Numerical and experimental identification of factors influencing the pressure homogeneity during an airtightness test in a large building

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ABSTRACT

Airtightness is the most important property of building envelopes to understand the ventilation. Airtightness refers to the flow measurement through the building envelope as a function of pressure across the building envelope. This relationship often fits to a power law, which is the most common way of expressing data. However, pressure homogeneity during airtightness tests can crop up, especially in large buildings. Recently, as buildings have become larger and higher, air infiltration and leakage have increased, leading to a growing awareness of the energy and environmental problems caused thereby. In addition, poor airtightness might lead to large infiltration rates and corresponding energy consumption, draught problems, reduced acoustical performance and dysfunctioning HVAC (Heating Ventilation and Air Conditioning) systems.

The present work deals with a numerical study and an experimental protocol to identify parameters likely to influence the pressure distribution during an airtightness test in a large building. To prevent the test from being stated improper, the French standard (NF EN ISO 9972, 2015) and its application guide (FD P50-784, 2016) require checking the pressure distribution throughout all the building during the test. Pressure deviations inside the building during the airtightness test should not be more than 10% of the building pressure differential. To better identify these parameters, air leaks were modelled either as an equivalent air gap or by real air leaks. To achieve the aim seeked, an experimental study was conducted in a single family house. Afterwards, these parameters were tested via numerical models using the commercial code Comsol Multiphysics. Note that the wind effects and outside temperature have been neglected and all walls have been considered watertight. Besides, the flow is steady and laminar. The obtained results show that the homogeneity of the pressure is influenced when the air leakage is located in an incorrectly connected location and/or the leak is located in one place. Indeed, parts that are poorly connected to the rest of the building disturb both the pressure distribution and uniformity. In such cases, additional fans must be installed in these parts to properly ensure the ventilation connection.

KEYWORDS

Air leakage; Blower Door; Large buildings; Heterogeneity of pressures; CFD.

1 INTRODUCTION

In recent years, interest on airtightness in buildings has significantly grown. The European Directives (van Dijk and Hogeling, 2008) set the need to enhance the energy performance of buildings, which is affected by uncontrolled air leakage through the building envelope (Poza-Casado and *al*., 2018). Buildings represent a large share of global energy consumption and associated CO2 emissions (Amasyali and El-Gohary, 2018). Indeed, the building sector represents 40% of energy consumption and 36% of CO_2-emissions in Europe (Ahmad et al., 2014). Lack of airtightness can also cause problems of over-ventilation, thermal comfort, noise, uncontrolled air flows, poor indoor air quality (IAQ) and, thereby affect the health of its occupants. The authors (Poza-Casado and *al*., 2018) studied the ventilation rates due to air leakage and their energy impact to design guidelines with real data, which is obtained from tests. The scale of these problems in large buildings would be expected to increase relative to the potential size of potential leakage areas (Sharples and *al*., 2005). An experimental study (Meiss and Feijó-Muñoz, 2015) was carried out in various buildings in northern of Spain to study the effect of air infiltration index on the energy efficiency of buildings. The airtightness test results showed that the incidence of air infiltration influences the energy balance of buildings by 10 to 27%.

For this reason, energy efficiency in buildings has now become a priority objective of energy policy at regional, national and international levels (Pérez-Lombard and *al*., 2008) and (Meiss and Feijó-Muñoz, 2015). Air leakage through the building envelope inside buildings has a considerable impact on energy loads and, thereby, on energy demand (Graham and *al*., 2013). Several authors (Laverge and Janssens, 2013) have confirmed that when it comes to controlling parasitic air leaks, especially low-energy buildings, the airtightness is better, which increases the efficiency of the ventilation system. Airtightness is a key parameter for an energy-efficient building since it influences the heating load and disrupts the performance of the ventilation systems, and influences the flow of extracted air (Boulanger, Xavier and *al*., 2012).

