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Fig. 1 System with failed
tape, and omitted fasteners,
in USA [© Weldin Engineering]



Fig. 2 Circular ducts in a
compact Norwegian plant room
[foto: SINTEF]

Duct System Air Leakage – How Scandinavia tackled the problem

Apart from Scandinavia, many countries in Europe have generally very leaky ventilation systems ^[16]. Most people are unaware of this 'out-of-sight' problem. Inferior rectangular ductwork is widely used and poorly installed, yielding leakage rates up to 30 times higher than is observed in Scandinavia. Duct leakage is detrimental to indoor air quality (IAQ), comfort, and energy efficiency. It is often accompanied by other problems, such as inferior commissioning and cleaning. Airtight circular (round) ductwork is known to have many other benefits over rectangular ductwork, including cost. But why do designers, installers, and building owners forego airtight duct systems? It is due to: (i) lack of awareness of the benefits, (ii) lack of performance requirements and penalties for noncompliance, and (iii) no one is found accountable, as there is no commissioning.

Conversely, in Scandinavia, high-quality airtight systems are the norm. 90–95% of ductwork in Scandinavia is now circular steel ductwork with factory-fitted airtight gasket joints (Class C or better). Sweden has spearheaded this development. This impressive result has come about after the problem of leakage was first identified in the 1950s, leading to the first contractual requirements on ductwork airtightness in the 1960s (e.g. Swedish VVS AMA). Since then, the requirements have been tightened concurrently with advances in duct technology. There is strict control in Sweden, Finland and Denmark, so most installations comply with these stringent requirements after commissioning.

This paper describes the Scandinavian approach, giving recommendations on how it can be adopted in other countries. More details are given in the full ASIEPI WP5 Technical Report ^[1]. This paper focuses on metal ductwork, but mentions other materials.

1 > Today's situation

Duct airtightness classes A to D (see Fig.3) are defined in European Standard EN 12237 ^[10] for circular ducts and EN 1507 ^[6] for rectangular ducts. A new standard for airtightness of ductwork components is in preparation: prEN 15727 ^[14]. The leakage test method for system commissioning is described in EN 12599 ^[11]. Airtightness classes for air handling units (L1 to L3) are defined in EN 1886 ^[7]. ASHRAE's classes are different. System standards, in particular EN 13779 ^[12], give further recommendations for airtightness class selection for different purposes.

Table 1 Duct airtightness classes, measured at a test pressure of 400 Pa. Area is calculated according to EN 14239

Airtightness class	Limiting leakage (l/s)/m ²
A - worst	< 1.32
B	< 0.44
C	< 0.15
D - best	< 0.05

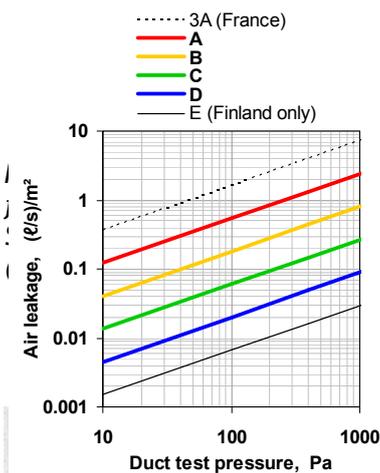


Fig.3 Illustration of duct leakage classes listed in Table 1 (with exponent 0.65) Special classes in France (3A) and Finland (E) are also shown

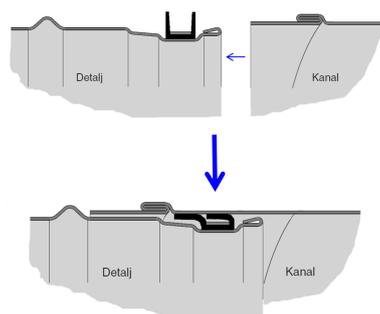


Fig.4 Cross section of circular duct joint with double gasket, giving airtightness Class D. Single gaskets generally achieve Class C, but there are other factors that affect airtightness, such as roundness and flatness of seams at the joints. [Lindab]

Duct systems used in Scandinavia

The Scandinavian countries have similar climates and architecture. Requirements on IAQ and building services are therefore largely harmonized. The Nordic Committee on Building Regulations (NKB, now disbanded) published Nordic guidelines on 'Indoor climate - Air quality' [3] which give recommendations for duct systems and its commissioning. This consolidated a common stance on ductwork airtightness in Scandinavia.

