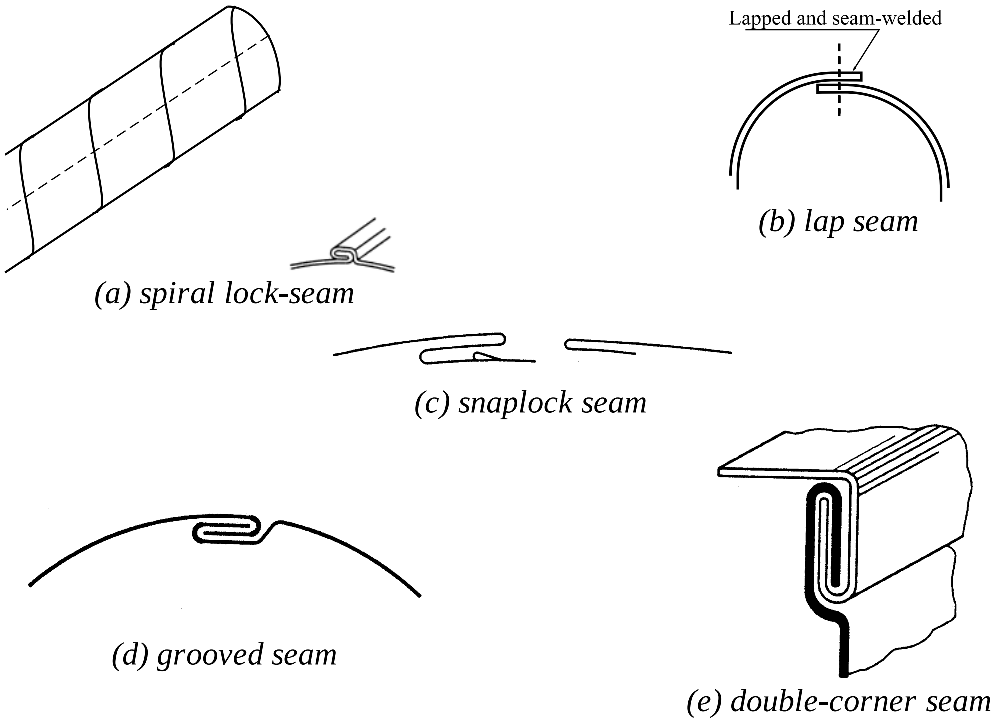



*Figure 11: Examples of seams.*

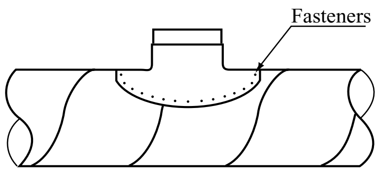



*Figure 12: Saddle tap with spot-welds or fasteners.*

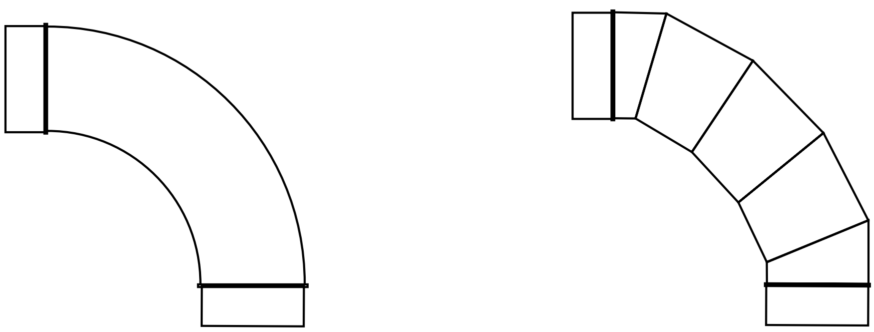


*Figure 13: Pressed bend (left). Segmented bend (right).*

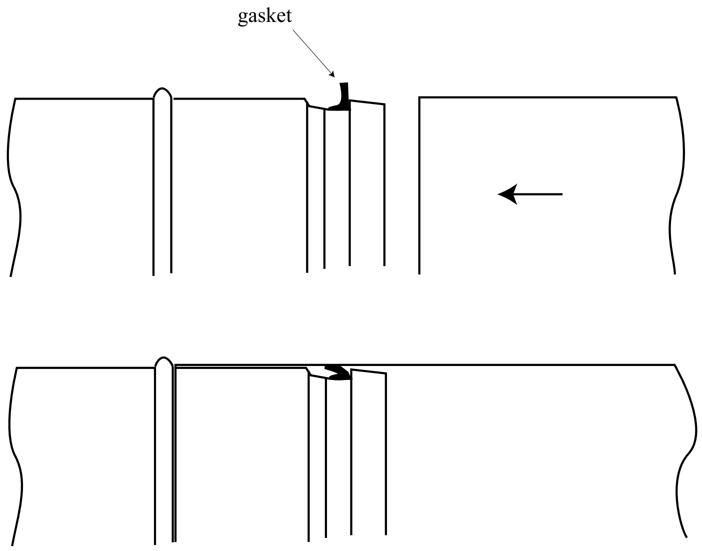



*Figure 14: Pre-fitted sealing gaskets for circular ducts. Airtight rivets or plate-screws may be necessary to ensure the mechanical stability of the joint.*

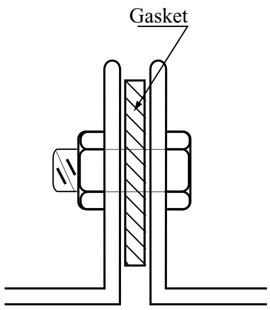



*Figure 15: Sealing gasket at flange joint. Drive slips, fasteners, rivets or bolts are used to hold the pieces together.*

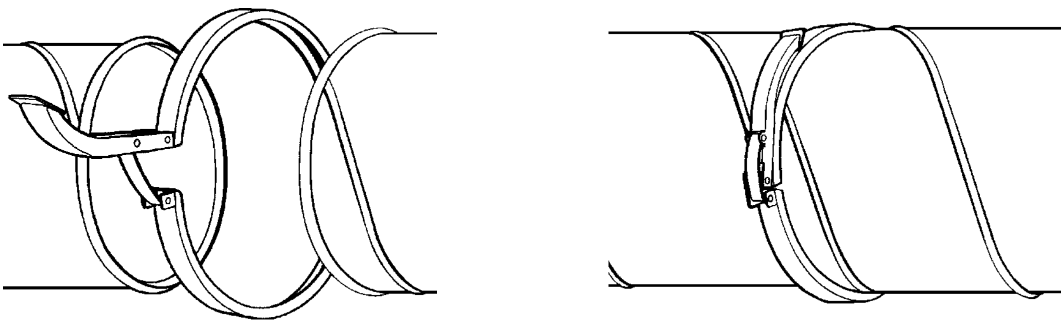


*Figure 16: The clips ensure a good airtightness and the mechanical stability of the joint. These systems are mainly used for non permanent ductwork or ductwork which has to be cleaned regularly. LindabTransfer® system (Courtesy Lindab Ventilation AB).*

### *4.3 Installation*

To obtain an airtight system, particular attention should be given to leakage:

- at seams and joints;
- due to unnecessary holes or physical damage in duct runs;
- at air terminal devices;
- in the air handling unit.

The key advantage of ductwork components with factory-fitted sealing devices (e.g. gaskets, clips) for joints lies in the ease and rapidity in obtaining airtight duct runs. When quality products are used, the installation work mostly consists of ensuring the mechanical stability of the ductwork. Alternatively, when the components do not have pre-fitted sealing devices, additional work is needed at installation to avoid leakage at joints. Also, the installers should seal off unnecessary holes (for screws, rivets, measuring devices, etc.). Installation, inspection or rehabilitation work should be performed with caution so as to avoid physical damage to the ducts. Typically, significant leakage is found at the air terminal devices either because of poor connections to the ducts and against building materials, or because of internal cracks. Particular attention should be given to these parts. Finally, leakage in air handling units should be avoided using adequate sealing devices at maintenance panels and paths for electric wires, fluid pipes, etc. However, where intentional holes are necessary for fire protection reasons (to cool the motor), they should not be sealed.

In general the use of quality-products with factory-fitted sealing devices does not eliminate completely on-site sealing (for example the fastening against the body of a building). Nevertheless, they can spare the installers from doing much time-consuming and tedious tightening work. However, they are, in general, more expensive to purchase but the payback period decreases with increasing local costs of labour and energy. In fact, in many countries it is quite common to perform most of the sealing at installation although ‘pre-tight’ systems are available. These sealing methods could also be chosen for retrofitting leaky duct systems.

For site tightening of systems, five major methods are used:

- Gaskets;
- Tapes;
- Sealing compound;
- Internal duct lining;
- Aerosol-sealant.

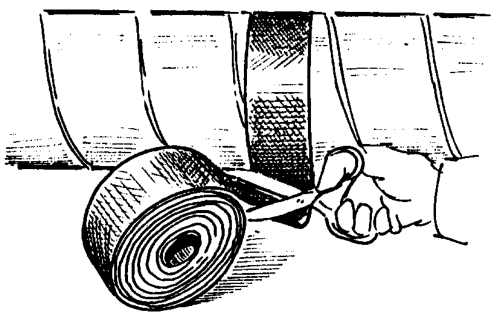
Sealants or sealing devices should be non-combustible unless any addition to the spread of fire can be considered to be negligible. They should not constitute any health hazard to the worker applying them or to the building occupants. The choice of a suitable sealing method should be based on criteria applicable to the studied duct installation such as type of ductwork, leakage status, required durability of the work performed, maintenance procedures, operation experience and costs, available space for installation or rehabilitation work.

### 4.3.1 External-access techniques

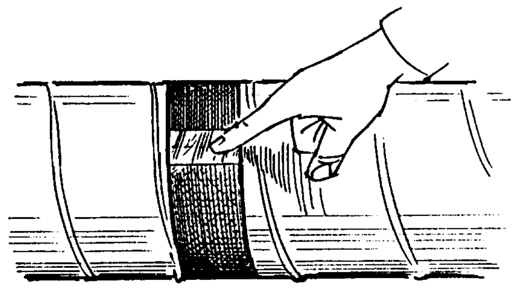
On site, (non-extruding) gaskets are put primarily on flange joints in new installations (similarly to Figure 15). Table 11 gives a summary of the other sealing media that may be used when the ducts are accessible from the outside.

| | Heat shrink tape | Self-vulcanising tape | Sealing compound |
|---|---|---|---|
| Round ducts | yes | yes | yes |
| Rectangular ducts | no | no | yes |
| Flexible ducts | no | yes | yes |
| Joints | Butted or sleeved | Butted or sleeved | Any |
| Temperature range (application) | Heat to 125°C | -5°C to 80°C | > 5°C |
| Temperature range (service) | -30°C to 70°C | -40°C to 80°C | -20°C to 80°C |

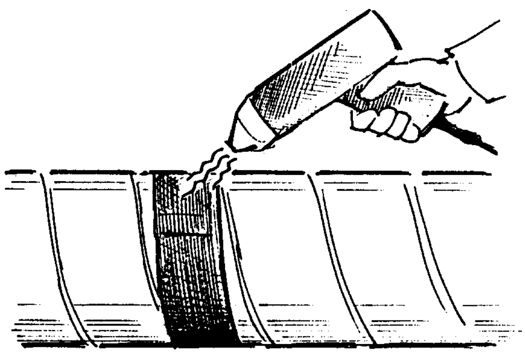
*Table 11: External sealing methods.*



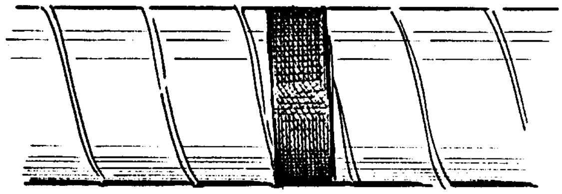
1. Wind the band around the duct. Cut it off with margin according to the manufacturer's instructions



2. Apply special fastening tape at the overlap



3. Heat to the tape on all sides



4. Finished sealing

*Figure 17: Use of heat shrink tape of polyethylene with a surface of thermoplastic glue (Courtesy Swedish Council for Building Research).*

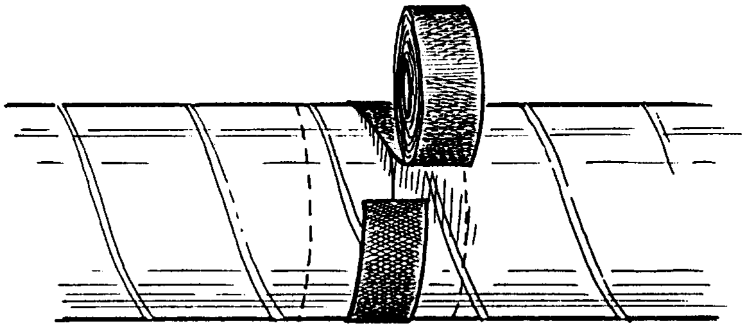
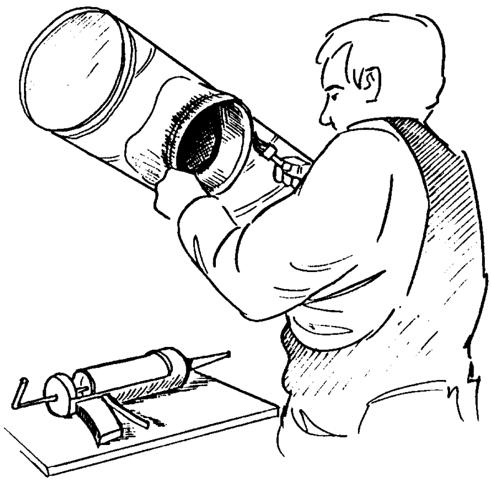


*Figure 18: Self-vulcanising sealing tape applied around the duct with overlap. This method does not require any heating of the joint (Courtesy Swedish Council for Building Research).*



The tightening is done with an elastic sealing compound either of butyl rubber base or acrylic latex with good adhesive capacity on steel. The sealing compound can be applied to the duct with a paintbrush from the outside. Adhesive tape or fibreglass bands are sometimes applied over the sealing compound. The sealing compound is also available in cartridges for plunger guns.

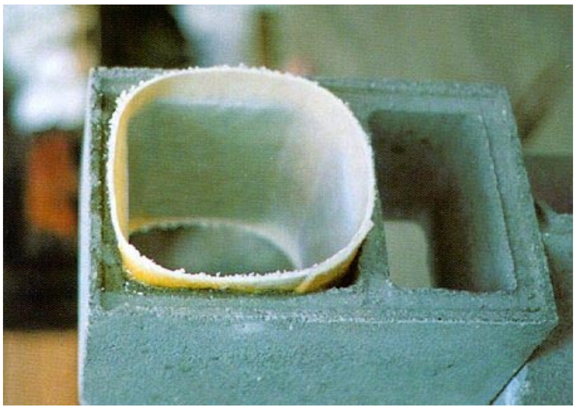
*Figure 19: Application of sealing compound (Courtesy Swedish Council for Building Research).*

### 4.3.2 Internal-access techniques

Two internal-access methods are summarised in Table 12. The common factor for these methods is that the sealing work is mainly performed from the ends of the ducts, which reduces the need to work on other building elements.

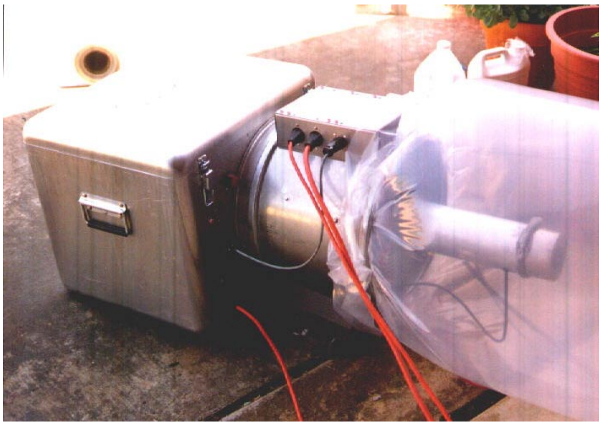
| | Flexible plastic insertion | Aerosol-based sealant |
|---|---|---|
| Building materials | yes | Tested on wooden cavities used as ducts |
| Round ducts | no | yes |
| Rectangular ducts | no | yes |
| Flexible ducts | no | yes |
| Temperature range (application) | | > 5°C and < 70°C (surface) |
| Temperature range (service) | < 80°C | < 80 °C (surface) |

*Table 12: Internal sealing methods.*



This method is normally used to improve the airtightness of existing vertical concrete shunt ductwork. It consists of the insertion of a synthetic lining (Rolyner®) from the roof into the ductwork. Once the lining is put in place, it is pressurised with warm air. Consequently, the lining takes the form of the inside of the ductwork and hardens in that way afterwards. The ductwork airtightness is significantly improved (often by more than 95 %), without reducing significantly the cross-section (the thickness of the lining is about 3 mm). By the insertion of the lining the secondary ducts of the shunt system are blocked from the main duct. Therefore, the lining has to be perforated afterwards to establish the connections to the ventilation system of each apartments.

*Figure 20: Insertion of plast ic lining (Courtesy Bergschenhoek).*



The method involves blowing an aerosol through the duct system to seal the leaks from the inside, the principle being that the aerosol particles deposit in the cracks of the ductwork as they try to escape because of the pressure-driven flow. Before the sealant is sprayed in, the registers are blocked and sensitive equipment (e.g. heat exchangers) should be isolated. To minimise the sealing time, large holes (larger than 6 mm across) should be sealed manually unless they are inaccessible. The device can also be used to measure the airtightness of the system before, during, and after the sealing process. The leakage area of a typical residential system can be reduced by more than 80 %. A duct improvement certificate that includes documentation of the time history of the sealing and the estimated annual savings is issued by the contractor. The technique is commercialised and increasingly used in US residences. At present, it is not commercially-available in Europe.

*Figure 21: Aerosol injection device (Courtesy Aeroseal Inc.).*

### 4.4 Field test with aerosol-based duct sealant

In the framework of the SAVE-DUCT project, the aerosol injection technique was tested on a 17 $m^2$ section of a rectangular sheet-metal duct system in a building of the BBRI (Belgian Building Research Institute). The airtightness was measured by the Aeroseal device itself at the beginning of the experiment and showed that the system was initially very leaky ($ELA_{100} \approx 4\ cm^2/m^2$, i.e. more than 9 times Class A).

Figure 22 shows the evolution of the leakage airflow rate at 100 Pa during aerosol injection. The sudden drop of the leakage after about 70 minutes is due to the manual sealing with tape of a large gap; the sharp increase after about 100 minutes is due to the fact that the part that was sealed manually came loose. It should be noted that fibreglass-reinforced mastic sealants can be used to perform manual sealing during the aerosol injection process. Significant aerosol deposition was observed in some leaks (Figure 23). However, the sealing rate slowed down after about 2 hours when the leakage airflow rate was at approximately 30 % of its initial value, which is still insufficient to reach Class A. It should be noted that the equipment used was not designed to produce the lower leakage levels desired in Europe. For European tightness levels, a smaller particle size, and a fan that maintains a flow at higher pressure would be desirable. Also changes in the design of the equipment is suggested since this experiment allowed the particle injection rate to be increased by 50 %.

In fact, there is an absolute leakage airflow rate limit associated with the equipment currently being utilised. At present, this device is designed for US residences, i.e. for very leaky systems (see chapter 6), and goes down to leakage flow rates of about 5-10 l/s at 25 Pa (12-24 l/s at 100 Pa). Although it is successfully commercialised in the US with the present design, Class A can be reached only for systems with a surface area larger than about 40 $m^2$. This is due to the fact that the particles are transported by the carrying (leakage) airflow, which tends to drop off as the pressure mounts in the system during sealing, due to the fan-curve of the device. Remember that the flow through the injector fan is all that is being forced through the leaks. As the leaks get smaller, the pressure seen by the injector fan increases, which reduces its flow. To maintain the flow rates needed to keep the particles in suspension, the fan would have to be particularly suited to the high duct pressures at low leakage levels. This problem could be solved by using a higher-pressure fan, however a more practical, more cost-effective solution could be to use an opening at the end of the ductwork to reduce duct pressure at the required flow rates.

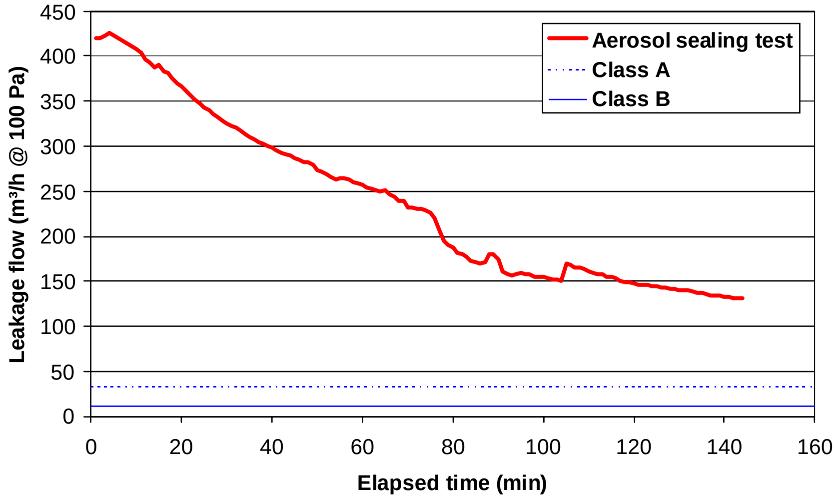



*Figure 22: Leakage airflow rate at 100 Pa versus elapsed time during the aerosol injection test in a building of the BBRI.*

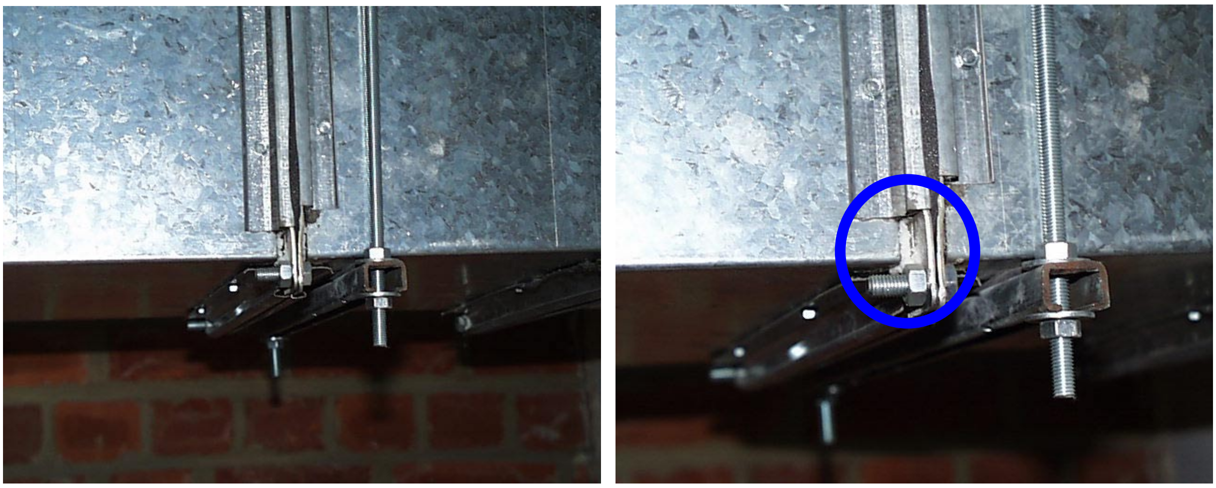


*Figure 23: Detail of a leak during and at the end of the test. The white material indicated by the circle on the right hand-side is the seal created by the deposition of aerosol particles.*

In Figure 25 the BBRI aerosol sealing test is compared with two experiments performed in two residences in the USA. The initial and final leakage factors are shown in Figure 26. Because both US tests were demonstrations, they were terminated prematurely (less than 1 hour - the complete sealing procedure usually lasts ½ - 3 hours for a typical residential duct system, depending on the initial leakage level and the size of the leaks). Still, leakage airflows were reduced to 26 % and 32 % of their initial values. Approximately the same result was obtained in the Belgian test, but the duration of the experiment was nearly three times greater. Also, the sealing rate was significantly lower in Belgium (Figure 25), which is partly due to much lower leakage flow rates. In addition, the system used for the Belgian test was a new prototype, which was later found to need straightening vanes to avoid swirl-induced deposition on the plastic tubing used to connect the aerosol injector to the duct system. Also, the fan did not have the same fan curve using a 50 Hz power -supply (as opposed to 60 Hz in the US). For the same leakage characteristics of the system, the fan delivers a lower (carrying) airflow rate at 50 Hz (see Figure 22).

In summary, this aerosol-based technique seems promising, however to be successfully used in Europe, development work should be undertaken to increase aerosol penetration in the system by using:

- Filtered openings at the ends of the duct run;
- A different fan that would be able to operate at higher pressures with a large enough carrying airflow;
- A different aerosol generator that would produce smaller particles that have lower settling velocities (note however that smaller particles also imply lower deposition efficiencies at the leaks).