In France, from 1 January 2013, a new thermal regulation (TR 2012) for new constructions or new building parts is in effect. Its goal is to reduce the energy consumption of new buildings by limiting in particular the heating needs of buildings. Unfortunately, at a time when all building actors are involved in the challenge of reducing energy consumption, designers cannot lean on effective tools to help them in their decision making process about airtightness (Prignon and Van Moeseke, 2017). The energy performance regulation requires an airtightness treatment for each new residential building (Bailly and *al*., 2012). Airtightness measurements shall be carried out by a certified operator and according to the EN 13829:2001, 2001 replaced by standard EN ISO 9972:2015, 2015. The building's airtightness is conventionally assessed using a steady state fan pressurization technique (Sharples and *al*., 2005). In the case of large-scale buildings (collective residential buildings and tertiary buildings), measurement by this method raises many technical queries. On one hand, methodological issues arising out of concern to obtain a representative measure of the real permeability of the building envelope. On the other hand, as far regulations are concerned, the standards in effect under TR 2012 (case of EN ISO 9972:2015, 2015) and its application guide (FD P50-784, 2016)) require certain conditions to be fulfilled during the permeability measurement. The measurement of airtightness for small buildings can be readily conducted through existing fan pressurization methods. However, it can be difficult to achieve accurate measurement results for large buildings as their height and volume can significantly affect them. In France, a building is considered large when its thermal surface according to the thermal regulation (SRT) is strictly greater than 3.10^3 m^2.

The year of construction, windows type, insulation type, and building orientation are key parameters to determine the leakage level of the building. Recent studies indicate that, in southern European countries, the incidence of infiltration on the energy balance of buildings can vary from 10 to 27% (Šadauskienė and *al*., 2014). There is currently little information on the air permeability of large-scale tertiary-type buildings. The reasons for this lack of on-site measurement results and analyzes are technical and financial. Indeed, the tests are not practiced because their cost is very high and very few teams have the appropriate measuring equipment. The European standard EN ISO 9972:2015, 2015 does not require the use of specific equipment for air permeability measurements in large buildings. However, it requires checking the pressure homogeneity. Indeed, the pressure is uniform and does not change if there is a pressure difference of less than 2 Pa or 10% of each measured pressure difference, taking into account the greater of these two values. At this stage, it seems impossible to determine the real airtightness of a building and the measurement error cannot be estimated only by a numeric protocol (Bailly and *al*., 2012). Therefore, control of sealing defects and unintentional air leakage becomes impossible. Thereby, Prignon and Van Moeseke (2017) proposed two predictive models for airtightness to enable building designers to identify the airtightness level in the design phase of buildings.

This study presents results of a measurement campaign on a single-family house (small building) located on the CEREMA site (Center for Studies and Expertise on Risks, Environment, and Mobility). The determination of the airtightness performance of the buildings must also make it possible to assess such buildings in terms of air permeability in relation to the levels required by the RT 2012. In this context, envelope airtightness treatment becomes crucial, especially for low-energy dwelling. Since airtightness measurements in large buildings are not always easy and very expensive, a numerical modeling method was used to perform several models by modifying some parameters influencing the airtightness measurements. The purpose of this study is to identify factors that influence uniformity and homogeneity of the pressure field inside the tested building. Several studies have been conducted to explain factors affecting accuracy and analyze the results of leakage measurements for large buildings. To go even further, it is necessary to characterize various factors influencing the measurement in large buildings and to find out an experimental protocol allowing to carry out measurements of air permeability so as to avoid the problem of non-homogeneity of pressure. To better understand the factors influencing the pressure field distribution and its homogeneity in the building under test, and to better control these factors during the test of air permeability, a numerical study using Comsol Multiphysics has been achieved to improve the reliability of air permeability measurements in high-volume buildings knowing that, in-situ, it is difficult to test all the parameters likely to alter the pressure homogeneity. Finally, the complexity of measuring permeability in large buildings has led to studies towards airframe modeling.

2 METHODOLOGY OF EXPERIMENTAL STUDY

Leakage assessment is performed in accordance with the EN ISO 9972: 2015 (2015) and its application guide FD P50-784 (2016), used for the determination of the air permeability of buildings by the fan pressurization approach, commonly referred to as the blower door test (Figs. 1-2).

2.1 Testing method

There are other measurement techniques such as the tracer gas method, which is more precise. However, it requires mastery of the techniques while having a prohibitive cost (Salehi and *al.*, 2017). For this, the blower test is considered the most appropriate technique because of its simplicity and relatively low cost. The generation of a high-pressure differential (50 Pa) is conceited to mitigate the wind and temperature actions on the envelope. In addition, it is properly accurate and reproducible (Sherman and Chan, 2004). Initially, we performed the air permeability test in a single-family house (Figure 1-Figure 2). The aim of performing an air permeability test on this low-volume house (V_{int}=173.4 m^3) is to reach all factors influencing air permeability, viz., factors disrupting the pressure homogeneity criterion imposed by the ISO 9972. The air permeability test was carried out by a simple blower door with a maximum flow fan of 7,200 m^3/h.

