Proposal of a More Reliable Model and Procedures for Estimating Operational Leakage in Air Systems.

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ABSTRACT

The European Directive2024/1275 issued in April 2024 reiterates the goal of having zero-emission buildings in 2050.The consequences in terms of lost energy and performance of poorly tight air ducting are among the biggest waste factors related to HVAC systems and have to be considered.

Nowadays, with the exception of a few specialist sectors, designers, installers and end users are not aware of the impact of leakage and are generally not in a position to measure or estimate it easily.

The current regulatory framework also refers to models that were formalized in the 1980s for classification purposes only, at a time when the technology available for testing was very different from what it is today; namely, the model that it was decided to apply and subsequently inherited is based on a power law that expresses the dependence of the exfiltrated flow rates on the difference in static pressure between the inside and outside of the channel raised to a constant exponent and equal to 0,65.

Both theory and experimental tests conducted and also reported by numerous authors in the scientific literature show that the exponent can vary in a range between 0.5 and 1, nevertheless the procedures reported by international standards and used to estimate operational leakage refer to that 0,65 model, introducing further ambiguities in the choice of pressure to be used in the evaluation under working conditions.

Modern measuring devices today allow for more complete automated tests than those required by the DALT standard for classification and would allow for a more refined characterization of leakage behavior with a little effort. The paper proposes a critical review of the original framework inherited from modern standards and makes an attempt to point out the issues that could allow a more reliable estimation today, proposing more effective measurement methods for the characterization of a reliable model, in analogy to what is done today in related fields such as the tightness of buildings.

The application of the advanced model shows, on the tests conducted for this study, a very high reliability, verifying, in one case tested, leakage exponents between 0.53 and 0.57 with values of the coefficient of determination R^2 regularly exceeding 0,99.

KEYWORDS

Air Systems Leakage, Air tightness, DALT, HVAC efficiency

1 INTRODUCTION

The European Economic Community Directive 2024/1275 issued on 24 April 2024 [1] sets 2050 as the target year to achieve zero-emission building stock within the union.

The goal is very ambitious and its pursuit cannot avoid considering all the so far neglected aspects that can lead to energy waste, and the subject of airtightness of both buildings and mechanical ventilation systems is explicitly mentioned. In particular, Article 4 requires all member states to have suitable methodologies for quantifying consumption and in Annex I - Common general framework for the calculation of the energy performance of buildings, the requirement for a calculation that takes into account the tightness of mechanical ventilation systems is explicitly mentioned.

Leakage faults in air systems have important consequences both in terms of performance and energy consumption; with regard to the latter, it is worth highlighting at least two aspects:

i) Increased fan consumption when leaks are compensated by an increase in the operating speed. This can occur e.g. as a result of an adjusting action required in the TAB operations of constant flow systems, or as compensation achieved by an automatic flow control in the case of variable flow systems; this type of increase is not easy to quantify because the calculation of fan power increases cannot be carried out by applying traditional fan laws, as the leakage phenomenon does not respect the quadratic relationship between pressure and flow rate that is generally assumed to be valid in HVAC systems [2].

ii) Increase in thermal energy consumption from thermal generators. This increase is primarily due to the increase in the flow of outside air passing through the treatment section of the air handling units but may also be linked to a deterioration in the performance of the heat recovery section due to the partial dilution of the expulsion air with potentially untreated air; In addition, in the case of recirculation, unconditioned air infiltration into the return ducts also constitutes an extra heat load.

Finally, although not strictly pertinent to the present discussion, it should be remembered that the infiltration of outside air into air-conditioned spaces due to tightness faults in the building envelope is often counteracted by creating overpressure conditions in the spaces through the imbalance between the flow rates of incoming and outgoing outside air. This imbalance has as a side effect the more or less significant reduction of the flow rate from which energy can be recovered.

Many studies and simulations have been conducted to quantify the energy cost of poorly sealed air systems, among others the 2022 work of N.Hurel et al. [3], 2018 and 2019 V. Leprince et [2,4] and the less recent ones by Soenens et al. from 2011 [5], by P. Stroo from 2011 [6] and by C.P. Wray et al. from 2010 [7] are significant.

These evaluations are based on the application of the models provided by the Standards in force or on the implementation of analytical models and lead to quantifications indicating that systems with good tightness can have lower consumption in the range of 30% to 46% when compared to systems with poor tightness.

