The unintended consequences of improved airtightness levels on the operation of pressurization systems in tall buildings

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The Unintended Consequences of Improved Airtightness Levels on the Operation of Pressurization Systems in Tall Buildings.

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ABSTRACT: This paper introduces the potential negative impact on smoke control pressurization systems for maintaining fire safety levels within buildings, caused by making buildings more air tight by reducing air leakage paths within them.

INTRODUCTION

Could the drive for 'greener' buildings be making them less safe in the event of fire? As buildings get more air-tight and highly insulated, the ability for heat to escape is greatly reduced; this is especially true in the event of fire. Research has shown that the intensity of fire is significantly greater in such buildings [1] [2]. This has the potential to have a negative impact on fire safety levels within buildings by reducing air leakage paths within them.

In tall buildings, escape stairs are designed to be kept free of smoke during an outbreak of fire, one of the main methods of achieving this is by using a smoke control system known as a pressure differential system (PDS). Such systems are a form of mechanical smoke control that uses fans to force input air into an escape route to maintain pressure within the escape route higher than that in the adjacent spaces (see figure 1). This creates a pressure difference between the protected route of escape (stairs) and the adjacent parts of the building. This difference in pressure between the accommodation side of the building and the escape stairs should make the movement of smoke or toxic gases into the protected route of escape less likely. The pressure difference created should be sufficient to overcome the pressure of the fire gases in the adjacent spaces and to create an airflow away from the pressurized stair into the accommodation, which is where the fire is most likely to originate.

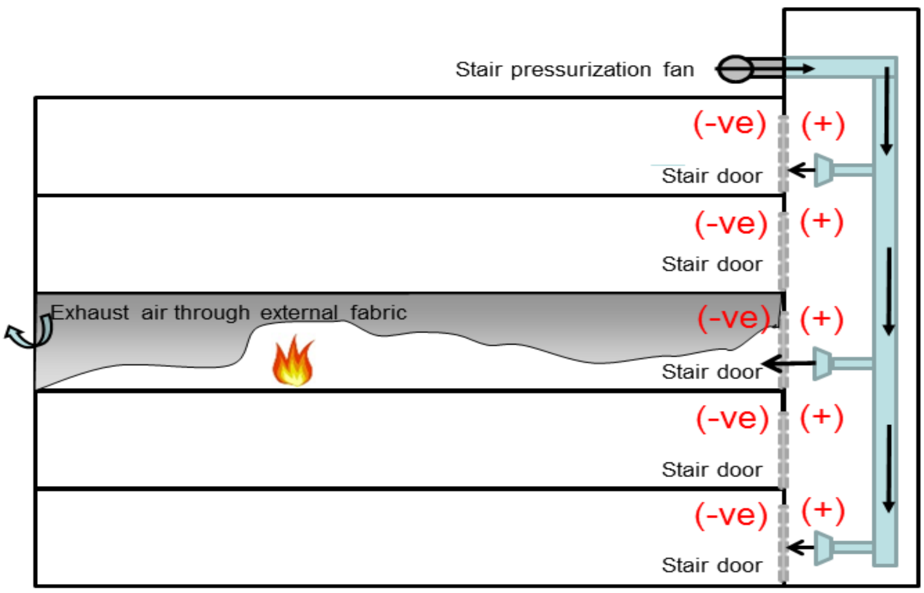

Figure 1 – Pressurization Creates an Air Flow Away from Stairwell

In air-tight buildings however, the pressure created by fire may increase until it equals or exceeds that within the pressurized stairwell allowing smoke to enter and compromise the ability of occupants to escape safely.

LIFE SAFETY AND THE REDUCTION OF CARBON EMISSIONS FROM BUILDINGS

As part of the global drive to improve energy efficiency in support of climate change, targets, countries are aiming to reduce air leakage paths within new and existing buildings by using such measures as external wall insulation [3].

Uncontrolled air leakage paths through the fabric of a building can have a significant adverse effect on the energy efficiency of a building.

This is of particular concern in tall buildings, as occupants rely on protected stairwells as a ‘safe place’ from which to make their escape from the building. The time occupants take to escape from a tall building can be significant [4] and as such these stairwells must remain free of smoke during the evacuation period. In tall residential buildings, smoke spread can have far more serious consequences as escape routes may become untenable before occupants are aware of a fire and decide to leave or if required, be rescued by the fire service.

To protect the stairwell in tall buildings, one of the main recommendations in the building codes throughout the world, is that a form of smoke control known as a pressure differential system (PDS) is installed. This aims to restrict the passage of smoke into the escape stairwell, and protect occupants using them. PDS uses fans to keep the pressure in the stairwell higher than that in adjacent spaces thus restricting the passage of smoke into the stairwell.

In calculating the air supply needed for a PDS, assumptions are made about the air-tightness of the building. Estimating the air leakage rate can have a fundamental impact on the design [5].

The design guidance for PDS recognise that for the system to perform as intended, the design assumptions for air leakage need to remain constant over the lifetime of the building. The design codes provide tables with information on air leakage rates for doors, windows, floors and external walls [5]). This data has not changed since the introduction of design guidance on PDS in 1974 [6].

These air leakage rates were based on buildings constructed with air-tightness levels in excess of 10 - 15 $m^3/h/m^2$@ 50 Pa. Testing carried out on dwellings, constructed to the 2007 [Accredited Construction Details (Scotland) [7], and of similar constructions elsewhere in the UK, indicate that air-tightness levels greater than 5 to $7m^3/ h/m^2$@ 50 Pa are readily achieved and are often exceeded without intention [8].

Based on the airtightness levels that are desired for new and refurbished buildings in the UK of $10m^3/h/m^2$ or better, it can be seen that these changes will have a significant effect on the air flow through the building and that any design that was based on a leaky building would need to be re-evaluated.