Figure 1: The single family house considered

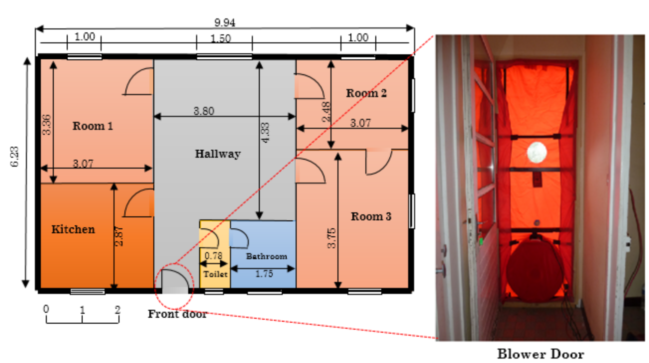


Figure 2: Air permeability test

Note that the air permeability is part of the medium requirements in the regulatory framework of TR 2012. In residential buildings (Table 1), the measurement of this coefficient is fundamental. Table 1 shows that TR 2012 does not impose any limit values for the measurement of air permeability in the tertiary sector where a default value of 1.70 $m^3/(h.m^2)$ can be taken into account during thermal calculation.

Table 1: The thresholds required by the TR 2012

Types of habitat	$Q_{4Pa-Surf}$ [m^3/ ($h.m^2$)]	Type of measure
Single-family houses	0.60	Mandatory measurement
Collective habitats	1.00	
Offices, Hotels, Education	1.70	Non-mandatory measurement
Other uses	3.00	

From a measurement standpoint, air tightness means measuring the flow through the building envelope as a function of the pressure across the building envelope. This relationship can be translated by a power law of the following form (Eq. 1):

$$q_{50} = C_L \left(50 P\right)^n \tag{1}$$

where C_L [$m^3/s.Pa^n$] is air leakage coefficient: $C_L = C_{env}\left(T_0/T_e\right)^{1-n}$, n being the pressure exponent that is of the order of 0.65 lying between its limit values of 0.5 and 1. T_e and T_0 are the outside air temperatures and under standard conditions, respectively.

There are two ways to express the leakage rate of a building, for a single-family dwelling. The airtightness requirement is $Q_{4Pa-Surf}$ = 0.6 $m^3/(h.m^2)$ (Eqs. (2) and (3)) that is around n_{50}= 2.3 h^{-1} (Eq. (4)).

$$Q_{4Pa-Surf} = q_4 / A_{Tbat} \tag{2}$$

$$q_4 = C_L * (4\,Pa)^n / A_{env} \tag{3}$$

$$n_{50} = C_L * (50\,Pa)^n / V \tag{4}$$

where $Q_{4Pa-Surf}$ is the air permeability at 4 Pa [$m^3h^{-1}m^{-2}$], A_{env} is the envelope area excluding the lowest floors [m^2], n_{50} is the air change rate, and V is the building's heated volume [m^3].

2.2 Experimental results

To determine the boundary conditions for the numerical model, the test of air permeability was performed in a low-volume single-family house (V= 173.39 m^3) located in the site of CEREMA in Autun. The house layout and different rooms characteristics are shown in Figure 2 and Table 2. The blower door was set up on the front door (Fig. 2). The blowing flow is 7,200 m3/h, and the meteorological conditions are presented in Table 3. To achieve the most uniform pressure distribution in a test zone, all interior doors are kept open.

Table 2: Dimensions of individual house and general building data

Parameter	Unit	Value
S_{RT}	m^2	61.93
H	m	2.80
V	m^3	173.39
A_{Tbat}	m^2	152.63

Table 3: Weather assessment

Variant	Unit	Value
Indoor temperature	°C	5.00
Outside temperature	°C	1.10
Altitude	m	325.00
Pressure at zero flow	Pa	-0.35
Wind speed (according to the Beaufort scale)	-	Force 1 (Light breeze) (EN ISO 9972:2015, 2015)

The building was pressurized in decreasing steps. The initial measurements establish the relationship between the airflow through the fan, q_{50}, and the differential pressure, ΔP_{50Pa}, observed across the building envelope (Eq. (2)). The results of the test allow to draw a bi-log graph for the calculation of the air leakage rate (Figure 3) which is based on the power law.

