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Proposal of a new method for the characterization and operational air leakages assessment in HVAC systems

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ABSTRACT

Reducing air leakages in HVAC systems is potentially one of the actions with the best potential for energy savings in the residential sector. The assessing of air leakages in HVAC systems is currently addressed in two ways: i) the traditional DALT (Ducts Air Leakage Tests) to characterize and compare ductwork and ii) the ASHRAE 215:2018 standard method to measure leakage at nominal working conditions. In this paper an innovative experimental method for assessing air leakages in HVAC systems at operative conditions is proposed. The method is based on flow rate measurements at different pressures and performed with closed terminal dampers. The so called "Shut-Off Method" has been then experimentally validated in a real plant showing good agreement with the ASHRAE 215 procedure. Finally, on the basis of the Shut-Off model application, the leakage coefficient used by the standard DALT classification procedure was calculated, showing leakage performance 2,3 times worse than the Eurovent Class A requirements.

1. Introduction

The subject of airtightness is of increasing importance and represents one of the most promising fields of energy efficiency in new and existing buildings. Aeraulic systems, unlike hydronic systems, are characterized by construction methods that make them inherently non-tight, except in very specific cases generally found only in laboratories and in very special applications where the lack of tightness may have consequences considered unacceptable.

From the perspective of quantifying leakages, many international institutions refer to maximum admissible values that are not always consistent with each other. In 2006, SMACNA [1] stated that 1 % air leakage rate for large HVAC duct systems is almost impossible to attain, and a large, unsealed duct system may develop air leakage well above 30 % of the total system airflow. In 2011, the Associated Air Balance Council [2] reported that a properly installed and sealed duct system can achieve air leakage values as low as 0.5 %; these values are however unattainable with the current construction techniques. More recent references can be found in the ASHRAE Handbooks [3], in which acceptable leakage values at working pressure shall be in the range between 1 % and 5 % of the total flow rate.

Compared to the above declared performance levels, the systems nowadays installed are very often inadequate. Recent measurements conducted in France by Moujalled et al. [4] showed that almost 50 % of the air systems tested in residential applications shows leakages equal to or worse than 2.5 times the A class as defined by all the currently applied European Standards. From the perspective of aeraulic network construction, an analysis by a large North American manufacturer [5] sums up that the air leakage of an aeraulic system depends only partly on how the ductwork is constructed and sealed, while a large part of it is attributable to the line components (e.g. HVAC system components, duct mounted equipment, accessories), sealants and sealing procedures. Furthermore, ASHRAE [3] highlights that: i) a major influence is the quality of the installation and thus of the manual work during assembly and sealing operations or non-automated work in general; ii) the performance of ductworks tends to decay anyway due to changes in the properties of sealing materials over time.

Therefore, the tightness of an aeraulic network cannot be derived from a simple analysis of construction specifications and materials characteristics but must be punctually assessed through plant-specific tests. From an energy point of view, the need to compensate for leaks leads to extra consumption of the fans, as well as to a proportional increase in air treatment costs. According to Soenens et al. [6], ventilation-related energy consumption could be reduced by 30 % by completely eliminating air leakages. The analysis of consumption due to air

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Nomenclature

Subscripts in formulas

exf	exfiltrations
fan	fan
diff	diffuser
damper 0%	referred to damper in fully closed position
s	static
Shut-Off	referred to the Shut-Off Model
TOT	total
DALT	referred to the DALT model originally adopted by Eurovent and related Standards
WC	working condition (operational condition)
T	tracer
model	referred to the analytical simulation based on Shut-Off model
4Band	referred to the 4-Band Procedure application
Std 215	referred to ASHRAE Standard 215 application
AHU	Air Handling Unit

Table 1
Limit values of coefficient *f* in eq. (1) for the definition of Air Tightness Classes according to Eurovent 2/2:1996.

Air Tightness Class	f_{max} [l s^{-1} m^{-2}]
A	0,027 x P ^{0,65}
B	0,009 x P ^{0,65}
C	0,003 x P ^{0,65}

leakages was investigated by Leprince et al. [7] through experimental tests applied to a real system and undergoing tightness improvement from a leakage class of 1,5 times class A to class C (reducing leakage by a factor of 13,5 times). In this case, a reduction of electricity consumption by 46 % (versus a value of 51 % estimated by the models) was found and the non-applicability of fan laws was also discussed.

The reasons why such a potential area for improvement has not yet been properly investigated may be many, among them the inherent difficulty in quantifying the leakages under operative conditions and the difficulty in applying economically viable technical solutions capable of reducing leaks. In fact, the lack of a methodology capable of correctly quantifying exfiltrations under operative conditions does not allow investment in improved tightness to be considered as part of a cost reduction strategy valued in a Life Cycle Costing analysis; this therefore leads to a general lack of interest from designers, manufacturers and installers.

1.1. Leakage tests according to DALT (Duct air leakage Test) Standards

The tests that are normally conducted to assess the tightness of air systems are called DALT tests and are described by different Standards in both Europe [8–15] and the US [16–21]. These tests involve pressurization of the ducts and measurements on a sample part of the ductwork large enough to be considered representative. The procedure requires to isolate a branch or a specific ductwork section under investigation from the rest of the system by inserting in-line sealing plates and closing all terminals with airtight caps in order to obtain a closed surface. The tested section is then pressurized to a defined ΔP [Pa] test value by means of an external fan. The flow rate required to compensate the exfiltrated flow rate m_{exf} [m^3/s] and needed to maintain the constant test pressure value is then measured. This measurement is then referred to the leaking surface *A* of the considered section and to the test pressure ΔP according to the relationship:

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

The value of the exponent *n* in eq. (1) is assumed to be constant and equal to 0,65 by cognizant International Organizations (EN, ASHRAE, SMACNA, EUROVENT), so that eq. (1) allows the indirect calculation of the coefficient *f*, whose value identifies the Class by comparison with the Class limit values provided. The coefficient *f* is therefore assumed to be valid as the average value of the ductwork section tested. Table 1 shows the classification proposed in 1996 by Eurovent [8] from which the Classes in all currently applied European Standards [8–15] were subsequently derived and which is also still referred to by ASHRAE in 2020 [3].

The characterization based on this model presents several practical issues preventing its application on a system under operative conditions. The procedure can solely be applied during the construction and commissioning of the plant and only on a limited section, assumed as representative of the entire system. Furthermore, the method cannot provide information on the amount of air lost under working conditions for two main reasons: i) the test pressure values required by the Standards (i.e. 400 Pa, 1000 Pa, 2000 Pa) are much higher (up to 10 times) than the operative pressure, and ii) the empirical assumption of $n = 0,65$ is only realistic for certain construction types; for these reasons the model results to be unsuitable for recalculating leakages at lower pressures.

High-accuracy measurements carried out by Aydin et al. [22], as well as simulations using CFD by Moujaes et al. [23], show that the value n = 0,65 is not valid in general and the results of the same DALT test conducted at different pressure levels show issues of non-full consistency with the DALT Model itself. For this reason, some Standards (ASTM E779 [24] and ASTM E1554/1554 M [25]) applicable for different situations such as tightness tests for building envelopes require a defined number of increasing pressure tests to be carried out to determine also the value of the *n* exponent valid for the specific case. A further reason why DALT tests do not provide information on leakage under working conditions is that during the test flow rate values are so low that the static pressure remains almost constant throughout the portion of the system tested with little variations depending on the tightness (Leprince et al. [26]). This situation is not representative of normal operating conditions, as air leakage under working conditions depends on a pressure value that varies progressively due to pressure losses caused by friction along the ducts and in fittings and balancing devices. Finally, since it is unlikely to test 100 % of the system, it can be concluded that the DALT test is certainly useful for the characterization of the ductwork construction quality but does not allow the measurement or estimation of leakages under operating conditions, activities that therefore require a different test.

1.2. Operational leakage assessment according to Standard ASHRAE 215–2018

Conceptually, the simplest way to assess air leakages under working conditions is to calculate the exfiltrated flow rate (m_{exf}) as the difference between the flow rate processed by the fan and the sum of the outlet flow rates at the diffusers:

$$m_{exf} = m_{fan} - \sum_{i=1}^{n} m_{i,diff} \quad (2)$$

The above-described approach has been standardized in 2018 by ASHRAE 215 [27] through the comparison of the flow rate at the inlet of the network (or part of the network) with the flow rate at the outlet (including the flow rate at the terminals served) under repeatable operative conditions. The Standard considers the criticality related to the measurement uncertainties of the instruments used and provides a

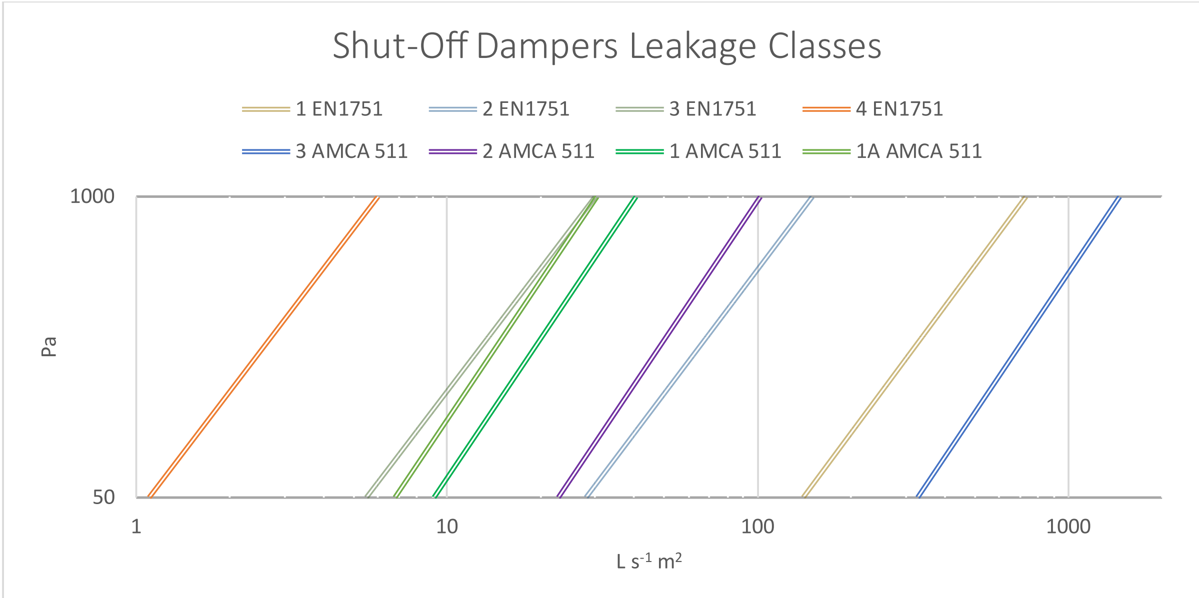

Fig. 1. Representation of limit curves ΔP[Pa] vs $m_{exf\,damper\,0\%}$[l $s^{-1}m^{-2}$] of the Leakage Classes of dampers in Shut-Off conditions according to EN1751 and ANSI/AMCA D511-13.

method for calculating the uncertainty by defining a confidence level. Compared to DALT tests, critical measurement issues arise from the fact that it is necessary to measure flow rates at both the fan and the terminals.