90-95% of ductwork installed in Scandinavia is spiral-seam steel circular ducts (Fig.2) with factory-fitted sealing gaskets (Fig.4), with airtightness Class C or better. This product is gaining popularity in other countries, including The Netherlands and Germany. The gasket system enables easy joining and dismantling. To prevent the joints from sliding apart, they are fixed in position using special screws or rivets [9]. One manufacturer has recently introduced a clickable system that makes screws/rivets obsolete, and thus can speed up installation (not dismantling!). Duct products are generally certified by 3rd-party laboratories.

Sweden

Nearly all Swedish buildings and their installations fulfil the voluntary AMA specification guidelines ('General Requirements for Material and Workmanship'). AMA is referenced in building contracts between the owner and contractors. One section of the guidelines concerns HVAC ('VVS AMA'). The current version of VVS AMA is from 1998 [2]. AMA refers to national and European standards. AMA's ductwork airtightness classes are the same as those defined in European standards. VVS AMA specifies which airtightness class shall be used in different situations, and commissioning rules/protocols. Installations that do not fulfil the requirements when installed are eventually corrected, due to the strict commissioning regime.

VVS AMA requirements for duct system airtightness

- > **Class A** (the lowest level allowed) applies to visibly installed ducts in the space being served. A leakage here will not have any real significance, as the leakage airflow is beneficial to the space.
- > **Class B** (3 times tighter than A) applies to all rectangular duct systems, and any duct systems with surface area ≤ 20 m². Surface area is according to EN 14239 [13]. This generally applies to small houses.
- > **Class C** (3 times tighter than B) applies to round duct systems with surface areas > 20 m². This applies to the vast majority of buildings.
- > **Class D** (3 times tighter than C) is not a standard requirement, but can optionally be specified for systems in which airtightness is essential. This normally calls for round duct systems with double gaskets (Fig.4).

VVS AMA requirements on commissioning of duct systems

- > This is done by HVAC contractors as part of the contract. AMA requires contractors to include the cost of testing in their contract price.
- > The contractor can conduct the measurements themselves if they have the necessary competence and equipment. More often, they engage specialised subcontractors to do the testing.
- > The owner's consultant, is normally also present during the test
- > The parts to be measured are chosen by the owner's consultant
- > For round duct systems, 10 % of the duct surface area is tested; For rectangular duct systems, 20 % of the duct surface area
- > A one-pressure leakage measurement is taken, normally at 400 Pa (a flow exponent of 0.65 is assumed).

It is expensive for contractors to install inferior duct systems, because they have to pay for both remedial work and additional tests. This motivates contractors to ensure that the work is done properly in the first place.



Fig.5 Collar saddle for in-situ tees [source: L.A.Matsson]



Fig.6 Factory made tee with low flow resistance and airtightness Class D (©Lindab)



Fig.7 Rectangular duct with standard length [Lindab]

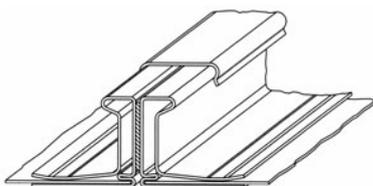


Fig.8 Close up cross-section of a flange for connecting two rectangular ducts. Cleat slides on the top to hold the two flanges together.

Other Commissioning and Maintenance Issues

VVS AMA is much broader than just covering duct airtightness. Commissioning includes criteria related to safety (e.g. fire protection installations), energy performance and indoor environment (e.g. cleanliness, airflow). All extracted and supplied airflows in the building shall be measurement and adjusted if needed; the result should be within $\pm 15\%$ of design (including uncertainty). For this, measurement points shall be provided in the main ducts for measuring total airflow, both for commissioning and for future monitoring. VVS AMA also requires that all commissioning details shall be included in the building's Operation and Maintenance manuals, to ease maintenance and retrofit. This shall include detailed drawings of ductwork installations, specifications for the materials and devices, and a maintenance schedule.