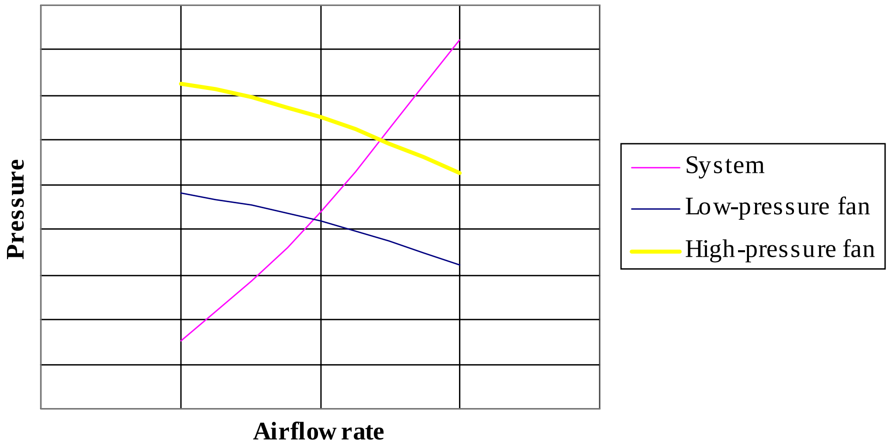



*Figure 24: Effect of using a higher-pressure fan on (carrying) airflow rate.*

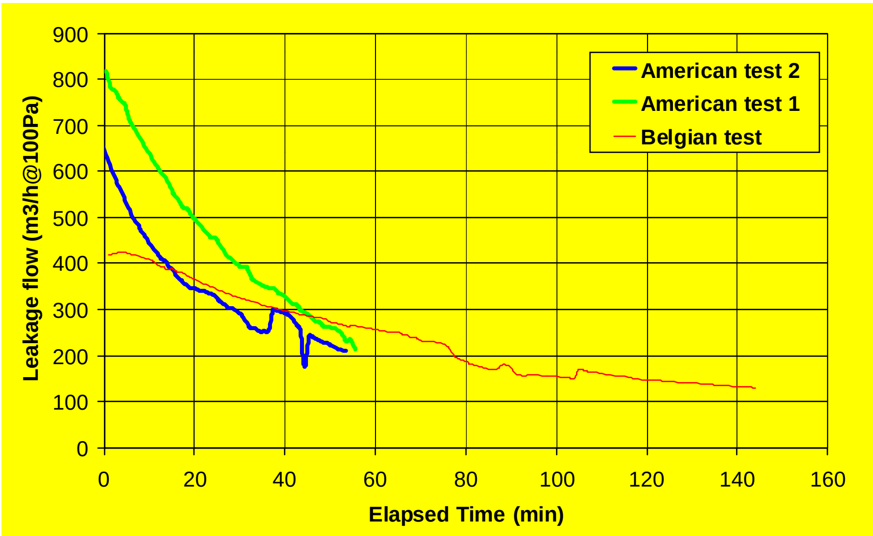



*Figure 25: Leakage flow rate versus elapsed time during three aerosol injection tests.*

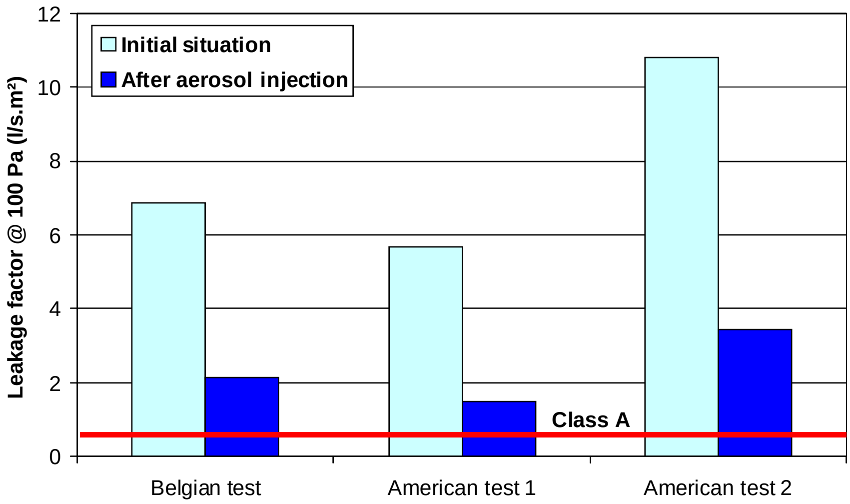



*Figure 26: Initial and final leakage factor at 100 Pa for aerosol sealing tests on one Belgian and two US buildings (Class A: $f_{100}$ = 0.54 l/s per m²). The tested surface areas are: Belgian test: 17 m²; American test 1: 40 m²; American test 2: 17 m².*

### *4.5 Renovation*

When retrofitting buildings with old and leaky systems, the replacement of the ductwork with new, clean, and tight ducts should be seriously considered. Where possible and compatible with the budget, it will be more effective than any rehabilitation techniques both on tightness and cleanliness aspects.

### *4.6 References*

1. HVCA. DW/143. A practical guide to ductwork leakage testing. Heating and Ventilating Contractor's Association. London, UK. Copyright 1983.
2. HVCA. DW/144. Specifications for Sheet Metal Ductwork Heating and Ventilating Contractor's Association. London, UK. 1998.

# Chapter 5 Traditions in the design, installation, and maintenance of duct systems

**Small-scale survey**

**Traditions**

**Implications on ductwork airtightness**

**Incentives and barriers to better systems market penetration**

### *5.1 Introduction*

Duct system designs can vary considerably depending on the building type (single-family houses, multi-family buildings, or commercial buildings) and local customs. This may have a negative impact on the system's operation and maintenance because of the wide price and performance range of the many commercially-available products. Traditions in the installation (that differ considerably between countries) can also contribute to poor performance.

This chapter aims at giving improved knowledge about these aspects to help with drawing up a statement of habits in European countries. It is mainly based on ALDES' experience over the past 25 years. A small-scale survey among 25 professionals (HVAC design offices, installers, maintenance contractors) is also used as an illustration on some issues.

### *5.2 Small-scale survey*

25 HVAC professionals were surveyed in Belgium, France, Italy, Spain, and Sweden (Table 13). It is clear that the sample is not representative, however, it provides an interesting picture of the traditions and common thoughts of some experienced professionals who work on air ducts from the design table to the actual installation. The questionnaire was divided into 3 parts aimed at the different types of professionals surveyed. It was filled out by the interested parties without any assistance from us.

The major issues addressed by the survey are listed below:

- Frequently-used types of systems (types of ducts, components, etc);
- Practical ways of installing;
- Costs;
- Incentives and barriers to using higher-quality materials or more effective techniques;
- Rehabilitation techniques;

- Need for skilled labour;
- Cleanliness of installations;
- Maintenance.

| | Belgium | France | Italy | Spain | Sweden |
|---|---|---|---|---|---|
| Design office/Architect | 3 | 2 | 2 | | 3 |
| Installation contractor/Manufacturer | 5 | 4 | 3 | 2 | 1 |
| Maintenance contractor/Manager | 2 | | | | 2 |
| Total | 10 | 6 | 5 | 2 | 6 |

*Table 13: Sample of the small-scale survey.*

## *5.3 Traditions*

### 5.3.1 Type of systems

As regards the most frequently-used ducted systems in new construction, the European Union can roughly be divided in three major zones:

| | Frequently-used ducted systems |
|---|---|
| Nordic regions | Balanced mechanical ventilation with heat recovery; air heating or cooling with heat recovery |
| Middle regions | Mechanical exhaust ventilation; air heating or cooling |
| Southern regions | Air conditioning (commercial buildings) |

*Table 14: Frequently-used ducted systems.*

### 5.3.2 Duct Material

Metal is the most frequently used material either for rectangular or round ducts. Plastic is another material that is often used in single-family houses as it is cheap and compatible with the fire regulations for air ducts. On the other hand , fibre glass boards and brick are not used very much. The reason certainly lies in health and safety issues. Note that in several European countries (e.g. Germany) blowing air through fibre glass ductwork is forbidden.

### 5.3.3 Duct shape

Especially in the Nordic countries, both designers and contractors would rather use round ducts as they are manufactured with standard sizes. However, the market penetration of rectangular ducts is significant in the other regions and especially in the Southern countries.

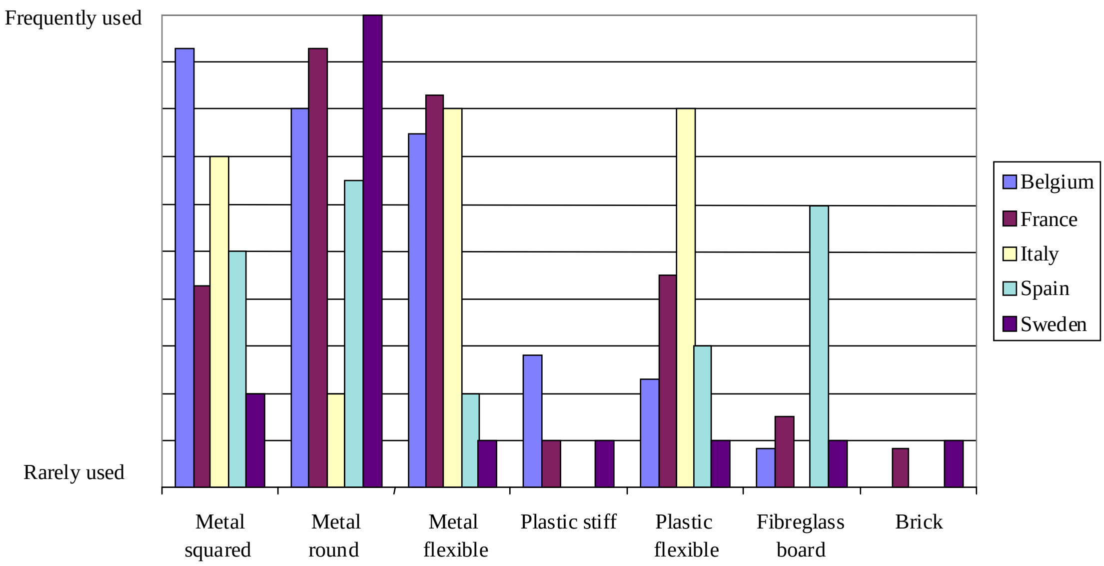



*Figure 27: Type of ductwork frequently used. Data from small-scale survey.*

### 5.3.4 Connecting systems at joints

In Nordic countries, the factory-fitted lip-seal system (that is airtight and that can be dismantled) is widely used. Although, this technique is increasingly used in some other countries such as the Netherlands or Germany, in other countries, ducts are most commonly sealed on site using adhesive tapes in combination with mastic or screws (note that the use of mastic or screws is not systematic). Flange systems are often used with rectangular ducts or with systems that need to be dismantled regularly for maintenance purposes. The parts are connected with screws and the sealing media is either mastic or rubber gaskets.

### 5.3.5 Clean ducts

The Nordic countries appear to be aware of the need to have clean systems. Thus, inspection hatches are frequently encountered to provide access to the interior of the ductwork. Cleaning is undertaken if needed after (regular) inspecti ons. The inspection interval lies between 2 to 9 years although it is sometimes reduced in special applications (e.g. hospitals). Robot cleaning is not used very much because of the significant investment for the equipment. Furthermore, the robots may be hindered by obstructing screws or rivets stretching inwards. In the remaining countries however, cleaning access is in general fairly poor and duct systems are rarely inspected or cleaned. In these instances, maintenance is often restricted to a minimum. Furthermore, when being installed or being repaired, installations are rarely cleaned.

When high Indoor Air Quality (IAQ) is required an installation that has just been completed usually runs for a while before it is actually used (parts like filters are replaced at that time).

### 5.3.6 Rehabilitation

Duct systems are rarely rehabilitated.

### 5.3.7 Context of standards and regulation

In practice, although designers are not necessarily aware of duct leakage issues, they know about guidelines, standards and regulations (whether international, European, or national) related to ductwork airtightness. Note, however, that they frequently refer to these in the building specifications only in the Nordic regions and few other states. Consequently, the contractors in other countries are not very familiar with ductwork airtightness needs and requirements. This can lead to a significant gap between the design stage and the field work. However, as regards the cleanliness of the installation when it is handed over, installers seem to be aware of specific needs, standards and regulations on specific installations.

### *5.4 Implication on ductwork airtightness*

Inadequate product selection and poor installation can severely affect the leakiness of an HVAC system. Special attention should be paid to the connecting parts and the connections themselves since these are the weakest points. Also, some (complex) components (e.g. air handling unit) are very difficult to get airtight. Conversely, it is fairly easy to have airtight straight ducts (either rectangular or circular) provided that the accessibility and the durability of the sealing media be taken into account. Professionals generally agree with this, although they do not seem to be quite aware of how leaky the components can be.

Insufficient care when maintaining and/or inspecting an installation can also lead to poor airtightness. Although professionals consider that inspection hatches do not induce significant leakage, they are sometimes found improperly sealed after a cleaning procedure. Also some sealing media in common use can be damaged by chemicals.

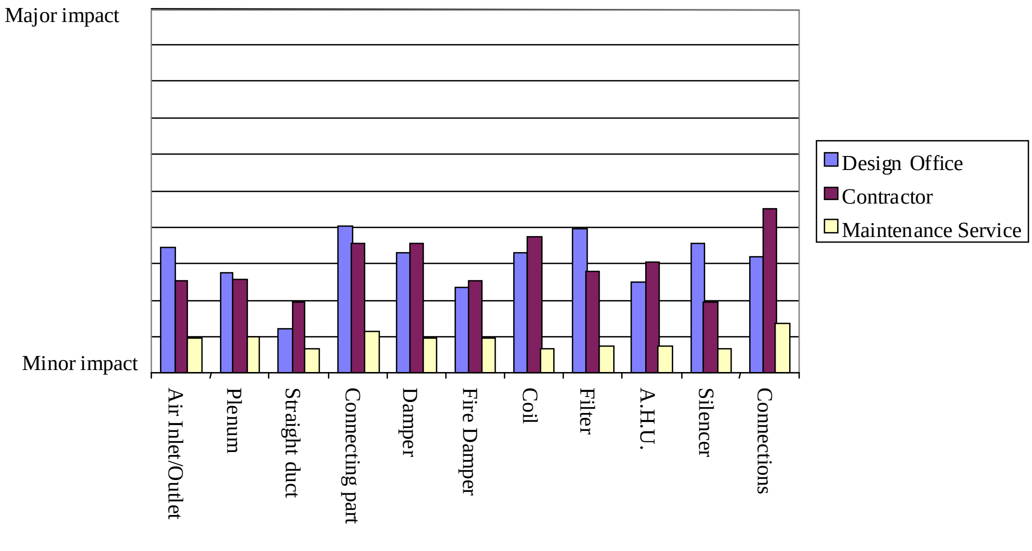



*Figure 28: Perceived impact of several components on duct leakage. Data from small -scale survey.*

### *5.5 Incentives and barriers to better systems market penetration*

#### 5.5.1 Cost issues

**➤Material cost**

In general, adhesive tape, either on a textile or aluminium base, results in the lowest material cost to connect air duct components. Mastic is mostly used in combination with tape to obtain tighter and more durable co nnections. It is slightly more expensive and therefore some professionals in Southern Europe use tapes alone. In general, factory-fitted rubber gaskets or O-rings on components result in a price increase of 10% to 50% depending on the components and market penetration in the different countries. Flange and clip systems lead to the highest costs but are of great interest where installations need to be dismounted.

### ➤Labour cost

It is generally estimated by manufacturers that the use of factory -fitted sealing gaskets results in airtight systems as well as a reduction of the installation time (which is estimated to be an average of 25% compared to conventional sealing with tape and/or mastic). Thus, the additional material cost may be compensated by a lower labour cost. However, this does not seem to be well-known especially among the contractors.

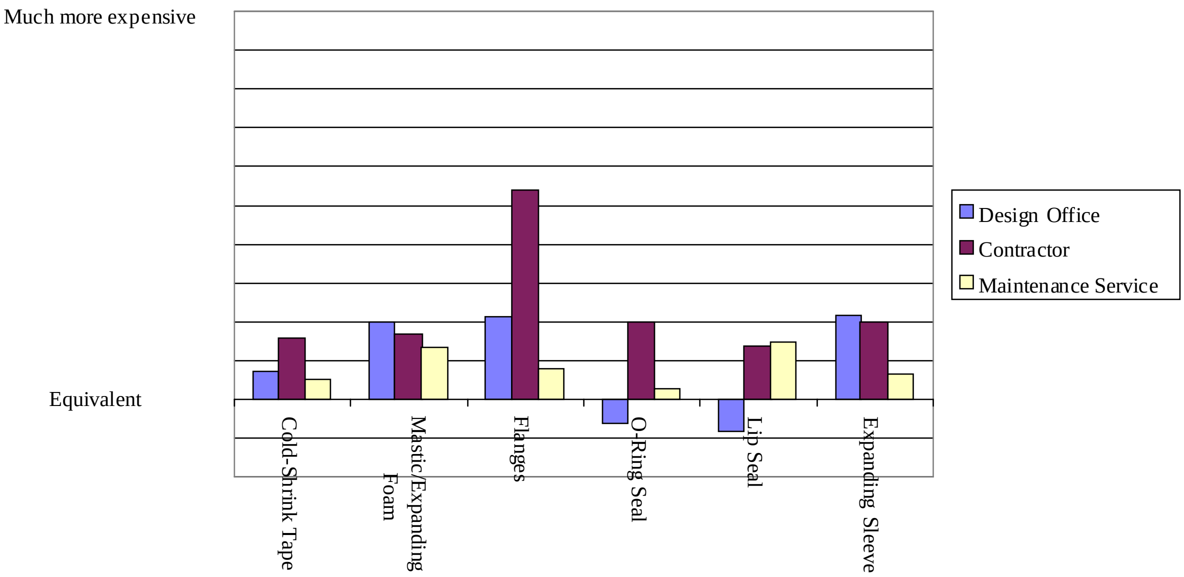



*Figure 29: Perceived labour cost of several techniques compared to that of duct tape. Data from small-scale survey.*

### ➤Maintenance costs

In general, professionals are aware of the interest of dismountable solutions such as O -Rings, lip seals, flanges or expanding sleeves to perform efficient maintenance on the ductwork.

### ➤Life Cycle Cost

Investment and operating budgets are evaluated sequentially and almost never globally, which leads to conflicts of interest between the different parties.

### 5.5.2 Possible actions

The major bottle-neck lies in the higher material cost of quality products combined with the sequential evaluation of the budget (as opposed to a Life Cycle Cost approach). An adequate regulation would probably be an effective way to promote air tight systems (see chapter 10). Although it may not be very well perceived by the manufacturers, designers, contractors, and investors, it presents the advantage of minimising the conflicts of interest between the end-users, the contractors and the designers.

Another way would be to better inform all interested parties of the benefits of tight systems and technologies such as pre-fitted sealing gaskets. Indeed designers and contractors seem to be sensitive to convincing arguments such as mounting ease and quickness, cleaning ease, or installation costs. As for end-users, they are receptive to issues such as safety, reliability, and lower operating cost.

### *5.6 Conclusion*

Leaks in air distribution systems are most often encountered at connections and at special components or accessories since these are particularly difficult to get airtight (e.g heat exchanger). This is well-known among the professionals but the solutions adopted to limit leakage are extremely different depending on the local customs, requirements, and control procedures. For instance, whereas factory-fitted sealing gaskets are widely used in the Nordic regions and increasingly demanded in countries such as the Netherlands, more conventional techniques (e.g. tape plus mastic) are frequently used in Belgium, Italy, France, or Spain. In such countries, little attention is paid to duct leakage at installation and the airtightness o f the systems is often poor (see chapter 6).

Although there is an increasing concern for well-maintained systems, this need does not seem to be either clear or taken into account by the interested parties in most countries. This need is better identified in the Nordic countries where the impact of poorly maintained systems on IAQ performance is well understood. This is probably linked to the widespread use of balanced systems with heat recovery (due to the severe climate conditions), which encourage one to pay particular attention to the cleanliness of the supply ducts.

Another key problem lies in the gap between the prescriptions at the design stage and the actual performance on site. Significant efforts should be undertaken to convince people to use adequate techniques to guarantee good performances on site. Control at commissioning is also an important aspect.

Possible actions towards better quality systems market penetration include incentives in new regulations and better marketing. It is important to stress techniques that bring together better quality in air distribution systems and significant energy savings (see chapter 7). However, any measure for improvement should take into account the fact that the major barrier lies in the cost issues as investment and operating budgets are evaluated sequentially and almost never globally.

# Chapter 6 Field measurements

**Measuring ductwork airtightness**

**Leak detection**

**Overview of existing European measurements**

**Field measurements on 22 duct systems in France**

**Overview of duct leakage status in US buildings**

**SAVE-DUCT field measurements**

### *6.1 Summary*

Although duct leakage can be a source of considerable problems, little is known about the ductwork airtightness status in most of the European member states. However, field experiments conducted in various countries suggest that air distribution systems are in general very leaky. Except in Sweden, low-quality ductwork is widely used and poorly installed, yielding leakage rates typically 30 times greater than those of EUROVENT 2/2 Class C systems. Typical problems include:

- Inadequate ductwork component selection;
- Insufficient sealing work at installation;
- Ill-fitted components;
- Worn tapes;
- Physical damage during inspection or maintenance work.

In addition, in some cases, ducts are found to be completely disjointed. All of these airtightness deficiencies, along with other problems often reported (dirty systems, inadequate design, absence of commissioning, poor maintenance, etc.), show the lack of attention paid to those systems.

## *6.2 Measuring ductwork airtightness*

### 6.2.1 Flow through leaks

The airflow rate through a leak will vary depending on the pressure acting across it and the geometry of the opening. The most commonly used pressure / leakage relationship is:

$$Q = C\,\Delta p^{n} \qquad \textit{Equation 3}$$

where:

$Q$ is the leakage flow rate ($m^3/s$);
$\Delta p$ is the pressure differential across the leaks (Pa);
$C$ is the leakage coefficient ($m^3\ s^{-1}\ Pa^{-n}$);
$n$ is the flow exponent (-).

### 6.2.2 Fan pressurisation

By artificially creating a series of pressure differentials in the test section and by measuring the leakage flow rates, one can calculate the $C$ and $n$ defined in Equation 1. This measurement technique, called fan pressurisation, is by far the most commonly used to characterise the airtightness of ductwork systems and building envelopes.

### 6.2.3 Effective Leakage Area

The Effective Leakage Area (ELA) concept is commonly employed to characterise the leakiness of a building envelope. The equation linking the pressure differential to the leakage flow rate is re-arranged as follows:

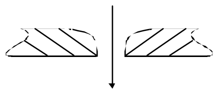
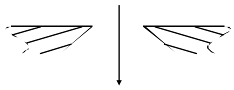
$$Q = C_d\ ELA_{ref}\sqrt{\frac{2\,\Delta p_{ref}}{\rho}}\left(\frac{\Delta p}{\Delta p_{ref}}\right)^{n} \qquad \textit{Equation 4}$$

where:

$C_d$ is the discharge coefficient (-);
(perfect nozzle $C_d$=1; perfect sharp-edged orifice $C_d \approx 0.6$)
$ELA_{ref}$ is the effective leakage area ($m^2$);
$\Delta p_{ref}$ is a reference pressure differential across the leaks (Pa);
$\rho$ is the density of air ($kg\ m^{-3}$).

The physical meaning of the Effective Leakage Area is that, at the reference pressure differential, the flow rate passing through the leaks would be the same as that leaking through an orifice of this same area under the same pressure differential. The reference pressure differential is set according to the typical pressure across the leaks.

There are two common sets of reference conditions to evaluate the airtightness of a building envelope:

| Orifice type | $C_d$ (-) | $\Delta p_{ref}$ (Pa) |
|---|---|---|
| Perfect nozzle  | 1.0 | 4 |
| Sharp-edged  | 0.6 | 10 |

For duct leakage applications, the operating pressure of the system should be taken as the reference pressure.

### 6.2.4 Leakage factor and leakage coefficient

In Europe, most ductwork airtightness standards propose a one-point measurement of the leakage flow rate at a given pressure differential ( $\Delta p_{ref}$) and classify the installations similarly to EUROVENT 2/2, i.e. in terms of the leakage coefficient per square metre of duct surface area defined in Equation 3:

$$\frac{Q}{A} = f_{ref} = K\,\Delta p_{ref}^{\;0.65} \qquad \textit{Equation 5}$$

where:

$A$ is the (tested) duct surface area ($m^2$);
$f_{ref}$ is the leakage factor at $\Delta p_{ref}$ ($m^3\ s^{-1}\ m^{-2}$);
$K$ is the leakage coefficient per $m^2$ of duct surface area ($m^3\ s^{-1}\ m^{-2}\ Pa^{-0.65}$).

It is noteworthy that this classification relies on an arbitrary flow exponent of 0.65 which according to DW/143 (1983) is justified by Swedish tests performed on a variety of constructions. However, measurements performed in other countries show a broad range of values. As for the reference test pressure itself, it can vary considerably. EUROVENT 2/2 is based on a mean operating pressure of the duct system. In European pre-standard prEN 12237 (1998), $\Delta p_{ref}$ should be adjusted to 400 Pa, for Class A, to 1000 Pa for Classes B and C. In prEN 12599 (1997) (meant for *in situ* measurements), $\Delta p_{ref}$ should be adjusted to 200, 400 or 1000 Pa, whichever is closest to the mean operating pressure of the system.

### 6.2.5 Apparatus

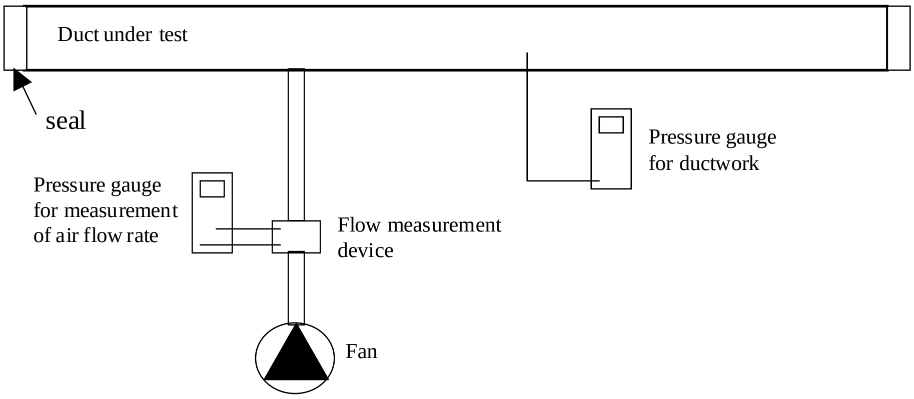



*Figure 30: Fan pressurisation measurement principle and equipment*

According to CEN prEN 12237 (1998), the test equipment should have the following accuracy:

- Airflow meter: 4 % or 0.1 l/s (whichever is the greater value);
- Pressure gauge meter: 2 % or 10 Pa (whichever is the greater value).