It should be noted that in eq. (2), the two amounts to be compared by subtraction can be measured by methods whose uncertainty is hardly less than 5 %, and that the two values can be so close together (depending on the level of tightness) that the resulting value m_{exf} is of the same order of magnitude of the associated combined uncertainty, with evident criticality in evaluating the error. Uncertainty values of 5 % can be obtained in real systems assessment by measurements with tracer gas, while the methods traditionally used for flow measurement within air systems (e.g. pitot tube) and at diffusers (e.g. balometer) are characterized by even greater uncertainties. This weakness of the method is well considered by the Standard 215, which therefore deals with the analysis of uncertainty and pays due attention to the search for suitable measuring instruments to limit it; the presented uncertainty analysis will be considered as a reference and applied for the experimental validation of the models and method proposed.

1.3. Research relevance

The technical and scientific contribution of this work can be sought in the effort to identify a possible methodology to address the issues arising from a critical analysis about the two above-described strategies for the characterization of air leakage: DALT and Standard 215. Both methods present theoretical and operational shortcomings and/or critical issues. The DALT test gives no indication for the quantification of leakage during operation, the Standard 215 test, on the other hand, requires sophisticated instrumentation that is difficult to apply commercially.

In this paper, the authors present an approach as a synthesis of DALT and ASHRAE Standard 215 methodologies.

The proposed method involves a test mode with closed terminal dampers and is therefore called the Shut-Off method and is developed in four basic steps: 1) Enhancement of the DALT model into a Shut-Off Model with the aim of making it more reliable at operational pressure values. 2) Definition of a test mode capable of characterizing the model referring to the entire circuit by means of a single test; the so defined Shut-Off Test, unlike the DALT test, doesn't need for the ductwork partitioning and sealing by means of end caps and exploits technical information about the diffusers' dampers which are normally installed due to balancing requirements; the needed information, related to the dampers' leakage, is governed by existing standards and currently prescribed by manufacturers' associations. 3) Proposal for a methodology (4-Band Procedure) in which geometric and dynamic information normally made available during the design phase are combined in order to obtain an equivalent pressure value to which to report the Shut-Off Model for the quantitative estimation of operating leaks. 4) Formalization of how the parameters of the Shut-Off Model is processed in order to calculate the value of the equivalent coefficients necessary for the DALT standard classification.

2. Materials and methods

The proposed method assesses leakages in HVAC air systems. It can be applied to both supply systems (under positive pressure) and return systems (under negative pressure) and it's based on measurements taken with closed terminal dampers and is therefore referred to as the 'Shut-Off Method'. Furthermore, in order to overcome the criticalities highlighted for the DALT and Standard 215, the new method has been conceived to meet the following metrological requirements:

1) Applicability: it must be easy to apply without the need for specialized tools and instruments and possibly using a standard DALT test equipment; then, it must be possible to perform the test without to operate on hardly accessible parts and/or components.
2) Accuracy: must be consistent from the point of view of uncertainties and be able to guarantee a reliable measurement by applying methods traditionally used in HVAC assessment procedures.
3) Reconductability: must allow for traceability to DALT-type tests, i.e. obtaining a measured value of f analytically traceable to the DALT test f_{DALT} coefficient and, so, to the Classification by Standards.
4) Consistency with purpose; it must allow direct estimation of leakages under working conditions over the entire ductwork.

The proposed method is a hybrid method that minimizes field measurements by exploiting information made available by components manufacturers and combining them with information achievable during the typical ductwork design process.

2.1. Shut-Off model and method

Aeraulic systems are normally equipped with terminal dampers installed for balancing purpose. These components are factory-built according to production standards with high automation and low construction tolerance. It is assumed that all dampers belonging to the same production cycle (model) show the same air tightness behavior, which is subject to classification and certification according to existing standards. Among the tests that manufacturers are expected to perform on dampers, the Shut-Off leak test is a key part of the proposed method.

The Shut-Off leak for dampers test is standardized by EN 1751 [12] and ANSI/AMCA Standard 500-D [19] and requires the use of suitable instruments and procedures to guarantee a defined accuracy within 5 % of the leakage flow rate through closed fins. For each damper model, the test provides the curve $m_{exf\ damper0\%}$ (flow rate exfiltrated by the fins) vs ΔP within a specified range of pressure. Damper tightness is then characterized according to the Classes 1, 2, 3 and 4 as defined by EN1751 [12] and Classes 1A, 1, 2 and 3 as defined by the ANSI/AMCA D 511–13 Standard [20].

Fig 1. shows the limit curves for both classifications.

Damper manufacturers are requested to provide the classification according to the standards in force for the relevant market; in the case of return systems, the dampers constructively non-symmetrical are supplied with an indication of the flow direction for correct installation.

A real system where all the terminal dampers are closed and maintained at operative pressure values is only flushed by the leakage flow. This flow is significantly smaller than the nominal, so the resulting internal pressure drops are irrelevant. This operative condition is the same of DALT tests, with the remarkable difference that operative pressure is much lower than the DALT test, so that the exfiltrations result to be correspondingly lower although they include the shut-off leakage of the dampers. In addition to that the whole system can be considered at constant static pressure and it is possible to estimate the contribution of the leakage flow rate through all the terminals' dampers simply by referring to the test pressure while reading leakage curves provided by the manufacturer.

The ductwork leakage flow rate at the pressure value ΔP_S can then be obtained as follows:

$$m_{exf\,\Delta P_S} = m_{fan\,\Delta P_S} - m_{dampers\,0\%\,\Delta P_S} \tag{3}$$

where:

- $m_{exf\,\Delta P_S}$ [m^3s^{-1}] is the flow rate exfiltrated from the ducts at the test static pressure ΔP_S.
- $m_{fan\,\Delta P_S}$ [m^3s^{-1}] is the measured flow rate required to maintain the pressure ΔP_S.
- $m_{dampers\,0\%\,\Delta P_S}$ [m^3s^{-1}] is the estimated flow rate through the terminal dampers, in the closed position, obtained from the manufacturer's data at the pressure ΔP_S,according to [12] and [20].

Flow rate measurements can be performed by directly measuring the flow rate elaborated by the system's own fan, which is driven at the velocity needed to reach the requested pressure level. In this case the fan section has to be provided with a low-range flow meter. As an alternative, a traditional DALT test measuring device can be used, which flow rate measuring range shall be consistent with the flow at the maximum pressure to be tested.

The test, performed at different pressure levels allows to estimate both the leakage coefficient $f_{Shut-off}$ and the actual value of the exponent $n_{Shut-Off}$ for the whole system under investigation, through the following equation:

$$m_{exf} = f_{Shut-Off} \times A \times \Delta P^{n_{Shut-Off}} \tag{4}$$

where A [m^2] is the leakage surface of the circuit estimated according to EN 14239 [28].

The calculation of the coefficient $f_{Shut-Off}$ and exponent $n_{Shut-Off}$ can be carried out starting from a number of test performed at different pressure values by linear-logarithmic regression as shown in Appendix1 of Standard ASTM A779 [24].

The approach described can be evaluated on the basis of its capability to provide answers to the requirements expressed in terms of Applicability, Accuracy, Reconductability and Consistency.

2.1.1. Applicability

The proposed Shut-Off method was designed with the objective to provide a greater flexibility of use than the traditional DALT tests. For example, the method does not require the air system to be partitioned, since it is performed at pressures comparable to operating pressures (i.e. 300–400 Pa) and much lower flow rates, allowing the entire system to be characterized in a single test, for example using a native DALT instrument. In these conditions it is sufficient to be able to operate on the diffuser dampers and the starting section of the ductwork.

On the other hand, the use of the presented method is limited to those systems for which the characterization of the dampers under closed conditions prescribed by the standards is available. When these data are not available and, above all, when there are a large number of terminals (and related dampers) of the same type, a special measurement can be carried out with the same DALT instrument, provided that one damper per type is removed and tested as carried out in the experimental validation of the method.

The method can easily be applied in combination with balancing procedures prior to start-up, as it is simple to set the system to shut-off conditions and arrange the fan for the manual speed control required for the test. If balancing is conducted according to the Progressive Flow Method [29], the preliminary closure of all terminal dampers is also the first step to take. This allows TAB (Testing, Adjusting and Balancing) operations to be carried out right after and in continuity with the Shut-Off test. On the other hand, when the leakage test is performed on already balanced system, the position of all dampers must be registered before the test is carried out, aiming at returning the system to the balanced condition at the end of the test. Having the appropriate instrument available, the method also allows the entire network to be tested at the same time, provided that the flow rates circulating due to exfiltration alone are not so relevant as to create pressure drops and consequent causing significant static pressure variations within the network. It is in any case possible to carry out static pressure measurements at different points of the system during the test to confirm this hypothesis.

2.1.2. Accuracy

The direct measurement of leakages at operative conditions, through the difference between fan and terminal flow rates as indicated by the ASHRAE Standard 215 [27] suffers from significant uncertainty issues, which are mitigated, under Shut-Off conditions, by the increase of the flow rates difference. The uncertainty of leakage values of certified dampers is within 5 %. Since Shut-Off leakage flow rates are normally small compared to those exfiltrated by the ducts, the error of the estimation of $m_{dampers\,0\%}$ results in little impact in absolute terms, especially for low tightness systems.

In the Shut-Off method, the only flow rate measured is the flow rate at the fan, then it must be measured with the best possible accuracy. To this aim, the most common available instruments (hot-wire anemometer, Pitot tube, laser-doppler velocimeters) require repeated readings in different measuring points of the same section and show accuracy within 2–5 % [16]. The main uncertainty contributions of the insertion techniques are represented by the positioning (alignment) of the sensor (especially for asymmetrical profiles), the presence of installation effects (e.g. swirls), the flow profile and the difficulty of measuring velocities at near-wall positions. The use of calibrated flanges is also popular in industries, thanks to widespread international standardization and the reliability shown in a wide variety of application areas. The typical accuracy of these methods adopted in real systems is within 5 % [16] depending on the positioning of the static pressure taps and correct knowledge of the fluid density. Alternatively, tracer gas techniques (ASTM E2029 [30]) generally show higher accuracy, even though more complex instrumentation and procedure (R. A. Bryant [31], S. Riffat [32]) are needed. However, although their use is widely diffused and debated in the literature for applications related to ventilation and air exchange rate measurements in buildings, there is still little contribution regarding their use to measure airflow in ducts (C. J. Ghazi [33]). Taking into account the different measurement uncertainties, it can be stated that the results obtained with the tracer gas techniques (with particular reference to the constant injection method - constant dose) are always in good agreement with those obtained with insertion techniques and, for flow rates of 72 m^3/h and above, the constant dose technique tends to show an uncertainty up to 2 % at a 95 % confidence level [27]. In tracer gas techniques, the correct estimation of the integral of the concentration evaluated in the measuring section is crucial, and to this aim increasing the number of samplings or favoring the mixing of the tracer in the air flow (i.e. by positioning the dosing and sampling before and after the fan where possible) could be beneficial. As far as the constant dose technique is concerned, the greatest uncertainty contribution is still represented by the measurement of the tracer concentration downstream of the dosing point. This is due to the combined effect of the accuracy of the tracer flow rate measurement with the repeatability of the analyzer used and whether the measured concentration values are close to the calibration values of the sensor. Furthermore, the degree of tracer mixing in the air stream is also crucial which can weigh over 10 % of the whole uncertainty. To this aim, simultaneous measurements in several points or preliminary uniformity evaluations are always recommended. For these reasons, tracer measurements are considered to be simpler and more reliable if carried out after the fan and with an adequate tracer flow rate. On the other hand, they are less reliable and require a large number of measuring points and/or repetitions if conducted at points where it is difficult to effectively guarantee the degree of mixing downstream of the dosing, such as in terminal sections. With regard to the measurement required by the Shut-Off method, this is carried out at the fan.