Norway

The building regulations state merely that "Ducts and air-handling units shall be satisfactorily airtight". Neither the building regulations, nor the national standard for building specs (NS 3420), give quantitative minimum requirements for airtightness; so it is up to the building owner to specify in each case. In practice, the specified minimum requirement is normally Class B ^[20]. Despite this, over 90% of installed ductwork is round with Class C. This is because most ductwork suppliers deliver Class C (with gaskets) to the Scandinavian market; it is cost effective and simple to fit.

Leakage tests were common until the mid 1990s. Norway has exactly the same commissioning approach as AMA. Since the 1990s, testing has become uncommon as it is now rarely a contractual obligation. Nevertheless, major ventilation contractors still recommend their own employees to perform pressure tests on their own systems to uncover installation faults at an early stage of construction, not just before handing over. This is especially true for critical ductwork (i.e. with high operating pressures, and main duct risers before they are built-in), not small ducts near air terminals (operating pressure < 100 Pa). If such a leakage test is done, then the results are handed over as part of the handover documentation. Few systems are tested this way, maybe < 10% of large buildings.

Why is testing no longer required? It may simply be because duct leakage is no longer regarded as an issue, now that Class C has become the *de-facto* standard product in the Scandinavian market. However, this is a false premise. Measurements have shown that there can be a significant difference between leakage in a real building and that documented in laboratory conditions ^[25]. Air leakage can amount to 5-7 % of the total ventilation flow rate in a commercial Norwegian building ^[21]. The reason for this is that, in a real installation, many components are connected without gaskets, which creates numerous opportunities for leakage, particularly on branch ducts as opposed to main ducts ^[24]. Examples are flexible ducts, plenum collars, VAV-box collars, and pressed saddle taps (Fig.5) ^{[22][25]}. The latter are a popular alternative to tee pieces (Fig.6, which are both more airtight and aerodynamic) because they simplify fitting, but poor workmanship can leave gaps between the collar and the duct.

Finland

The Finnish situation is similar to that in Sweden. The building regulations (Part D2 'Indoor climate and ventilation') require minimum Class B for the whole system, and gives experience-based recommendations to generally use ducts and components of Class C (minimum default) or better, and air handling units of Class L3 or better. Compliance with the regulations is tested during the building process in all buildings except in single family dwellings, for which also use of Class C products is strongly recommended.

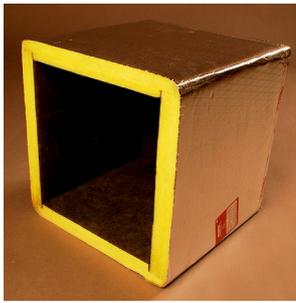


Fig.9 Example of duct-board

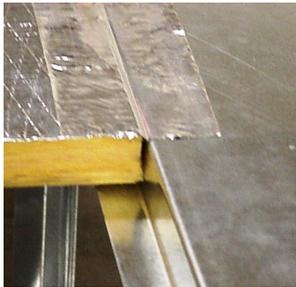


Fig.10 Duct-board tape seal



Fig.11 Conventional duct tape (i.e., fabric-backed tape with natural rubber adhesive) fails more rapidly than all other duct sealants^[22]. It has also been shown that the trade standard for advanced tapes (UL 181) does not guarantee durability^[22].

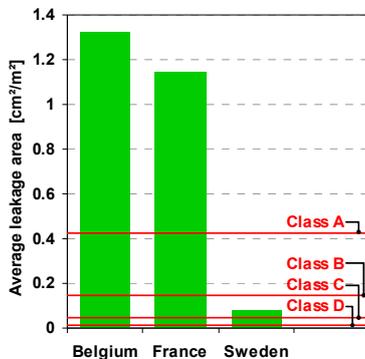


Fig.12 Comparison of average measured duct leakage in Belgium, France & Sweden^[16]

For commissioning, Finland has adopted the Swedish principle of random tests but permits random tests if the duct system components are Class C or better. The random tests shall cover 20% of the ductwork surface area in the case of Class C, and 10% in the case of Class D or better. In case of failure in the random test, or if inferior or non-tested components have been used, then the whole system shall be measured.