1.1 Direct measurement of operational leakages according to the ASHRAE Standard 215:2018

From a theoretical point of view, an effective methodology for determining operating leaks is to measure the difference between the flow rate measured at the fan and the sum of the flow rates measured at the terminals. This methodology is very simple in theory but presents significant metrological problems, as the uncertainty with which the two terms of the subtraction can be measured in practice is usually comparable or even greater than the magnitude of the expected result itself. The propagation of the measurement uncertainty on the leakage value obtained results in the uncertainty range of the measurement being greater in absolute value than the flow rate to be estimated.

This methodology is the subject of ASHRAE Standard 215 [8] which deals specifically with measurement uncertainty and instrument selection.

The main result is that, in the absence of efficient flow meters with very low uncertainty, direct measurement of leakage can lead to inconsistent measurements.

This criticality is amplified when the value of exfiltrations is low and consequently direct measurement may be easier (i.e. based on cheaper instrumentation) for the evaluation of low leakage systems, which, moreover, represent the majority of installations today [9].

Considering the future prospect of improved tightness systems, the above-mentioned complications make the method difficult to apply in the absence of expensive instrumentation.

Furthermore, the main problem for the large-scale application of the Standard 215 could be in the fact that the proposed procedure cannot be carried out with the instrumentation already available to professionals in the field due to classification requirements.

2 MATERIAL AND METHODS

Faced with a need for calculation and assessment that is becoming increasingly explicit and the fact that direct measurement can be complicated, it is evident that little has been done to date to make the assessment of operational leakage as something feasible on a large scale, and almost all that has been done at the regulatory level is based on extending the application of the DALT models originally proposed for classification.

2.1 The DALT model.

As mentioned above, the trend is to use the reference models that were adopted in the 1980s and 1990s with the aim of implementing a method of classifying air components and systems that would be easy to apply with the technologies available at that time.

At the time, the idea was to prioritize the simplicity of measurement, and consequently a relationship was constructed that was able to provide the necessary elements for the classification of a system or (more often) a section of a system by means of a single measurement made at a reference pressure; nearly all the standards governing the characterization of the tightness of air systems for HVAC in both Europe and the United States (originally referring to SI and IP systems respectively) have adopted this strategy [10–26] and in the following we will refer to this relationship as the DALT model.

The DALT model is expressed in the form of a power law:

$$m_{exf} = f \times A \times \Delta P^{n} \qquad (1)$$

Where m_{exf} [l s^{-1}] (or [m^{3} s^{-1}]) is the leaked flow rate,

f [l s^{-1} m^{-2}] (or [m^{3} s^{-1} m^{-2}]) is the leakage coefficient that depends on the manufacturing characteristics of the air system, A [m^{2}] the surface area of the duct, ΔP [Pa] the static pressure difference across the duct surface, n leakage exponent currently assumed to be equal to 0,65.

Experimental evidence shows that indeed the power law form is correct, but that nevertheless the value of the leakage exponent n may vary, and this fact will be further explored later in this paper.

Using 1) in its form with n=0.65, it follows that by measuring the flow rate required to maintain at a certain pressure a section of plant whose leakage area is known, it is possible to determine the leakage coefficient f, this type of test is called Duct Air Leakage Test or DALT.

The DALT is carried out by closing the inlet section of the part of the ducting under test with a plate, capping all diffusers, and supplying compensation air via an external device equipped with a dedicated fan capable of modulating and measuring the flow necessary to reach and maintain the Test Pressure. This mode of operation allows, for systems with acceptable tightness, to consider the static pressure within the tested part of the system as constant, and consequently 1) can be applied by associating the flow rate dispersed across the entire surface of the part of the system under investigation with the test pressure value.

The calculation of f can be carried out downstream of the test as

$$f = \frac{m_{exf}}{A \times \Delta P^{0,65}} \qquad (2)$$

With the sole exception of systems for which the value of n actually happens to be 0.65, this method of calculation leads to a different f-value for each pressure value, and it was therefore decided to consider for the classification of ducts and components the test conducted at a reference pressure indicated on tables in the Standards and referred to the expected tightness class and the pressure class of the system tested (EN1507, EN 12237) [16,17].

Once the value of the leakage coefficient f has been determined, it is compared with threshold values that define the different air duct tightness classes.