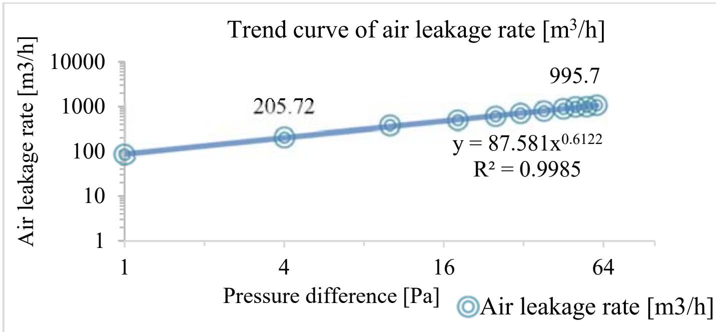


Figure 3: Air leakage rate

Table 4: Results of the air permeability test

Property	Unit	Value
n	-	0.61
C_{env}	$m^3.h^{-1}.Pa^{-n}$	85.65
C_L	$m^3.h^{-1}.Pa^{-n}$	87.58
R^2	-	0.99
q_{50}	$m^3.\ h^{-1}$	995.70
n_{50}	h^{-1}	5.74
q_4	$m^3.\ h^{-1}$	205.72
$Q_{4Pa\text{-}Surf}$	$m^3.\ h^{-1}.m^{-2}$	1.35

Table 4 presents the results of the CEREMA house air permeability test. The $Q_{4Pa\text{-}Surf}$ coefficient that defines the sealing level has been determined, as well as the air change rate n_{50} (Eq. (4)). Figure 3 shows the air leakage rate evolution vs. ΔP_{50Pa}. The coefficients C_L and n (Eq. (1)) were obtained using a regression law to obtain C_L = 87.58, n = 0.6122 and a correlation coefficient R^2 of 0.9985 (Table 4). The air permeability was measured in $Q_{4Pa\text{-}Surf}$ =1.35 $m^3.h^{-1}.m^{-2}$. It can be seen that the water-tightness of the building is not good, since the regulatory threshold is 0.6 $m^3/(h.m^2)$ in new individual houses (Table 1). This is a prerequisite for measurement in a large building, which allows for a reproducible model method on other buildings. Among these parameters that influence the flow and distribution of the internal pressure of the house include air leakages (equivalent holes or actual leaks), shape and geometry of air leakages, leakages position, leakages distribution and their numbers, and impact of internal partitions and aeraulic connection.

The variation of all these parameters is to find the right modeling of the air leaks with a simple geometry and an optimal computation time, and to validate the computation assumptions allowing to model properly the construction of big volumes.

3 PHYSICAL MODEL OF NUMERICAL STUDY

The air permeability test performed on the single-family home revealed the main leakage defects and the air intake speed required to bring the house to -50 Pa depressurization. We tested several parameters influencing the pressure distribution inside the house. The physical model studied is presented in Figure 4. First, we modeled the air leak in 2D, then in 3D to test the influence of the leak shape. A leak has been located in different positions with different shapes. The leak was based on the equivalent hole principle by calculating the pressurization air flow rate. The international standard NF EN ISO 9972 shows how to calculate the effective leakage area, ELA_{pr}, at Δp_r (Eq. (5)).

$$ELA_{pr} = 1/3600 \cdot C_L \cdot \left(\rho_0/2\right)^{0.5} \cdot \left(\Delta p_r\right)^{n-0.5} \quad (5)$$

where ELA_{pr} is the effective leakage area at reference pressure difference [m²] and ρ_0 is the air density [kg.m^{-3}].

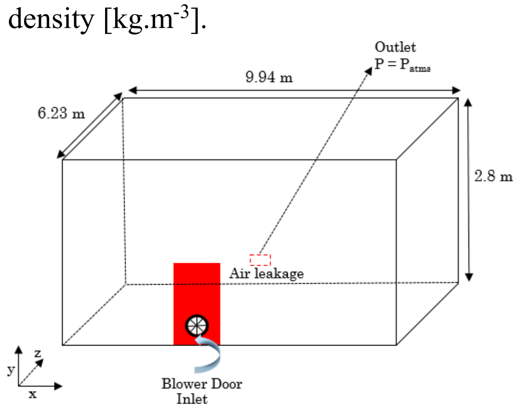


Figure 4: Adopted physical model and equivalent hole

Table 5: Effective leakage area

Property	Unit	Value
Δp_r	Pa	50
C_L	$m^3.h^{-1}.Pa^{-n}$	85.65
φ	%	92
T	°C	5
P_{bar}	Pa	1 013.25*10²
n	-	0.6122
ρ_0	$Kg.m^{-3}$	1.2652
ELA_{pr}	m^2	0.0297

The main parasitic leaks have been identified visually in all windows and in the different walls openings. Since it is impossible to assess the water-tightness of a building by a simple visual inspection, the air permeability test is essential to quantify the different leaks in the building envelope. To determine the sealing defects surface, we applied a calculation convention (Eq. (5)). The equivalent leakage zone is considered as a single orifice through which air can enter or exit under a reference pressure (50 Pa) and under actual conditions of the air permeability test.