A viable alternative to the presented measurement solutions can be the use of traditionally used DALT-type test instrumentation; this equipment can be used in a Shut-Off procedure by shutting off the fan via a seal plate positioned immediately downstream of the fan and connecting the DALT instrument directly to the duct system. From the perspective of size and range adequacy, the DALT instrument must be able to provide and measure the flow rate and maintain the pressure values required by the Shut-Off procedure. This depends on the tightness of the system, its dimensions and on the measuring range of the instrument; however, it should be noted that Shut-Off tests take place at pressures equal to or close to working pressures (200 ÷ 300 Pa), which are significantly lower than those of DALT tests (1000 ÷ 2000 Pa depending on the Standard adopted). This implies that with the same instrument suitable for performing DALT tests on a part of the system, it is potentially possible to perform Shut-Off tests on the entire system.

2.1.3. Reconductability to DALT tests

The Shut-Off procedure requires tests at different pressure values and allows the circuit to be characterized by the two coefficients $f_{Shut-off}$ e $n_{Shut-off}$ and thus the leakage at any pressure value can be estimated using (4). It will be possible to use the Shut-Off model to estimate the exfiltrated flow rates even at the pressure at which the DALT test is to be performed. This enables to virtually perform a DALT test for pressure ΔP and evaluate the result in application of the model characterized by $n = 0,65$:

$$m_{exf} = f_{DALT} \times A \times \Delta P^{0,65} \tag{5}$$

where m_{exf} is obtained from the Shut-Off model and thus (4) and (5) can be combined:

$$f_{Shut-off} \times A \times \Delta P^{n_{Shut-off}} = f_{DALT} \times A \times \Delta P^{0,65} \tag{6}$$

hence

$$f_{DALT} = \frac{f_{Shut-off} \times A \times \Delta P^{n_{Shut-off}}}{A \times \Delta P^{0,65}} = \frac{f_{Shut-off} \times \Delta P^{n_{Shut-off}}}{\Delta P^{0,65}} = f_{Shut-off} \times \Delta P^{(n_{Shut-off} - 0,65)} \tag{7}$$

Unless the special case in which $n_{Shut-off} = 0,65$, the value of f_{DALT} will depend on the pressure value chosen for comparison.

In order to ensure reconductability to the DALT tests, the evaluation should be carried out at the same reference pressures set by the Standards (e.g. ± 500 Pa for class A, +1000 Pa/-750 Pa for class B according to EN 12237 [9]).

2.1.4. Consistency

The measurement strategy illustrated up to this point is capable of defining the loss coefficient and fulfils the criteria of Applicability, Accuracy and Reconductability, but not yet the Consistency, as the simple determination of the coefficient f does not, however, lead to a direct estimation of leakage in real operation. A methodological procedure based on the Shut-Off characterization was therefore investigated with the aim of covering this requirement as well.

2.2. Operational leakage assessment

First of all, the evaluation of air leakages in a system under real working (operative) conditions must consider some fluid dynamics issues. First, air leakages depend on the pressure component orthogonal to the duct surface, which is only static in straight ducts, whereas in the presence of changes of the section or of curves and double curves, a dynamic pressure component should also be considered. However, the ducts geometries are usually shaped to ensure orderly fluid dynamics without too abrupt changes of direction, the velocity components of fluid fillets orthogonal to the surface are generally limited; for this reason, a legitimate simplification is to consider leakages dependent only on static pressure P_S. The ΔP [Pa] value to be considered for the evaluation at operative conditions will therefore refer to a static pressure level within the range between the maximum value (at the fan) and the minimum operative value specified by the manufacturer of the air terminals.

Second, in DALT tightness tests, the friction losses can be neglected in small systems and/or higher tightness classes (Leprince et al. [26]), so that the pressure can be assumed as constant along the whole system. This hypothesis is also relevant for Shut-Off test, however, as in this case test pressures are much lower than those of DALT, these will be more easily verified. Taking these two assumptions into account, in order to obtain an estimate of the real leakage over the whole system (supply or return), the aim is to identify the test pressure value $\Delta P_{S_{eq}}$ (equivalent for leakage assessment purposes) for which it is valid:

$$m_{exf\left(\Delta P_{S_{eq}}\right)} \cong m_{exf\,WC} \tag{8}$$

where

- $m_{exf\left(\Delta P_{S_{eq}}\right)}$ is the exfiltrated flow value at the equivalent pressure measured by a Shut-Off test.
- $m_{exf\,WC}$ is the flow rate actually lost under working conditions.

Unlike the DALT and Shut-Off tests, at operative conditions the pressure varies throughout the system. In order to identify the correct equivalent pressure value, a simplified model was considered in which the max–min operative pressure range is divided into four bands and a so-called "4-Band Procedure" for the determination of equivalent pressure is proposed.

2.3. The 4-Band procedure

With reference to a supply system that has been balanced, under working conditions, the total pressure inside the ducts decreases due to friction losses and therefore sees its highest value at the fan and its lowest value at the ambient terminals.

During the sizing phase, the pressure losses of each section of the ductwork are calculated starting from the terminals and moving back along the system, in order to identify the pressure at each node. At the confluence points, the designer compares the pressure required by each of the joining branches; the branch that requires the highest pressure is identified as the disadvantaged one and a balancing damper is placed on the other path to compensate for its lower pressure drop. The pressure required by the disadvantaged path is then taken as a reference for the further upstream calculation. Eventually, proceeding in this way and going up to the fan, its working pressure is determined.

This calculation is usually conducted through software or a spreadsheet that applies standard drop losses calculation procedures [16] and makes available, among other things, (i) the static pressure of each node, (ii) the size of the ducts and (iii) the external surface area associated with each section of ductwork [28]. By processing this data, it is possible to divide the static pressure working range (from fan to diffusers) into four equal bands $\Delta P_a; \Delta P_b; \Delta P_c; \Delta P_d$ and associate each band with a corresponding fraction of the leaking surface.

The share of leaking area S_i associated with each pressure band ΔP_i is then expressed in terms of a parameter α_i, and the ductwork is characterized by the value of the 4 parameters:

$$\alpha_i = \frac{S_i}{S_{TOT}}; i = a, b, c, d$$

where, by definition, $\sum_{i=a,b,c,d} \alpha_i = 1$

The graphic visualization of the meaning of the alpha coefficients and their determination is shown in Appendix A.

Analitically, the four pressure bands referred to as $\Delta P_a; \Delta P_b; \Delta P_c; \Delta P_d$ can be determined in relation to the minimum and maximum values at the diffuser P_{Sdiff} and at the fan P_{Sfan}, and to the corresponding ratio defined as $C = \frac{P_{Sdiff}}{P_{Sfan}}$.

$\Delta P_a = P_{Sdiff} + \frac{7}{8}\left(P_{Sfan} - P_{Sdiff}\right) = CP_{Sfan} + \frac{7}{8}\left(P_{Sfan} - CP_{Sfan}\right) = \left(\frac{7+C}{8}\right)P_{Sfan}$;

$\Delta P_b = P_{Sdiff} + \frac{5}{8}\left(P_{Sfan} - P_{Sdiff}\right) = \left(\frac{5+3C}{8}\right)P_{Sfan}$;

$\Delta P_c = \left(\frac{3+5C}{8}\right)P_{Sfan}$;

$$\Delta P_d = \left(\frac{1+7C}{8}\right)P_{Sfan}$$

Introducing the constants $C_a; C_b; C_c; C_d$ defined as follows:

$C_a = \frac{7+C}{8}$; $C_b = \frac{5+3C}{8}$; $C_c = \frac{3+5C}{8}$; $C_d = \frac{1+7C}{8}$ (9).

it results in

$\Delta P_a = C_a P_{Sfan}$; $\Delta P_b = C_b P_{Sfan}$; $\Delta P_c = C_c P_{Sfan}$; $\Delta P_d = C_d P_{Sfan}$ (10).

At this point, having discretized the distribution of the pressure and of the leaking surfaces over the 4 bands, it is possible to determine the equivalent test pressure $\Delta P_{S_{eq}}$ aiming at estimating the flow leakages at operative conditions.

Assuming that the Shut-Off method was previously applied to the system, the values of $f_{Shut-off}$ and $n_{Shut-off}$ are known.