The European standards dealing with the classification of air tightness of systems that have been published over time deal with systems characterized by certain construction specificities such as material, section geometry (circular or rectangular) of the type of component (ducts or line components) and provide for tests carried out on the individual component and also tests carried out on the installed system, however they have practically in common the DALT model, the criterion of class assignment and the indications on the of test pressures.

The reference to the same relationship 1) offers the advantage of harmonizing the characterization of the components with the characterization of the installed systems, although a crucial role is played by the assembling operations, so it is not possible to state that a system composed of components belonging to a specific class belongs to that class without having carried out a field measurement.

As an indication, Table 1 conforming to EN 16798-3-2 (2017) [14] which is the most recent standard and contains cross-references to almost all previous standards, is given. The table shows the Class limits to consider for the leakage factor f.

Table 1. Classification of system air tightness according to EN 1698-3-2, with reference to the old Class nomenclature.

Air Tightness Class		**$f_{\max}$ [m^3 s^{-1} m^{-2}]**
Old	**New**	
	ATC 7	$0{,}0675 \times P^{0,65} \times 10^{-3}$
A	ATC 5	$0{,}027 \times P^{0,65} \times 10^{-3}$
B	ATC 4	$0{,}009 \times P^{0,65} \times 10^{-3}$
C	ATC 3	$0{,}003 \times P^{0,65} \times 10^{-3}$
D	ATC2	$0{,}001 \times P^{0,65} \times 10^{-3}$
	ATC1	$0{,}00033 \times P^{0,65} \times 10^{-3}$

Table 2 shows the pressures at which the tightness test of ducts should be carried out with reference to the expected working pressure classes and tightness class according to EN 1507 (rectangular sheet metal ducts) and EN 12237 (circular sheet metal ducts) [16,17].

Table 2. Pressure reference values for leakage testing according to EN 1507:2006 and 12237:2003

	EN 1507 rectangular sheet metal ducts				**EN 12237 circular sheet metal ducts**	
Air Tightness Class	**Static pressure limits [Pa]**				**Static pressure limit [Pa]**	
	Negative at all pressure classes	Positive at pressure class			Negative	Positive
		1	2	3		
A	200	400			500	500
B	500	400	1000	2000	750	1000
C	750	400	1000	2000	750	2000
D	750	400	1000	2000	750	2000

It can be seen that Table 2 refers to the measurement of the ductwork only and that the values given in the table are values above or far above the pressures at which the systems are normally operated.

With regard to tests on the installed system complete with all components, EN 12599:2012 [27] (also referred to by EN 16798), indicates in its appendix D (point *D.8.1 Air Leakage - Measuring Method*) lower pressure levels by explicitly referring to the level as close as possible to the average operating pressure of the system, indicating as preferably the values of 200Pa, 400Pa or 1000Pa in the case of supply systems and 200Pa, 400Pa and 750Pa in the case of extract systems.

The same standard, however, admits that these pressure levels might be impossible to achieve during a DALT in the case of a poor seal and therefore considers the possibility of carrying out the test at lower pressures by applying the relationship 1) with $n = 0{,}65$ to bring the values obtained in this way back to the reference pressure of the test. This in fact legitimises the application of 1) as a wide range model and is equivalent to assuming that the f-factor calculated at lower pressures is equal to that which would have been obtained by performing the test at the pressures indicated as preferable for the test. This assumption is incorrect because it implies that 0,65 is the true value for all systems whereas the experimental evidence proves that this is not the case.

The definition of the value n=0.65 adopted for the exponent n in the Dalt models comes from a collaborative study conducted in 1985 by SMACNA, ASHRAE and TIMA (Thermal Insulation Manufacturers Association) with the aim of identifying a unique value. This study was formalised in an ETL report No. 459507 *Investigation of Duct Leakage*, 1985 [28,29] and in the same year transposed into the SMACNA manuals [30]. The tests considered different geometries (rectangular, circular, flexible ducts), materials (metal or fibreglass ducts) and types of sealing, and the n = 0.65 value identified for the characterization of leakage at the test conditions was established in terms of an average value within the range of 0.5÷0.93 found experimentally.

Ultimately, it can be concluded that the DALT model formalised by relation 1) can be used for classification, however, it requires that the test pressures are defined and are the same for all systems or components that are to be combined or compared with each other. Otherwise, if it is accepted to carry out tests even at lower pressures, relation 1) may lead to a mischaracterization. In the case of certain situations, it may also happen that the same system tested at different pressures may turn out to belong to different classes. These considerations lead to the conclusion that there is a need to review the model applied and adopt one that can make the measures more flexible and the results more consistent, also in terms of Classification.