Special attention has to be given to the range of application of measurement devices. One ready-to-use duct leakage tester that is primarily commercialised in the US for low-pressure (operating pressure less than 250 Pa) residential and light commercial duct systems was found to be often inappropriate to check the compliance with European airtightness standards. The specific device combines the fan and the airflow measurement (minimum airflow about 10 l/s). Depending on the leakage airflow rate, different rings can be installed on the fan inlet in order to modify the measurement range. The airflow rate is determined by means of a pressure measurement in the fan of the device, by using equations provided by the manufacturer.

Laboratory tests (see Figure 31) were performed in the laboratory at BBRI and showed that at low flow rates (i.e. low fan pressures) significant errors can be made on the airflow rate, especially if the pressure behind the fan (= pressure in the ductwork) is significantly higher than the pressure in the fan (which occurs frequently in airtight systems).

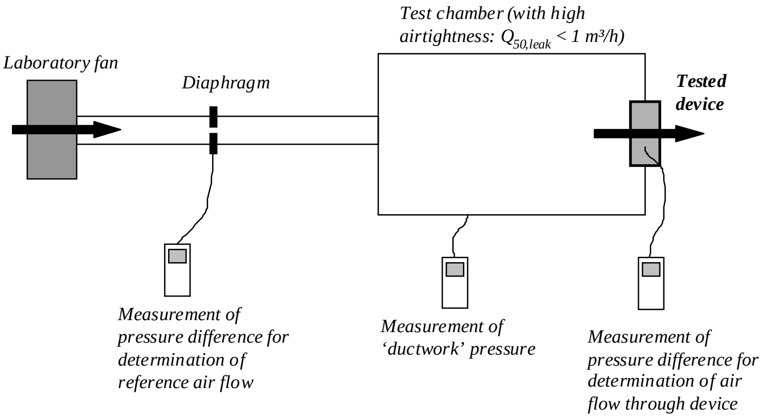



*Figure 31: Set-up of the laboratory test performed at BBRI. The pressure in the chamber is changed with the laboratory fan.*

This appears clearly in Figure 32 where the relationship between the error in the airflow measurement and the fan pressure (for the air flow measurement) is given for different ductwork pressures. According to the manufacturer, the pressure for the airflow measurement should not be lower than 25 Pa, in order to limit the error on the airflow rate. The figure below reveals that this minimum pressure is not a constant value but depends on the relationship between the fan pressure and the ductwork pressure.

It is clear that, to obtain reliable results from these laboratory tests, the airtightn ess of the test chamber is very important. This is because both airflow measurements are compared to determine the error by the device. As a consequence, the leakage airflow rate of the test chamber will cause additional errors, which should not be taken into account. The most critical situation appears for the lowest air flow (25 Pa pressure difference for the air flow measurement) and the highest duct pressure (200 Pa). In this case the airflow through the diaphragm is about 97 l/s (350 m³/h), while the leakage air flow from the chamber is about 0.55 l/s (2 m³/h), i.e. less than 1% of error. This means that the leakage of the chamber has little affect on the results presented in Figure 32.

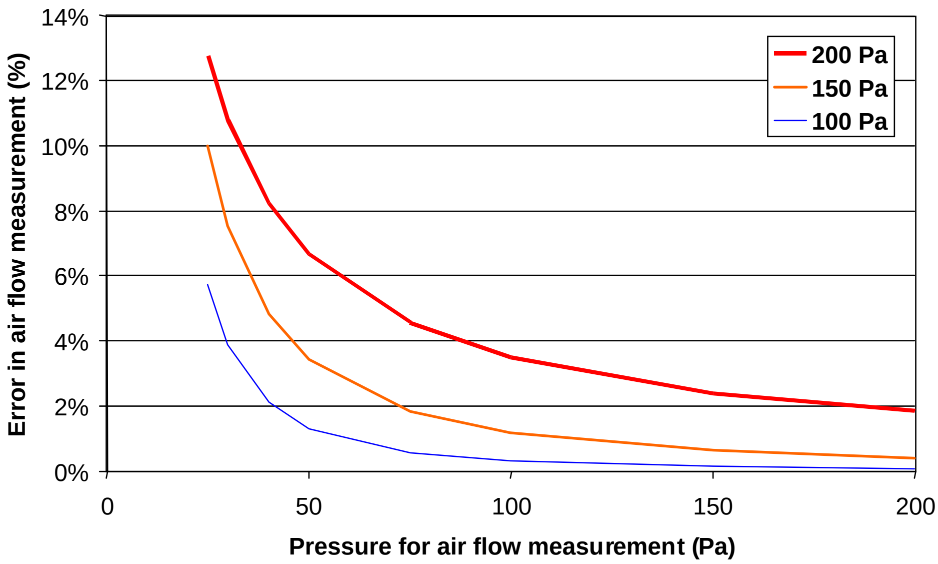



*Figure 32: Influence of the ductwork pressure on the error of the airflow measurement at duct pressures of 100, 150 and 200 Pa.*

By taking a fan pressure of 25 Pa, errors on the leakage airflow rate up to more than 10% can be made (overestimation of the leak).

### 6.2.6 Measurement uncertainties

It may be required to evaluate the level of accuracy of the measurements for certification, quality assurance, or research purposes. This is a complex field of study when the quantities to be defined are not directly measured (e.g. leakage flow at a reference pressure). Sherman and Palmiter (1995) have raised this issue for fan-pressurisation measurements. A pre-standard on building airtightness (ISO 9972) proposes a method to evaluate random errors (noise) alone. However, neither bias errors (i.e. systematic departures from the reference value), nor errors due to the model approximations are taken into account in this pre-standard. Attempts can be made to evaluate systematic errors based on numerical (Monte-Carlo) analyses, i.e. by assessing the impact of the modification of the measured values (pressure and flow rate) by values set according to the accuracy of the devices. The problem often lies in setting those values as bias errors are usually highly correlated.

### *6.3 Leak detection*

Leak detection can be particularly useful for rehabilitation purposes. It is used to rapidly and reliably identify the location of duct leaks. Seven main techniques are used.

#### 6.3.1 Smoke detection

Visible smoke is injected into the pressurised ductwork and escapes through the leaks. The detection is easy when the ducts are accessible. This method is commonly used in building applications. If a significant air barrier separates a substantial portion of the system from the conditioned spaces, a blower-door may be used to pressurise both the building and the ductwork. The air system is switched off and fresh air intakes as well as exhausts are sealed. The smoke is released (with a smoke stick) near each register. A large draft into the system indicates that air leaks to outside near that register. This method is commonly called the *smoke stick method.*

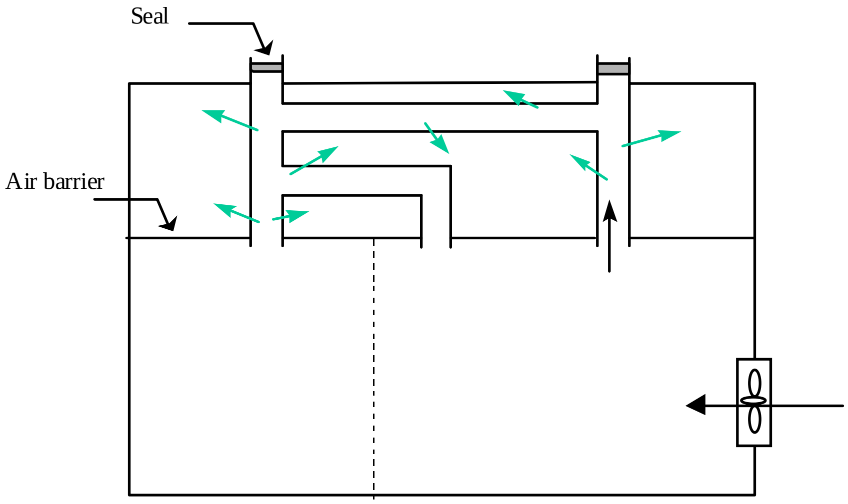



*Figure 33: Blower-door set-up for smoke stick method.*

#### 6.3.2 Soap bubbles

The ductwork is pressurised and liquid soap is applied on the exterior surface. Bubbles appear at the leaks.

#### 6.3.3 Pressure pan

The set-up and restrictions are the same as for the smoke stick method. A cake pan that has a pressure tap is used to cover each register one at a time (Davis and Roberson, 1993). If the pressure across the pan is high, this means that large leaks to outside are near that register. This method is commonly called the *pressure pan method.*

#### 6.3.4 Blocked register pressure

A fan is used to pressurise the ductwork. All the registers are blocked and the pressures across the register seals are recorded using a small probe. The lowest pressure drop indicates potentially large leakage near that register.

### 6.3.5 Foam injection

Foam is injected in the pressurised ductwork and produces bubbles at the leaks. Similarly, special bubbles that produce foam at the leaks can be injected. The foam generally comes in ready-to-use pressurised cans.

### 6.3.6 Video camera inspection

A video camera is set up on a rolling mechanical cart and transported through the ductwork system. This technology is mainly used in cleaning procedures as it is possible to visualise the dust accumulated on the interior surfaces; however, one may take advantage of the cleaning procedure to detect major leaks. Restrictions apply to the dimensions and shape of the duct (small ducts, bends or wyes) and small leaks are difficult to detect.

### 6.3.7 Aerosol duct sealing

An aerosol of sealant particles is injected into the pressurised ductwork. The sealant particles find and seal the leaks automatically because of the pressure-driven flow. This method is described in more details in § 4.4.

## *6.4 Overview of existing European measurements*

Among the member states, Sweden is probably the most advanced on this issue. Nearly every duct system is leak-tested and airtightness Class C (see EUROVENT 2/2) is commonly required and fulfilled in new installations. The situation appears to be quite different in the other European countries. Tests are very seldom performed in standard buildings, and t hus the knowledge about the ductwork airtightness mainly relies on a few studies.

In the UK, Babawale *et al.* (1993) have investigated one forced air-heating system and have come to worrying conclusions in terms of energy use and comfort conditions. They recommend a research effort to ascertain the extent and impact of duct leakage in new and old building stock in the UK, especially when the ducts run through unconditioned spaces. However, such installations are not used very much in European countries in general. In Belgium, Ducarme *et al.* (1995) monitored a demand-controlled ventilation (DCV) system installed in an office building in 1993. It was shown that the ductwork airtightness is a key aspect for fully benefiting from the energy savings potential of the DCV. In this specific case, the initial ductwork airtightness was so poor that no savings at all could be achieved: whatever the demand was, the same airflow rate was supplied to the building, either to the occupied offices or to the corridor through t he leaks. Afterwards, it proved to be very difficult and time consuming to improve the ductwork airtightness so as to meet EUROVENT Class A. Figure 34 shows the effect of different sealing activities on the airtightness of the ductwork. It is worthwhile mentioning that the working pressure of the system is about 100 Pa and the nominal ventilation airflow rate is about 180 l/s (650 $m^3/h$), which means that in the initial situation the fan had to provide about 360 l/s (1300 $m^3/h$) instead of 180 l/s (650 $m^3/h$) !

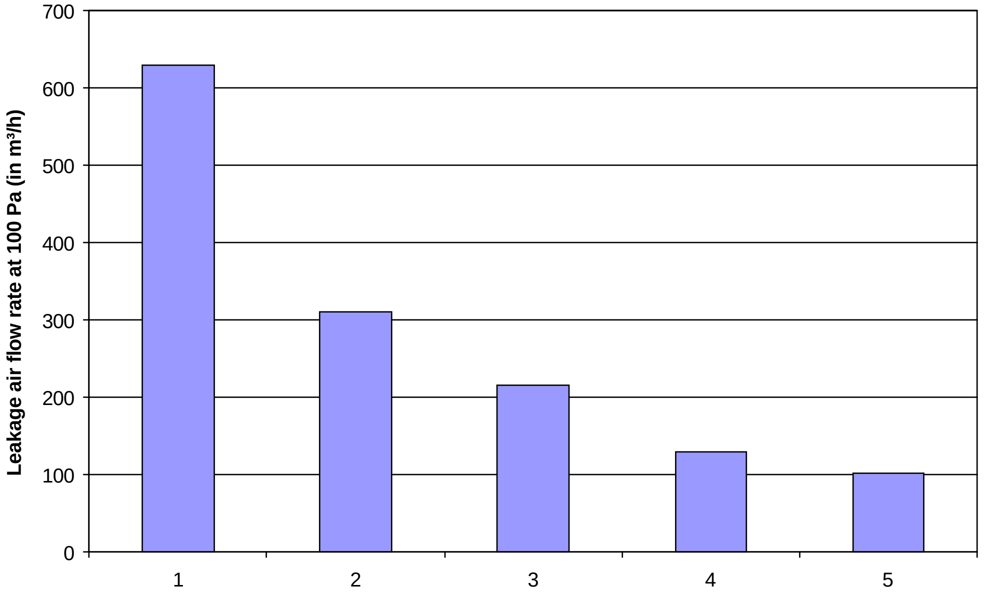



*Figure 34: Systematic improvement of the airtightness of the ductwork in a Belgian office building with demand-controlled ventilation.*

Pittomvils *et al.* (1996) investigated in detail, balanced ventilation systems equipped with heat recovery used in more than 170 very low energy houses built in the Flemish Region of Belgium by field and laboratory testing. The ductwork was so leaky that about one third of the air supplied by the fan at medium speed escaped through leaks before even reaching the ventilated rooms.

In France, Riberon *et al.* (1992) found "insignificant" duct leakage in 19 new single-family houses. However, Carrié *et al.* (1996) measured very large leakage rates in 9 duct systems in multi-family buildings, 8 in schools, 2 in a day-care centre, and 3 in office buildings. Their analyses show potentially large indoor air quality and energy use impacts at a national level.

### *6.5 Field measurements on 22 duct systems in France*

This paragraph focuses on the field study conducted by CETE Lyon and ENTPE (Carrié *et al.*, 1996) that was funded in part by Ademe, and which is the basis of the SAVE-DUCT project. The sample included 9 duct systems in multi-family buildings (4 to 5 storeys), 8 in schools, 2 in a day-care centre, and 3 in office buildings. All of the buildings were located in the vicinity of Lyon, France. Significant deficiencies were observed, as shown in Figure 35.

*Figure 35: Photograph of poorly installed duct connections.*

The results are represented in Figure 36, and summarised in Table 15. It appears that the flow exponent has an average value considerably different from 0.65. Furthermore, i t is found that except for one system, none can be classified according to the EUROVENT 2/2 airtightness classes. *K* is on average well above that of Class A ($K$ < 0.027 $10^{-3}$ m $s^{-1}$ $Pa^{-0.65}$).

| | Flow exponent *n* (-) | *K* ($l\ s^{-1}\ m^{-2}\ Pa^{-0.65}$) | $ELA_{100}/A$ ($cm^2/m^2$) |
|---|---|---|---|
| Multi-family buildings (9) | 0.59 (0.05) | 0.125 (0.050) | 2.0 (0.8) |
| Non-residential buildings (13) | 0.57 (0.04) | 0.066 (0.035) | 1.0 (0.5) |

*Table 15: Duct leakage field measurement results. Average values of n, K, $ELA_{100}/A$. The standard deviations are shown in parenthesis.*

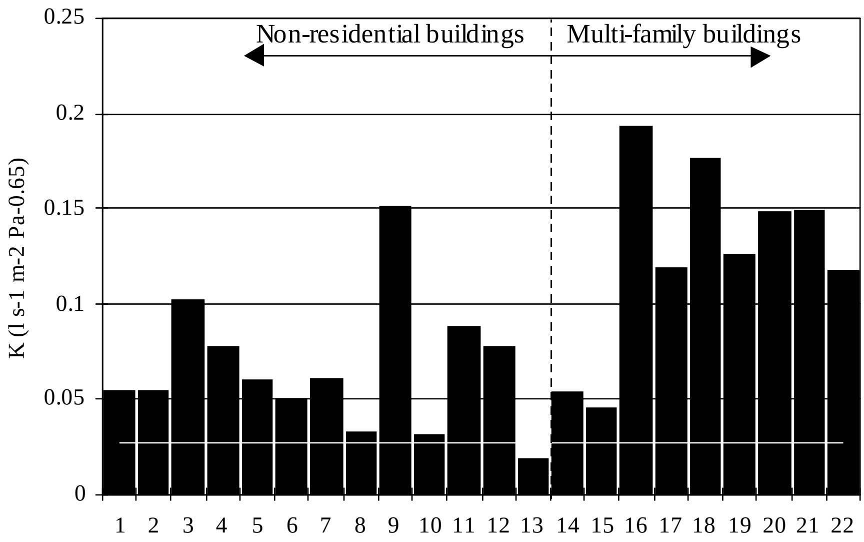



*Figure 36: Duct leakage field measurements - Leakage coefficients.*

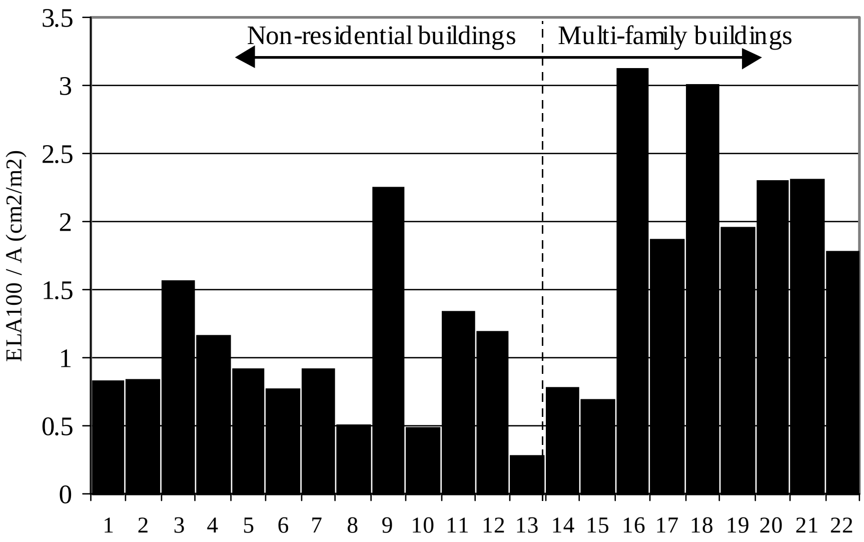



*Figure 37: Duct leakage field measurements - ELA at 100 Pa normalised by the (tested) duct surface area.*

### 6.6 Overview of duct leakage status in US buildings

Outside Europe, field studies have been conducted mainly in US residences. In the southern regions of this country, a typical residential forced-air distribution system has supply and return flexible plastic ducts in unconditioned spaces, but no outdoor air intake or exhaust (Figure 38). In the northern regions, rectangular sheet-metal trunk ducts with round sheet-metal branch ducts is most likely. The primary goal of these systems is to heat or cool the building spaces while fresh (ventilation) air is provided by other means (e.g. infiltration through the building shell or local exhaust).

Over the past ten years, effective leakage areas have been measured in many residences for certification, retrofit, or research purposes. According to Lawrence Berkeley National Laboratory field studies, effective leakage areas for plastic flexduct systems are found to be typically of the order of 1.3 $cm^2$ ($ELA_{25}$) per $m^2$ of floor area (Jump and Modera, 1996), which translates into about 5 $cm^2$ per $m^2$ of duct surface area (Modera, 1998) i.e. more than 12 times leakier than tightness Class A. Major deficiencies (worn tape, torn or damaged ducts) are frequently encountered. Moreover, the area-normalised leakage of typical sheet-metal duct systems in basements is approximately twice that which is found in plastic flexduct systems.

Research has quantified the impacts of US residential duct system leakage on HVAC energy consumption and peak electricity demand. A typical California house with ducts located in the attic or crawlspace wastes approximately 20 % of heating and cooling energy through leaks and draws approximately 0.5 kW more electricity during peak cooling periods (Modera, 1993). Therefore, significant efforts have been undertaken on retrofitting techniques (Jump *et al.*, 1996; see also aerosol-based technique in chapter 4).

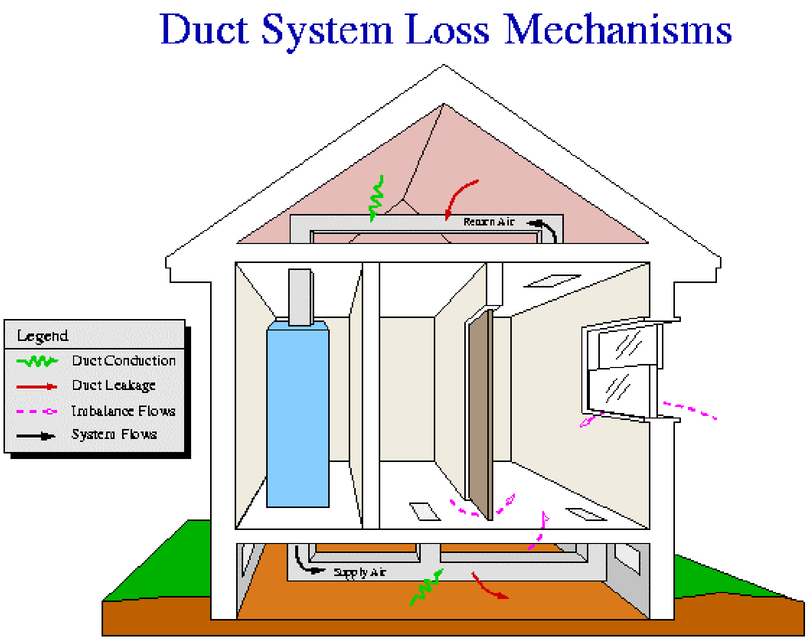



*Figure 38: Typical US residential duct system (courtesy Lawrence Berkeley National Laboratory).*

More recent research at LBNL has been focused on "light commercial buildings" - primarily one- and two-storey buildings with individual HVAC package roof-top units serving floor areas less than 1000 $m^2$ - that represent a large fraction of the build ing stock in the US (Delp *et al.*,1997). These systems use duct materials and construction techniques similar to residential systems. Although the ducts are most often located in a drop ceiling, the primary thermal barrier is frequently found at the ceiling tiles, in which case the ducts are entirely outside the conditioned space. However, little is known about the performance of these systems. Duct leakage measurements were performed in 43 buildings by the Florida Solar Energy Center (Cummings *et al.*, 1996) and on 15 systems by the Lawrence Berkeley National Laboratory (Delp *et al.*,1997). In both studies, effective leakage areas were found to be significantly greater than those for residential duct systems (Figure 39).

Field data from large commercial buildings is in very short supply, however, evidence suggests that they are leaky as well (Modera, 1998).

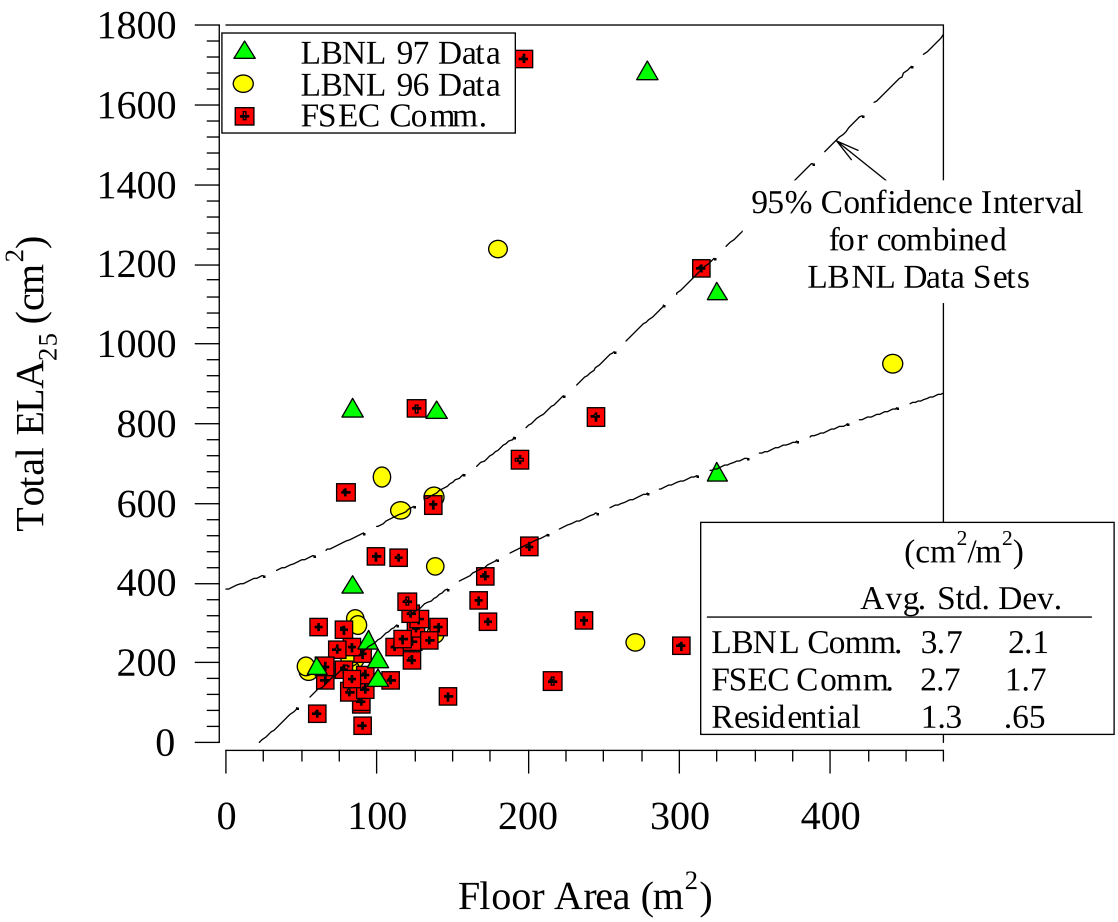



*Figure 39: Combined leakage area ($ELA_{25}$) –vs- floor area using LBNL (Delp et al.,1997) and FSEC (Cummings et al., 1996) commercial data along with residential (Jump et al. 1996) summary information. Combined leakage areas includes both supply and return leakage. Graph from (Delp et al.,1997).*

### *6.7 SAVE-DUCT measurements*

In the framework of the SAVE-DUCT project the airtightness of 42 ductwork systems was measured in France (21) and Belgium (21). In Sweden, nearly all installations are leak-tested commissioning and as a consequence a lot of data is already available. Therefore, a randomly selected sample of 69 Swedish control measurements was collected.