The value of the leakages will be estimated from the sum of the values of the exfiltrated flow rates for each i-pressure band, where i = a, b,c,d:

$$m_{exf\,WC} = m_{exf\,a} + m_{exf\,b} + m_{exf\,c} + m_{exf\,d} = \sum_{i=a,b,c,d} m_{exf\,i} \tag{11}$$

where

$$m_{exf\,i} = f_{Shut-off} \times S_i \times P_i^{n_{Shut-off}} = f_{Shut-off} \times \alpha_i S_{ToT} \times \left(C_i P_{Sfan}\right)^{n_{Shut-off}} \tag{12}$$

$$m_{exf\,WC} = f_{Shut-off} \times S_{ToT} \times \sum\left(\alpha_i \times \left(C_i P_{Sfan}\right)^{n_{Shut-off}}\right)$$

$$m_{exf\,WC} = f_{Shut-off} \times S_{ToT} \times \sum\left(\alpha_i \times C_i^{n_{Shut-off}} \times P_{Sfan}^{n_{Shut-off}}\right)$$

$$m_{exf\,WC} = f_{Shut-off} \times S_{ToT} \times P_{Sfan}^{n_{Shut-off}} \times \sum\left(\alpha_i \times C_i^{n_{Shut-off}}\right) \tag{13}$$

The equivalent pressure value ΔP_{Seq} is the value for which the flow rate m_{esf} calculated according to eq. (13) assumes the same value as that the Shut-Off model:

$$m_{exf\,WC} \cong m_{exf\left(\Delta P_{S_{eq}}\right)} \tag{14}$$

where

$$m_{exf\left(\Delta P_{S_{eq}}\right)} = f_{Shut-off} \times S_{ToT} \times \Delta P_{Seq}^{n_{Shut-off}} \tag{15}$$

And by combining (13), (14) e (15):

$$f_{Shut-off} \times S_{ToT} \times P_{Sfan}^{n_{Shut-off}} \times \sum\left(\alpha_i \times C_i^{n_{Shut-off}}\right) = f_{Shut-off} \times S_{ToT} \times \Delta P_{Seq}^{n_{Shut-off}} \tag{16}$$

$$P_{Sfan}^{n_{Shut-off}} \times \sum\left(\alpha_i \times C_i^{n_{Shut-off}}\right) = \Delta P_{Seq}^{n_{Shut-off}} \tag{17}$$

ΔP_{Seq} can be expressed as

$$\Delta P_{Seq} = P_{Sfan} \times \left[\sum\left(\alpha_i \times C_i^{n_{Shut-off}}\right)\right]^{\frac{1}{n_{Shut-off}}} \tag{18}$$

The pressure at which to refer to the Shut-Off test in order to estimate directly in field the system leakage under real operative conditions therefore depends on the fraction of leakage surface area relative to each band $(\alpha_a, \alpha_b, \alpha_c, \alpha_d)$ and on the exponent $n_{Shut-off}$. This pressure value will be within the range P_{Sfan} and P_{Sdiff}, and the corresponding flow rate value can either be measured in a specific Shut-Off test or calculated by means of eq. (15) if the parameters of $f_{Shut-off}$ and $n_{Shut-off}$ are known.

2.4. Case study

The proposed characterization procedure was tested on an existing supply system installed in a tertiary building.

At first, the Shut-Off test was performed on the installation by taking the necessary measurements and the values of $f_{Shut-off}$ and $n_{Shut-off}$ were calculated.

The Shut-Off model for leakage was then applied analytically using a spreadsheet; starting from the construction drawings and the design flow rates at the terminals, a detailed calculation of the pressure values of all nodes and the exfiltration estimation for each section were carried out. This made it possible to analytically determine the flow rates (exfiltration-included) according to the model at each point of the ductwork.

A first validation of the model was then performed by measuring the flow rate at a number of significant points in the system with a tracer and comparing the measured values with the values estimated by the model and taking into account the uncertainty of the measurements.

Then, the 4-Band Procedure indicated for the assessment of leakage under operating conditions was applied. The parameters α_i were calculated by means of the construction drawing analysis and the value ΔP_{Seq} was calculated by means of relation (eq. (18) and the value of the operating leaks $m_{exf\,WC}$ was estimated by means of eq (15) and eq (14).

The value of the leakage under operating conditions was also measured by applying the procedure indicated in the ASHRAE 215 Standard; the measurements at the terminals and at the fan were conducted using the probes already present for variable flow control. The

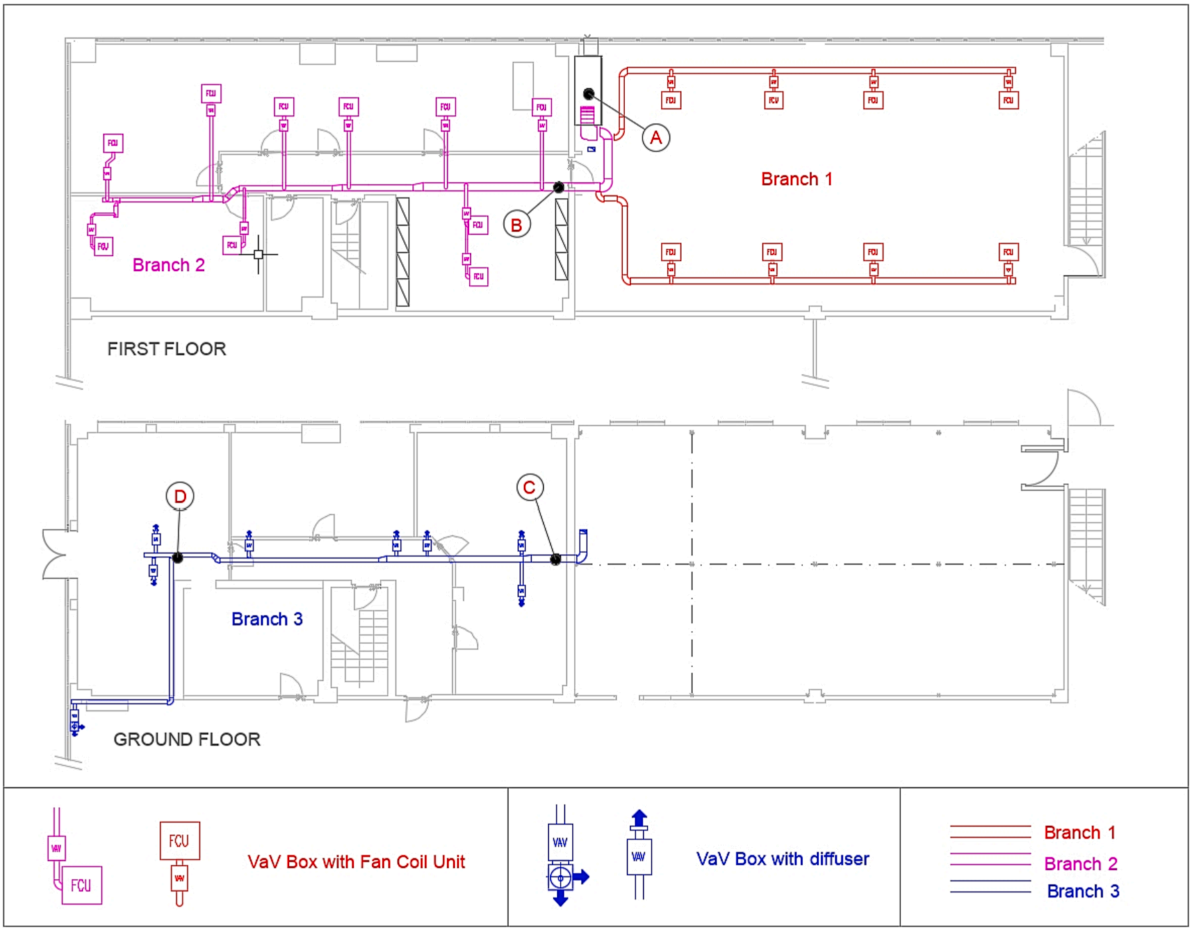

Fig. 2. Construction drawing of the supply system under test, branches by colors and measurements position references.

comparison between the values obtained through the 4-Band Procedure and the measurement according to ASHRAE 215 was accompanied by the analysis of the uncertainty.

Finally, the f_{DALT} coefficient was calculated by means of the application of the Shut-Off model at the reference pressure value prescribed by the DALT Standards and the tightness Class of the tested system was estimated.

2.4.1. Description of the tested system

The system tested is a primary air system serving a two-storey building with individual offices and meeting rooms and is a variable air volume system characterized by the presence of VaV dampers for all terminals, which are either fan coil units or air diffusers.

The control of the system is based on the control of the CO_2 concentration value: local controllers connected to room sensors manage the primary air flow rate through the VaV boxes, the fan is equipped with an inverter and the entire system is monitored via bus. This type of control includes a centralized management system that can be used to force the dampers into shut-off position for the test.

The general scheme of the tested supply system is shown in Fig. 2. The nominal flow rate is 1950 m^3h^{-1} and there is no recirculation.

The system examined is the supply system and consists of three branches, two of them serving two areas on the first floor and one serving the ground floor:

- Branch 1 (red color in Fig. 2) supplies 8 diffusers serving a large meeting room on the first floor.
- Branch 2 (magenta color in Fig. 2) supplies primary air to 10 fan coils located in the offices on the first floor.
- Branch 3 (blue color in Fig. 2) serves the ground floor and supplies fan coils as well as some diffusers positioned in the reception area for a total of 8 terminals.

2.4.2. Characterization of dampers

Given the lack of complete documentation of the leakage test reports conducted according to EN1751 or AMCA511by the manufacturer of the terminal VaV dampers, the procedure was supplemented by an on-site leakage test measurement of the dampers, simplified by the fact that all terminals are equipped with VaV boxes with dampers of the same size and model (Belimo CMV-100-MP).

The characterization was carried out on site with a small test bench equipped with a hot-wire meter with a declared uncertainty of 0,1 m/s and a pressure meter with an accuracy of $\pm$ 2 %, measurements were conducted on different pressure values within the range of the operating pressure values. The measurements were analyzed using the linear-logarithmic regression technique. The result is the correlation between leakage flow rate and static pressure:

$$m_{exf\ damper0\%} = \left(1,5\times10^{-5}\right)\times\Delta P^{0,5843} \tag{19}$$

This leakage Class corresponds to Class 3 of the AMCA Standard 511 [20] and a description of the measurements can be found in Appendix B to this paper.

2.4.3. Measuring instruments

The different tests were conducted with different measurement methods, depending on the type of test.

Tracer gas tests were carried out by using SF_6 tracer gas in constant dose mode. Specifically, a known flow rate of tracer m_{Tracer} is injected

Table 2
Flow measurement at fan in shut-off condition.

Fan Velocity [%]	Pressure [Pa]	Tracer Concentration [mg/m^3]	Air Flow rate [m^3/h]
30 %	40	24,84 ± 0,38	297,72 ± 5,70
35 %	60	18,90 ± 0,29	390,96 ± 7,57
40 %	89	16,46 ± 0,26	448,92 ± 8,76
45 %	120	13,13 ± 0,21	563,04 ± 11,12
50 %	155	12,08 ± 0,20	612,00 ± 12,16
55 %	196	10,59 ± 0,17	698,04 ± 14,01
60 %	248	9,94 ± 0,16	743,40 ± 15,00
65 %	297	9,02 ± 0,15	819,36 ± 16,68
70 %	343	8,26 ± 0,14	894,96 ± 18,37

Table 3
Calculation of exfiltrated flow rates in application of the Shut-off Method.

Pressure[Pa]	Fan Flow rate [m^3/h]	Dampers$_{0\%}$ Flow rate [m^3/h]	m$_{exf}$ [m^3/h]
40	297,72	12,11	285,81 ± 6,18
60	390,96	15,35	375,61 ± 8,06
89	448,92	19,33	429,59 ± 9,23
120	563,04	23,02	540,02 ± 11,55
155	612,00	26,74	585,26 ± 12,54
196	698,04	30,67	667,37 ± 14,29
248	743,40	35,20	708,20 ± 15,21
297	819,36	39,11	780,25 ± 16,76
343	894,96	42,54	852,42 ± 18,30

upstream of the fan or of the position where air flow rate has to be measured. The measurement of tracer concentration $C(t)$ downstream of the fan allows the dilution air flow rate to be determined, provided the absence of tracer in the outside air is verified.

$$m_{air} = \frac{m_{Tracer}}{C(t)} \tag{20}$$

The combined uncertainty of this measurement results from the consideration of the equations for calculating the flow rate value and the accuracy characteristics of the instrument and of the dosing unit. The instruments used for measurements are: an INNOVA 1312 Photoacoustic Monitor, with SF_6 filters, water compensation and declared accuracy $u_{C(t)}$: ±2, 5% of measured concentration value, in combination with an INNOVA 1303 Multiplexer with accuracy $u_{m_{Tracer}}$: ±2% of the declared tracer flow rate.