2.2 Quantification of operational leakages according to EN 16798-5

Part 5-1 of the European Standard issued in 2017[13], deals with Calculation methods for energy requirements of ventilation and air conditioning systems, and proposes a simplified method for quantifying the lost flow rates in aeraulic systems. In Section 6*.3.2.2 duct leakage factors*, the amount of air leaked in the whole system is estimated by using the DALT model with n=0.65 and applying the coefficients f associated with the leakage classes defined by EN 12237 and EN 1507 to the total area of the system estimated according to EN 14239 [31]. The pressure value considered for the calculation is "*the average between the pressure difference at the AHU outlet and the pressure difference right upstream of the air terminal device"*.

A discussion of the critical issues related to this methodology and the formulation of proposals that can be considered as an alternative is proceeded with.

3 DISCUSSION

The procedure for calculating operating losses proposed by EN16798, although simple and although based on an accepted model that has been in technical regulation for a long time, is weak for essentially three reasons:

1) The reliability of the model;
2) The consideration of prevalence calculated as an arithmetic mean;
3) The evaluation of the surface area using the procedures of EN 14239.

The three different aspects are developed below.

3.1 Model Reliability

The critical issues introduced by the constant exponent model already emerged when analysing how the model is also used for classification alone. In order to better address the issue of using the DALT model also for the assessment of operating leaks, it was decided to proceed with a quantitative approach. The first assessment that can be made relates to the potential error in the leakage assessment of three systems that when tested using DALT at a test pressure of 400Pa were found to have the same leakage consistent with Class A. The three systems, indistinguishable from each other at 400Pa, differ in the value of the leakage exponent which will be 0.5, 0.65 and 0.93 respectively with reference to the range identified by the 1985 collaborative study mentioned above.

Figure 1 shows the behaviour of the three systems in the pressure range between 50Pa and 500Pa.

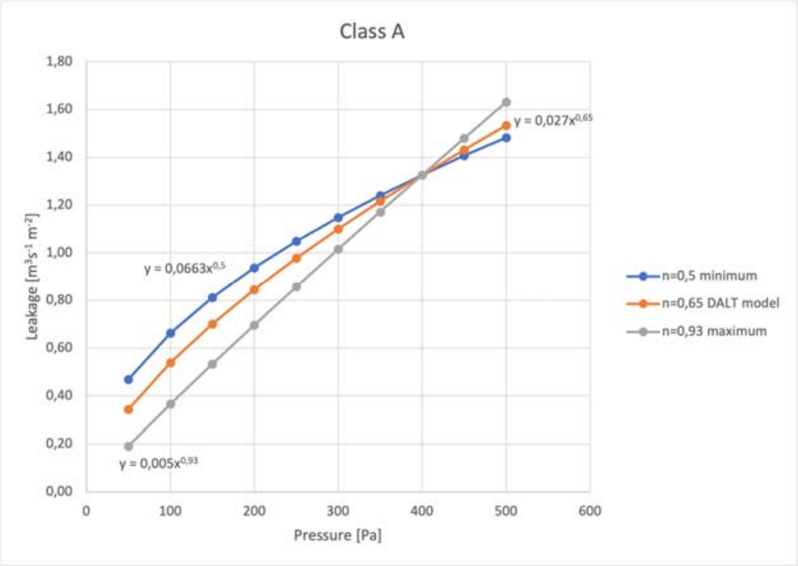

Figure 1: Comparison of systems with exponents other than n=0,65

Assuming the Operating Leakage to be evaluated at an equivalent operating pressure of 100Pa, the calculation of the exfiltrated flow value shows that the system characterized by $n = 0{,}65$ loses 47% more air than the system with $n = 0{,}93$ and 19% less air than a system with $n = 0{,}5$. These differences are unacceptable and do not allow, for example, useful results to be obtained in an evaluation scenario of an investment to improve the tightness of an existing system.

Finally, in order to better highlight the criticalities of the constant exponent model, experimental tests were carried out on a real system. Figure 2 shows the leakage trend measured on a section of an existing system serving an office building located in Northern Italy. The tests were conducted by using a DALT native instruments (TSI - PAN341 model, Pressure probe accuracy 1%±1Pa in the range ±2500Pa, Flowmeter accuracy ±2,5% of reading or ±0,01l/s in the range 3,6÷720m^3/h, Barometric Pressure measurement accuracy ±2%) and were conducted at pressure steps increasing by 50Pa from within the range 50Pa to 500Pa. Table 3 shows the results of the test performed.