3.1 Mathematical model

The Navier-Stokes equations were simplified according to the calculation assumptions that were adopted. The viscous dissipation and the work of the forces of pressure are neglected since the wind speed is very low. The flow is laminar, Newtonian and incompressible. The air inlet velocity was calculated as a function of the cross section and the air flow rate at 50 Pa. All leakage inter-zones are eliminated and all walls are waterproof. The flow is considered steady. Thereby, the governing equations can be written as follows:

$$\nabla.\vec{V} = 0 \tag{6}$$

$$(\vec{V}.\nabla)\vec{V} = -\nabla p + \nabla.(\mu\nabla\vec{V}) \tag{7}$$

3.2 Boundary conditions (BCs)

The system of Eqs. (6)-(7) is supplemented by appropriate BCs. The walls are impermeable (u=v=0) and without any applied stress. The airflow generated by the blower door fan is equal to the airflow of the air leaks. The blowing speed at 50 Pa was calculated according to the Eq. (8). Table 6 gathers the BCs of the numerical model.

$$V_{Inlet} = q_{Fan} / A_{Fan} = q_{Air\,leakage} / A_{\mathrm{Air\,leakage}} \tag{8}$$

Table 6: Boundary conditions (BCs)

Air inlet			Air outlet		
Property	**Unit**	**Value**	**Property**	**Unit**	**Value**
q_{50}	$m^3.h^{-1}$	995.7	Equivalent hole f_0	$N.m^{-2}$	0
V_{Inlet}	$m.s^{-1}$	6.5	p_{bar}	Pa	1.01325*10^2
n_{50}	h^{-1}	5.74			

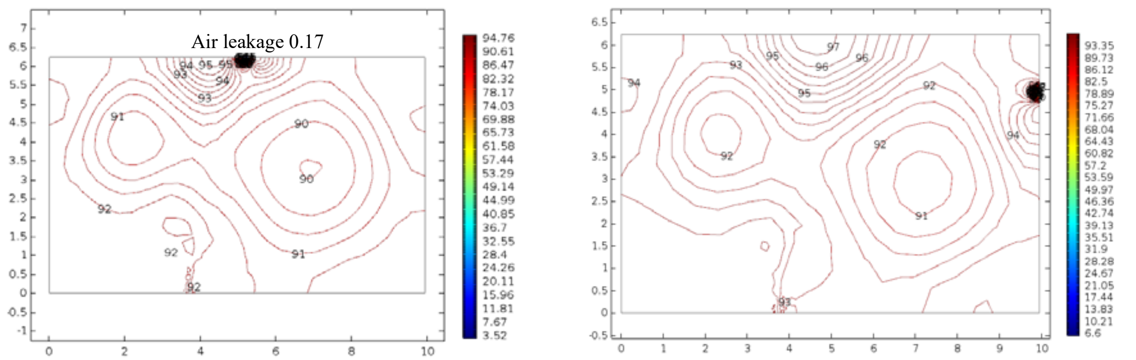
4 RESULTS AND DISCUSSION

To carry out the numerical study, we chose a multi-zone model. However, the results of Mora (2011) showed that a better model depends on the association of a zonal model with a CFD model having a coarse mesh to optimize memory space and computation time. Initially, the air leaks were modeled in 2D by changing the position each time. The pressure field was exhibited in terms of isovalues. The homogeneity of the pressure has been checked according to the requirements of EN ISO 9972: 2015, 2015.