The tests referred to Standard 215 were carried out by using the measuring equipment available at the fan and flow rate probes on all terminal VaV boxes; the measurement of the flow rate m_{fan} is carried out by measuring the pressure drop across the inlet cone of the plug-fan, whose discharge coefficient is provided by the manufacturer with a declared accuracy of 5 %. The flow rates at the *i-th* terminal $m_{i,diff}$ are measured by means of the VAV boxes velocity probes with declared accuracy of $\pm$ 0.1 $m\ s^{-1}$.

3. Results and discussion

3.1. Characterization of the system by means of Shut-Off model.

The method has been applied following the proposed procedure. Having previously characterized the leakage through the closed damper blades, the only measurements required were related to the flow rate at the fan in Shut-Off condition. The dampers were thus forced in their closed position by a command sent via bus to each VaV box. Tests were therefore carried out at different pressure levels obtained by operating

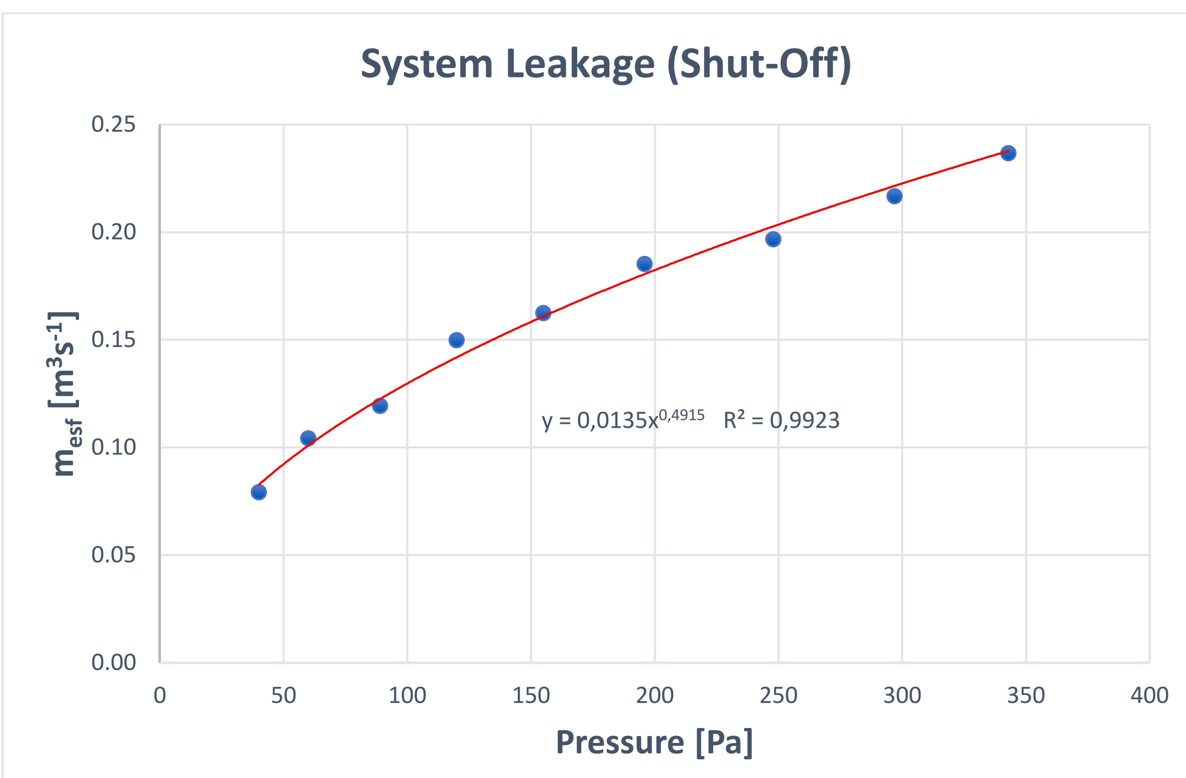

Fig.3. Shut-off test: profile of the total exfiltrated flow rate in m^{3}s^{-1} as a function of the pressure.

Table 4
Comparison values between measurement and model at points A, B, C and D.

Measuring point	Measured flow rate (Tracer), [m^3/h]	Estimated flow rate (Model) [m^3/h]	Deviation [%]
A (Air Handling Unit)	2388	2312	−3%
B (Branch 2)	775	835	+7%
C (Branch 3)	764	800	+5%
D (Diffusers)	320	281	−14 %

Table 5
Calculation of synthetic parameters for the analyzed system.

Pressure Band	C_i	ΔP_i[Pa]	S_i [m^2]	α_i
a	0,896	110,8	2,48	0,03
b	0,689	85,2	30,27	0,36
c	0,481	59,5	30,51	0,37
d	0,274	33,8	19,74	0,24
Whole System	C = 0.170	$\Delta P_{s,fan} = 124$ $\Delta P_{s,diff} = 21$ $\Delta P_{s,eq} = 62$	83.0	–

the fan at different speeds and taking care to investigate the range of values between the expected nominal pressure after the fan (150 Pa) and the nominal working pressure at the diffusers (20 Pa).

The flow rate was measured using SF_6 tracer gas and a known flow rate of the tracer m_T has been injected upstream of the fan.

Table 2 reports the flow rates and pressures at which the measurements were conducted and the corresponding fan speed references:

The leakage flow rates at each test pressure, reduced by the estimated leakage flow rates of the closed dampers and calculated according to the Shut-Off method procedure are given in Table 3.

The uncertainty associated with the exfiltrated flow value is obtained by propagating the uncertainty contributions [34] associated with, respectively, the measurement method of the flow rate at the fan (tracer) and the measurement method used to characterize the dampers (hot wire anemometer).

Fig. 3 shows the linear-logarithmic regression curve that best approximates the relationship between exfiltrated flow and static pressure $m_{exf} = 0,0135 \times \Delta P^{0,4915}$, where $f \times A = 0,0135$.

The flow rate is converted in $[m^3/s]$, so that the value of n is consistent with the expression of f referred to a time in seconds, in accordance with current DALT Standards time reference. The leaking surface analytically calculated from the construction drawings is A = 83,01 m^2, it therefore results.

$$m_{exf} = 0,163 \times 10^{-3} \times A \times \Delta P^{0,4915}\ m^3 s^{-1} \tag{21}$$

$f_{Shut-off} = 0,163 \times 10^{-3}(\pm 2,3 \times 10^{-5})\ m^3 s^{-1} Pa^{-1}$.
$n_{Shut-off} = 0,49\ (\pm 0,02)$.

3.2. Validation of the leakage model reliability using tracer measurements

The Shut-Off model was then implemented in a spreadsheet to obtain an estimation at each point of the flow rates (leakages-included) under nominal operating conditions. In order to validate the model, a number of points considered to be significant was selected and flow measurements with tracer-gas constant-dose technique were taken and compared with the values predicted by the model.

With reference to Fig. 2, flow rate measurements were carried out under nominal operative conditions at the points indicated as A, B, C, D. Table 4 shows the results of the comparison between flow rate values

Table 6
m_{exf} uncertainty according to ASHRAE Standard 215 [27].

Source of uncertainty	Symbol	Value	Standard uncertainty u	Measurement unit	Coverage factor	Sensitivity coefficient	Expanded uncertainty U
Fan flow rate	m_{fan}	2390,0	68.99	m^3h^{-1}	1.732	1	119.5
Flow rate measured at diffusers	Σm_{diff}	1965,8	22.67	m^3h^{-1}	3.464	1	45.35
Air leakage	m_{exf}	424,2	72.62	m^3h^{-1}	2.000		145.2

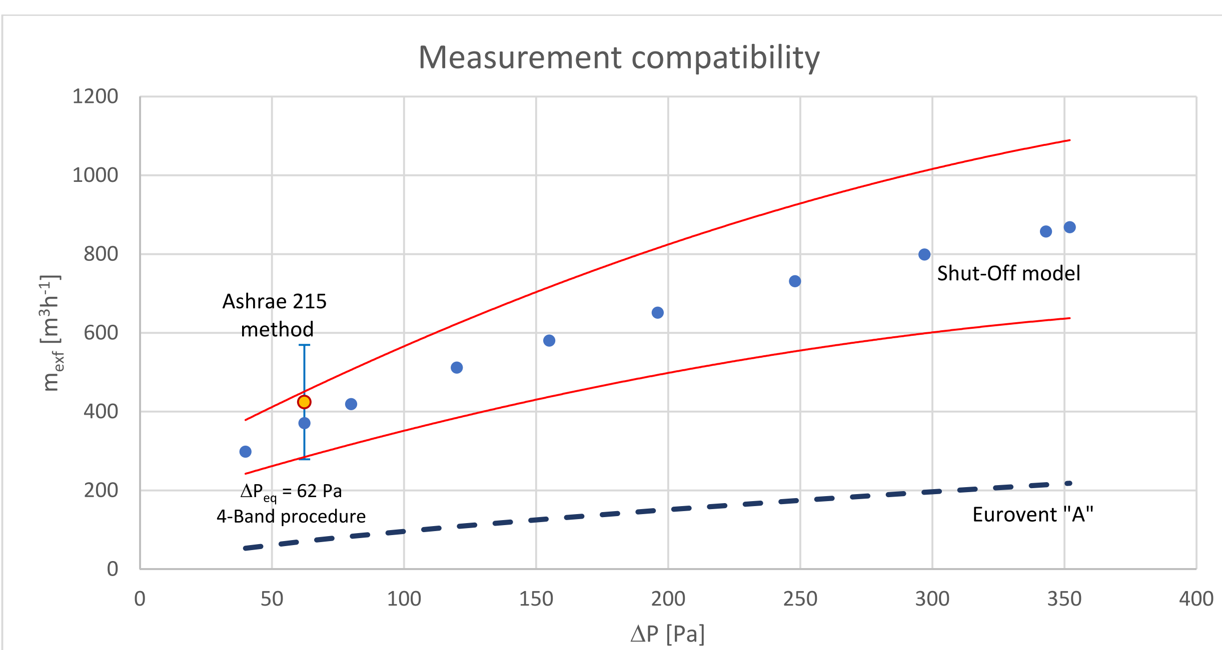

Fig. 4. Compatibility of leakage measurement via Shut Off with ASHRAE Std 215 and comparison of results with Eurovent Class A.