#### 6.7.1 Protocol

In Belgium and in France, the multi-point ductwork pressurisation method was used, i.e. the ductwork was pressurised at different pressure stations to calculate the leakage characteristics of the systems. The test was performed at pressures in the range of 50 % - 150 % of the operating pressure of the ductwork. In Sweden however, the measurement procedures are performed according to a different protocol. The one-point measurement method with an arbitrary flow exponent of 0.65 is used.

#### 6.7.2 Belgium

**Error! Reference source not found.** gives an overview of the 21 Belgian systems involved in the study and the results of the measurements. The sample included 12 ductwork systems in non-residential buildings, 5 in multi-family buildings, and 4 in single-family houses. The ductwork of all systems, except one (of concrete), consists of sheet-metal.

The results are represented in Figure 40, and summarised in Table 16. It appears that although the flow exponent has an average value close to 0.65 (0.64), it ranges from 0.55 to 0.73 and the standard deviation is large. It is clear that the majority of the systems have rather bad airtightness; only 4 systems fulfill the Class A requirement and one system reaches Class B. In Figure 40 a distinction is made between rectangular ductwork, circular ductwork, ductwork where a plenum is used for the connection at the registers and concrete ductwork. In this sample, rectangular ductwork is on average about 7 times leakier than circular ductwork. The positive effect of the use of circular ductwork seems to be partly lost if the registers are connected to the ductwork with plenums (see later in this chapter).

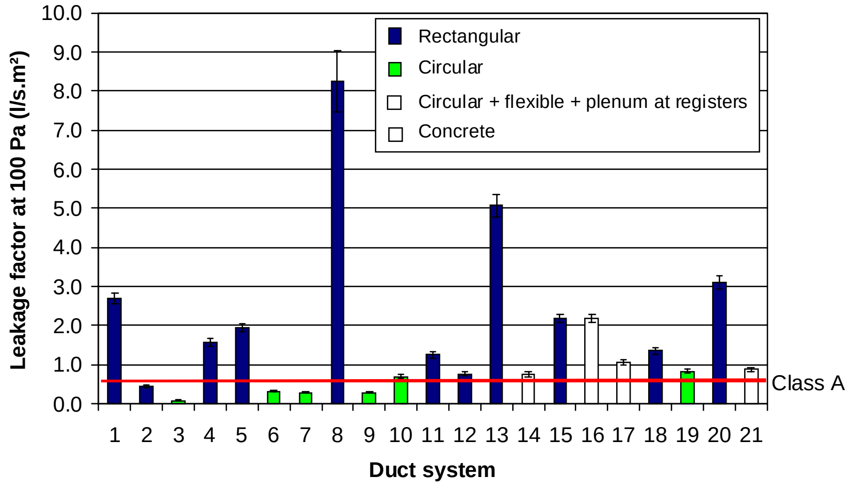



*Figure 40: Leakage factor at 100 Pa for the investigated systems in Belgium.*

| | Flow exponent $n$ (-) | $f_{100}$ ($l\ s^{-1}\ m^{-2}$) |
|---|---|---|
| Non-residential buildings (12) | 0.64 (0.05) | 2.30 (2.34) |
| Multi-family buildings (5) | 0.60 (0.05) | 0.84 (0.40) |
| Single-family houses (4) | 0.66 (0.03) | 1.02 (0.86) |

*Table 16: Duct leakage field measurement results (Belgium only). Average values of n and $f_{100}$. The standard deviations are shown in parenthesis. Maximum $f_{100}$ for Class A is 0.54 l/s per $m^2$.*

### 6.7.3 France

**Error! Reference source not found.** gives an overview of the 21 French systems involved in the study and the results of the measurements. The sample included 8 ductwork systems in non-residential buildings, 9 in multi-family buildings, 4 in single-family houses. The ductwork of all systems were made of sheet-metal.

The results are represented in Figure 41, and summarised in Table 17. The flow exponent ranges from 0.50[5] to 0.68. The average value is 0.60 with a standard deviation of 0.06. The airtightness of most of the systems did not meet Class A; only one system reaches Class B. The systems' airtightness in office buildings seems to be much better than that in multi-family buildings and single-family houses. This is probably due to the fact that, in the latter, the tested duct area is much smaller and, as a consequence, a small leak will have a larger impact on the leakage factor.

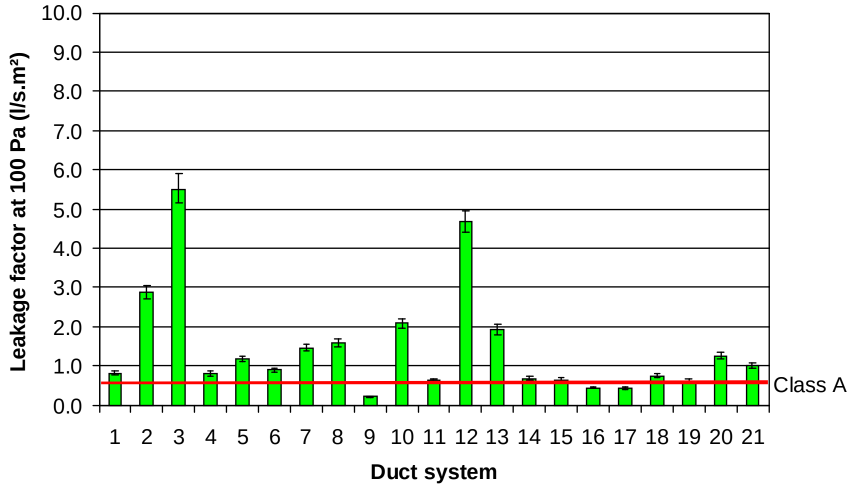



Figure 41: Leakage factor at 100 Pa for the investigated systems in France.

| | Flow exponent *n* (-) | $f_{100}$ (l s$^{-1}$ m$^{-2}$) |
|---|---|---|
| Non-residential buildings (8) | 0.59 (0.07) | 0.72 (0.28) |
| Multi-family buildings (9) | 0.58 (0.07) | 1.73 (1.63) |
| Single-family houses (4) | 0.63 (0.04) | 2.36 (1.76) |

*Table 17: Duct leakage field measurement results (France only). Average values of n and $f_{100}$. The standard deviations are shown in parenthesis. Maximum $f_{100}$ for Class A is 0.54 l/s per m$^2$.*

[5] In two cases, a value lower than 0.50 was calculated, which is not physically possible. It is probably due to large measurement errors.

### 6.7.4 Sweden

As already mentioned before, the airtightness of new Swedish installations for air distribution has to be checked at commissioning (since the 1983 version of VVS AMA: see § 3.3.2). This means that many measurement data are available from Swedish installations. Therefore it was not necessary to perform additional measurements in the framework of the SAVE-DUCT project. The measurement results from a randomly selected group of 69 installations were collected. In Sweden, the one-point measurement procedure is used at commissioning. The reference pressure is usually set to 400 Pa and a flow exponent of 0.65 is assumed. Figure 42 represents the $f_{400}$-values of all selected duct systems.

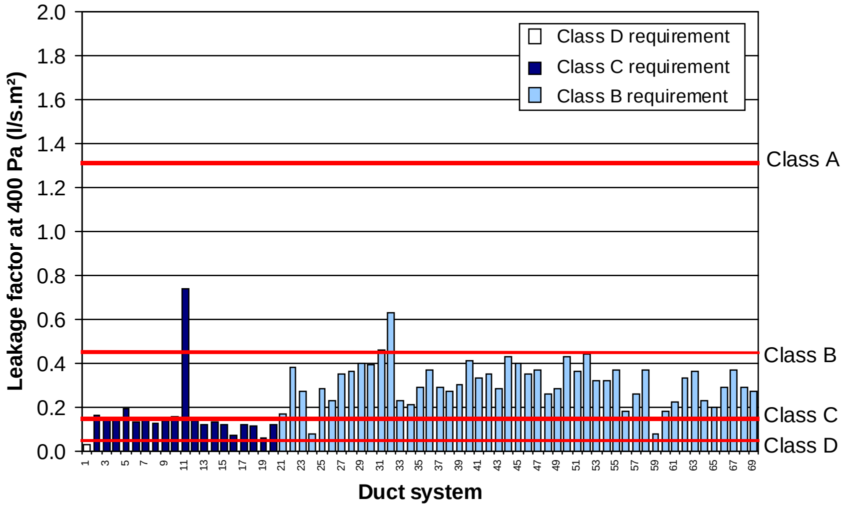



*Figure 42: Leakage factor at 400 Pa for 69 duct systems in Sweden. Leak-tests performed at commissioning.*

Nearly all new Swedish installations have to comply with airtightness requirements detailed in AMA 83 (see § 3.3.2) that depend on their type. In Figure 42 three groups of ductwork are represented: one system has to comply with Class D, 19 systems with Class C, and 49 with Class B. Most of the installations seem to meet the requirements, only 3 do not. It is noteworthy that installations that do not fulfil the requirements have to be tightened until they do; consequently, the 3 "bad" installations should eventually have at least the desired airtightness. In contrast with the Belgian measurements, which revealed that the airtightness of rectangular ductwork is generally worse than the airtightness of circular ductwork, there seems to be no significant difference between circular and rectangular ductwork in Sweden (Table 18).

| Type of ductwork | Average $f_{400}$ (l/s.m²) | |
|---|---|---|
| | Sweden | Belgium |
| Rectangular | 0.30 (16) | 6.47 (11) |
| Circular | 0.26 (38) | 0.94 (6) |
| **Rectangular / circular** | **1.15** | **6.90** |

*Table 18: Rectangular versus circular ductwork in Sweden and Belgium (the values between brackets represent the number of ductwork tested).*

### 6.7.5 Comparison between the 3 countries involved in the study

**➤Leakage factors**

The results from the different countries are compared in Figure 43. The determination of the classes was done on the basis of the $f_{400}$-value[6]. As the airtightness in France and Belgium is often much worse than Class A, additional classes were created based on the geometric progression of the existing classes (i.e. with a factor of 3).

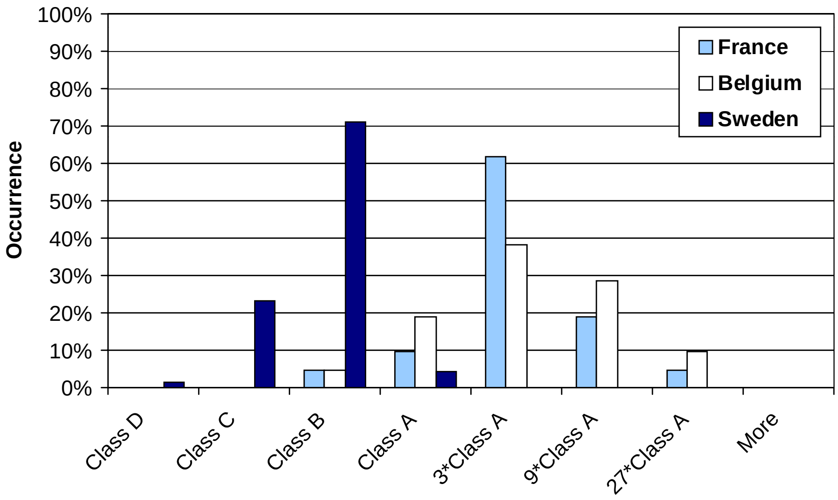



*Figure 43: Occurrence of the different tightness classes. Based on 21 systems in Belgium, 21 in France, and 69 in Sweden. Each stack represents the relative number of systems that comply with the specified Class.*

It is obvious that the situation in Sweden is by far the best: more than 95 % of the systems comply with Class B or better at commissioning; the remaining achieve Class B after improvement. The results from France and Belgium are comparable: most of the systems have an airtightness in the region of Class A to 9 * Class A. An airtightness better than Class A seems to be rather unusual in these countries. To give a better idea of the physical meaning of these results, the average leakage areas are represented in Figure 44. In Belgium and France the average $ELA_{100}$ seems to be higher than 1 cm² per m², while in Sweden it is lower than 0.1 cm²/m².

[6] Belgian and French measurements were extrapolated to 400 Pa.

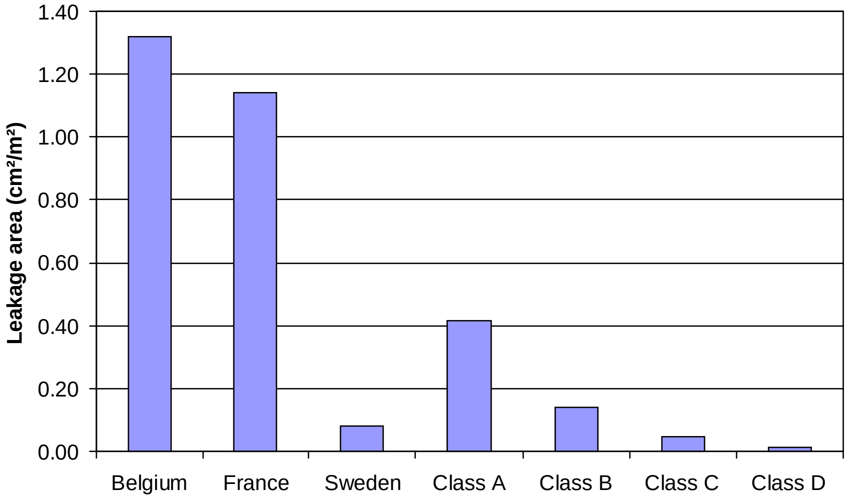



*Figure 44: Average leakage area per m² ($ELA_{100}/A$) for the different countries and comparison with leakage area for the classes A, B, C and D.*

### ➤Flow exponents

Figure 45 is a histogram representing the flow exponents of the Belgian and French results[7]. Although the average value is close to 0.65 (0.62), there is a significant spread in the data (standard deviation: 0.06).

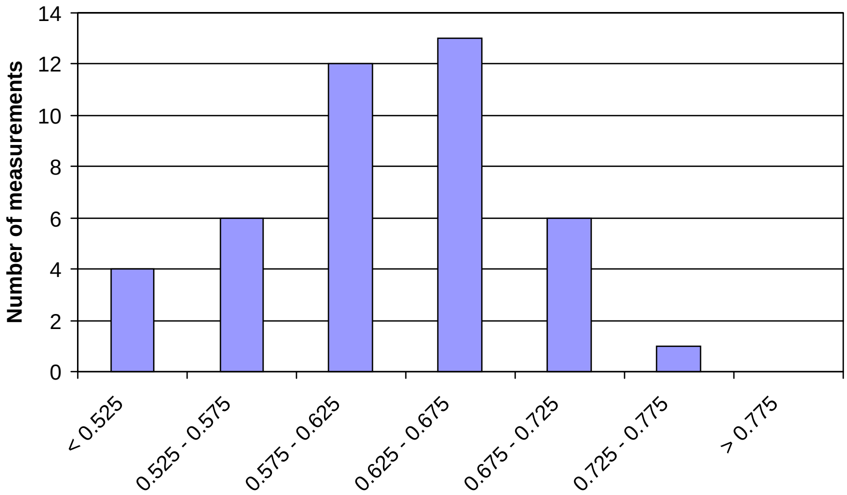



*Figure 45: Histogram of the flow exponents of the Belgian and French measurements.*

This can lead to significant errors when the test pressure is considerably different from the leakage factor reference pressure. In Figure 46 for instance, due to a flow exponent of 0.50, the installation does not comply with Class A at 10 Pa; the same installation complies with Class A at 1000 Pa.

[7] In Sweden the airtightness class is determined by a one-point measurement procedure, assuming a flow exponent of 0.65.

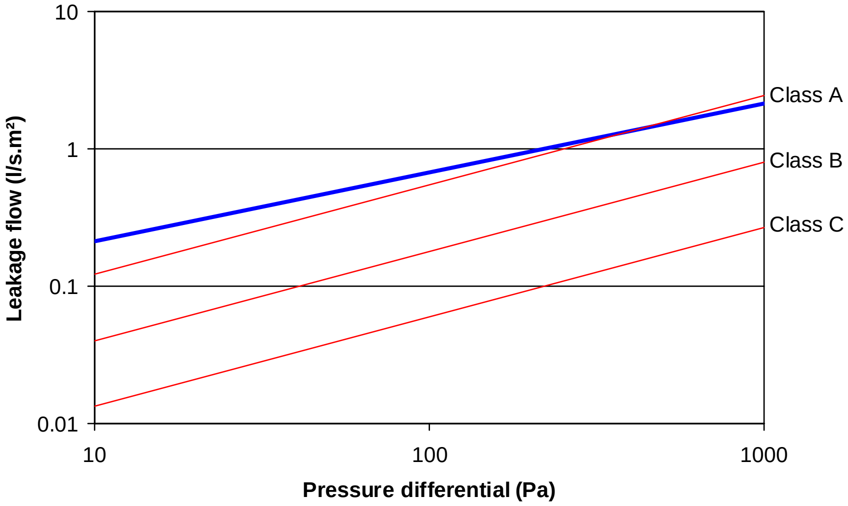



*Figure 46: Influence of flow exponent on classification (building 14 of the French sample).*

### 6.7.6 Air distribution impacts

Figure 47 shows the ratio of the leakage airflow rate (at 100 Pa [8]) to the design airflow rate [9], expressed as a function of the leakage factor ($f_{100}$).

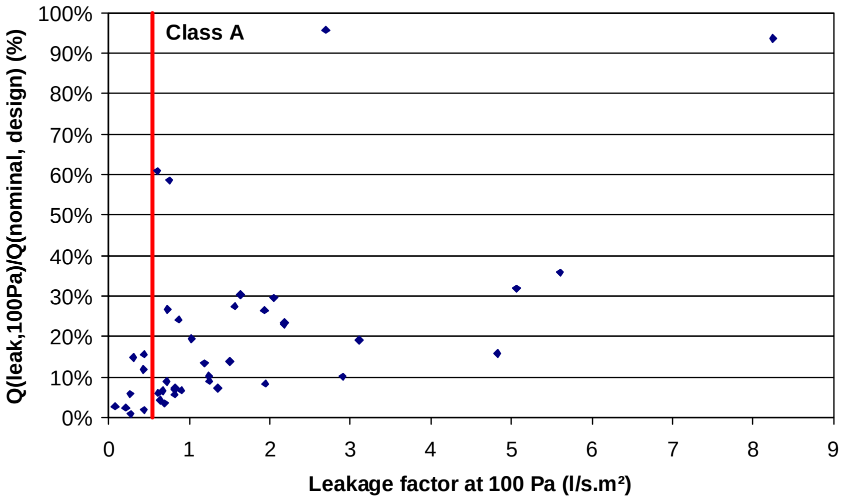



*Figure 47: Ratio between leakage airflow rate (at 100 Pa) and design airflow rate as a function of $f_{100}$ (l/s.m²).*

The following conclusions can be drawn:

- In some cases the leakage airflow rate can be comparable to the design airflow rate (assuming a pressure of 100 Pa);
- On average, the leakage airflow rate is of about 20 % of the design airflow rate (again assuming an operating pressure of 100 Pa);

[8] Since the operating pressure could not be measured in some new installations, leakage flow rates are estimated at 100 Pa which is close to the design operating pressure of many European systems. The implications of this choice are discussed below.
[9] Where for some reason, the data is not available, the measured airflow rate is used.

- The effectiveness of the air distribution **does not depend uniquely on the leakage factor**. A system with an "acceptable" leakage factor can have a significant leakage airflow rate compared to the design airflow rate. In Figure 47, one can see a system case where Class A is achieved although the ratio is of 60 %. Conversely, some systems that do not comply with Class A can have a relatively low leakage flow rate;
- Other parameters should be taken into account to evaluate in more detail the air distribution impacts of leaky ducts, e.g. energy losses through increased fan and ventilation load. These include the type of system (heating, cooling or ventilating), the location of the leaks, the operating pressure and surface area of the ductwork, etc. (see chapter 7).

### 6.7.7 Sensitivity of leakage airflow rates to operating pressures

For the above calculations an operating pressure of 100 Pa was assumed. The magnitude of this pressure has a very important impact on the leakage airflow rate of a system. This is shown in Figure 48 where (for the Belgian and French results) the average of the ratio between the leakage airflow rate and the design airflow rate is calculated for different operating pressures.

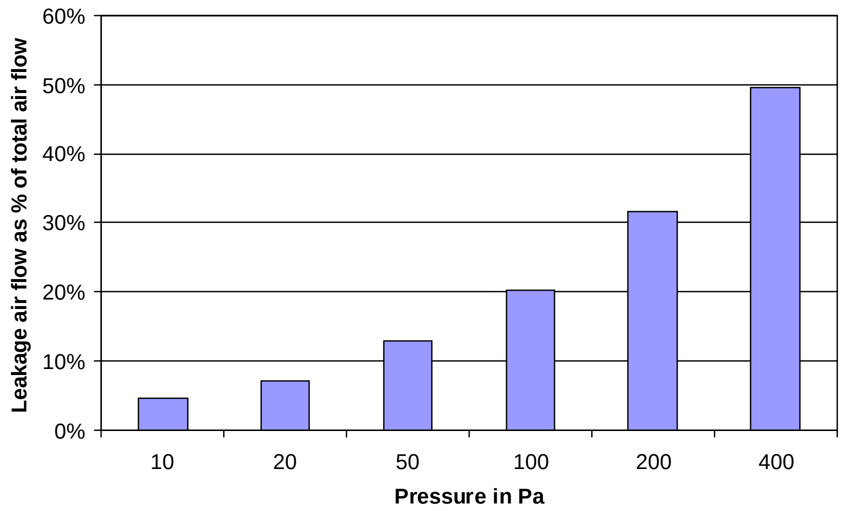



*Figure 48: Influence of the operating pressure on the average ratio between leakage airflow rate and design airflow rate (for Belgian and French measurements).*

Owing to this important impact, the requirement for ductwork airtightness depends on the operating pressure in some (national) standards (e.g. UK, Australia etc.). In some of the Belgian installations the operating pressure could be measured. Figure 49 shows the difference between the leakage airflow at 100 Pa and at the real operating pressure. Apparently, the pressure is lower than 100 Pa in most of the systems. In some cases the pressure is even lower than 10 Pa. This means that the leakage airflow rate was largely overestimated when a default 100 Pa operating pressure was taken. However, in such cases other issues, such as the problems to properly control the airflow rates at the registers, are likely to arise.

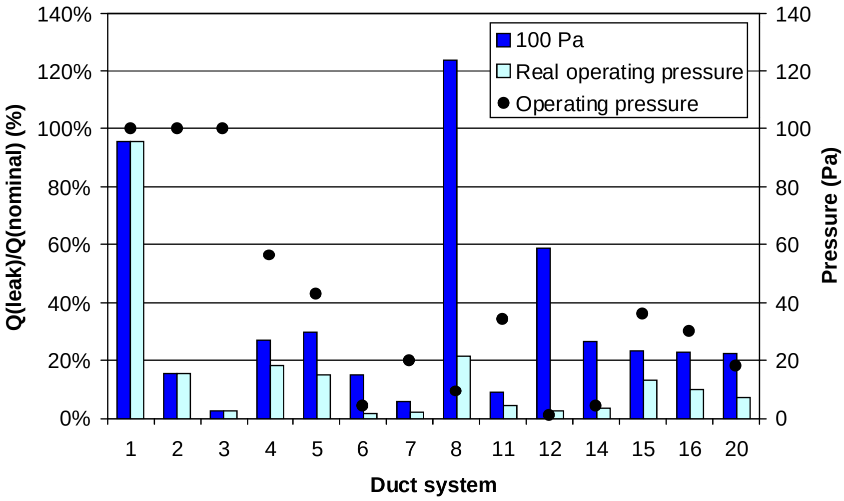



*Figure 49: Comparison between leakage airflow rate at 100 Pa and at real operating pressure for some Belgian installations.*

### 6.7.8 Some specific cases investigated in detail

**➤Replacement of rectangular ductwork by circular ductwork**

The Belgian field measurements revealed that rectangular ducts are generally much leakier than circular ones. However, the Swedish results showed that it is possible to achieve a similar airtightness with rectangular ductwork. It strongly depends upon the type of materials and the quality of the work. In the literature review, the steps towards the improvement of the airtightness of rectangular ductwork in a Belgian office building were explained (Ducarme *et al.*, 1995). After many person-hours of work, the leakage airflow rate could finally be reduced by a factor 6. As the leakage airflow rate still represented about 15 % of the nominal airflow rate, it was decided to replace the rectangular ductwork by circular ductwork on one of the two storeys of the building. The circular ducts had factory-fitted sealing gaskets (see chapter 4). Installation was fast and easy. Furthermore, the airtightness is excellent (Figure 50).

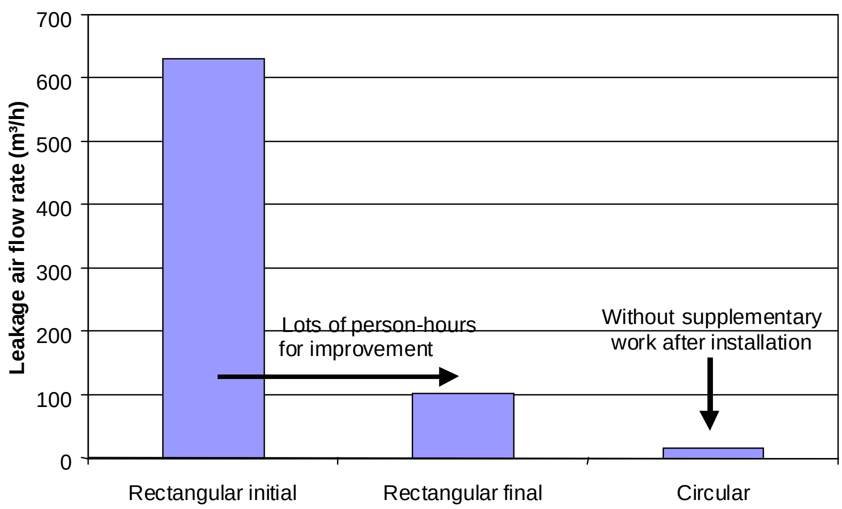



*Figure 50: Impact of the replacement of rectangular ductwork by circular ductwork in a Belgian office building.*

**➤Influence of plenums on the airtightness**

Sometimes plenums are used to make the connection between the registers and the ductwork. An example is shown in Figure 51. Usually the plenums are connected to the trunk ducts by flexible ductwork. In the Belgian sample, three duct systems of this kind were encountered. The measurements revealed that the airtightness of such installations is generally worse than duct systems without plenums.