The Finnish D2 regulations also have requirements for air handling units (Class L3 or better), and requires Class E (i.e. 1/3 of the leakage of Class D) for ducts & components for certain very special applications.

Denmark

The Danish code of practice for mechanical ventilation installations is DS 447^[5]. It has the same status as AMA in Sweden, in that it is not statutory, but ensures compliance with the building regulations. DS 447 states that airtightness of ductwork and air handling units shall be *documented* and satisfy the requirements in the building contract. The majority of systems are tested, even though other means of documenting airtightness are allowed besides leakage tests, such as referring to product documentation. Typically, the contractor bears the responsibility for documentation, which is presented at commissioning. Systems normally fulfill at least Class B and often Class C, just as in Norway and Finland.

Other countries

In other European countries, rectangular ducts are more common than in Scandinavia. Flange systems (Fig.7 & Fig.8) are often used with metallic rectangular ducts and with other components that need to be dismantled regularly for maintenance. Round ducts are still generally sealed in-situ using duct tape (Fig.11) in combination with screws or mastic (screws/mastic are sometimes omitted). Next to metal ducts, an important part of the market is site-assembled duct-boards, which are made of rigid insulation (mineral wool or foams) covered with aluminium foil (Fig.9). These are mainly used in warmer climates (South Europe and USA) where air-conditioned buildings need thermally insulated ducts. Mastic and fastening clamps are rarely used in practice even though they are recommended, and the clamps (if installed at all) and taped seals (Fig.10 & Fig.1) can fail or loosen with age^[22]. In conclusion, ductwork airtightness in these countries depends a lot on workmanship and materials.

Tests are very seldom performed in standard buildings, as there are no incentives to do so. This has led to poor ductwork installations in much of the building stock. Knowledge about the ductwork airtightness mainly relies on a few studies^{[16][18]}. Field studies suggest that duct systems in Belgium and in France are typically 3 times leakier than Class A (Fig.12). Studies in USA show a similar or worse pattern^[24]. Analysis of specific cases indicates that leakage drastically affects overall system performance. Duct leakage therefore probably has a large energy impact outside of Scandinavia.

2 > Other duct materials

Besides metal ducts, other available duct types include:

- > **Rigid insulation ducts:** These can be rectangular (made of 'duct-board', Fig.9) or round (Fig.13). Besides having providing thermal insulation, they are light to transport and have good acoustic properties (partly due to higher break-out noise than round metal ducts). Typical sealing methods include tapes or mastics applied around the joints in the system. Field examinations have shown that taped seals tend to fail over extended periods of time^{[22][24]}.

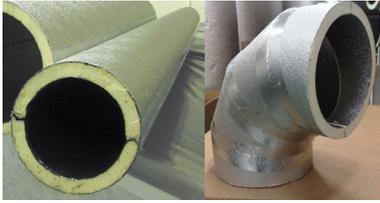


Fig. 13 Round foam duct



Fig. 14 Flexible duct



Fig. 15 Round plastic duct [23]

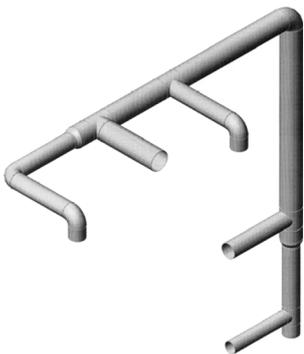


Fig. 16 Round plastic duct system with Class C [23]



Fig. 17 Example of a machine for manufacturing spiral ducts [Spiro Tubeformer]

In addition, the clamps required by the trade standard (UL 181^[4]) can fail and their durability has been questioned^[22]. Good airtightness can potentially be achieved with durable mastics applied with by good workmanship. In this case, round insulated foam ducts (Fig.13, which can achieve airtightness Class C when new) may share many of the benefits of round metal ductwork.