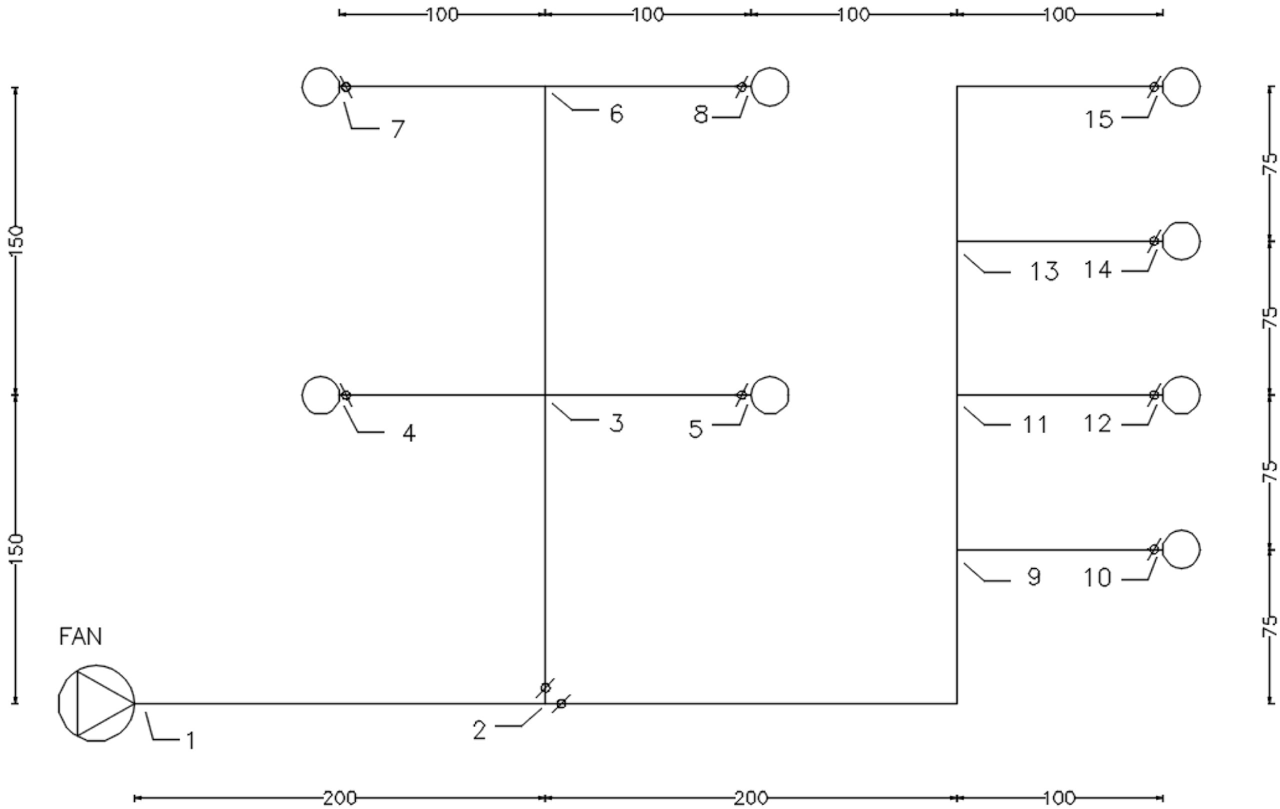

Fig. A1. Generic reference circuit, flow network with node indication, dimensions are given in cm.

Table A1
System analysis, geometric data, distributed and local losses, total pressure variations, balancing drops at the dampers.

Path m-n	flow rate		diameter	Section	air velocity	Perimeter	L	$A_{leaking}$	$\Delta P_{specific}$	ΔP_{dist}	ΔP_{local}	ΔP_{Tot}	ΔP_{Damper}	$A_{leaking}$ / ΔP_S
	Ls^{-1}	m^3h^{-1}	mm	m^2	ms^{-1}	m	m	m^2	Pa/m	Pa	Pa			m^2Pa^{-1}
15-13	100	360	200	0,031	3,2	0,63	3,5	2,198	0,7	2,5	8,8	11,3	0	0,20
14-13	100	360	200	0,031	3,2	0,63	2,0	1,256	0,7	1,4	1,4	2,8	8	0,45
13-11	200	720	250	0,049	4,1	0,79	1,5	1,178	0,8	1,2	17,1	18,3	0	0,06
12-11	100	360	200	0,031	3,2	0,63	2,0	1,256	0,7	1,4	1,3	2,7	47	0,47
11-9	300	1080	315	0,078	3,9	0,99	1,5	1,484	0,6	0,9	48,0	48,9	0	0,03
10-9	100	360	200	0,031	3,2	0,63	2,0	1,256	0,7	1,4	2,4	3,8	95	0,33
9-2	400	1440	315	0,078	5,1	0,99	5,5	5,440	1	5,5	24,0	29,5	0	0,18
8-6	150	540	250	0,049	3,1	0,79	2,0	1,570	0,5	1,0	2,7	3,7	0	0,42
7-6	150	540	250	0,049	3,1	0,79	2,0	1,570	0,5	1,0	2,7	3,7	0	0,42
6-3	300	1080	315	0,078	3,9	0,99	3,0	2,967	0,6	1,8	0,0	1,8	0	1,65
5-3	150	540	250	0,049	3,1	0,79	2,0	1,570	0,5	1,0	2,0	3,0	28	0,53
4-3	150	540	250	0,049	3,1	0,79	2,0	1,570	0,5	1,0	2,0	3,0	28	0,53
3-2	600	2160	400	0,126	4,8	1,26	3,0	3,768	0,6	1,8	2,1	3,9	94	0,97
2-1	1000	3600	500	0,196	5,1	1,57	4,0	6,280	0,5	2,0	0,0	2,0	0	3,14

measured with tracer and the corresponding values estimated by the shut-off model.

Table 4 shows results that are non-homogeneous but in line with what is expected. First of all, it is useful to point out that the Shut-Off model, in full analogy with the DALT model, has been chosen to be based on a single $f_{shut\text{-}off}$ value which represents the average value obtained in an experimental test applied to the whole supply ductwork; it follows that the only fully meaningful result of the model vs measurements comparison is the one performed at the point where the measured flow rate value is affected the leakages of the whole system (i.e. at point A) and this is also the point at which the minimum error is found, namely −3%. The other measurements (B,C,D) show the comparison carried out on partial sections of the ductwork and are therefore affected by leakage inhomogeneities. Also the −14 % underestimation of the model with respect to the measured value in point D is justified for the same reason: the measurement is carried out in the end section of the air duct, characterized by locally larger leakage since the ducts are smaller (cf. Fig. 2) and the presence of longitudinal joints and perimetric flanges is significantly more impactful than in the sections closer to the fan, where the perimeter / passage area ratio is lower. Finally, although the error at point D seems significant if related to the measured values, it is much less so if expressed in relation to the flow rate, keeping in mind that it must be referred to a share of 12 % of the total flow rate, whereas the measurements at A, B and C points are referred to shares of 100 %, 36 % and 34 %.

The good agreement between measurement performed at the A point and the model entitles the use of the latter for the evaluation of leakages under working conditions by using a spreadsheet; the value estimated by the Shut-Off model is $m_{exfWCmodel} = 384$ m^3/h, corresponding to

Table A2
Ductwork analysis, geometric data, velocity, Total, Velocity and Static Pressure at each node.

Point	flow rate		Diameter	Section	air velocity	Total Pressure	Velocity Pressure	Static Pressure
	Ls^{-1}	m^3h^{-1}	mm	m^2	ms^{-1}	Pa	Pa	Pa
1	1000	3600	500	0,196	5,1	139	16	124
2	1000	3600	500	0,196	5,1	128	16	112
3	600	2160	400	0,126	4,8	31	14	17
4	150	540	250	0,049	3,1	25	6	19
5	150	540	250	0,049	3,1	25	6	19
6	300	1080	315	0,078	3,9	29	9	20
7	150	540	250	0,049	3,1	25	6	19
8	150	540	250	0,049	3,1	25	6	19
9	400	1440	315	0,078	5,1	98	16	83
10	100	360	200	0,031	3,2	20	6	14
11	300	1080	315	0,078	3,9	50	9	41
12	100	360	200	0,031	3,2	20	6	14
13	200	720	250	0,049	4,1	31	10	21
14	100	360	200	0,031	3,2	20	6	14
15	100	360	200	0,031	3,2	20	6	14

$$\frac{m_{exfWCmodel}}{m_{AHUmodel}} = \frac{384}{2312} \times 100 = 16,60\%$$

of the calculated flow rate at the fan. This result will be compared with the experimental results.

3.3. Air leakages assessment under working conditions: 4-Band procedure application

Following the verification of the reliability of the model, the 4-Band Procedure, dedicated to the quantification of leakage under nominal conditions based on the Shut-Off characterization, was applied.

According to the procedure the first step consists in calculating the value of ΔP_{Seq}; the design calculation tables based on construction drawing were analyzed to extrapolate the values of the coefficients α_i for the four pressure bands considered by the method, then the value of ΔP_{Seq} was calculated via equation (18) with the given result of $\Delta P_{Seq} = 62Pa$.

The results of the system analysis and calculation have been summarized in Table 5:

Therefore, by applying eq. (21), the exfiltrated flow rate$m_{exfWC4Band} = 371\ m^3h^{-1}$ at working conditions is estimated. Such value represents a share of

$$\frac{m_{exfWC4Band}}{m_{AHU}} = \frac{371}{1950 + 371} \times 100 = 19,0$$

where m_{AHU} is calculated as the sum of the AHU design value and with $m_{exfWC4Band}$.

The leakages value obtained can be compared with the value previously obtained through the analytical evaluation $m_{exfWCmodel}$ to show how much the approximations introduced by the four discrete bands technique affected the result. The comparison of the two leaking estimations shows a percentage difference calculated as

$$\frac{m_{exfWC4Band}}{m_{exfWCmodel}} = \frac{371}{384} \times 100 = -3,3\%$$

This deviation incorporates the simplifying assumptions of the 4-Band model and the way the coefficients α_i are obtained from design procedure documentation.

3.4. Comparison with the ASHRAE Standard 215method

The availability of a measuring equipment at the fan and flow probes on all terminal VaV boxes allows the value obtained to be compared experimentally using the method proposed by the ASHRAE Standard 215.

The measurement of the flow rate at the air handling unit AHU (point A) is carried out by measuring the pressure drop across the inlet cone of the plug-fan and results$m_{AHUStd215} = 2390\ m^3/h$.

This value, compensated with the air density at operative conditions, is consistent with the value obtained using tracers in the same point (i.e.$m_{AHUTracer} = 2388\ m^3/h$).