*Figure 51: Registers connected to ductwork by plenums.*

The contribution of the plenum on the total leakage was investigated in two systems of the Belgian sample. Two leakage measurements were performed: one with the plenums (by sealing the registers with tape) and without the plenums by disconnecting the flexible duct from the plenum and inflating a balloon at the end of the duct (see Figure 52).

*Figure 52: Measurement with disconnected plenum (in this case plenum for linear register)*

The results of both measurements are summarised in Table 19.

| Building | $ELA_{100}$ with plenums | $ELA_{100}$ without plenums | Leakage of plenums (% of total) |
|---|---|---|---|
| 16 | 24.8 cm² | 5.4 cm² | 78 % |
| 21 | 14.2 cm² | 4.8 cm² | 66 % |

*Table 19: Contribution of plenums in total duct leakage. Leak tests performed with and without plenums in Belgian buildings.*

It can be seen that, in both cases, most of the leaks are situated at the plenums. This could also be visualised using smoke. Leaks were encountered at the corners and the welds of the plenums. However, to evaluate the real contribution of the leaks at the plenums, the operating pressure in the plenums should be compared with the operating pressure in the trunk of the ductwork (see further).

### ➤Concrete ductwork

In Belgium, concrete ducts are regularly used for ventilation purposes, especially as exhaust ducts from “humid” rooms in apartments (shunt-type). In most of these cases ventilation is driven naturally, but sometimes a fan is connected to the ductwork on the top of the roof.
In the past, concrete ductwork seemed to have an unsatisfactory airtightness, mainly due to the fact that concrete ducts are constructed from small pre -fabricated concrete elements and, as a consequence, have many joints. The main advantage of small elements is the manageability, but to improve the airtightness there was a need for other installation techniques. It is clear that the leakage area can be decreased by reducing the number of joints or by assuring a better quality of the joints. A Belgian manufacturer of concrete du ct elements opted for the last approach by starting the production of storey-high elements. Each element consists of several small elements which are put together in the factory. As opposed to the small pre-fabricated elements, it cannot be placed manually on site: a crane is needed. However, the airtightness of the pre-fabricated joints is much improved. Laboratory leakage tests on these storey-high elements showed that the airtightness seemed to be between Class A and Class B.

However, the small number of joints that have to be made at the building site are likely to have a major impact on the final airtightness. Indeed, a smoke test, which was performed on one system, showed that joints made on site were very leaky (unlike the prefabricated ones, see Figure 53). Furthermore, field measurements on this system showed that the concrete ducts were about 4 times leakier compared to laboratory measurement data (Table 20).

| | Laboratory | Field measurement |
|---|---|---|
| $f_{40}$ (l/s.m² at 40 Pa) | 0.165 | 0.639 |
| $ELA_{40}$ (cm²) | 6.1 | 23.8 |
| Tightness Class (-) | Between A and B | Twice as leaky as Class A |

*Table 20: Comparison between laboratory test and field measurement for concrete ductwork. Test pressure for laboratory measurements was close to 40 Pa. A flow exponent of 0.65 is assumed to calculate $f_{40}$ and $ELA_{40}$.*

The presence of leaks at these joints may include:

- Use of inadequate material to make the joint on site;
- Bad instructions for the installers: e.g. elements placed too quickly on one another, yielding cracks in the joints during drying, etc.;
- Insufficient training of the installers, yielding bad application;
- Others.

*Figure 53: Smoke visualisation of leaks in a concrete ductwork.*

### ➤What should be taken as the reference pressure to evaluate duct leakage impacts?

The operating pressure in the ductwork plays a major role on the magnitude of duct leakage impact since it greatly affects the leakage flow rate (Figure 48). However, the determination of the operating pressure is not always trivial, because it depends strongly on where it is measured; it also requires a careful positioning of the probe in the air stream to avoid picking up some dynamic component. Therefore, one has to perform careful measurements at several places in the system, fairly close to the fan as well as at the end of the ductwork. If the pressure is relatively constant, the leakage airflow rate can be calculated using the average value.

When the pressure is not constant however, the determination of the leakage airflow rate becomes more complicated. As an example, in building 21 from the Belgian sample (Figure 40) in which the installation consists of circular sheet-metal ductwork with flexible ductwork for the shunts and plenums at the registers, a constant airflow regulator is included in the flexible duct. It is designed to ensure a constant airflow rate provided that the pressure drop across the device is kept within given limits. Typically, the operating pressure drop range for such device lies between 50 and 150 Pa. The actual measured pressure was:

- In the trunk duct: 160 Pa;
- In the plenums: ± 5 Pa.

As mentioned before, the airtightness of this installation was measured with and without the plenums and showed that most leaks were located at the plenums (Table 19). However, in this case, duct repairs at these locations will probably not improve the overall performance of the system as much as duct repairs in the rest of the system. Indeed, calculation of the “real” leakage airflow rates (at the operating pressures) shows that the plenums only have a limited impact i.e.:

- Leakage airflow main duct (at 160 Pa): 8 l/s (29 m³/h);
- Leakage airflow plenums (at 5 Pa): 1.9 l/s (7 m³/h) (approximately).

Thus, although 66 % of the total leakage area is located at the plenums, these leaks are responsible only for 20 % of the total leakage airflow! The total nominal airflow rate for the tested part of ductwork is 78 l/s (280 m³/h). This means that the leakage airflow of the main duct and the flexible connection represents about 10 % of the nominal airflow rate, while the leaks at the plenums only represent 2 % of the nominal airflow rate.

**➤Comparison of the airtightness obtained with different connection systems**

In a Belgian test house, a duct system was installed using different types of joints between the different elements. As the installer knew that airtightness measurements were planned, extra care was probably taken during the installation. Therefore the results are not included in the synthesis presented before. The ventilation installation consists of a mechanical supply in the "dry" rooms and a mechanical exhaust in the "humid" rooms. The unit consists of two fans and a heat exchanger. Three types of joints were used in the three different parts of ductwork:

- Fresh air intake: PVC-tape;
- Supply ductwork: rubber gasket;
- Exhaust ductwork: cold shrink tape.

An airtightness measurement was performed on each part. The results are represented in Table 21. It can be seen that the airtightness is rather good in all the cases. It is noteworthy that the airtightness is the best for PVC-tape sealed ducts. This can be explained by:

- The small tested area (only 2.5 m²), which makes it difficult to draw correct conclusions;
- The fact that the installer knew that tests were going to be performed, resulting in a better execution of the work.

About the same airtightness is achieved with cold shrink tape or pre-fitted rubber gaskets. It would be interesting to see how these results evolve in time. Also, it is important to note that for the interested parties, other aspects should be taken into account besides the airtightness performance alone, e.g.:

- Material cost;
- Labour cost;
- Life cycle cost.

Cost issues are discussed in chapter 7.

| | | Rubber gasket | Cold-shrink tape | PVC-tape |
|---|---|---|---|---|
| *A* | (m²) | 10.2 | 6.4 | 2.5 |
| Joints | (number) | 25 | 18 | 5 |
| *C* | (l/s.m² at 1 Pa) | 0.0046 | 0.0042 | 0.0014 |
| *n* | (-) | 0.62 | 0.65 | 0.65[10] |
| Class | (at 400 Pa) | Class B | Class B | Class C |
| $ELA_{100}$ | (cm²/m²) | 0.062 | 0.067 | 0.022 |
| $ELA_{100}$ | (cm²/joint) | 0.025 | 0.024 | 0.011 |

*Table 21: Comparison of the airtightness obtained with different types of joints.*

[10] This is an assumption; the leakage flow was measured at only one pressure station.

### 6.7.9 Conclusions from the SAVE-DUCT measurements

- Air distribution systems in Sweden seem remarkably tight compared to Belgian and French systems. This is probably due to the absence of performance requirements and control measurements in these countries. Since there is severe control in Sweden, most of the installations seem to comply with these stringent requirements at commissioning;
- Based on the Belgian measurements, it seems to be more difficult to obtain a good airtightness with rectangular ductwork. This does not seem to be the case in Sweden;
- The leakage factor normalised by the duct area is not sufficient to evaluate the air distribution impacts of leaky ducts. Among other important parameters are the operating pressure(s), the area of the ductwork and the ratio between the leakage airflow rate and the nominal airflow rate transported through the system;
- In Belgium and in France, the ratio between the average leakage airflow rate and the nominal airflow rate is of about 13 % at 50 Pa and 21 % at 100 Pa (both are pressures which are often found in European duct systems). There is room for improvement.

## *6.8 References*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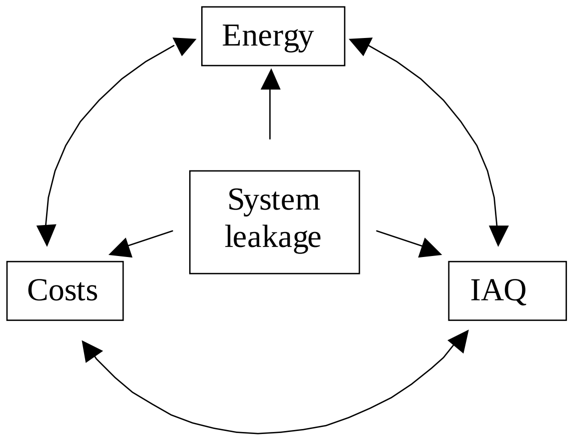
# Chapter 7 Air distribution system leakage versus energy, indoor air quality and costs

**Impact of duct leakage on ventilation rates**

**Peak load and energy use impacts**

**Indoor Air Quality**

**Costs**




***7.1 Summary and introduction***

In general, designers, installers, building managers and building owners, mostly ignore the benefits of airtight duct systems. Field measurements suggest that over the years this has probably lead to very leaky systems in most European countries (see chapter 6). In fact, leakage rates up to 30 times greater than those of EUROVENT 2/2 Class C systems are commonly encountered. However, several studies have shown that duct leaks can significantly affect the ventilation rates in a building, which in turn modifies the amount of energy used for heati ng or cooling. Furthermore, as the fan power demand is a function of the airflow rate passing through it, additional energy losses may occur due to inadequate sizing and leakage airflow compensation. Poor airtightness can also contribute to the entry of pollutants and insufficient "effective" ventilation rates.

In summary, duct leakage is detrimental to energy efficiency, comfort effectiveness and indoor air quality. This chapter gives an overview of the methods that can be used to quantify those impacts. Several practical examples are discussed. Simple analyses on a balanced ventilation system with heat recovery show that the overall effectiveness of the system is reduced drastically when the ducts are leaky. Also, the cost implications of tight air ducts are discussed on an investment and Life Cycle Cost basis.

### *7.2 Impact of duct leakage on ventilation rates: some examples from the literature*

Duct leakage can have a severe impact on the ventilation rates of a building, either directly when the desired airflow rates are not met at the registers, or indirectly, when the house pressure is affected (Figure 54).

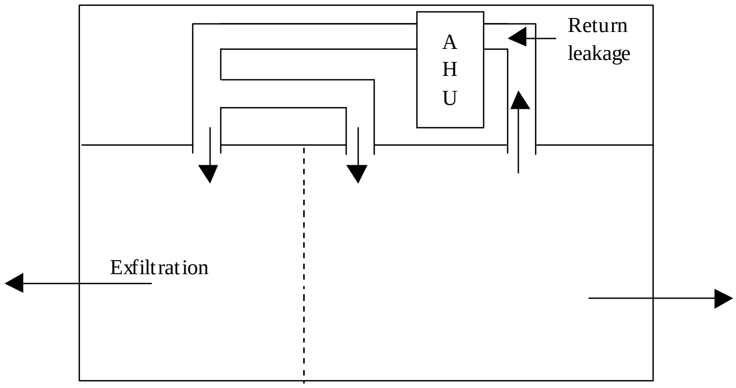



*Figure 54: Effect of return leakage on exfiltration. Inversely, leaks on the supply side tend to de-pressurise the building.*

In general, the infiltration rate can be estimated using the following equation (Sherman, 1980):

$$Q_{vent} = \sqrt{Q_{wind}^2 + Q_{stack}^2 + Q_{unbalanced}^2} + Q_{balanced} \quad \textit{Equation 6}$$

where:

$Q_{vent}$ is the total ventilation rate ($m^3/s$);
$Q_{wind}$ is the wind-induced ventilation rate ($m^3/s$);
$Q_{stack}$ is the stack-induced ventilation rate ($m^3/s$);
$Q_{balanced}$ is the balanced ventilation rate ($m^3/s$);
$Q_{unbalanced}$ is the unbalanced ventilation rate ($m^3/s$).

In the case described in Figure 54, this equation can be used to estimate the impact of leaky ducts. Then, $Q_{balanced}$ and $Q_{unbalanced}$ represent the balanced and unbalanced components of duct leakage, i.e.:

$$Q_{balanced} = \min\left(Q_{supply\ leakage}, Q_{return\ leakage}\right) \quad \textit{Equation 7}$$

$$Q_{unbalanced} = \max\left(Q_{supply\ leakage}, Q_{return\ leakage}\right) - Q_{balanced}$$

Using Equation 6 for one residential forced-air heating system investigated in the UK, Babawale *et al.* (1993) found a significant contribution of the duct system leakage to the house infiltration:

- 0.1 air changes per hour (ach) when the ductwork is isolated from the house;
- 0.2 ach with ducting when the circulation fan is off;
- 0.5 ach with ducting when the circulation fan is on.

It should be noted that, in this system design, balanced leakage does not provide fresh air to the rooms. Thus, the total ventilation rate may be increased while the amount of fresh air delivered to the rooms decreases. In Belgium, Ducarme *et al.* (1995) monitored a demand controlled ventilation system (DCV) installed in an office building in 1993. Because of duct leakage, they observed large deviations between the measured and expected performances of the system.

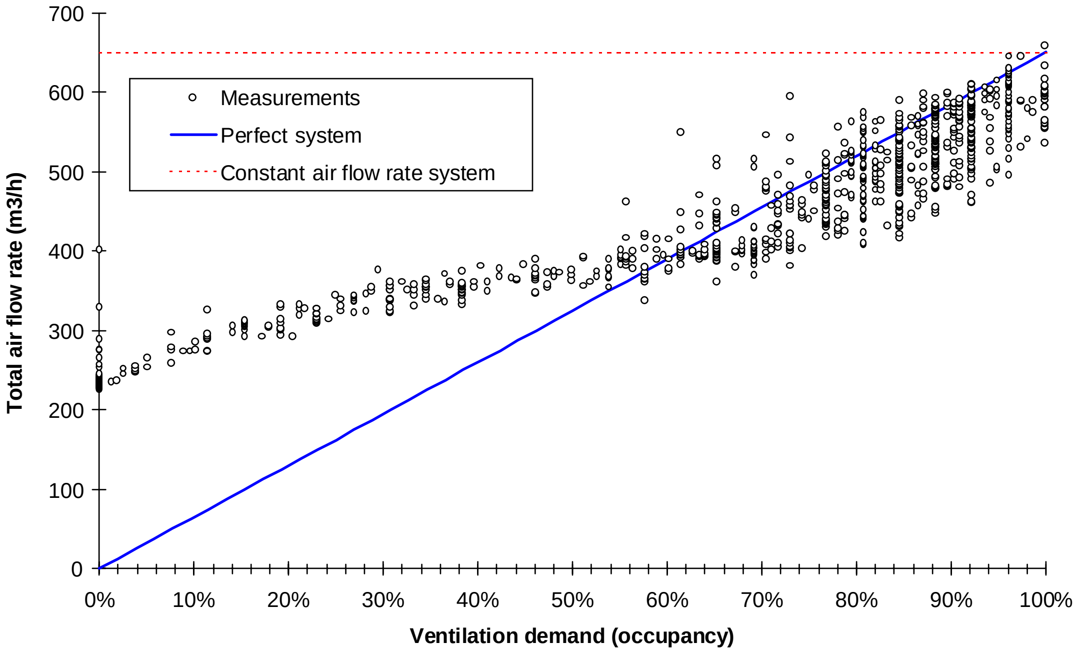



*Figure 55: Airflow rate supplied as a function of the ventilation demand in a Belgian office building with demand-controlled ventilation.*

As shown in Figure 55 the airflow rate is much higher than expected at low ventilation demands, which is due to a combination of incorrect pressure control (the system should keep the pressure between 70 Pa and 130 Pa,  but values up to 180 Pa are measured) and ductwork leakage. The total airflow rate becomes closer to the expected airflow rate as the ventilation demand increases, which is due to a decreased pressure in the ductwork.

In France, Carrié *et al.* (1996) found that the ratio between the leakage airflow rates measured in 9 multi-family buildings and the minimum airflow rates set by the French regulation was an average of 13 % (Figure 56). Although they have not performed detailed ventilation measurements, these numbers suggest that the total ventilation rates of the buildings are affected.

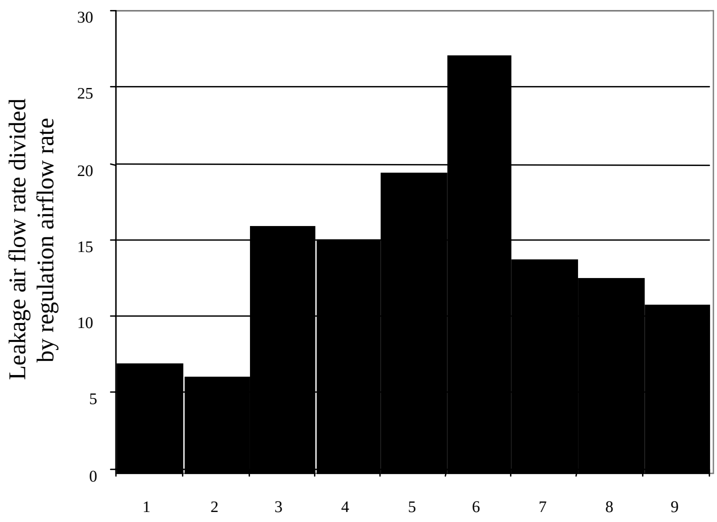



*Figure 56: Leakage airflow rate at 100 Pa divided by regulation airflow rate in 9 multi-family buildings.*

### *7.3 Peak load and energy use impacts*

The energy loss linked to duct leakage may be itemised as follows:

- Fan power demand;
- Ventilation losses.

Conduction losses are, in general, highly correlated with duct leakage losses because they have a direct impact on the system's operation. In an air heating system, for example, transmission losses may imply a larger fractional on-time to maintain the desired temperature, thus resulting in increased fan energy use with potentially more ventilation losses. Equations are given hereafter to evaluate all of those losses assuming quasi-steady state conditions.

#### 7.3.1 Fan power demand

Typically, the fan power demand lies between 1 W to 3 W to provide each l/s of air to a space. A commonly used fan law is that the power increases with the third power of the airflow rate.

$$P_{fan} \sim Q_{fan}^3$$ *Equation 8*

This law is true only when the flow conditions stay similar as the fan speed changes. In particular, caution should be exercised when regulating devices are used.

The fan power demand can be calculated as follows:

$$\mathrm{P}_{fan} = \frac{Q_{fan}\,\Delta p_t}{\eta}$$ *Equation 9*

where:

$\mathrm{P}_{fan}$ is the fan power demand (W);
$Q_{fan}$ is the airflow created by the fan ($m^3/s$);
$\Delta p_t$ is the total pressure difference across the fan (Pa);
$\eta$ is the global fan efficiency (-).

### 7.3.2 Ventilation losses

The energy loss associated with ventilation is due to the difference in enthalpy of the incoming and outgoing air streams. Thus, it will depend on where these streams come from.

The specific enthalpy of air is:

$$h = \underbrace{c_{pa}\,\theta + x\,c_{pw}\,\theta}_{\text{sensible heat}} + \underbrace{x\,L_0}_{\text{latent heat}} \qquad \textit{Equation 10}$$

where:

- $h$ is the specific enthalpy (J/kg);
- $c_{pa}$ is the specific heat capacity of dry air (J/kg K);
- $c_{pw}$ is the specific heat capacity of water vapour (J/kg K);
- $x$ is the water content of air (kg of water / kg of dry air);
- $\theta$ is the air temperature (°C);
- $L_0$ is the latent heat of vaporisation of water at 0°C (J/ kg of water).

For a circulation system, we obtain:

$$\begin{aligned} P_{vent} &= \rho Q_{vent}(h_{in} - h_{out}) + \underbrace{\rho Q_{leak,s}(h_s - h_{in})}_{\text{return air lost in supply}} - \underbrace{\rho Q_{fan}(h_r - h_{out})}_{\text{return air}} \\ &= \rho Q_{vent}(h_{in} - h_{out}) + \underbrace{\rho Q_{leak,s}(h_s - h_{in})}_{\text{return air lost in supply}} - \underbrace{\rho Q_{-}(h_{in} - h_{out}) - \rho Q_{leak,r}(h_{rz} - h_{out})}_{\text{return air}} \end{aligned} \qquad \textit{Equation 11}$$

where:

- $P_{vent}$ is the load due to ventilation (W);
- $Q_{fan}$ is the fan flow rate ($m^3/s$);
- $Q_{leak,s}$ is the supply duct leakage flow rate ($m^3/s$);
- $Q_{leak,r}$ is the return duct leakage flow rate ($m^3/s$);

$h_r$, $h_s$ and $h_{rz}$ represent the specific enthalpy of the air respectively in the return ducts (at the air handling plant), in the supply ducts, and in the zone where the return ducts are located.
The case of a balanced ventilation system with heat recovery is discussed below.

### 7.3.3 Conduction losses

When make-up air is transported in the ductwork, it has been shown that conduction losses can be substantial especially when the ducts pass through unconditioned spaces.
Interactions between transmission and duct leakage energy losses can be significant. These effects can be estimated through computer simulations.

Steady-state conduction losses can be calculated with the following equation:

$$P_{cl} = U\,A\,\Delta T_m \qquad \textit{Equation 12}$$

where:

- $P_{cl}$ is the conduction loss (W);
- $U$ is the estimated U-value of the ductwork ($W/m^2.K$);
- $A$ is the duct surface area ($m^2$);
- $\Delta T_m$ is the logarithmic mean temperature difference (K), i.e.: $\dfrac{\Delta T_{beg} - \Delta T_{end}}{\ln\left(\dfrac{\Delta T_{beg}}{\Delta T_{end}}\right)}$.

### 7.3.4 Simplified calculations

To evaluate these losses under quasi steady-state conditions at a given time *t*, the previous equations may be used.

**➤Example 1: Multi-family building with exhaust ventilation system - Fan power demand**

Using Equation 8, it is possible to estimate the fan power demand implications of duct leakage. The results presented in Table 22 and Figure 57 assume:

- A total airflow rate of about 209 l/s (750 $m^3$/h) delivered to 5 apartments;
- A mean fan power of 63 W per apartment (1.5 W per l/s) for a leakage coefficient $K = 0.12$ l $s^{-1}$ $m^{-2}$ $Pa^{-0.65}$ (about 5 times worse than Class A);
- A (leakage) flow exponent of 0.65;
- An operating pressure of 100 Pa;
- A duct surface area of 15 $m^2$.

In this example it appears that it is beneficial to go to Class B on an electric energy use basis. Going to Class C or D does not change significantly the results in this case as the ratio of leakage flow rate to the nominal airflow rate stays within reasonable limits.

Ventilation losses are discussed in the following example.

| | | | | EUROVENT 2/2 | | | |
|---|---|---|---|---|---|---|---|
| | | | | Class A | Class B | Class C | Class D |
| $K$ (l $s^{-1}$ $m^{-2}$ $Pa^{-0.65}$) | 0.12 | 0.1 | 0.05 | 0.027 | 0.009 | 0.003 | 0.001 |
| Total flow rate (l/s) | 244 | 238 | 223 | 216 | 211 | 209 | 209 |
| Fan power per apartment (W) | 63 | 58 | 48 | 43 | 40 | 39 | 39 |

*Table 22: Fan power demand per apartment versus leakage coefficient.*

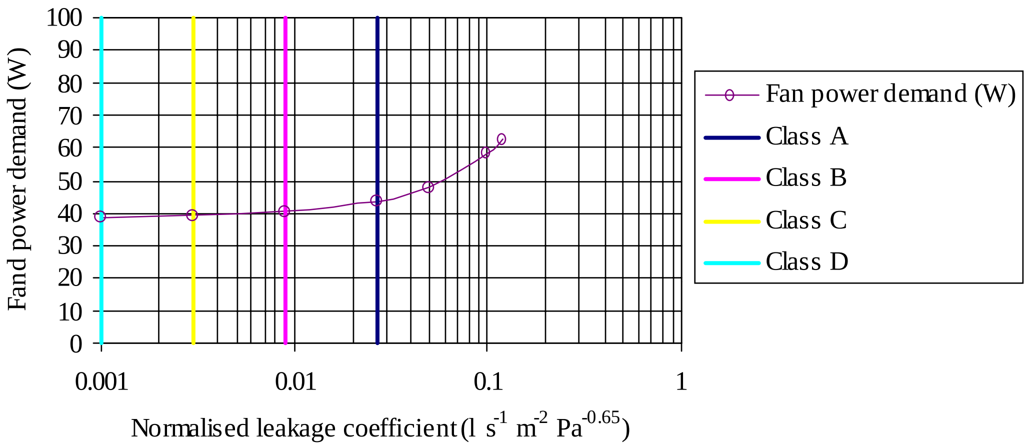



*Figure 57: Fan power demand per apartment versus leakage coefficient.*

### ➤Example 2: Office building with balanced ventilation system with heat recovery unit (HRU)

Assume the building described in Figure 58. In the analysis that follows, conduction losses are neglected.