Table 3. Result of exfiltrated flow measurement conducted at different pressures..

Pressure (Pa)	**m_{exf} [m^3/h]**	**m_{exf} [l s^{-1}m^{-2}]**
50	156	0,52
100	230	0,77
150	285	0,95
200	332	1,11
250	373	1,25
300	411	1,37
350	445	1,49
400	477	1,59
450	510	1,70
500	535	1,79
Instrument: TSI - PAN341 model		
Surface 83,1 m^2		

Standard 1507 provides for the possibility of testing at different pressures; Section 6.*2 Leakage Test Report* and Section 6.2.2 *Test Result* refer to the possibility of testing at different pressures, in which case, however, instead of considering the evaluation of a different exponent, it requires plotting the different values of f obtained from the report at $n = 0{,}65$ in relation to the different test pressures.

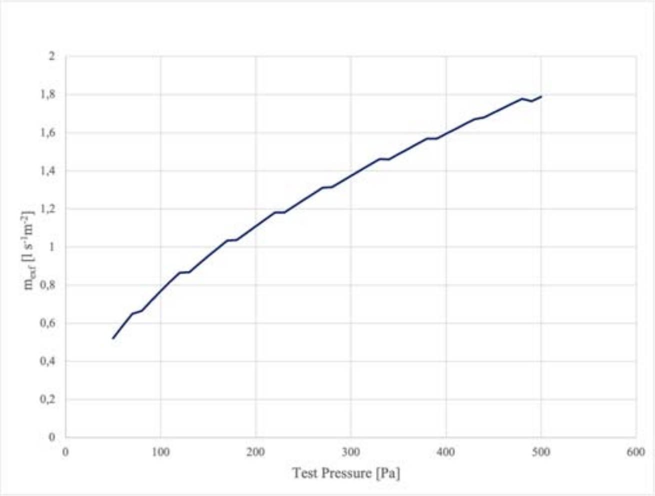

Figure 2: Trend of the model at n=0,65 fitted to measurements at different test pressures

Figure 2 shows the reconstruction of the system's trend by associating a section of a curve at n=0.65 around each pressure value tested, showing a step-like behaviour which is obviously far from any physical sense. Similarly, the required representation of the different values of f for each pressure value shows a discontinuous variation of the same (Figure 3) which is difficult to justify from the point of view of the fluid dynamics of leakage. The percentage variation from the mean value of f in the pressure range investigated goes from -9.8% to +17.5%.

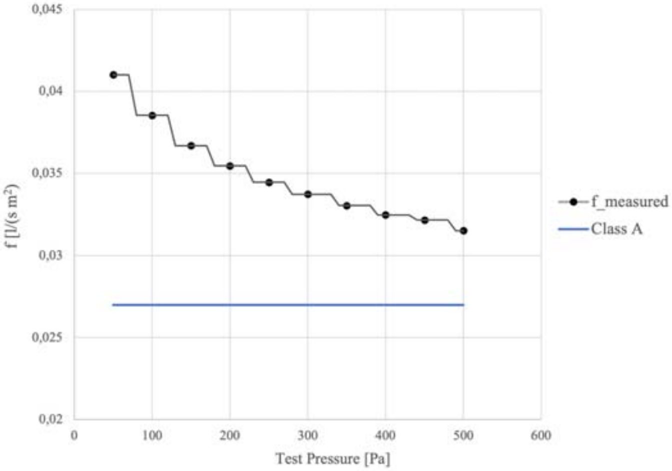

Figure 3: Trend in the value of the f coefficient calculated on the basis of the model forced at n=0.65 obtained from tests at different pressure values, A Class limit is also represented.

Finally, the same measurements were analyzed by admitting the possibility of identifying an unblocked exponent trendline. The behavior of the resulting model is depicted in Figure 4.