- **Flexible round ducts** (Fig.14): These are generally composite ducts made of plastic, metal, and possibly insulation fibre. They come in wide range of qualities, from flimsy ducts with thin plastic foil walls to semi-rigid ducts with walls of aluminium sheet with a concertina form. These ducts a convenient means of connecting components such as ducts to air terminals, and also act as duct silencers. However, they are known to be difficult to clean and the less rigid varieties can easily become compressed. Their use should therefore generally be kept to a bare minimum. Just as ductboard, they flexible ducts pose a challenge with respect to achieving airtight connections (see [22]).
- **Plastic ducts** (Fig.15): Round plastic ducts exhibit the same benefits as round metal ducts. Because of their flammability, they should not be used in systems spanning multiple fire cells. They are therefore mainly limited to residential ventilation, except connections to kitchen hoods. One particular Finnish product is made of low-emitting antistatic polypropylene, with many components (bends, tees etc., Fig.16) available with the same self-sealing joint that achieves Class C airtightness^[23]. Other types of plastic ducts are used for underground ductwork, with watertight joints, because of their corrosion resistance.

3 > HOW DID WE GET TO WHERE WE ARE?

The evolution of duct airtightness in the last 50 years

Here we summarize the chain of events that led to the solution of the ductwork airtightness problem in Scandinavia^{[15][16]}. More details are given in the full ASIEPI WP5 report^[1]. The problem of leakage was first identified in the 1950s, when mainly rectangular, prepared on site, and little attention was given to airtightness, balancing, or energy performance. This decade also saw the world's first Spiro Tubeformer (Fig.17), a machine for making revolutionary spiral ductwork. In 1966 the seminal AMA defined two airtightness 'norms' A and B, to be spot-checked by the contractor. The 1970s and 80s saw growing use of round ductwork, and further breakthroughs in product quality, such as rubber gaskets which replaced putty and tape that had been used before. Airtightness Class C was introduced in the 1983 revision of AMA; later Class D was added in 1998. In the early 2000s CEN standards on airtightness were published, based largely on Nordic experiences.

4 > RECOMMENDATIONS : The 3 ingredients for success:

The Scandinavian experience has shown that there are 3 basic steps in a market transformation to more airtight duct systems: (i) awareness, (ii) requirements, and (iii) compliance testing. Obviously, if quality is not demanded, there are no penalties or incentives, and no checks made, quality will not be provided^[15].

(i) Increased awareness of the benefits quality round ductwork

The first step along the path of a market transformation is to increase awareness of the consequences^[16] of air leakage, and that commercially-available airtight round duct systems have many additional benefits over both rectangular duct systems and round ducts without gaskets.

An important decision that must be taken early in the design of an HVAC system, is whether to use round, rectangular, or flat-oval ductwork, or maybe even ductless solutions. Often, a combination of these is used.

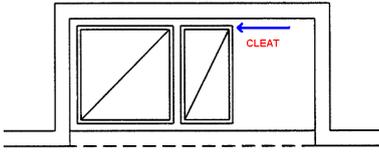


Fig.18 The need for access space to install cleats makes it difficult to use the whole shaft area with rectangular ducts [16]

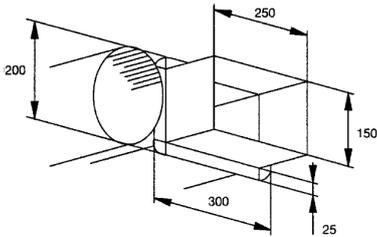


Fig.19 Rectangular duct (with flanges) and circular duct with same height requirement and same free duct area [16]

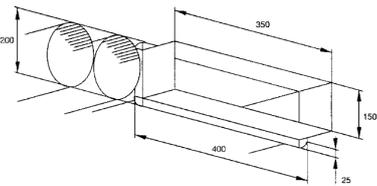


Fig.20 A flat rectangular duct can often be replaced by several parallel round ducts. The example here shows equal height and free duct area [16]

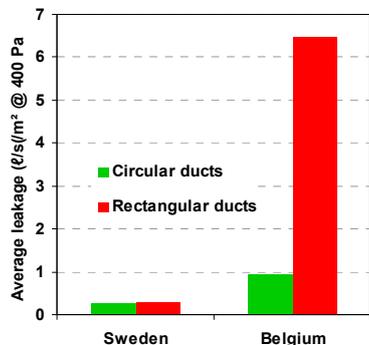


Fig.21 Rectangular versus circular ductwork in Sweden and Belgium [16]

In Scandinavia, HVAC designers take it for granted that round ducts are used throughout the whole system, using rectangular ductwork only where it is unavoidable, such as connection plenums at the air handling unit. This maxim is echoed in ASHRAE Fundamentals, which simply says 'Use round ducts wherever feasible'.