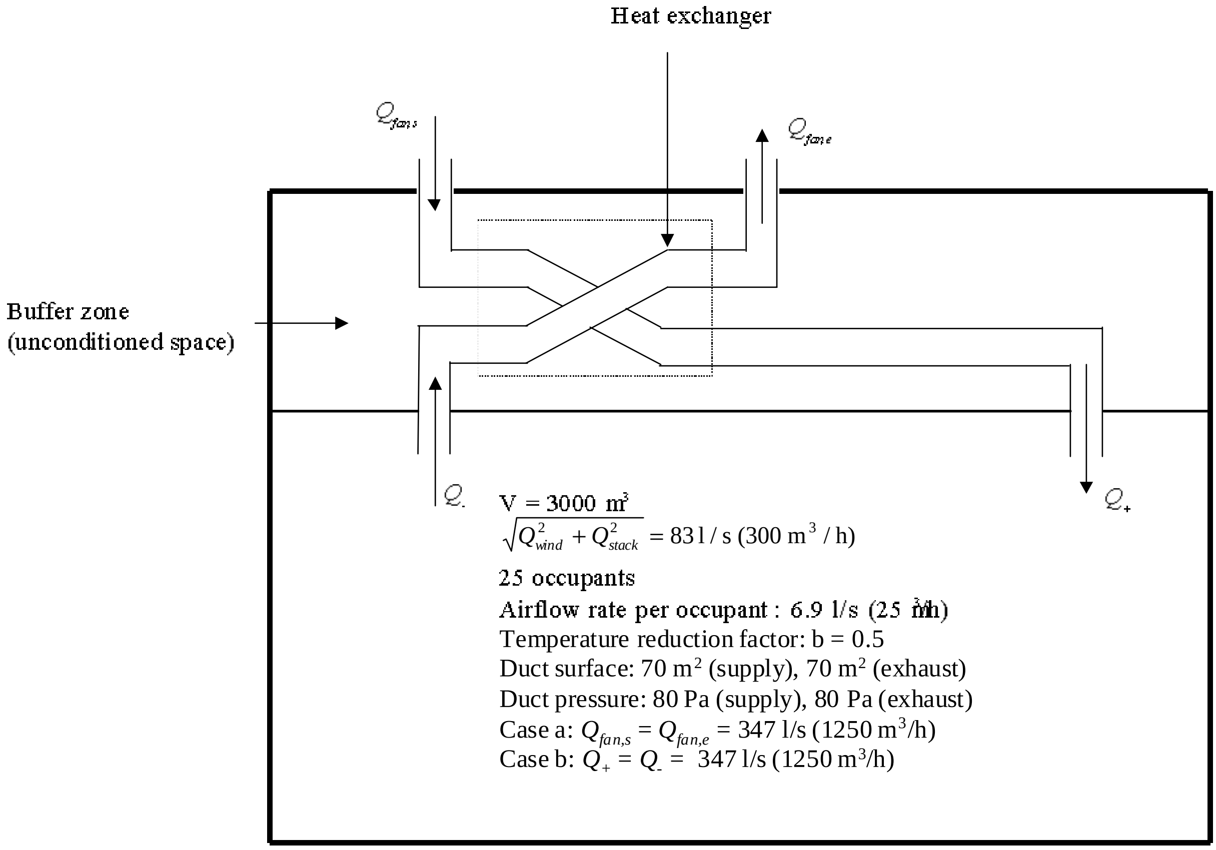



*Figure 58: Schematic diagram of an office building equipped with a heat recovery system.*

It can be seen in Figure 59, Figure 60, and Figure 61 that the effective heat recovery is severely affected by duct leakage. The ventilation rate and load as well as the fan power demand are normalised with respect the results of Class D. It can be seen that going to Class C or D does not change significantly the results as the leakage airflow rate becomes negligible compared to the nominal airflow rate as soon as Class B is achieved. It should be noted that if this ratio is made larger (e.g. by increasing the duct area), Class C or even Class D may be considered (Figure 62).

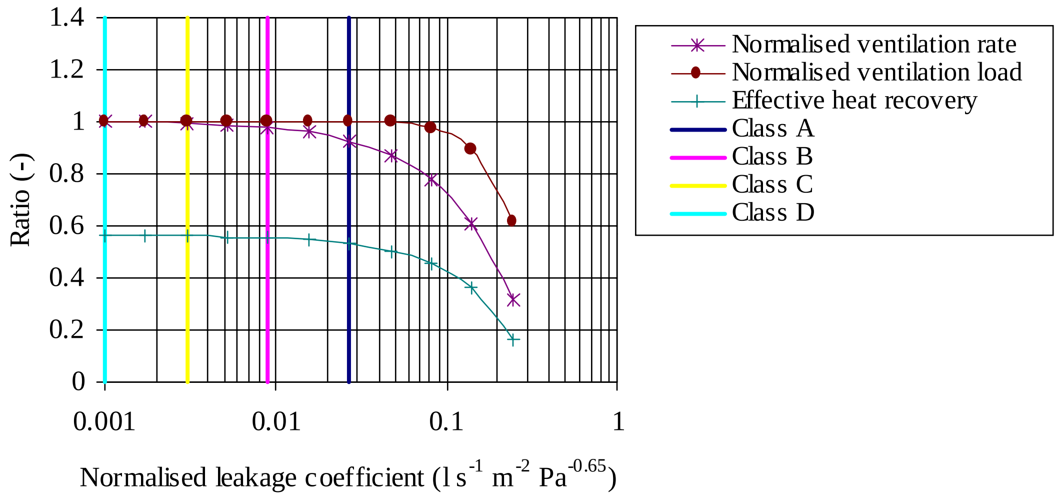



*Figure 59: Ventilation rate and load impacts of duct leakage. The calculations are performed for the system described in Figure 58 - case a.*

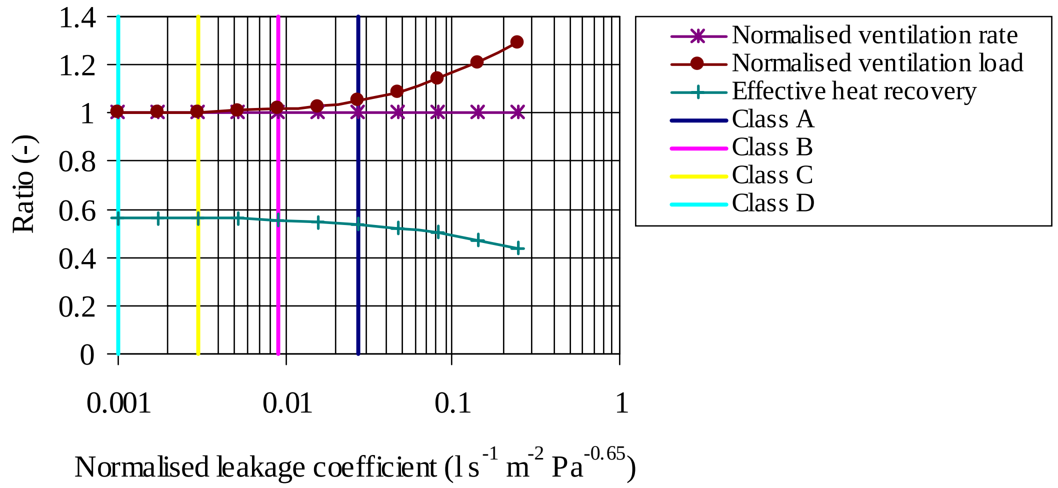



*Figure 60: Ventilation rate and load impacts of duct leakage. The calculations are performed for the system described in Figure 58 - case b.*

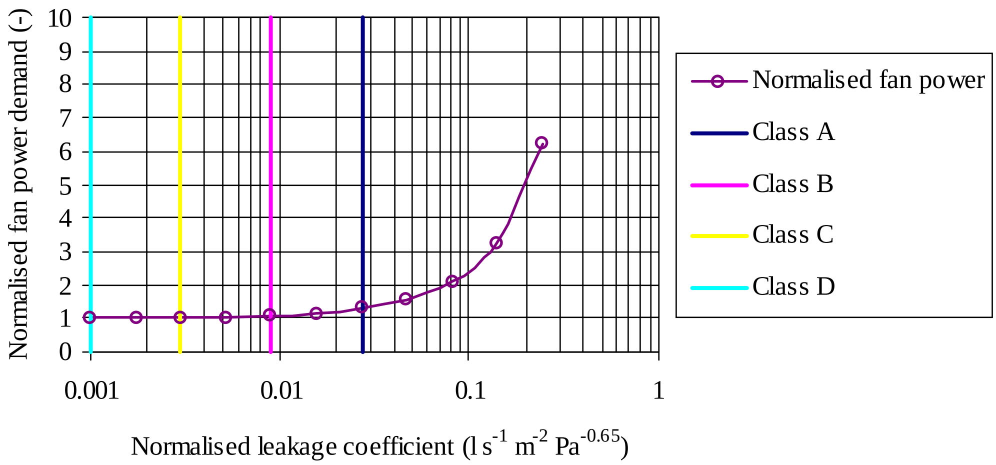



*Figure 61: Fan power demand as a function of duct leakage. The calculations are performed for the system described in Figure 58- case b.*

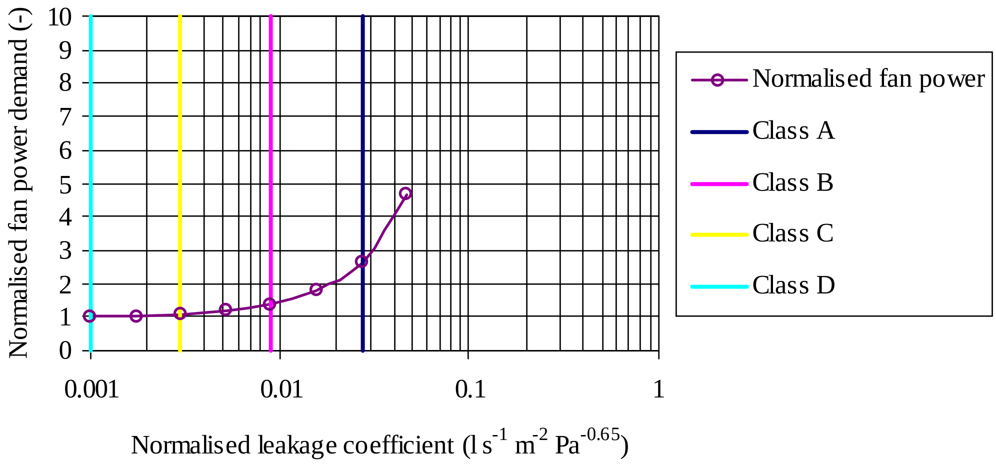



*Figure 62: Fan power demand as a function of duct leakage. The calculations are performed for the system described in Figure 58- case b. The duct area is changed to 300 $m^2$.*

The load due to ventilation can be computed by using the following equation:

$$\mathrm{P}_{vent} = \rho\, Q_{vent}\,(h_{in} - h_{out}) + \underbrace{\rho\, Q_{leak,s}\,(h_s - h_{out})}_{\text{outdoor air lost in supply}} - \underbrace{\eta_v\, \rho\, Q_{fan,e}\,(h_e - h_{out})}_{\text{heat recovery}}$$ *Equation 13*

where:

$Q_{fan,e}$ is the extract fan airflow rate ($m^3/s$);
$h_e$ is the specific enthalpy of the extract air before entering the HRU (J / kg);
$\eta_v$ is the efficiency of the HRU (-).

If we neglect the effect of the water vapour, this equation becomes:

$$\mathrm{P}_{vent} = \rho c_{pa}\left(Q_{vent} - \frac{Q_+}{Q_{fan,s}}\eta_v\left(b\,Q_{leak,e} + Q_-\right)\right)\Delta T$$ *Equation 14*

where:

b is the reduction factor in the unconditioned buffer zone (-) $\left(b = \frac{T_{buf} - T_{out}}{T_{in} - T_{out}}\right)$;
$Q_{fan,s}$ is the supply fan airflow rate ($m^3/s$);
$\Delta T$ is the temperature difference between inside and outside (K).

The effective heat recovery of the system is:

$$\eta_{v,eff} = 1 - \frac{\left(Q_{vent} - \frac{Q_+}{Q_{fan,s}}\eta_v\left(bQ_{leak,e} + Q_-\right)\right)}{Q_{vent}}$$ *Equation 15*

### ➤Detailed analyses through computer simulations

More detailed analyses can be performed using computer tools (Modera, 1993; Babawale *et al.*, 1993; Parker *et al*, 1993). The key advantage is to be able to take into account the interactions between energy loss mechanisms.

## *7.4 Indoor air quality*

Added infiltration due to duct leakage is uncontrolled and does not mean that additional fresh air is delivered to the occupied rooms. Thus, it may be detrimental to comfort and indoor air quality. Also, if the fan is not properly sized to counteract the leaks, the building may be insufficiently ventilated. This means that the desired airflow rates will not be obtained at the registers, which can have a severe impact on the indoor climate.

Figure 63 displays the effect of duct leaks on the steady-state concentration of $CO_2$. It can be seen that in the extreme case the concentration of the pollutant is increased by about 30 %.

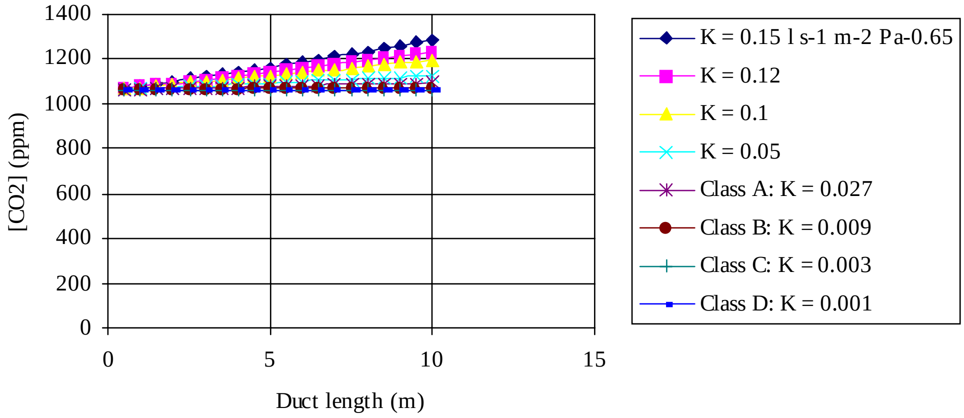



*Figure 63: Room steady-state concentration of $CO_2$ versus duct length for various leakage coefficients. For these calculations, the initial airflow rate is 56 l/s (200 $m^3$/h) through a 0.16 m diameter duct. The initial pressure is equal to 100 Pa and the pressure drop is of 0.7 Pa/m. Source strength of $CO_2$ is based on 8 persons (i.e. about $7.1*10^{-5}$ kg/s).*

### *7.5 Costs*

The cost of an air distribution system can be divided into 3 major components:

- Capital or initial costs;
- Operating costs;
- Replacement costs.

The last item goes beyond the scope of this handbook.

#### 7.5.1 Initial costs

In general, many parameters have to be considered when comparing costs between two options For example, for two installations with round and rectangular ducts respectively, special attention should be paid to the following items:

- Material cost for round ductwork, factory price;
- Material cost for rectangular ductwork, factory price;
- Transport cost factor, factory to site. Cost difference round vs. rectangular ductwork due to larger transport volume for rectangular ducts than round (normal volume ratio 3:1);
- Packing cost factor for transport factory to site. Cost difference round vs. rectangular ductwork due to larger transport volume for rectangular ducts than round (normal volume ratio 3:1), and rectangular ducts (flanges) being more sensitive to transport damages;
- Waste cost factor due to alterations, adjustment and wrongly measured duct lengths. Cost difference round vs. rectangular ductwork due to the fact that the rectangular ducts have to be made exactly to measure while the round ducts can be adjusted on site to correct length. Wasted rectangular ducts can normally not be used at other locations due to the tailor made dimensions while round ducts and components normally can be re-used;
- Normal installation time for round ductwork installation as calculated. The time includes moving of necessary scaffolding etc.;
- Normal installation time for rectangular ductwork installation as calculated. The time includes moving of necessary scaffolding etc.;

- Basic wage cost (net wage) per hour;
- Social cost factor based on net wage;
- Cost factor for tools, machines, huts, scaffolding, etc., based on net wage;
- Costs factor for insurance, fees, site cleaning, etc., based on net wage;
- Cost factor for site organisation, administration, profit, based on net wage;
- Inspection and supervision time factor based on installation time. Time factor difference round vs. rectangular ductwork due to the fact that the rectangular ducts have to be made exactly to measure while the round ducts can be adjusted on site to correct length. The rectangular duct installation thus needs more supervision than the round one. Rectangular ducts are normally more difficult to inspect due to less free space around ducts, e.g. when mounted tight to the ceiling in narrow corridors;
- Testing (airflow measurements and adjustments, duct tightness testing) time factor based on installation time. Time factor difference round vs. rectangular ductwork due to the fact that the rectangular ducts are less dimension standardised and normally more difficult to test due to less free space around ducts, e.g. when mounted tight to the ceiling in narrow corridors;
- Waiting time factor based on installation time. Part of the installation time is non-productive and used in waiting for missing parts, etc.;
- Building cost time factor based on ductwork installation time. This factor includes higher building site costs due to the fact that round ducts are more close -fitting to holes in walls and need less tightening after the installation of the duct (the tightening is especially needed when ducts pass through fire-classed walls but normally also in ordinary walls to reduce noise transmission). This factor also includes higher building site costs due to the fact that rectangular ducts often need more tight time schedule coupled to other building works (e.g. corridor walls can not be installed before the rectangular ducts' top flanges have been mounted) and to the testing and commissioning of the ductwork installation.

All these expenditures vary from one country to another, even from one city to another and especially from one time to another. Therefore, the only accurate method to compare initial costs is to ask for prices for the building in question.

In Table 23, we have itemised the cost of a balanced ventilation system wit h heat recovery in a small office building in France. In the base case, it is assumed to be sealed on site. Then, it is possible to perform sensitivity analyses to evaluate the cost implications of different options. For this, weight factors were applied separately to the labour and the ductwork components (ducts and accessories). Assuming that using accessories with pre-fitted sealing devices implies an additional cost of 20 % to 30 %, and that the labour cost can be reduced by 25 % (which is claimed by some manufacturers), Table 23 shows that the capital cost remains equivalent to the base case.

| | Base case | | | |
|---|---|---|---|---|
| **Additional cost for ducts and components (in %)** | 0 % | +20 % | +30 % | 0 % |
| **Additional cost for labour (in %)** | 0 % | -25 % | -25 % | +10 % |
| **Airflow rate ($m^3/h$)** | 300 / 240 | 300 / 240 | 300 / 240 | 300 / 240 |
| **Surface of ventilation system ($m^2$)** | 50 | 50 | 50 | 50 |
| Air handling unit (EURO) | 2582 | 2582 | 2582 | 2582 |
| Ducts accessories (EURO) | 593 | 712 | 771 | 593 |
| Registers (EURO) | 642 | 770 | 834 | 642 |
| Margin (EURO) | 763 | 813 | 837 | 763 |
| Labour (EURO) | 1432 | 1074 | 1074 | 1575 |
| Insulation (EURO) | 162 | 162 | 162 | 162 |
| Total ADS (EURO) | 6174 | 6112 | 6261 | 6317 |
| **Normalised cost of ADS (EURO/$m^2$)** | 123 | 122 | 125 | 126 |
| **Cost percentage for ducts and accessories (%)** | 9.6 % | 11.6 % | 12.3 % | 9.4 % |
| **Normalised cost of ducts and accessories (EURO/$m^2$)** | 12 | 14 | 15 | 12 |
| **Normalised cost of registers (EURO/$m^2$)** | 13 | 15 | 17 | 13 |
| **Relative cost (compared to base case) (in %)** | 0.0 % | -1.0 % | +1.4 % | +2.3 % |
| **Additional cost (EURO)** | 0 | -62 | 87 | 143 |
| **Normalised additional cost (EURO/m2)** | 0 | -1 | 2 | 3 |

*Table 23: Capital cost comparisons on a balanced ventilation system with heat recovery (real case).*

### 7.5.2 Operating costs

These options should not be compared on an initial cost basis alone. For example, the ductwork airtightness should be considered if it has an impact on energy use, thus on operating costs. Life Cycle Costing is a useful tool for such comparisons as it brings the different cost components together. In such studies, it is common to express a stream of expenditure over a number of years in terms of its Net Present Value (i.e. it is brought back to its value in year 0). Calculations were carried out in the case described in Figure 58. The cost performance of a leaky and a tight system (Class D) are compared in figure 64. The results are based the following figures:

| | |
|---|---|
| Normalised cost of the system: | 120 EURO/m$^2$ |
| Cost for heating energy: | 0.03 EURO/kWh |
| Cost for electric (fan) energy: | 0.105 EURO/kWh |
| Additional initial cost of tight system: | 10 % |
| Fractional on-time: | 0.75 |
| Discount rate: | 5 % |
| Interest rate for energy: | 1 % |

*Table 24 Input parameters for life-cycle cost calculations.*

Figure 64 clearly shows the key role of the ductwork airtightness.

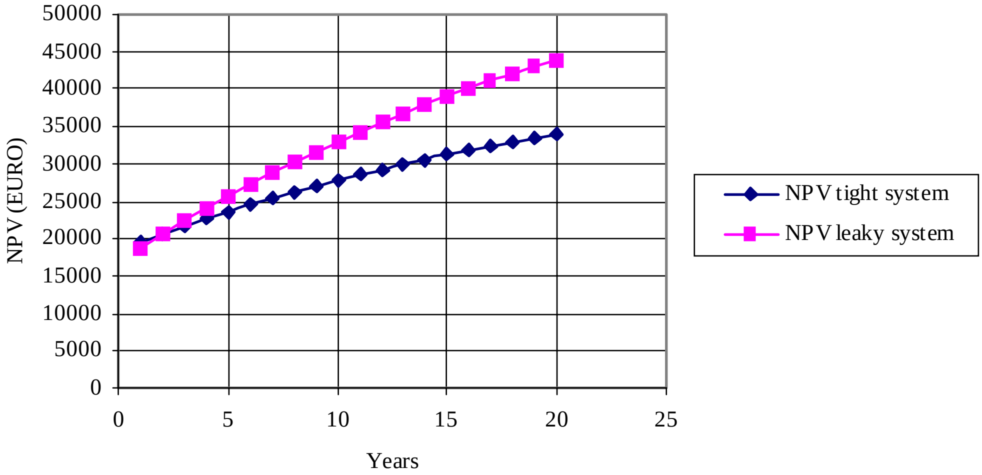



*Figure 64: Comparisons of Net Present Values of a leaky and an airtight duct system. Calculations are based on the system described in Figure 58 and Table 24.*

$$NPV = CC + OC \times \sum_{k=1}^{n} \left( \frac{1+j}{1+i} \right)^{k} + RC \times \sum_{p} \left( \frac{1+j}{1+i} \right)^{n_p}$$

*Equation 16*

where:
*NPV* is the Net Present Value (currency);
*CC* is the capital cost (currency);
*OC* is the operating cost (currency);
*RC* is the replacement cost (currency);
*i* is the discount rate (-);
*j* is the interest rate (-);
*n* is the number of years over which the analysis is performed (-);
and each $n_p$ is a year during which a replacement cost is foreseen.

## *7.6 Nomenclature for chapter 7*

| | |
|---|---|
| $A$ | duct surface area ($m^2$) |
| b | reduction factor in the unconditioned buffer zone (-) $\left(b = \frac{T_{buf} - T_{out}}{T_{in} - T_{out}}\right)$ |
| $c_{pa}$ | specific heat capacity of dry air (J/ kg K) |
| $c_{pw}$ | specific heat capacity of water vapour (J/ kg K) |
| $h$ | specific enthalpy (J / kg) |
| $h_{in}$ | specific enthalpy of the inside air (J / kg) |
| $h_e$ | specific enthalpy of the extract air (J / kg) |
| $h_r$ | specific enthalpy of the air in the return ducts (J / kg) |
| $h_{rz}$ | specific enthalpy of the air in the zone where the return ducts are located (J / kg) |
| $h_{out}$ | specific enthalpy of the outside air (J / kg) |
| $h_s$ | specific enthalpy of the air in the supply ducts (J / kg) |
| $L_0$ | latent heat of vaporisation of water at 0°C (J / kg of water) |
| $P_{cl}$ | conduction loss (W) |
| $P_{fan}$ | fan power demand (W) |
| $P_{vent}$ | ventilation load (W) |
| $Q_+$ | sum of the airflow rates at the supply registers ($m^3$/s) |
| $Q_{balanced}$ | balanced ventilation rate ($m^3$/s) |
| $Q_{fan}$ | fan flow rate ($m^3$/s) |
| $Q_{fan,e}$ | extract fan airflow rate ($m^3$/s) |
| $Q_{leak,r}$ | return duct leakage flow rate ($m^3$/s) |
| $Q_{leak,s}$ | supply duct leakage flow rate ($m^3$/s) |
| $Q_{stack}$ | stack-induced ventilation rate ($m^3$/s) |
| $Q_{unbalanced}$ | unbalanced ventilation rate ($m^3$/s) |
| $Q_{vent}$ | total ventilation rate ($m^3$/s) |
| $Q_{wind}$ | wind-induced ventilation rate ($m^3$/s) |
| $Q$- | sum of the airflow rates at the exhaust registers ($m^3$/s) |
| $T_{buf}$ | temperature of unconditioned (buffer) zone (K) |
| $T_{in}$ | inside temperature (K) |
| $T_{out}$ | outside temperature (K) |
| $U$ | estimated U-value of the ductwork ($W/m^2K$) |
| $x$ | water content of air (kg of water / kg of dry air) |
| $\Delta p_t$ | total pressure drop across the fan (Pa) |
| $\Delta T$ | temperature difference between inside and outside (K) |
| $\Delta T_m$ | logarithmic mean temperature difference (K) i.e.: $\frac{\Delta T_{beg} - \Delta T_{end}}{\ln\left(\frac{\Delta T_{beg}}{\Delta T_{end}}\right)}$ |
| $\eta$ | global fan efficiency (-) |
| $\eta_v$ | efficiency of the HRU (-) |
| $\eta_{v,eff}$ | effective heat recovery of the system (-) |
| $\rho$ | density of air ($kg/m^3$) |
| $\theta$ | air temperature (°C) |

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# Chapter 8 Potential energy impacts of a tight air duct policy at the European level

**Potential savings in Belgium**

**Potential savings in Europe (exc. FSU)**

**Assumptions about market penetration**

### *8.1 Introduction*

This chapter aims at making very approximate estimates of the order of magnitude of the energy wastage and supplementary peak power demand due to the duct leakage at the European level (excluding the Former Soviet Union - FSU). First calculations are made for Belgium and afterwards these are extrapolated to the whole of Europe (excluding the FSU). The savings potential of an airtight duct policy is calculated a) assuming that all buildings are equipped with mechanical ventilation systems; b) based on estimates of the number of buildings equipped with mechanical ventilation systems; c) assuming market penetration scenarios of rehabilitation techniques.