4.1 Influence of the position of air leaks in the family house in 2D

To identify the leak location influence on homogeneity of the pressure, we considered two cases by changing the position of the same equivalent leakage. First, a single air leak (equivalent hole) was taken into account by eliminating all internal walls and connections. Figure 5a shows that the pressure distribution is homogeneous throughout the individual house. The variation of the pressure does not exceed 2 Pa according to EN ISO 9972:2015, 2015 and Eq. (9). Figure 5b shows that the results are the same even if the two air leak locations are different. In addition, we noticed that there is a slight difference in the minimum value of the pressure which is negligible. At the level of the air leak, the pressure variation is greater than 90 Pa, which is due to the air surface decrease of the equivalent hole (outlet). The leakage is considered as an open boundary, and the pressure is canceled at the level of the leakage exit. The same air leakage is also considered in Fig. 5b, but the position of the leak has been changed. To examine the position influence of the air leaks on the homogenized pressure and its distribution, we have removed all internal walls and connections. So, the results do not allow to state that the leak position has no influence on the pressure homogeneity. Thereby, we have studied other cases whose internal partitions and cones have been integrated.

$$\Delta P \leq Max\left\{2\ Pa\ ; 10\%\,\Delta P_{Measured}\right\} \quad (9)$$

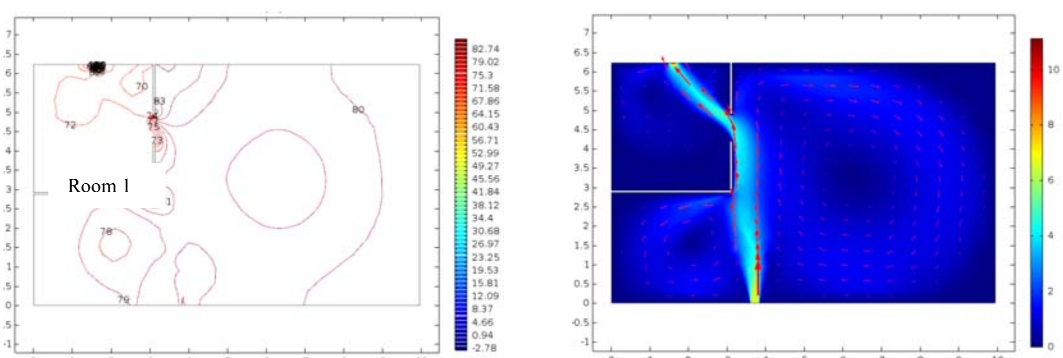


a) Air leakage in the top wall b) Air leakage in the right wall

Figure 5: Isovalues of pressure (Pa) with an air leak

4.2 Influence of internal walls and connections

Note that we located one air leakage (width 0.17 m) in the room 1. Figure 6a shows that the pressure variation inside the house exceeds 8 Pa. According to the application guide EN ISO 9972:2015, 2015 and FD P50-784, 2016, the pressure is considered non-homogeneous. So, the air permeability test is “non-compliant”. Figure 6b shows that the air particles passed through the room 1 door and they came out via leakage. From the results obtained, we determined a factor influencing the pressure homogeneity. So, during an air permeability test, the operator should check air leakages or the remote fan. If this is the case, another fan must be provided to ensure a good aeraulic connection in order to create the same pressure. Indeed, the pressure inhomogeneity may be due to the leak location in one place. In addition, it can be caused by a poor internal connection. We have, therefore, made other simulations to fix the source that can cause a pressure inhomogeneity.

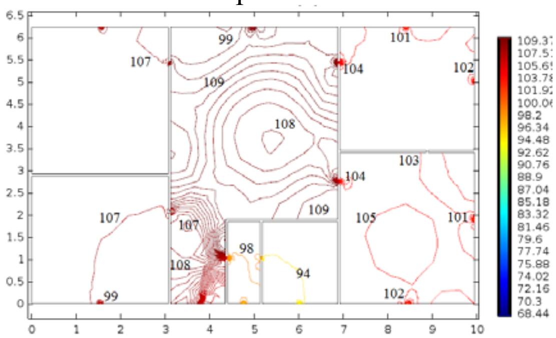


a) Isobar b) Velocity vector

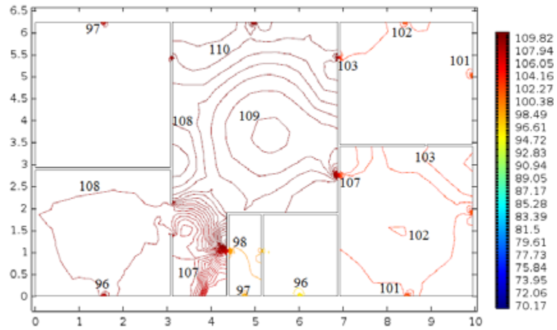
Figure 6: single air leakage located in one place (room 1) with one internal connection