Below are some moments that illuminate the benefits of round ducts:

Space efficiency

It is commonly believed that rectangular ducts have the advantage that they make maximal use of limited rectilinear spaces. However, this belief needs moderation. Here are three examples:

- > A common practice is to use rectangular ducts near the fans, where the airflow is large, and large ducts are needed in a cramped space. Further away, the smaller branch ducts can be round. However, one problem with this is that ductwork near fans experiences a higher operating pressure than smaller ductwork near air terminals, so its airtightness is more critical. Rectangular ducts are known to be leakier.
- > To the inexperienced designer, rectangular ducts seem a logical choice in rectangular service spaces (risers, shafts). However, in practice, one must provide access space to slide cleats onto all the flanges (Fig.18). This access space must be as wide as the widest rectangular duct. Round ducts often need less installation space than rectangular ducts with the same pressure drop (Fig.19 & Fig.20) [17].
- > One advantage of rectangular ductwork is that it can have virtually any aspect ratio. For example, flat-&-wide ducts can be used in ceiling voids above rooms with crossing beams or in corridors with little headroom. However, the flanges around rectangular ducts protrude 20-40 mm, so round ducts do not necessarily occupy more space. The alternative is to use multiple parallel round ducts. Incidentally, this can simplify balancing and enable zoning (See Chapter 8 in [17]). If considered early in the design phase, it is possible to influence the architectural planning to ensure sufficient space for round ductwork.

Leakage

- > Fig.21 compares average leakage from on-site measurements of round and rectangular duct systems in Sweden and Belgium. The Swedish data shows little difference between round and rectangular systems in this particular data set because the round and rectangular systems in this particular data set had approximately the same airtightness requirement (Class B). In Belgium, which has neither strict tightness requirements nor any testing, rectangular ducts are very leaky, while round duct systems perform only slightly worse than in Sweden (Class A). This shows us that huge reductions in duct leakage can be achieved simply by adopting round ducts as an industry standard, even if testing is not practiced as part of commissioning.
- > Round ducts are tighter. Larger duct systems ($\geq 50 \text{ m}^2$ duct surface area) are, according to VVS AMA 83 (1984), required to be three times tighter than a rectangular duct system;
- > Connecting two round spiral wound ducts only requires one fitting, whereas rectangular ducts are connected by use of a completely separate flanging system (Fig.22 & Fig.23). Round ducts can have any length between the connections, a duct length of 3 m is standard but 6 m is also frequently used. The length of a rectangular duct is limited by the size of the steel sheet, which is usually less than 2 m, which requires more connections.

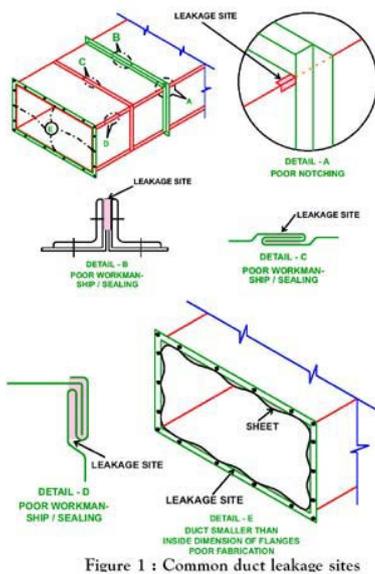


Figure 1 : Common duct leakage sites

Fig.22 Illustration of typical leakage points for rectangular ductwork [source: AC&R J.]