### *8.2 General assumptions*

1. The air leaving the ductwork through leaks (in false ceilings, technical rooms, attics etc.) does not contribute to the indoor air quality. Therefore, air leakage from ductwork results in higher airflow rates through the air handling unit and through outdoor air intakes. This implies a higher fan power and more energy for air treatment;
2. A specific fan energy of 1.5 W per l/s is assumed;
3. The leakage airflow rate is set to 15 % of the nominal airflow rate (this can be roughly concluded from field measurements in Belgium and in France, see chapter 6);
4. The figures assumed for number of employees, total energy consumption, number of degree days, etc. (see below) are only orders of magnitude;
5. There is no heat recovery from exhaust air.

### *8.3 Potential savings in Belgium*

#### 8.3.1 Offices

The following assumptions are made:

- 1 million office workers (total population of 10 million);
- Required airflow rate: 7 l/s per person;
- Total energy consumption for heating for all office buildings together: 5 TWh/year (18 PJ/year), from:
  - 200 kWh/m² *(BRE, 1991);*
  - Available surface per worker: 25 m²;
- 1400 degree days during working hours;
- year-round efficiency of heating system: 70 %;
- available electrical power (peak-value) in Belgium: 15 GW.

This gives the following results for mechanical ventilation in all buildings:

⇨ Nominal airflow rate for all office workers: 7 million l/s;
⇨ Total air leakage rate: 1.05 million l/s;
⇨ Heating energy consumption due to leaks: 60.5 GWh/year (0.22 PJ/year);
⇨ Share of leaks in total heating energy: 1.2 %;
⇨ Required additional fan power: 1.57 MW;
⇨ The additional fan power corresponds to about 0.01 % of the available electrical power.

Assuming that 25 % of the workplaces in Belgian office buildings are mechanically ventilated, this becomes:

⇨ **Heating energy consumption due to leaks: 15 GWh/year (0.054 PJ/year);**
⇨ **Share of leaks in total heating energy: 0.30 %;**
⇨ **Required additional fan power: 0.4 MW;**
⇨ **The additional fan power corresponds to about 0.003 % of the available electrical power.**

#### 8.3.2 Dwellings

The following assumptions are made:

- Nominal airflow rate (supply) per dwelling is about 80 l/s *(BBRI, 1998);*
- Year-round efficiency of the heating system is about 70 %;
- 2000 degree days;
- Total energy consumption for heating for all Belgian dwellings together: 90 TWh/year (324 PJ/year) , from:
  - typical average heating energy consumption for a Belgian dwelling: 30 000 kWh/year *(BBRI, 1998) (figure typical for new single-family dwelling)*;
  - about 3 million dwellings.

This gives the following results in the case where all buildings are assumed to be mechanically ventilated:

- ⇨ Total nominal airflow rate: 240 million l/s;
- ⇨ Total air leakage rate: 36 million l/s (this is probably an overestimation: the duct surface in dwellings is normally a lot smaller than the duct surface in office buildings);
- ⇨ Heating energy consumption due to leaks: 3.0 TWh/year (10.8 PJ/year);
- ⇨ Share of leaks in total heating energy: 3.3 %;
- ⇨ Required additional fan power: 54 MW;
- ⇨ The additional fan power corresponds with about 0.36 % of the available electrical power

The number of dwellings with a permanent mechanical ventila tion (supply or exhaust or both) is very limited in Belgium. Assuming that 5 % of the Belgian dwellings are equipped with permanently working mechanical ventilation devices, this brings us to:

- ⇨ **Heating energy consumption due to leaks: 150 GWh/year (0.54 PJ/year);**
- ⇨ **Share of leaks in total heating energy: 0.16 %;**
- ⇨ **Required additional fan power: 2.7 MW;**
- ⇨ **The additional fan power corresponds with about 0.02 % of the available electrical power.**

### *8.4 Potential savings in Europe (exc. FSU)*

The previous results are extrapolated to the rest of Europe. However, the reader should keep in mind that the Belgian estimates apply to the Belgian climate, and the number of dwellings situated in the Mediterranean area is bigger than the number of Scandinavian dwellings. Moreover, the leakage flow rate is probably much smaller in Scandinavian countries (see chapter 6). Therefore, caution should be exercised when interpreting the savings estimates calculated below.

The following assumptions are made:

- 50 million office workers;
- 150 million dwellings (University of Oxford, 1998);
- the loss of cooling energy due to leaky ductwork is not taken into account.

These assumptions give the following results, assuming that all buildings are mechanically ventilated:

- ⇨ Heating energy consumption due to leaks in offices: 3 TWh/year (10.8 PJ/year);
- ⇨ Heating energy consumption due to leaks in dwellings: 150 TWh/year (540 PJ/year).

Making the same assumptions for the occurrence of mechanical ventilation as for the Belgian situation (i.e. 5%), this brings us to:

- ⇨ **Heating energy consumption due to leaks in offices: 0.75 TWh/year (2.7 PJ/year);**
- ⇨ **Heating energy consumption due to leaks in dwellings: 7.5 TWh/year (27 PJ/year).**

### *8.5 Assumptions on the market penetration*

In the previous calculations the energy savings were estimated assuming that all new and existing ductwork systems were airtight. This market transformation can occur only step by step, especially for existing buildings. In order to give an idea of the potential savings in the short term, new calculations were performed for dwellings.

The assumptions were the following:

- The total number of existing dwellings at the European level is about 150 million;
- The heating loss by leaks in ductwork is 1000 kWh/year (from the previous calculations);
- The number of newly constructed dwellings is 1.7% of the existing dwellings (according to the Belgian situation) (BBRI, 1998);
- 5% of the dwellings are equipped with a permanently operating mechanical ventilation system;
- Airtight ducts are placed in all new and rehabilitated dwellings.

With these assumptions, the energy savings of tight air ducts were calculated for different rehabilitation scenarios (market penetration: 0.0%, 0.1%, 0.5%, 1.0% and 2.0%). The results are presented in Figure 65.

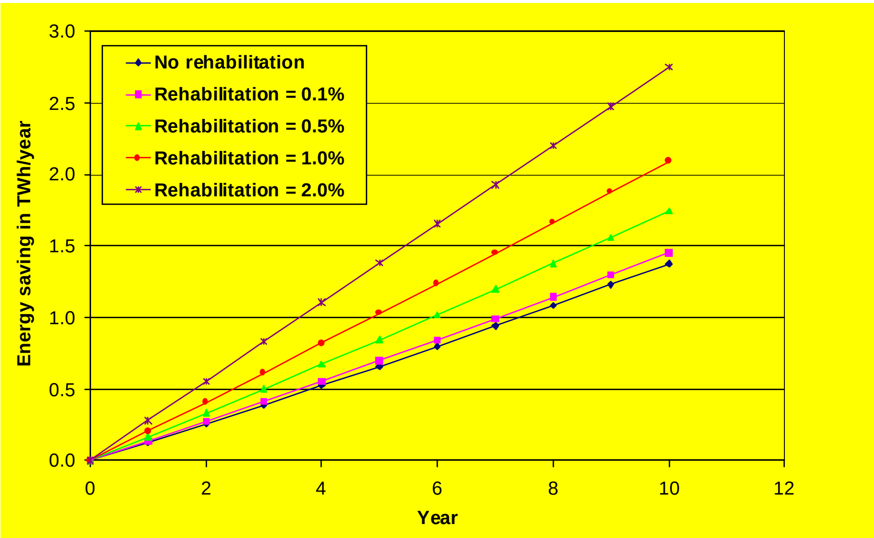


*Figure 65: Energy savings per year due to the installation of airtight ductwork in new and rehabilitated dwellings.*

In Figure 66 the cumulative energy savings over the first 10 years are represented for the same conditions.

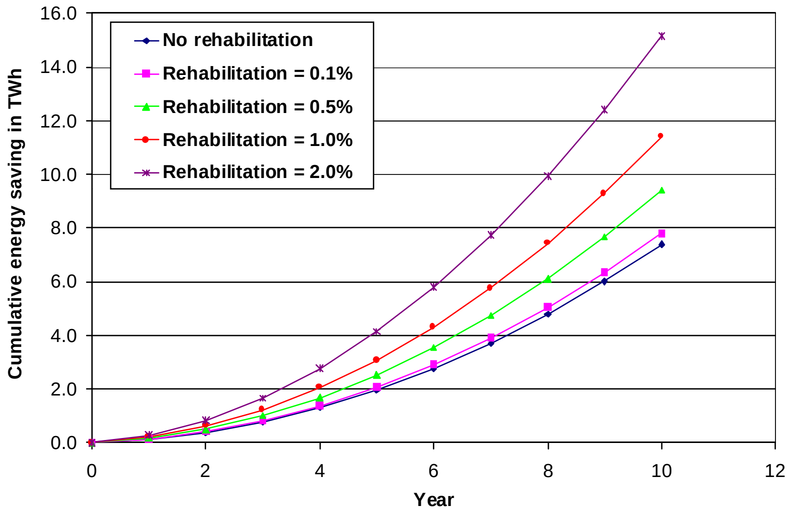


*Figure 66: Cumulative energy savings due to the installation of airtight ductwork in new and rehabilitated dwellings.*

### *8.6 Key conclusions and remarks*

- These results are very approximate estimates, based on simple calculations, but they demonstrate clearly that significant energy savings can be achieved by installing airtight ductwork. **The order of magnitude of the energy savings that can be achieved by using airtight ductwork in Europe is probably in the region of 1 to 10 TWh/year (3.6 to 36 PJ/year).** This is between 0.007 % and 0.07 % of the total European energy consumption per year (about 14000 TWh (50400 PJ) - figure from 1992 (EC DGXVII, 1994));
- It is important to mention that these savings cannot be obtained at once. It is very much dependent upon the market penetration scenario of rehabilitation techniques. Probably, the cumulated energy saving over a period of 10 years would be in the region of 10 TWh;
- One has to keep in mind that the use of ductwork will probably increase in the future, mainly due to:
  - the increasing importance of ventilation in the total energy consumption due to a better thermal insulation of the dwellings, which makes it feasible to install balanced ventilation (and thus ductwork) with a (recovery) heat exchanger;
  - the increasing number of active cooling installations in offices and dwellings, for which it is critical to have airtight ducts;
- A leakage airflow ratio of 15 % is based on results of measurements in France and Belgium. It is clear that this figure is an overestimation for a country such as Sweden. However, it is probably representative for the European situation as a whole, because in most countries there is nearly no control and as a consequence, the performances are probably comparable to those in Belgium and France;
- The share of duct leakage in the annual heating energy consumption is valid for typical dwellings and offices (according to the existing Belgian situation). For highly insulated buildings the energy loss due to ventilation will have a higher relative impact on the total energy use.

### *8.7 References*

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3. University of Oxford, DELight (Domestic Efficient Lighting), Final Report, UK, 1998;
4. European Commission, DG XVII, Annual energy review, Brussels, 1994.

# Chapter 9 Outcome of the international SAVE-DUCT seminar in Brussels, June 1998

### *9.1 Introduction*

An international seminar was organised by BBRI in Brussels (June 10-11 1998) in the framework of the European project SAVE-DUCT. Its main purpose was to inform the industry as well as the standardisation and governmental bodies of the recent findings in this project, and discuss measures that could be implemented to remedy the energy use and ventilation rate implications of duct leakage. Fourteen presentations were given. Most of the information is integrated in the various chapters of the handbook. The key findings and conclusions of the seminar that are not handled clearly in the handbook are described in this chapter.

A variety of people and institutes participated in this seminar, these included:

- SAVE-DUCT project partners: BBRI, ENTPE, Scandiaconsult, Aldes;
- Ductwork manufacturers and installers: Stork, Bergschenhoek, Lindab, ABB, Flanders Air Technique, LPS Klimatechniek;
- Research and/or technical institutes: BSRIA, AIVC, CETIAT, TNO;
- Government: Boverket (Sweden), Ministry of the Flemish Community (Belgium), Regie der Gebouwen (Belgium);
- Members of CEN TC 156, WG 3 (Ductwork);
- Architects, engineers, etc.

### *9.2 Ductwork in relation to indoor air quality and energy*

*Presentation given by M. Liddament from AIVC, UK*

In his presentation, M. Liddament described the reference framework for a discussion on ductwork performances. The achievement of an acceptable indoor air quality is the first priority, ventilation being essential in most circumstances. A limited energy use is an important boundary condition. Poor ductwork performances will have a negative influence on both the indoor air quality and the energy use of the building.

## *9.3 Experiences from Sweden*

### 9.3.1 Progress in ductwork design over the last 25 years

*Presentation given by K. Lennertsson from Lindab, Sweden*
An overview was given of the evolution in ductwork design in Europe, with special attention to airtightness. The most important points were the following:

<u>1970's:</u>
- Rectangular ductwork is used more frequently, but there is an increasing use of circular ductwork;
- First use of rubber gaskets;
- Change of the manufacturing process;
- Growing attention for cleaning and inspection of ductwork.

<u>1980's:</u>
- The Swedish guideline AMA 83 requires Class C for some applications in Sweden;
- Increasing use of circular ducts, especially in Northern Europe;
- Northern Europe 90 % circular ducts with 100 % rubber gaskets;
- Middle Europe 30 % circular ducts with 20 % rubber gaskets;
- Southern Europe < 30 % circular ducts without rubber gaskets;
- Increasing use of seam-welded products.

<u>1990's:</u>
- Development of CEN standards;
- Introduction of Class D in VVS AMA in Sweden;
- Increasing use of circular ductwork in Middle Europe: 50 % circular with 60 % rubber gaskets;
- Clean ducts and fittings at delivery (supplied with covers at the ends).

<u>Future developments:</u>
- ♦ Adoption of the CEN standards;
- ♦ More attention to:
  - ⇨ Airtightness;
  - ⇨ Easy to clean solutions;
  - ⇨ Noise attenuation;
  - ⇨ Pressure drops;
  - ⇨ Environmental impacts.

### 9.3.2 The Swedish experience with inspection protocols

*Presentation given by B. Lindström from Boverket, Sweden*

In 1992 a regulation came into force in Sweden, requiring performance checks of ventilation installations according to Table 25. Results from the first checks were presented by Boverket (Swedish National Board of Housing, Building and Planning) during the seminar.

| Buildings | Last date for first inspections of existing building | Inspection intervals | Inspector qualifications class |
|---|---|---|---|
| Day-care centres, schools, health care centres, etc. | 31 Dec. 1993 | 2 years | K |
| Blocks of flats, office buildings, etc. with balanced ventilation | 31 Dec. 1994 | 3 years | K |
| Blocks of flats, office buildings, etc. with mechanical exhaust ventilation | 31 Dec. 1995 | 6 years | N |
| Blocks of flats, office buildings, etc. with natural ventilation | 31 Dec. 1995 | 9 years | N |
| One- and two-family houses with balanced ventilation | 31 Dec. 1995 | 9 years | N |

*Table 25: Requirements for performance checks of ventilation systems in Sweden. Class N qualified inspectors can investigate only simple installations; Class K qualified inspectors can investigate all types of installations.*

The following activities are always included in a ventilation performance check: check of availability of operation/maintenance instruction manual, airflow rate measurement, humidity, fans and air handling units, recirculated air, radon, deposits in ventilation ductwork, noise and eventually a more detailed inspection.

Analysis of more than 8000 reports shows that only 37 % of the systems have been ap proved. The following distribution of approved systems is found for the different types of buildings:

- Apartment building: 25 %;
- Office building: 43 %;
- Schools: 37 %;
- Day-care centres: 51 %;
- Health-care centres: 32 %.

The most common defaults are summarised in Table 26:

| | |
|---|---|
| Wrong airflow rate | 61 % |
| Missing maintenance manuals | 48 % |
| Deposits in fans | 40 % |
| Deposits in ducts | 37 % |
| Defects in fans | 30 % |
| Control and guidance equipment | 27 % |
| Deposits in filters | 25 % |
| Defects in supply and exhaust devices | 23 % |
| Deposits in supply air devices | 22 % |
| Defects in filters | 20 % |

*Table 26: Most common defaults found during inspection of Swedish ventilation systems.*

### 9.4 Status in the USA

*Presentation given by M. Modera from LBNL and Aeroseal Inc., USA*

M. Modera gave an overview of the duct leakage status in US buildings. Considerable work has been undertaken over many years on the performance of residential air distribution (heating or cooling) systems. A major conclusion is that ductwork airtightness is very poor and that this results in very significant energy wastage, especially because in more than 50 % of the cases, the ducts are located in unconditioned spaces. More recent studies were also presented, namely:

- Measuring and improving the performance of commercial-building duct systems (see chapter 6);
- Aerosol-based duct sealing (that is increasingly used in the US, see chapter 4);
- Standards for duct efficiency (ASHRAE standard 152 P, see chapter 3).

### 9.5 Standards and regulations: CEN TC 156 WG3

*Presentation given by B. Göstring from the Swedish Association of Air Handling Industries, Sweden*

The work programme of CEN TC 156 / WG 3 (Ductwork) was presented in detail, with special attention to the most recent decisions of WG3 for the different work items.

- ENV 12097: Requirements for ductwork components to facilitate maintenance of ductwork systems;
- EN 1505: Sheet metal air ducts and fittings with rectangular cross section – dimensions;
- EN 1506: Sheet metal air ducts and fittings with circular cross section – dimensions;
- EN 12220: Dimensions of circular flanges for general ventilation;
- prEN 12236: Supports for ductwork, requirements for strength;
- prEN 1507: Strength and leakage of sheet metal air ducts and fittings with rectangular cross section;
- prEN 12237: Strength and leakage of sheet metal air ducts and fittings with circular cross section;
- prEN 13180: Dimensions and mechanical requirements for flexible ducts;
- WG3 N147: Measurement of duct surface area;
- WG3 N207: Ductwork made of insulation ductboards;
- WG3 N204: Identification of ductwork.

prEN 1507 and prEN 12237 that are detailed in chapter 3 have to be submitted to a new public inquiry as a result of the large number of comments on the initial documents.

### *9.6 Testing ductwork according to prEN 12237*

*Presentation given by W. F. de Gids from TNO, the Netherlands*

TNO carried out a number of laboratory measurements to determine the airtightness of ductwork according to prEN 12237 (November 1995 version). It is likely that this standard will be modified in the future.

Tests were performed on round ductwork, for 10 different diameters (ranging from 125 to 1250 mm). All tested ducts were from the same company. The following measurements were performed:

- Air leakage:

  For all diameters, the airtightness was measured for the following 4 sets of conditions:

| Pressure in the ductwork | External loading |
|---|---|
| Overpressure | Yes |
| Underpressure | No |
| Overpressure | Yes |
| Underpressure | No |

  Although prEN 12237 only requires a single-point measurement procedure to determine the airtightness, the leakage flow rate was measured at several pressure stations at TNO to be able to determine the flow exponent. The pressure in the ductwork was always in the region of 50 to 750 Pa;

  The following conclusions could be drawn:

  ⇨ In all cases the airtightness in the laboratory was better (up to a factor of 5) than the best class in prEN 12237 (which is Class C). This indicates that for laboratory tests an additional class (Class D) should be introduced;

  ⇨ The flow exponent is in the region of 0.51 to 0.84, with an average of 0.76. This indicates that the one-point measurement procedure can cause significant errors when the test pressure is significantly different from the reference pressure at which the leakage flow rate is calculated. Therefore the application of a multi-point measurement procedure should be considered in prEN 12237;

  ⇨ Performing the tests in underpressure always leads to the best result from the point of view of airtightness. This is probably caused by the fact that seams and joints are pressed open in the case of an overpressure in the ductwork;

  ⇨ External loading of the ductwork does not seem to affect considerably the airtightness in the case of underpressure. However, in the case of a positive pressure in the ductwork the loading can have a significant influence;

- Deflection:

  The deflection was determined with a positive pressure in the ductwork and an external loading (1.5 times the weight of the tested ductwork). The deflection of the different ducts were between a factor of 4 to 120 better than the requirement in the standard;

- Ovality

The ovality was also determined with a positive pressure in the ductwork and an external loading (1.5 times the weight of the tested ductwork). The ovality of the different ducts w ere between a factor of 2 to 25 better than the best class in the standard.

# Chapter 10 Recommendations for future technical and governmental measures

### *10.1 The Swedish experience: an interesting concept for other countries*

The measurements and literature review performed within the SAVE-DUCT project suggest that duct systems are very leaky in Belgium and in France. Conversely, the installation of high-quality airtight (Class C or better) systems prevails in Sweden. One reason for this lies, most likely, in the fact that the need for tight systems has been identified in this country since the early sixties. This has resulted in a series of quality-requirements now detailed in the VVS AMA 98 guideline (1998) (see also chapter 3). These are made valid when they are referred to in the contract between the owner and the contractor - which is practically always the case in Sweden.

AMA requires that all ventilation and air conditioning systems be carefully commissioned. The procedures include:

- Measurement and adjustment of all supplied or extracted airflows at the registers. The result should be within ± 15 % including the measurement error. The result is to be presented on standard AMA protocols;
- The duct system leakage has to be verified, normally by the contractor as part of the contract. This is undertaken as a spot check where the parts to be checked are chosen by the owner's consultant. For round duct systems 10 % and for rectangular ducts 20 %, of the total duct surface has to be verified. In case the system is found to be leakier than required, the tested system shall be tightened and another, equally sized, part of the system shall be verified in the same manner. Should this part also be found to leak more than accepted the complete installation has to be leak tested and tightened until the requirements are fulfilled.

Class C was introduced in 1983 and is required for duct systems with a surface larger than 50 $m^2$. This met resistance from the contractors who considered that is was too high a demand. However, one year later it was found that the AMA requirements were easier to fulfil than first thought, so the opposition died and the demands were accepted.

Furthermore, the concern about an increasing part of the Swedish population becoming allergic and asthmatic, often due to “sick buildings” and inadequate dilution of indoor emissions by inferior ventilation systems, lead the Swedish Parliament and Government to decide on compulsory inspection of ventilation systems (Government Bill 1990/91:145, and Ordinance SFS 1991:1273, about the performance checks on ventilation systems). The rules for the inspection were issued by the Swedish National Board of Housing, Building and Planning (General Guidelines 1992 : 3 “Checking the performance of ventilation systems” based on BFS 1992 : 15 “Regulations about performance checks on ventilation systems”). The intervals between the checks depend on how sensitive the building occupants are and how complicated the ventilation system is. The intervals range from 2 years for day-care centres, schools, health care centres, etc., up to 9 years for one - and two-dwelling houses with balanced ventilation. The performance checks are to be carried out by an inspector who is authorised either nationally by the Swedish National Board of Housing, Building and Planning or locally by the municipal committee(s) responsible for planning and building matters. The inspector qualifications differ between these different buildings and systems and whether the authorisation is local or national.

### *10.2 Integrated ductwork performance in an energy performance concept*

In the past, many building regulations focused on the thermal insulation level of buildings or the net heating demand. Since the beginning of the nineties, several countries have developed a so-called energy performance standardisation concept. The aim is to have a requirement on the total energy consumption of the building for standardised boundary conditions (external climate, indoor climate) and the energy analysis includes the energy demand for heating and cooling, the efficiency of the heating and cooling systems, the energy for hot water production, fans, pumps, humidification, etc.

Examples of such an approach are the Dutch energy performance standardisation (NEN 5128 for dwellings, NEN 2916 for utility buildings), the French global thermal performance calculation method (ANFNOR DTU P 50-708 (1988), règles Th-C, under revision), the German Energiesparverordnung (which is revised every three years).

In order to stimulate the construction of buildings with improved energy efficiency, it is important that the ventilation system receives appropriate attention. Demand controlled ventilation concepts, heat recovery, etc. should be included in the energy performance calculation as well as the airtightness performances of the ductwork. The better the performance of these components, the lower the normalised energy performance index. To be most effective, the airtightness of ductwork should probably be included only if the final calculation of the energy performance index can be undertaken at the end of the works (i.e. after commissioning). In most countries, the legislation requires proof of performances at the granting or issuing of the building permit (i.e. before the performance of the ductwork can be tested). Therefore, it is important that the regulations foresee the possibility of performance calculation after commissioning. This concept is illustrated in Figure 67. The constraints apply to the sum of the energy flows and the ductwork airtightness item appears under the ventilation related issues. There are two options at this level:

1. The ductwork airtightness is tested on site. Then the values determined on site may be used in the energy calculations;
2. The ductwork airtightness is **not** tested on site. Then default (typical) values are used in the energy calculations.

Because the energy impact of duct leakage is expected to be large, severe requirements on the ductwork airtightness appear to be a cost effective solution compared to increasing the insulation level or improving the efficiency of thermal systems. This should be a great incentive to use airtight ducts. Finally, this approach is compatible with specific duct leakage requirements that are not related to energy issues.