The total flow rate measured from the VaV boxes positioned at the terminals is$m_{DiffStd215} = 1966\ m^3/h$, and by difference from the value at the fan is obtained an exfiltrated flow rate value of$m_{exfWC215} = 424\ m^3/h$, which represents a share of

$$\frac{m_{AHUStd215} - m_{DiffStd215}}{m_{AHUStd215}} = \frac{m_{exfWC215}}{m_{AHUStd215}} = \frac{424}{2390} \times 100 = 17,7\%$$

This latter value is then in good agreement with both that obtained by applying the simplified Shut-Off method (i.e. 19.0 %) and that estimated by the analytical Shut-Off model (i.e. 16,6%).

3.5. Compatibility analysis

In order to evaluate the compatibility of the results obtained with the ASRAHE 215 method and the Shut-Off one, the measurement uncertainty associated with the two air leakage flow rates $m_{exfWC4Bands}$ and $m_{exfWC215}$ was evaluated.

It should be noted that the Shut-Off model is able to estimate leakage over the whole pressure test range 40–350 Pa, the ASHRAE 215 method measures leakage directly and only at the operative conditions in terms difference between the flow rate measured at the fan (m_{fan}) and the sum of the flow rate values measured at the diffusers ($\sum_{i=1}^{n} m_{i,diff}$). The associated uncertainty is therefore obtained from the propagation of the respective instrumental contributions summarized in Table 6, according to ISO/IEC 98–3 [34]:

As regard the Shut-off method, the air leakage is evaluated with eq. (15), therefore the associated uncertainty is obtained from the propagation of the respective instrumental contributions [34] summarized in:

$$u_{m_{exf}}^2 = \left(\frac{\partial m_{exf}}{\partial f_{Shut-Off}} u_{f_{Shut-Off}}\right)^2 + \left(\frac{\partial m_{exf}}{\partial \Delta P} u_{\Delta P}\right)^2 + \left(\frac{\partial m_{exf}}{\partial n_{Shut-Off}} u_{n_{Shut-Off}}\right)^2 + \left(\frac{\partial m_{exf}}{\partial S_{TOT}} u_{S_{TOT}}\right)^2$$

where, for the uncertainty of the pressure sensor ΔP, an accuracy of 5 Pa and a resolution of 1 Pa were assumed, while the standard uncertainties of the coefficients $f_{Shut-off}$ and $n_{Shut-off}$ correspond to the standard deviation of the regression polynomial obtained from initial on-site leakage test measurement of the dampers.

The comparison between the two results is reported in Fig. 4 and the

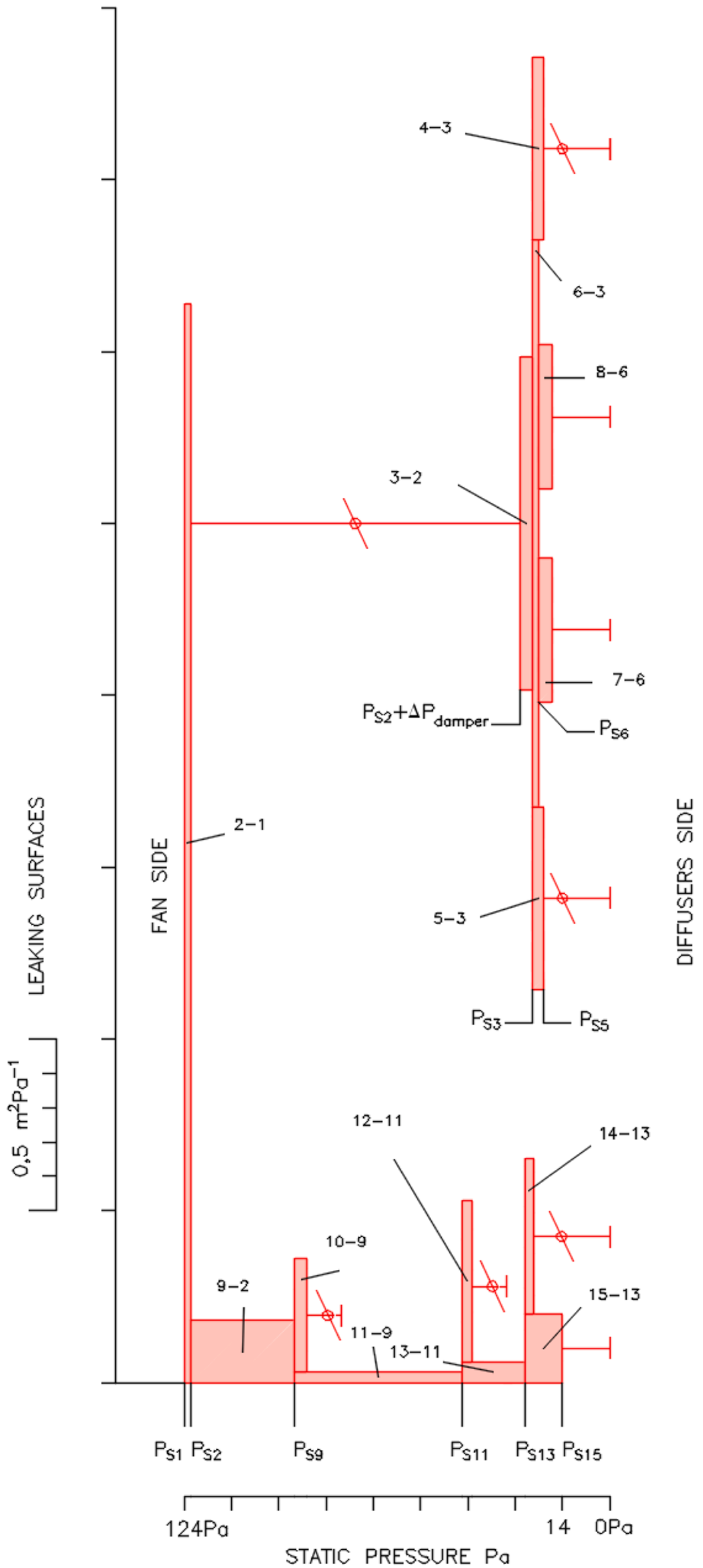

Fig. A2. Arrangement of the leaking surfaces of the circuit: the Area of each section is allocated between the inlet and outlet values of the Static Pressure.

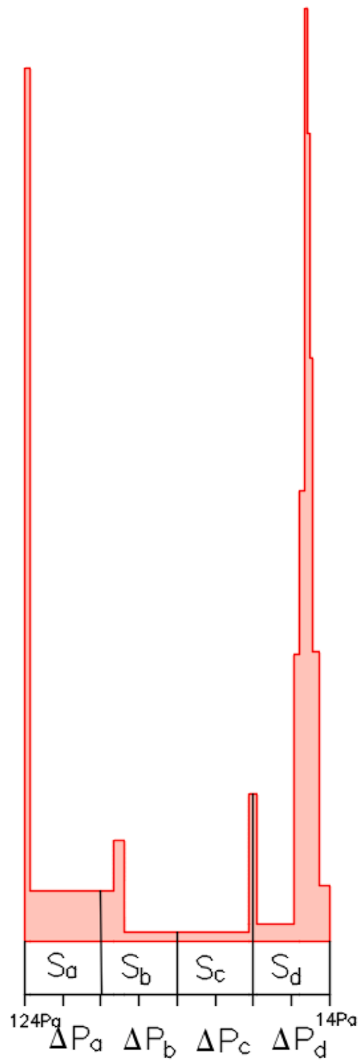

Fig. A3. Graphical compaction of the leaking surfaces with respect to static pressures and identification of the four pressure bands.

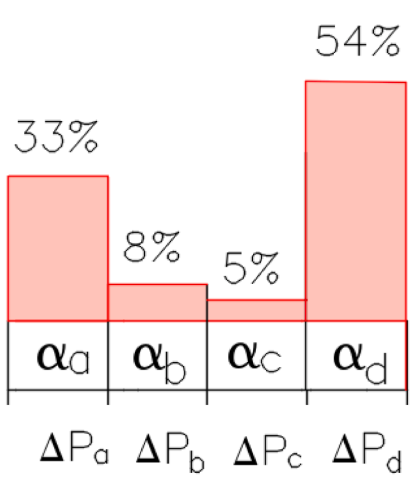

Fig. A4. Determination of parameters.α_i

compatibility of the two methods has to be evaluated considering the exfiltration value given by the Shut-Off estimation curve at the equivalent pressure $\Delta P_{Seq} = 62Pa$ determined by the application of the 4-Band Procedure.

Table B1
Characterization of the leakage flow rate (with accuracy) of VaV mod Belimo CMV-100-MP dampers.

Test	Pressure [Pa]	Flow rates [m3/s]
1	40	1,06E-04 ± 0,27E-04
2	85	2,18E-04 ± 0,27E-04
3	112	2,65E-04 ± 0,27E-04
4	142	2,92E-04 ± 0,27E-04
5	205	3,61E-04 ± 0,27E-04
6	280	4,14E-04 ± 0,27E-04
7	370	4,67E-04 ± 0,27E-04
8	450	5,15E-04 ± 0,27E-04
9	640	5,84E-04 ± 0,90E-04

The same figure also shows the permissible values for a class 'A' according to Eurovent 2/2 [8].

The estimated leakage value for the tested system is approximately 4 times greater than the value expected for the worst leakage class of the Eurovent classification (Class A). It should be noted, however, that the standard's reference classification for ducts is commonly compromised by the tightness characteristics of line components and fittings (e.g. control and balancing dampers, VaV boxes, post-heating coils, fire dampers) and inaccurate installation procedures.

3.6. Reconductability to DALT type tests

As a final task, the Shut-Off model was compared with the model adopted by the DALT Standards (§1.1) and a parameter f_{DALT} to be used for classification was extrapolated from the characterization obtained through the Shut-Off test and the application of the related model. This is made possible by applying the relation (7):

$f_{DALT} = f_{Shut-off} \times \Delta P^{(n_{Shut-off} - 0,65)} = 0,163 \times 500^{(0,49-0,65)} = 0,061 \quad l\ s^{-1} m^{2}$.

Since the value of the exponent $n_{Shut-off} = 0,49$ differs from the value 0,65, this evaluation depends on the pressure value at which the exfiltrated flow rate values are evaluated and matched. In the case examined, the pressure of 500 Pa prescribed for A Class [9] is taken as reference.

As expected, the comparison of this value with the classification tables of the standard shows that the tightness of the tested system is far worse than expected for A Class ($f_{AClass} = 0,027\ l\, s^{-1} m^{-2}$), with a leakage coefficient approximately 2,3 times greater than the reference coefficient for that class; this value, although high, is reflected in analyses and measurements conducted and reported in literature [4].

4. Conclusions

In this paper the authors propose an innovative method to assess the air leakages in HVAC systems. The method is distinguished by its practical simplicity and the significance of the measurements obtained in terms of direct quantification of the air leakage of the whole system under operating conditions.