4.3 Effect of internal partitions

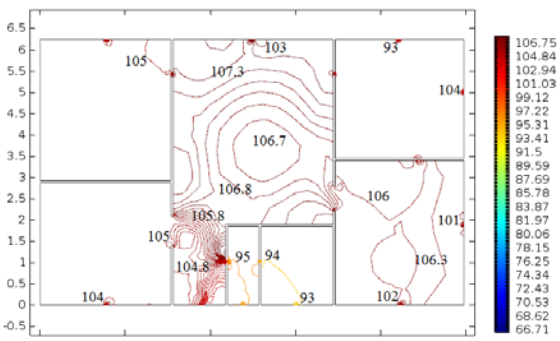
Here, we have integrated all partitions and internal connections to determine their effects on pressure distribution and homogeneity. We hand out the leakages based on the actual leakages distribution observed when performing the air permeability test. Figure 7 shows the results with all internal connections (communication doors) were closed, the pressure being not uniform inside the room. The variation of the latter has exceeded 14 Pa. According to EN ISO 9972: 2015, the air permeability test is non-compliant. In fact, the doors must be open during the air permeability test to ensure a better pressure distribution. The numerical results show that the pressure distribution field is influenced by this parameter. When performing the air permeability test, the operator must open all communication doors. This requirement is very important when testing air permeability in complex or high volume buildings. Air leaks cannot be modeled in their real shapes in the 2D study. This makes it difficult to obtain a pressure difference of 50 Pa inside the room. As a result, a 3D model is needed to represent the leaks actual shape.



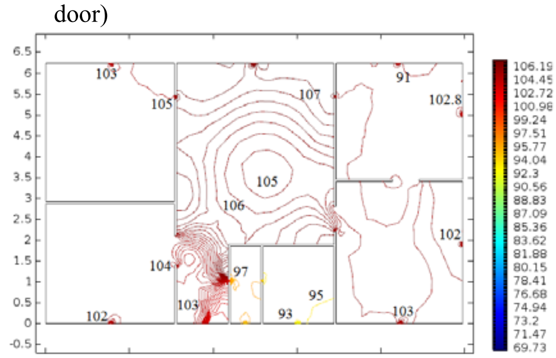
a) All communication doors are closed



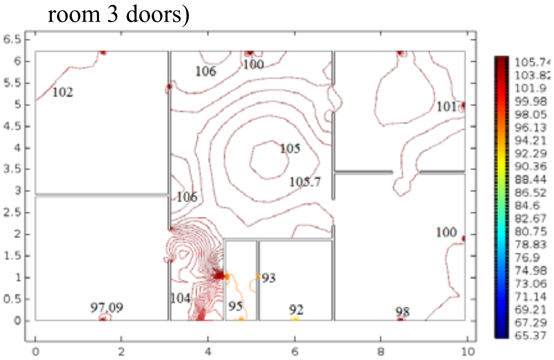
b) Only one internal connection 0.70 m (kitchen door)



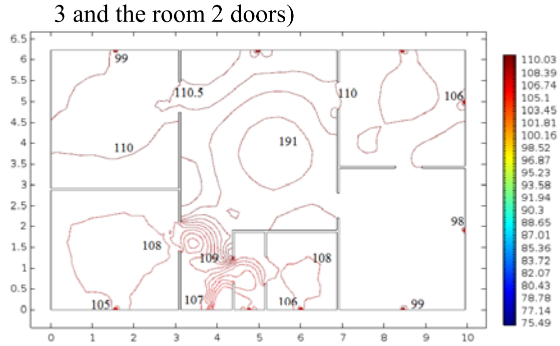
c) Two internal connections 0.70 m (kitchen and room 3 doors)



d) Three internal connections 0.70 m (kitchen, room 3 and the room 2 doors)



e) Six internal connections 0.70 m (kitchen, room 3, room 2 and the bathroom doorst)