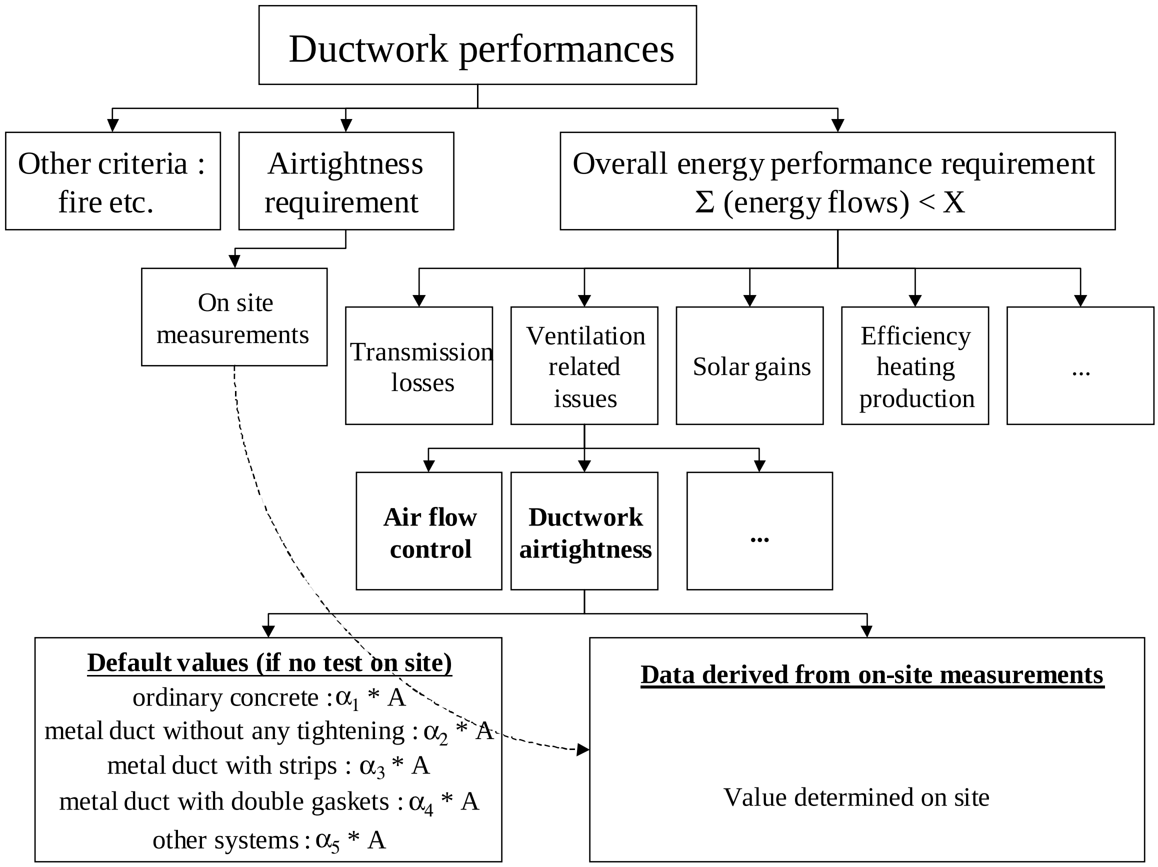


*Figure 67: Flow chart of the philosophy of the integration ductwork performances in an energy performance concept.*

### *10.3 Integrating the ductwork airtightness in the system performance*

Although some adjustments are needed (see § 10.7.3), currently used leakage tests that express requirements in terms of the leakage factor appear satisfactory for industry standards for sheet-metal ducts as they are compatible with product certification constraints and may be checked on site.

However, integrating ductwork leakage in the system performance goes beyond performing "classical" leakage tests as the way the whole system operates should be taken into account. In principle, performance tests should apply to all types of systems (sheet-metal, fibre-glass board, etc.). It appears natural to express leakage flows as a percentage of the delivered airflow. This system performance approach appears as a very attractive measure towards energy efficiency.

Duct leakage requirements could be as follows:

| System class | Maximum value of leakage flow divided by delivered airflow (%) | Increase of fan power demand (%) (assuming cube law, see chapter 7) |
|---|---|---|
| I | 6 % | 20 % |
| II | 2 % | 6 % |
| III | $\frac{2}{3}$ % | 2 % |
| IV | $\frac{2}{9}$ % | 0.7 % |

*Table 27: Proposal for system classes. Requirements are expressed in terms of a maximum value of leakage flow divided by delivered airflow.*

It should be noted that as there is no direct relationship between the delivered airflow rate and the system's surface area, the leakage factor concept (on which are based EUROVENT tightness classes) cannot be directly utilised. At the design stage however, a leakage factor class requirement can easily be derived from the desired system class. Thus, there should not be any difficulties to go back and forth between leakage factor and system classes.

Given the commercially-available airflow measurement devices that are practical for in-situ applications, it seems reasonable to require to demonstrate that the leakage airflow rate of the whole system measured by fan-pressurisation at the operating pressure be determined with an accuracy of 0.3 l/s (1 $m^3$/h) or 10 %, whichever is the greater. Leakage flow rates lower than 0.3 l/s for a typical system should not have a significant impact on its performance. Therefore, the tested area should be chosen such that it is large enough to enable the test apparatus to register a measurable flow with the required accuracy. Large tight systems may require that the whole plant be leak-tested.

### *10.4 Installation*

The issue of proper installation of duct systems is often thought to be linked to the installers' competence. This is certainly true for cleanliness aspects and some components that require careful on-site adjustments. For instance, particular attention should be paid to the connections at the registers (to the ducts and to the building) and at the air handling unit. To obtain improved results with this site work, installation procedures should be well documented and installers should be well trained.

Today, manufacturers propose pre-clean systems that are delivered on site with end-caps to give protection from pollutants (airborne particles, water, etc.). Therefore, it is no longer difficult to obtain clean systems at installation provided that simple rules be observed. Namely, on-site cutting of ducts should be performed with shears as opposed to hacksaws (that produce dust).

The ductwork airtightness is also very sensitive to the workers' skills and the sealing media when conventional sealing techniques are used. However, today's commercially-available products considerably reduce the human factor (chapter 4). In addition to reduced installation time (about 25 % according to the manufacturers), these products are cost-effective both on an investment and on Life Cycle Cost basis despite their initial higher purchase cost[11].

[11] These analyses are presented in Chapter 7 on a real duct system in France. The results are certainly very sensitive to the type of system and the local cost of labour.

### *10.5 Commissioning*

Evidence suggests that commissioning and maintenance plays a major role in securing optimum system performance. Special care should be given to:

- The cleanliness of the system;
- Damaged ducts;
- The airflows at the registers;
- Ductwork airtightness;
- Accessibility (e.g. for filters or cleaning procedures);
- Documentation (detailed drawings of the system, specifications for the materials and devices, instructions for the maintenance) that shall be provided to the building owner or manager;
- The correct functioning of the whole system.

Detailed commissioning protocols can be found in e.g. VVS AMA 83 (1984).

### *10.6 Operation and maintenance*

The management of an air distribution system is a serious task that involves some knowledge on health, and technical background on the operation and maintenance of such systems. Therefore, it certainly deserves a higher status than at present. Also, the technicians whose task is to ensure the proper functioning of these systems should be trained adequately.

### *10.7 Further work*

#### 10.7.1 Rehabilitation

Field measurements performed in Belgium and in France suggest that there is a large building stock that needs rehabilitation. However, as discussed in chapter 4, retrofitting with conventional external-access techniques is tedious, time-consuming, possibly unhealthy, and sometimes even inefficient. Internal-access techniques seem more appropriate for such work. However, very few internal-access sealing techniques are available. The Rolyner® developed by Bergschenhoek seems to be adequate for concrete ducts. The aerosol-based technique commercialised by Aeroseal seems to be promising for other types of ductwork systems, although some development is necessary to adapt it to the European market.

#### 10.7.2 Better knowledge of duct leakage status in Europe

Our knowledge of duct leakage in Europe (except Sweden) relies on about 60 field measurements on a variety of buildings (residential, office, schools, etc.) in Belgium and in France. Whereas the systems were consistently poor as regards airtightness, more leakage measurement data is needed in these countries and in the other member states to enable definite conclusions about the duct leakage status in Europe.

#### 10.7.3 Duct leakage testing

EUROVENT 2/2 guidelines and similar documents have been used for a number of years in Europe for testing ductwork airtightness. However, some aspects of the test procedures need to be clarified. Furthermore, a different protocol should be used if tests are to be performed according to § 10.3.

### ➤System part to be tested

In the system performance approach, the requirements should not be based uniquely on the air distribution system between the air handling plant and the air terminal devices as it is in most standards. They should be based on the system as a whole. AMA includes the possibility to test a part of a system with most types of equipment, however, the owner decides whether these components shall be part of the leakage test or not. Given the sensitivity of the plant performance to these parts (chapter 6), it appears necessary to give precise requirements on this issue.

### ➤Test pressure

The reference test pressure varies considerably between different standards. For instance, EUROVENT 2/2 is based on a mean operating pressure of the duct system, whereas in the European pre-standard 12599, $\Delta p_{ref}$ should be adjusted to 200, 400, or 1000 Pa, whichever is closest to the mean operating pressure of the system. As for DW/143, recommended test pressures are given although “the choice of test pressure shall be at the discretion of the test operator”. Although this may not look like major differences, the extrapolation of a leak flow to a pressure different from the test pressure can lead to large uncertainties in the final results.

Therefore, the test pressures should be well-defined and harmonised. For best results in a system performance test, the test pressure should be set to the operating pressure. For industry standards however, tests should be performed at different pressure stations to ease the comparison between the products. The pressure stations should be representative of the range of operating pressures to which the products will be subjected.

### ➤Surface area calculation

Most ductwork airtightness standards do not give guidelines on how to calculate the surface area of all parts of an air distribution system. This makes them inappropriate to test systems that include air handling equipment such as a heat exchanger. These calculations are detailed in AMA in which these components are sometimes given a “surface bonus” due to the difficulties to get these parts as tight as the connecting ducts.

This can have a considerable impact on the leakage factor as it is inversely proportional to the tested surface area. Therefore, surface area calculation procedures should be harmonised.

### ➤Uncertainty analyses

It should be clear how to calculate the uncertainty of the measurements and how to include them in the test report. Uncertainties shall include both bias errors (due to the instruments) and random errors (noise). This remains an area where scientific work is needed.

### ➤Ready-to-use leakage testers

Ready-to-use duct leakage testers developed by US companies do not seem appropriate for the European market (chapter 6). This is unfortunate as they would be very useful for commissioning or certification purposes in the member states.

### 10.7.4 Going towards Class D ?

Work has been undertaken for the next AMA generation (AMA 98). Class D (3 times tighter than Class C) is introduced as an option for large circular duct systems.
Indeed, given today’s technology, it seems reasonable to include Class D in CEN ductwork airtightness industry standards.

It also seems reasonable to give incentives for people to require the proposed system Class IV (Table 27). The energy performance approach (§ 10.2) could be an incentive by itself if it includes duct leakage, since severe requirements on airtight ducts appear to be a cost effective solution compared to increasing the insulation level or the efficiency of thermal systems.

### 10.7.5 Products

Although quality products that quasi-ensure airtight (Class C or D) systems are already commercially-available, research and development in the manufacturing industry would be useful to ease installation, reduce further the human error factor, and obtain even better systems. Namely, the quality of the register–envelope fitting is still quite sensitive to the workers' skills. Also, air handling equipment such as heat exchangers, dampers, etc. should be tighter. Work should be undertaken to get systems with lower pressure drops and thus lower fan energy use. Noisy systems constitute a major source of complaints. In this area, as well, research and development is needed to minimise the noise transmission and generation in duct systems. The design of ventilation products should take into account the cleaning access of the components, as well as the dirt accumulation factor.

Finally, further research is needed to lower the environmental impacts of the manufacturing process of, and the materials used for, air handling equipment.

## *10.8 Reaching the target*

Attractive seminars aimed at HVAC professionals with product demonstrations and case studies could constitute a great complement to this handbook. Original information media should be sought out to reach designers, installers, building managers and building owners, who mostly ignore the benefits of airtight duct systems.

## *10.9 Cost issues: a major barrier*

Any measure for improvement should take into account the fact that a major barrier towards tighter air ducts lies in the cost issues as investment and operating budgets are evaluated sequentially and almost never globally.

## *10.10 Implications of market transformation*

The requirement of tight systems is likely to lead to an increasing use of high-quality ductwork with rubber-seals at the joints. This technology is not straightforward to implement and implies heavy machine-tools investments. However, at present, there exist many small sheet-metal ductwork manufacturers who rely on simple and relatively inexpensive machine-tools to produce their components. These will probably not be able to follow the market as it evolves towards higher technology standards.

## *10.11 References*


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# Chapter 11 Conclusions

Duct leakage is detrimental to energy efficiency, comfort effectiveness, indoor air quality, and sometimes even to health. However, in most countries designers, installers, building managers and building owners, ignore the benefits of airtight duct systems. Furthermore, as there are no incentives in most countries, over the years, this has (probably) lead to poor ductwork installations in a large fraction of the building stock. In these countries, installation is (probably) often undertaken using conventional *in situ* sealing techniques (e.g. tape or mastic), and therefore the ductwork airtightness is very much dependent upon the workers' skills. Field studies suggests duct systems in Belgium and in France are typically 3 times leakier than EUROVENT Class A (chapter 6).

Simple analyses on specific cases can be made to show that the overall performance of the systems is drastically affected when the ducts are that leaky (chapter 7). Furthermore, projections at the European level, based on available measurement data, suggest potentially large energy impacts of duct leakage (chapter 8). However, it is possible and easy to install tight duct systems with quality commercially-available products. In Sweden, where factory-fitted sealing gaskets are widely used, airtightness Class C is commonly required and fulfilled (chapter 6). Furthermore, the additional investment cost (if any) for these products is probably not very significant since the labour cost is considerably reduced. In addition, the duct systems installed today are likely to be used for at least the next twenty to fifty years. A possibly higher investment cost for a higher quality duct system should be considered on a Life Cycle Cost (LCC) basis and not just on the first cost (chapter 7).

Although the situation appears to be quite satisfactory in Sweden compared to other countries, even tighter requirements are being considered. Today's technology, and the increasing concern for energy conservation and environmental impacts are among the reasons that are raised for this step. In summary, the investigations presented in this handbook lead to the conclusion that the ventilation and energy use implications of leaky ducts are large and merit further examination. Namely:

1. Field work seems to be necessary to better evaluate the extent of duct leakage in the building stock;
2. There is a need for harmonised ductwork airtightness test and analysis protocols for all types of ductwork. Ready-to-use duct leakage testers should be designed accordingly;
3. Retrofitting of poor installations should be seriously considered. Further research and development work in this area seems to be necessary;
4. Cost analyses were performed on one real system. As the results are sensitive to many local parameters, such as the cost of labour, further analyses would be useful to better evaluate the cost implications of different options;
5. However, since it can be safely stated that quality products are very efficient and reasonably expensive, they have probably not been marketed correctly. Significant efforts should be made by the manufacturing industry in this area;
6. Finally, in the context of energy conservation, governmental measures such as those proposed in chapter 10 should probably be considered to promote tight air duct systems.

# Appendices

***Appendix A: Overview of the SAVE-DUCT project***

## Scope of SAVE-DUCT project

Since the efficient use of energy reduces the emission of pollutants to the atmosphere, it has been hailed as the single most important policy objective towards attaining the EU's stated goal of stabilising $CO_2$ emissions. In recognition of this fact, the SAVE programme ("Specific Action on Vigorous Energy Efficiency" - Directorate-General for Energy (DG XVII)) has been recognised by the Commission as a cornerstone of the Community's $CO_2$ reduction strategy.

SAVE is the European Union non-technological programme aimed at promoting the rational use of energy within the Union. SAVE II is the follow-up to the original SAVE which ran from 1 January 1991 to 31 December 1995. The SAVE II programme was adopted by the Council of Ministers on 16 December 1996 and will run until 31 December 2000 (Council decision 86/737/EC, OJ No L 335/ 24 12 96 p. 50).

The completion of this handbook depended upon investigations carried out within the framework of the DUCT project (1997-1998) that was funded in part by the SAVE II programme. The objectives of DUCT may be summarised as follows:

1. Quantify duct leakage impacts;
2. Identify and analyse ductwork deficiencies;
3. Propose and quantify improvements;
4. Propose modifications to existing standards.

DUCT involved five teams representing three different countries:

- Ecole Nationale des Travaux Publics de l'Etat, Lyon, France;
- Belgian Building Research Institute, Brussels, Belgium;
- ALDES Aéraulique, Lyon, France;
- SCANDIACONSULT, Stockholm, Sweden;
- Centre d'Etudes Techniques de l'Equipement, Lyon, France.

The following persons have contributed to DUCT :

François Rémi Carrié (ENTPE, co-ordinator), Johnny Andersson (SCANDIACONSULT), Emmanuel Balas (CETE), Emmanuel Berthier (CETE), Serge Buseyne (Quiétude Ingénierie), Alain Bossaer (BBRI), Pierre Chaffois (ALDES), David Ducarme (BBRI), Jean-Claude Faÿsse (ALDES), Olivier Faure (ALDES), Marc Kilberger (CETE), Vincent Patriarca (CETE), Peter Wouters (BBRI).

Kenneth Lennartsson (Lindab Ventilation AB) and Peter Bulsing (Bergschenhoek B.V.) are greatly acknowledged for his interest in the project and valuable input.

## Tasks and tasks allocations

DUCT was divided in four phases:

1. State of the art;
    1.1 Codes and standards (Task 1);
    1.2 Duct leakage data and rehabilitation techniques (Task 2);
    1.3 Survey of HVAC manufacturers and contractors (Task 3);
2. Field measurements (Task 4);
3. Data analysis (Task 5);
4. Implementing the results;
    4.1 International seminar on air distribution in buildings: airtightness aspects (Task 6);
    4.2 Publication (Task 7).

| Description | Task Leaders |
|---|---|
| 1. Codes and standards | BBRI |
| 2. Existing duct leakage data and rehabilitation techniques | SCANDIACONSULT |
| 3. Survey of HVAC manufacturers and contractors | ALDES |
| 4. Field measurements | CETE |
| 5. Data analysis | ENTPE |
| 6. Seminar in Brussels | BBRI |
| 7. Publication/final report | ENTPE |

## SAVE-DUCT project participants

| Designation | Address | Tel / Fax / http | Contact person |
|---|---|---|---|
| Ecole Nationale des Travaux Publics de l'Etat<br>Département Génie Civil et Bâtiment<br>URA CNRS 1652<br>Laboratoire des Sciences de l'Habitat (LASH) | 2 rue Maurice Audin<br>F - 69518 Vaulx en Velin Cedex<br>France | Tel : (+33) 4 72 04 70 31<br>Fax : (+33) 4 72 04 70 41<br>http://www.entpe.fr | François Rémi Carrié<br>(Remi.Carrie@entpe.fr) |
| Belgian Building Research Institute (WTCB - CSTC)<br>Division of Building Physics<br>and Indoor Climate | Rue de la Violette 21-23<br>B - 1000 Brussels<br>Belgium | Tel : (+32) 2 653 8801<br>Fax : (+32) 2 653 0729 | Peter Wouters<br>(wouters@bbri.be) |
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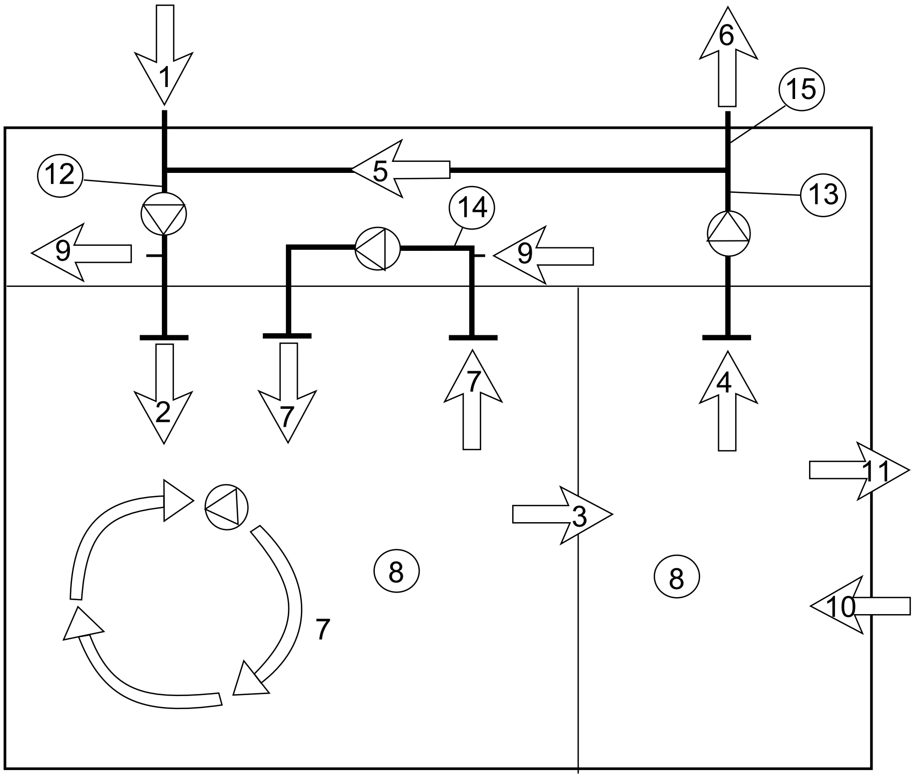
| SCANDIACONSULT | PO Box 4205<br>SE - 10265 Stockholm<br>Sweden | Tel : (+46) 8 615 6000<br>Fax : (+46) 8 702 1935 | Johnny Andersson |
| Centre d'Etudes Techniques de l'Equipement de Lyon<br>Groupe Habitat Economie Bâtiment | 46 rue Saint Théobald<br>BP 128<br>F - 38081 L'Isle d'Abeau Cedex<br>France | Tel : (+33) 4 74 27 51 51<br>Fax: (+33) 4 74 27 52 52 | Marc Kilberger |

## *Appendix B: Terminology, symbols, and useful constants*

### Terminology




| | |
|---|---|
| 1. Outdoor air | |
| 2. Supply air | Air brought to a room. Can be a mixture of outdoor air, circulated air, return air, or transferred air |
| 3. Transferred air | Air transferred from room to room |
| 4. Extract air | Air taken out of a room |
| 5. Return air | Extract air returned to a group of rooms |
| 6. Exhaust air | Extract air delivered to the outside |
| 7. Circulated air | Air circulated in a room |
| 8. Inside air | |
| 9. Duct leakage | Unintended inward or outward airflow through duct leaks |
| 10.Infiltration | Air leakage into the building through leakage paths in the structure separating it from external air |
| 11.Exfiltration | Air leakage out of the building through leakage paths in the structure separating it from external air |
| 12.Supply duct | Duct that carries supply air |
| 13.Extract duct | Duct that carries extract air |
| 14.Return duct | Duct that carries return air |
| 15.Exhaust duct | Duct that carries exhaust air |

## Quantities and Units

| Symbol | Quantity | Units | |
|---|---|---|---|
| $\Delta p$ | pressure difference | Pa | $(N/m^2)$ |
| $\Delta p_{ref}$ | reference pressure difference | Pa | $(N/m^2)$ |
| $A$ | surface area | $m^2$ | |
| $C$ | leakage coefficient | $m^3\ s^{-1}\ Pa^{-n}$ | |
| $C_d$ | discharge coefficient | - | |
| $c_p$ | specific heat capacity at constant pressure | $J\ kg^{-1}\ K^{-1}$ | $(kJ\ kg^{-1}\ K^{-1})$ |
| E | energy | J | (N m) |
| $ELA_{ref}$ | effective leakage area at $\Delta p_{ref}$ | $m^2$ | |
| $f_{ref}$ | leakage factor at $\Delta p_{ref}$ | $m^3\ s^{-1} m^{-2}$ | $(l\ s^{-1}\ m^2)$ |
| $h$ | specific enthalpy | J/kg | |
| $K$ | leakage coefficient normalised by duct surface area | $m^3\ s^{-1} m^{-2}\ Pa^{-n}$ | $(l\ s^{-1}\ m^2\ Pa^{-n})$ |
| $l, L$ | length | m | |
| $L_\theta$ | latent heat of vaporisation at temperature $\theta$ | J/kg | (kJ/kg) |
| $m$ | mass | kg | |
| $n$ | flow exponent | - | |
| $p$ | pressure | Pa | $(N/m^2)$ |
| P | power | W | (J/s) |
| $q, Q$ | airflow | $m^3/s$ | (l/s) |
| $t$ | time | s | |
| $T$ | thermodynamic temperature | K | |
| $U$ | estimated U-value | $W\ m^{-2}\ K^{-1}$ | |
| $x$ | vapour ratio | kg/kg | (g/kg) |
| $\theta$ | Celsius temperature | $^oC$ | |
| $\rho$ | density | $kg/m^3$ | |

## Useful constants

1 atmosphere = $1.01325\ 10^5$ Pa

Density of air at 20°C = 1.205 $kg/m^3$

Density of water at 20°C = 1000 $kg/m^3$

Latent heat of vaporisation of water at 0°C = 2490 kJ/kg

Specific heat capacity at constant pressure of air = 1.002 $kJ\ kg^{-1}\ K^{-1}$

Specific heat capacity at constant pressure of liquid water = 4.187 $kJ\ kg^{-1}\ K^{-1}$

Specific heat capacity at constant pressure of water vapour = 1.86 $kJ\ kg^{-1}\ K^{-1}$

Since the efficient use of energy reduces the emission of pollutants to the atmosphere, it has been hailed as the single most important policy objective towards attaining the EU's stated goal of stabilising $CO_2$ emissions. In recognition of this fact, the **SAVE programme** (“Specific Action on Vigorous Energy Efficiency” - Directorate-General for Energy (DG XVII)) has been recognised by the Commission as a cornerstone of the Community's $CO_2$ reduction strategy.

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The **Air Infiltration and Ventilation Centre** was inaugurated through the International Energy Agency and is funded by the following twelve countries:

Belgium, Denmark, Finland, France, Germany, Greece, Netherlands, New Zealand, Norway, Sweden, United Kingdom, United States of America.

The Air Infiltration and Ventilation Centre provides technical support in air infiltration and ventilation research and application. The aim is to provide an understanding of the complex behaviour of the air flow in buildings and to advance the effective application of associated energy saving measures in both the design of new buildings and the improvement of the existing building stock.

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