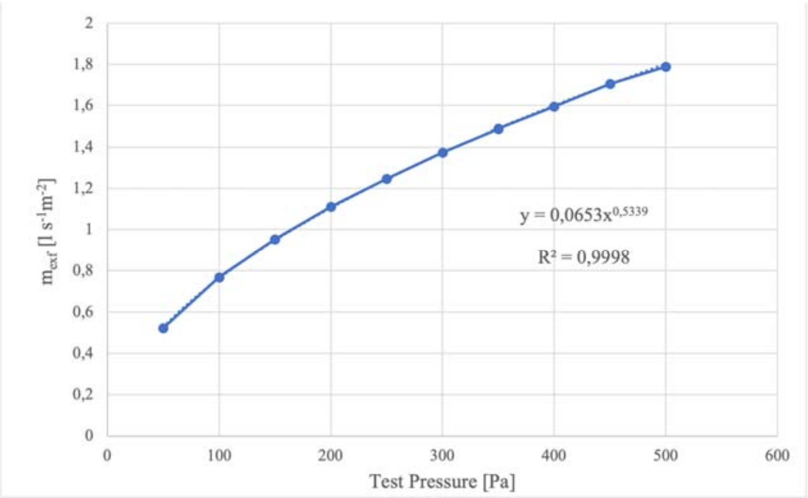

Figure 4: approximation curve obtained by calculating the value of n via logarithmic linear regression. n=0,5339

It can easily be seen that the obtained model proves, as was expected, a satisfactory consistency with the measurements and demonstrated through the evaluation of coefficient of determination R^2, whose value is very close to unity.

In terms of the usefulness of the application of the advanced model also for classification purposes, it can be seen that the leakage coefficient obtained from the regression process has a much smaller variation (-1.1% to +0.8% compared to the average value in the 50-500Pa range). Figure 5 shows the trend of f over the investigated pressure range.

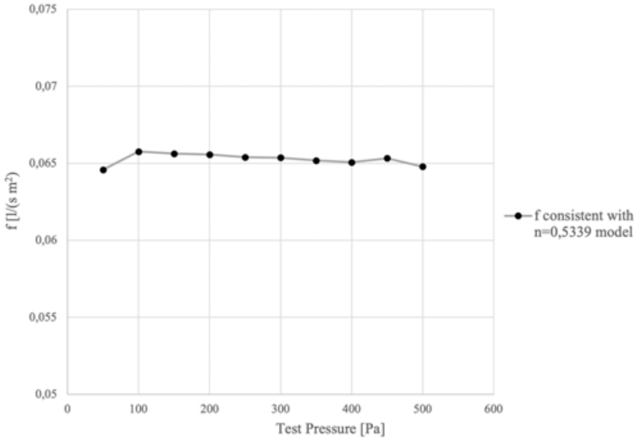

Figure 5: trend of f over the investigated pressure range 50÷500Pa and consistent with leakage exponent obtained by regression process.

Finally, it should be noted that the coefficient f calculated in the two modes incorporates the different contribution of the pressure term in the calculation, which is raised to different exponents and is consequently very different:

$$\frac{f_{n=0,5339}-f_{n=0,65}}{f_{n=0,5339}}\times 100 = \frac{0,065-0,032}{0,065}\times 100 = 50,1\% \qquad 3)$$

This shows how the imposition of an incorrect value of the leakage exponent can also affect the parameter used for classification.

In assessing the suitability of the constant exponent model, it is useful to emphasise that the additional effort involved in performing a multiple test at different pressures to determine the correct exponent is relatively low.

Furthermore, the methodologies for calculating the exponent from multiple pressure tests are also well proven and reported in standards developed for related topics such as the tightness assessment of building envelopes.

These results and considerations are confirmed by the Literature, measurements performed by Aydin et al. 2006 [32] show how different construction types lead to n values in the range 0,32÷0,66. In particular, it can be seen from the measurements carried out that the higher the construction quality, the higher the value of the exponent. Exponent values close to 0.5 can also be found in the literature in another work of 2012 by S. Moujaes, R. Gundavelli[33], where the exponents referring to different geometries in the leakages lie within the range 0,46÷0,5. From a theoretical perspective, the range between 0.5 and 1 derives from the fact that the leakages can be composed of leakage phenomena that follow a behavior assimilable to turbulent-type flow characterized by the value 0.5 and phenomena assimilable to a laminar regime characterized by the value 1. However, this interpretation does not explain the presence of measured values of lower than 0,5, values that are characteristic of systems built without any care for tightness. It is considered that these aspects deserve further investigation but are also a further reason for abandoning the old model. The leakage model characterized by a variable leakage exponent and to be measured experimentally is already used in applications related to building leakage assessment, in which the tightness tests involve measurements using blower door instruments at different pressure values. Standards ASTM E779:2019 [34] and ASTM E1554/1554M:2018 [35] refers to the performance of a defined number of tests under increasing pressure/de-pressure to determine the value of the n exponent valid for the specific case. The same standards apply the unweighted log-linearized linear regression tecnique (E779 – Annex I) to calculate the leakage factor and exponent, which in this case are referred to as envelope leakage coefficient C and pressure exponent n, as well as to quantify the estimated precision error.