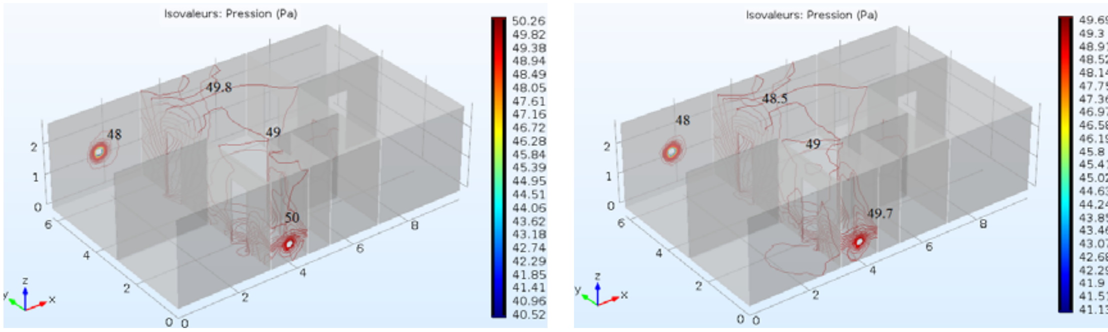


f) All internal connections (doors) 0.70 m are open

Figure 7: Effect of the internal connection on the homogeneity of the pressure

4.4 3D Modeling of the individual house

In the 2D model, air leaks can be modeled using segments. Leakage modeling in the ceiling and in the floor was not adequate with a 2D model. As a result, the use of 3D modeling is necessary. On the basis of the equivalent hole principle, air leakage has been modeled in three forms, namely square, rectangular and circular. The purpose of changing the shape of the equivalent hole is to test the influence of the geometric shape of the equivalent leakage on the internal pressure distribution. We modeled equivalent 3D air leaks to find the most suitable geometry for our model and test the influence of the geometric shape of the equivalent leaks on the distribution of the internal pressure and its homogeneity. We chose two forms of equivalent air leakages (square and circular). The effective leakage area at reference pressure, p_r, are calculated from the Eq. (5)) (square leakage: $a = \sqrt{ELA_{pr}}$ and circular leakage: $r = \sqrt{ELA_{pr}/\Pi}$).



a) Square leakage with internal walls b) Circular leakage with internal walls

Figure 8: Isovalues of the pressure field with different forms of air leakage

We located a single air leakage in room-1 with a square and circular shapes with the same surface. All internal walls and communication doors are integrated. The results Figure 8-a)-b) shows that the shape of the air leakage does not influence the homogeneity of the pressure in the case of a single leak located in one place with a very good aeraulic connection.

4.5 Modeling of real air leakages

The modeling of air leaks according to the equivalent hole principle in the building envelope does not reflect actual leakage. Figure 9 shows that there is a homogeneous pressure throughout the house and that the mean value of the pressure difference is of order of 50 Pa. Now, we can conclude on the method of modeling real air leaks. If the air leakages are calculated using the equivalent hole Eq. (5), we can consider spreading the equivalent area over the entire building to have the same location as in reality (locations being identified during air permeability test). The shape of the modeled leaks does not influence the results. For each part of the building, the number and position of the leak have little influence on the result, so that we can model, in each room, a single leak in the current part of a vertical wall.

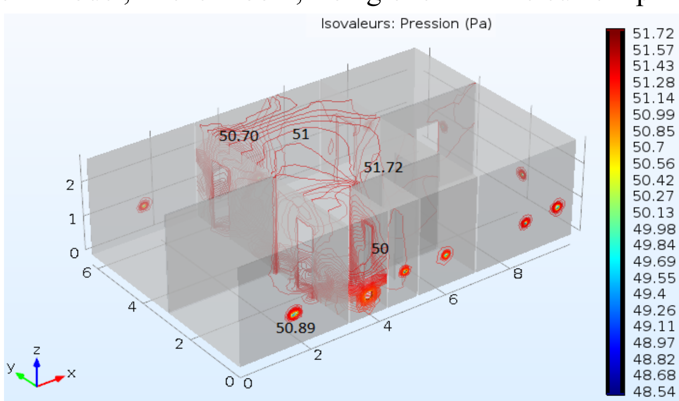


Figure 9: Isovalues of pressure in the case of the repair of the equivalent surface on the envelope of the house

5 CONCLUSIONS

The air permeability measurement in large volume buildings is not always obvious since we have to meet certain requirements of the EN ISO 9972:2015, 2015 and its application guide (FD P50-784, 2016). The difficulties encountered during an air permeability test, especially in buildings of large volume are:

- Respect for the measured maximum pressure difference,
- Check the pressure difference at zero flow rate,
- Check that the temperature gradient is not too high compared to the outside temperature,
- Check the homogeneity of pressure.

On the basis of the numerical results obtained, the following conclusions can be drawn:

- Target critical areas, which are generally the rooms furthest away from the fan, located on the top floor of the building, or in an area that could be poorly connected to the rest of the building, due to architectural specificities or reduced communications.
- Target parts where the leaks are located and try to connect them with the rest of the building.
- Use enough fans and try to spread them over the entire building to pressurize/depressurize the rooms.
- Avoid installing the fan door in isolated locations from the rest of the building,
- Identify major leaks before installing the blower door to avoid locating leaks in insulated rooms.

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