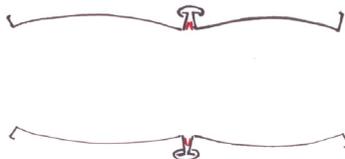


Fig.23 Cross section of a rectangular duct under pressure - causing the flange gasket seal to open [source: L.A.Matsson]



Fig.24

Indoor environment, health & safety

- > Reduced leakage means that the air needed to maintain the indoor environment flows exactly where it is intended to go. Hence the whole system can be dimensioned and balanced exactly as it should, providing good indoor environment.
- > Round ducts are easy to clean, as there are no sharp corners.
- > The noise generated in straight ducts is normally insignificant compared to the noise generated in e.g. elbows. Standardized round duct components have well known acoustic properties, whilst the properties of 'tailor-made' parts in rectangular ducts is often unknown.
- > It is easier to measure the airflow in round ducts, which can make for simpler and more accurate balancing.
- > The round 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 depends on the application.
- > Fire insulation of a duct to a specified fire safety class might be achieved with thinner insulation on round ductwork. Rectangular ductwork may need thicker insulation as it is compressed at corners.

Energy efficiency & environmental impact

- > The pressure drop in round duct systems is often lower than in a rectangular duct at the same air velocity due to industrially manufactured and aerodynamically designed duct components such as elbows and branches. This leads to lower fan power.
- > The total airflow rate can be lower due to less leakage, which further reduces fan power. Class C round ductwork has typically 30% less fan power than traditional Class A ductwork. Similarly, airtight systems facilitate exploitation of the full benefit of other energy efficiency measures, including demand-control, and heat recovery, and energy for heating & cooling is reduced by approx. 15%.
- > Less material (steel & insulation) is used. On a large scale, this has environmental benefits.

Costs

- > The installation time for a round duct system is normally shorter, approximately half that for a similar rectangular system [19]. Delivery times can also be shorter due to the standardized sizes & components.
- > Using round ductwork with standard sizes (the diameters of the ducts increase by 25 % upwards: 80, 100, 125, 250, mm, etc.) decreases the waste during installation. Short pieces of round duct, or surplus components, need not be scrapped, but can be used elsewhere. The investment cost for suspensions and insulation are also reduced. Thus total material costs can be 12-25% less than rectangular systems [19].
- > The overall cost (sum of material and assembly costs) is normally lower, approximately by 25% [19], at least in countries where round ducts have been in use for a longer period of time.
- > Any additional investment cost (if any) for round ductwork is probably not significant since labour cost is considerably reduced. Furthermore, any higher investment cost for a higher quality duct system should be considered based on Life Cycle Costs (LCC) due to the energy savings.

(ii) Establish guidelines & requirements, ideally with incentives

Trade guidelines

Each country should establish trade norm or requirements on duct systems in verifiable terms. This should be referred to/specified in tender and contract documents.

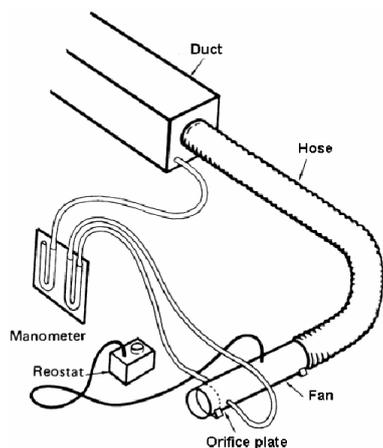


Fig.25 Illustration of test setup for leakage testing [20]



Fig.26 Example of Scandinavian duct leakage testing equipment [Swema]



Fig.27 Another example of Scandinavian duct leakage testing equipment [Lindab]

Energy performance requirements

Duct leakage can be included as a parameter in the national Energy Performance Calculation method. For example, in France, the default leakage rate corresponding to 15% of the nominal air flow rate (about 3 times worse than airtightness Class A in the EN standards). If no documentable information is available on the ductwork airtightness then one has to assume the default value.

Include them in building contracts

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, for example.

(iii) Verify them in each project, with predefined penalties

All ventilation and air conditioning systems should be carefully commissioned. Building contracts should include the cost of leakage testing, and describe what method is to be used, and what happens if the requirements are not met. VVS AMA is a very good model to use.

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