The authors found that the adoption of a more accurate model characterized by an exponent n other than 0,65 and obtained by specific characterization tests performed on the system leads to a more reliable estimation of leakage. In the case of the system tested, comparisons were made between the flow rate values calculated by the model and those obtained by measurement with a tracer; among the comparisons, the most significant one for the model validation, is the one that considers all the system's leakages as it is the only one that does not depend on any local non-homogeneity of the tightness grade, this measurement offered a percentage error of 3 %.

The application of the proposed 4-Band Procedure for the estimation of operational leakages and the application of ASHRAE Standard 215 Procedure led to results of 19,0% and 17,7% respectively in terms of percentage of air leaked compared to that processed by the fan. These results appear consistent each other even when considering

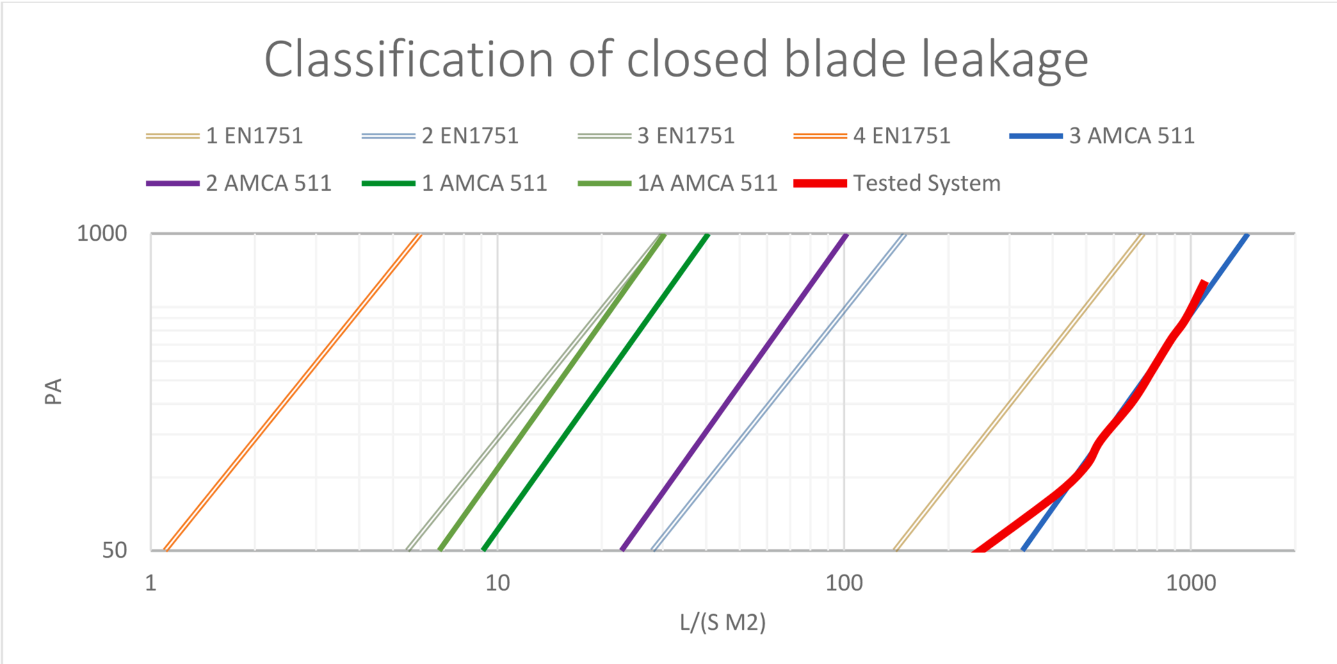

Fig. B1. Classification of the Belimo CMV100-MP damper's closed blade leakage according to EN1751 and AMCA511 classification standards.

measurement uncertainty and are also consistent with the same estimation made analytically by applying the Shut-Off model via spreadsheet, which gives a value of 16,6%.

The method meets the requirements of applicability, accuracy, reconductability, and consistency, and also provides the designer with a simple method to integrate the consideration of leakage into both fan sizing and energy consumption estimation. In particular, the proposed procedure finally makes it possible to exploit the application of a reliable way to estimate the tightness and the corresponding leakage DALT - Class even in systems with difficult accessibility.

CRediT authorship contribution statement

F. Pedranzini: Data curation, Writing – original draft, Writing – review & editing. **E. Alloni:** Investigation, Data curation, Visualization. **G. Ficco:** Formal analysis, Writing – review & editing. **A. Frattolillo:** Data curation, Validation, Formal analysis, Visualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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APPENDIX a. Alpha parameters determination

To better illustrate the methodology, a representation of a generic circular cross-section system is introduced, the single-line diagram of which is shown in Fig. A.1.

The system is labelled with numbered nodes at each point of splitting between straight sections, section changes, branches, bends or fittings. In order to establish the necessary static pressure references, the circuit was sized and evaluated using standard procedures (ASHRAE Fundamentals [16]) and in every node the static pressure value was calculated under the preliminary assumption of a perfect tightness and no leakage. The value of the pressure drop of each damper was assumed to be equal to the pressure drop required for balancing. In order not to introduce unnecessary nodes, the dampers were therefore merged with the constant-section section into which they are installed: For example, the damper positioned at the beginning of the path between node 2 and node 9 is characterized by a concentrated pressure drop at the beginning of the path. The value of the leakage area of the sections between the points has been approximated to the value of the cylinder with the same diameter and the same length as the median line. A more accurate value calculation can be carried out in accordance with EN 14239:2004 [28].

The analysis of the system and the respective calculated quantities is presented in Table A.1.

In Table A.1 the components belonging to the most disadvantaged path are highlighted in red and, consistent with a correct balancing of the circuit, the dampers belonging to the disadvantaged path are kept fully open [29].

Table A.2 shows, from the calculation data, the values of flow and velocity, total, velocity and static pressure at each node of the ductwork.

The Static Pressure, obtained by subtracting the Velocity Pressure value from the Total Pressure value, is highest (P_{Sfan} = 124 Pa) at node 1 downstream of the fan and lowest (P_{Sdiff} = 14 Pa immediately upstream of the diffusers.

For a clearer exposition of the method, it is considered useful to graphically represent the quantities on which the network air leaks depend.

Each component of the system, be it a straight section or a fitting, can be identified by the two nodes *n* and *m* between which it is positioned and individually characterized by three parameters: the static pressure value at the input node P_{Sn}, the static pressure value at the outlet node P_{Sm}, and its leaking surface. These values are reported on the Static Pressure column of Table A.2 and from the $A_{leaking}$ column of Table A.1, respectively. It is therefore possible to represent the distribution of the leaking areas as the pressure inside the duct changes in graphical form as in the diagram in Figure A.2.

On the horizontal axis the Static Pressure [Pa]; for each pair of nodes (*n-m*) the corresponding pressure values are indicated, on the vertical axis the specific surface area per pressure unit difference is represented. The sections between the nodes are represented as rectangular tiles whose height is calculated as:

$h_{(n-m)} = \frac{A_{Leaking}}{\Delta P_S} = \frac{S_{(n-m)}}{(P_{Sm}-P_{Sn})}$ [m^2 Pa^{-1}].

The calculated values of $h_{(n-m)}$ are given in the last column of Table A.2. In this way, the area of the tiles corresponds to the leaking surface area distributed over the effective working pressure range. The pressure drop associated with the dampers is represented by introducing a horizontal shift in the positioning of the tiles on the pressure reference.

In figure A.3, a subsequent graphic elaboration illustrates the area compaction of the tiles at different static pressure values.

The four pressure bands represent equal ranges $\Delta P_a; \Delta P_b; \Delta P_c; \Delta P_d$ and are analytically determined in relation to the minimum and maximum values P_{Sdiff} e P_{Sfan} and the corresponding ratio defined as $C = \frac{P_{Sdiff}}{P_{Sfan}}$.

$\Delta P_a = P_{Sdiff} + \frac{7}{8}(P_{Sfan} - P_{Sdiff}) = CP_{Sfan} + \frac{7}{8}(P_{Sfan} - CP_{Sfan}) = \left(\frac{7+C}{8}\right)P_{Sfan};$

$\Delta P_b = P_{Sdiff} + \frac{5}{8}(P_{Sfan} - P_{Sdiff}) = \left(\frac{5+3C}{8}\right)P_{Sfan};$

$\Delta P_c = \left(\frac{3+5C}{8}\right)P_{Sfan};$

$$\Delta P_d = \left(\frac{1+7C}{8}\right)P_{Sfan}$$

Introducing the constants $C_a; C_b; C_c; C_d$ defined as follows:

$C_a = \frac{7+C}{8}$; $C_b = \frac{5+3C}{8}$; $C_c = \frac{3+5C}{8}$;.$C_d = \frac{1+7C}{8}$

it results in

$\Delta P_a = C_a P_{Sfan}$; $\Delta P_b = C_b P_{Sfan}$; $\Delta P_c = C_c P_{Sfan}$;.$\Delta P_d = C_d P_{Sfan}$

By plotting the limits of the four bands on the graph, it is possible to display, for each band ΔP_i the share of leakage area S_i and express its weight α_i on the total as

$$\alpha_i = \frac{S_i}{S_{TOT}}; i = a, b, c, d$$

where by definition $\sum_{i=a,b,c,d} \alpha_i = 1$

Fig A4. shows the distribution of values α_i values for the analyzed system.

APPENDIX b. Dampers characterization

Given the lack of complete documentation of the leakage test reports conducted according to EN1751 by the manufacturer of the terminal VaV dampers, the procedure was supplemented by an on-site leakage test measurement of the dampers, simplified by the fact that all terminals in the system are equipped with VaV boxes with dampers of the same model (Belimo CMV-100-MP).

The installed damper model was characterized, and the leakage curve was identified using a hot wire instrument (Satema - Model: AP471S3), with a range of 0,1——40 m s^{-1} and declared accuracy of ± 0,1 m/s for velocities 0,1 ÷ 0,99 m s^{-1} and of ± 0,3 m/s for velocities 1 ÷ 9,99 m s^{-1}. The pressure was measured using a Dwyer Magnehelic pressure gauge characterized by a range of 0–1000 Pa and an accuracy of ± 2 %; the test was conducted by supplying the sample damper via a fan box equipped with a speed-controlled fan. The Shut-Off flow rate was measured downstream of a section reduction in order to have suitable velocities for the measurement. The shut-off leakage was measured at increasing pressures within a range that reaches and exceeds the test pressure of the Shut-off Method.

Table B.1 shows the uncertainty range characteristic of the instrumentation used. The measurements also make it possible to assess the leakage class of the damper according to international classification standards, the damper is in line with Class 3 of the AMCA511 standard. The measurement points and references for classification are shown in figure B.1.

The measurements were analyzed using the linear-logarithmic regression technique. The result is the correlation between leakage flow rate and static pressure:

$m_{esf\,damper\,0\%} = (1,5 \times 10^{-5}) \times \Delta P^{0,5843}$[m^3/s] (19).

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