Furthermore, it is useful to point out that the instrumentation used for DALT testing is already functionally adequate for carrying out the necessary measurements.

3.2 Equivalent Operating Pressure

The second critical issue related to the evaluation of operating losses according to EN 16798-5, concerns the choice of average head as the value to which the model should be applied. The head to be considered cannot by definition be the average pressure.

If a reliable model is available, the first possibility for estimating operating leaks is the analytical calculation whereby the model is applied section by section, associating each pressure level with the relative share of the leaking surface.

Since this procedure can be cumbersome, an alternative is to find a way to identify the equivalent pressure level that takes into account the distribution of pressure values over all sections of the ductwork and allows the model to be applied only once and to the total area. A method for calculating the equivalent pressure for the purpose of estimating operating leakages was presented by the same author in a 2024 paper [36]. The name of the proposed method is 4-Bands Methods, the idea behind the method is to divide the range of pressure between the value at the fan P_{Sfan} and the value at the terminals (diffusers) P_{Sdiff} into four equal pressure bands and to calculate the percentage share of leaking surface associated with each pressure band. This calculation can be rather easily automated and implemented in the duct design procedure and provides the necessary indexes for an analytical calculation of the equivalent pressure in the form:

$$\Delta P_{S_{eq}} = P_{Sfan} \times [\sum(\alpha_i \times C_i{}^{n})]^{\frac{1}{n}} \qquad (4)$$

Where $\Delta P_{S_{eq}}$ [Pa] is the equivalent operating pressure for leakage calculation purposes, P_{Sfan} [Pa] is the pressure at the fan, $\alpha_{i=1,2,3,4}$ [0÷1] are the shares of leaking area associated with each pressure band obtained from the preliminary analysis of the network, C_i are the calculation constants that depend on the ratio between the pressure value at the fan and the pressure value at the terminals, n is the leakage exponent proper to the system and determined experimentally as indicated in the previous point.

It should be noted that the equivalent operating pressure value depends on the exponent and therefore the experimental determination of the correct value of the latter is also essential for this reason.

3.3 Evaluation of the Leaking Surface

EN 14239-2004 provides a calculation method for the leakage surface of both circular and rectangular ducts. The methodology is highly simplified so that comparable results can be guaranteed even when applied by different operators. In particular, fittings such as bends, tees, converging and diverging sections are not considered in their real geometry, but as virtual extensions of straight ducts whose extent is obtained through a simple geometric criterion. Area values are calculated as the multiplication of a perimeter by an increased length to account for the presence of fittings.

for the purposes of accurate leakage calculations this logic reveals two critical issues : the first is that special pieces are constructively more complex and normally have a significantly higher frequency of localized leakage failure situations than channels, and the second is that this calculation generally leads to significant underestimation of actual values and thus can significantly affect the results.

Actually, it should be emphasized that a precise quantification of the surface area is very important at the classification stage because the loss factor f is inversely proportional to the surface area value entered into the calculation, however, the really important parameter to be used when applying the model for the purpose of calculating operating leaks is the product $A \times f$, and if this value is obtained experimentally by means of a measurement applied to the entire system, it is not necessary to calculate the two factors f and A separately.

4 CONCLUSIONS

The research addresses some evaluations with reference to the existing regulatory framework for air leakage in HVAC air systems. The critical analysis of the methodologies currently adopted for leakage characterization highlights how measurement and modelling problems underlie an insufficient awareness of leakage and the consequent difficulty in quantifying lost energy. Experimental and literature evidence shows that the model historically adopted and used was created for classification purposes only, and that if used improperly, it can lead to errors (i.e. ranging from -19% to +47% in the case study). Considering the capabilities of modern DALT instruments and the existence of established calculation procedures in related fields such as building envelope tightness, it is believed that both technology and professionals are ready for a change in methodology and that the publication of local and international Standards adopting more reliable models is therefore desirable. Without this change, quantification cannot be considered satisfactory and the problem of leakage in aeraulic systems will not be addressed effectively.

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