It is therefore reasonable to assume that air leakage rates recommend in the design tables are consistently not being achieved. As PDS are based on a ‘typical’ air infiltration rate of $\geq 10\ m^3/h/m^2$ @ 50 Pa they may not function as intended in buildings with improved airtightness levels.

AIM OF RESEARCH

The area of concern and the reason for undertaking this research project was to determine whether the desire for increasing airtightness within buildings to meet Government energy reduction targets is likely to have a negative impact on the ability of pressurization systems to adequately perform in the event of a fire.

There are currently limited amounts of data collected on the impacts of increasing airtightness of buildings. The research therefore had three main aims; these were:

- To investigate current design guidance for smoke control pressurization systems used for the protection of stairs in airtight tall buildings through a review of the research literature
- Survey companies that design install and / or commission smoke control PDS to appraise the awareness of design professionals of the impact of airtight buildings on PDS
- Undertake a series of experiments in a chambered test rig to monitor pressure and flow in three adjacent chambers under different levels of airtightness.

Current research [9] has already identified that some dwellings, tested for air-tightness, have been found to be tighter than the design value thus resulting in uncertainty about the adequacy of airflow rates. As a consequence, increasing levels of air-tightness may need to be considered as a part of the design of pressurization systems, to ensure that level of fire safety is not reduced otherwise the whole strategy of escape from tall buildings could be unsound.

This research project investigated current design guidance for pressurization systems used for the protection of stairs in airtight tall buildings through the review of the research literature, an examination of the factors involved in the design of PDS and of the changes taking place in the airtightness of buildings.

To demonstrate the impact such changes are having on the effectiveness of PDS experimental research was undertaken using a lab based test rig.

ORIGINS OF THE DESIGN CODES

This research challenges the accepted view of current design methodologies for designing smoke control pressurization systems. The established guidance has been based on empirical experimentalism and using a qualitative approach, in that various data was gathered, collated and analysed to fit the desired outcome.

FINDINGS OF LIRERATURE REIEW

The basis of the calculations for designing smoke control pressurization systems are the Ideal Gas Laws and Bernoulli's principle. These mathematical principles have been used by researchers to explain the behaviour and movement of gases.

Since the 1950s, the use of pressurisation as an effective means to protect the means of escape particularly escape stair enclosures from smoke has been recognised. Australia in 1957 published the "Fire Protection Code for Buildings over 150 ft in Height" [10] which permitted the use of Pressurisation as a fire protection method. Throughout the 1960's various research using Bernoulli's theorem to develop formula for the mass rates of flow of hot gases was undertaken by Sims et al [11], [12] [13], Thomas et a l [14] "and Malhotra and Millbank [15].

Within the guidance in the UK building codes it recommends a window be installed at the top of escape stairs to help ventilate smoke in the event of a fire. During the above research it was noted that the window provided at the top of the stair did not appear to have any significant effect on the clearance of the smoke. The tests showed that without a pressurization system sufficient quantities of smoke can penetrate through the gaps, to render the escape area untenable. With a pressurization system however, as used in these experiments the passage of smoke through the door gaps was prevented. The research carried out by Malhotra and Millbank concluded that a pressure difference of 0.028 in.wg (6.97Pa) was adequate to prevent smoke entering through door gaps but to allow for door buckling a higher pressure of 0.05 in.wg (12.45 Pa) should be employed.

Such tests helped demonstrate that a properly designed system could overcome pressures from a fire, adverse weather and stack effect. It was also acknowledged that leakage paths would also need to be taken account of when working out the necessary total air input. This is the concept still used in the British Standard – BS EN 12101 PART 6 [5]and the ASHRAE smoke guide[16]

This qualitative research has identified that there are currently limited amounts of data collected on the impacts of increasing airtightness of buildings.

SURVEY OF DESIGN PROFESSIONALS

To understand the awareness of design professionals of the impact of airtight buildings on PDS, a survey was carried out of companies that design, install and / or commission PDS.

There was a general belief from designers that increasing airtightness of buildings did not impact on the effectiveness of PDS in buildings as there is sufficient tolerance in the design that allows for adjustments to be made on site.

The survey however identified that many designers had examples of where the system did not function as designed due to a lack of air leakage paths. This was particularly the case where energy efficiency improvements had been made to existing buildings and the installed PDS did not have sufficient tolerances to function as originally designed due to lack of air leakage paths.

Such information provides anecdotal data on installed systems that indicate the original design may not be sufficient to accommodate significant reductions in leakage paths which the original design relied on, due to improving the air tightness of the building.

The survey identified the following:

- little awareness about the impact of air-tight buildings on their designs
- design data in the building codes are very old and not relevant to modern construction
- evidence that pressurization systems are not maintained.
- In particular, there was seen to be a need for guidance on re-commissioning of existing buildings when improvement works such as external cladding and window replacement have taken place.

EXPERIMENTAL TEST RIG

To evaluate the impact of improving airtightness ratios of the external envelope and how this impacts on pressure within the building a full scale test rig was constructed with three interconnecting spaces representing a stair, lobby and circulation area of a building (see figure 2 below). At one end of the test rig a variable speed fan of 610mm diameter was placed to pressurize the three areas and allow the airtightness of the test rig to be assessed. Once the airtightness of the test rig was established it was necessary to determine any pressure differential between the three zones. The testing was based on the BSRIA guide 'Commissioning air systems' [17] and required the following equipment:

- Data logger
- 12 Differential Pressure Transmitters (DPT)
- 12 bi-directional probes

The bi-directional test probes were placed in each of the three interconnecting spaces and on the external face of the test rig as per table 1.

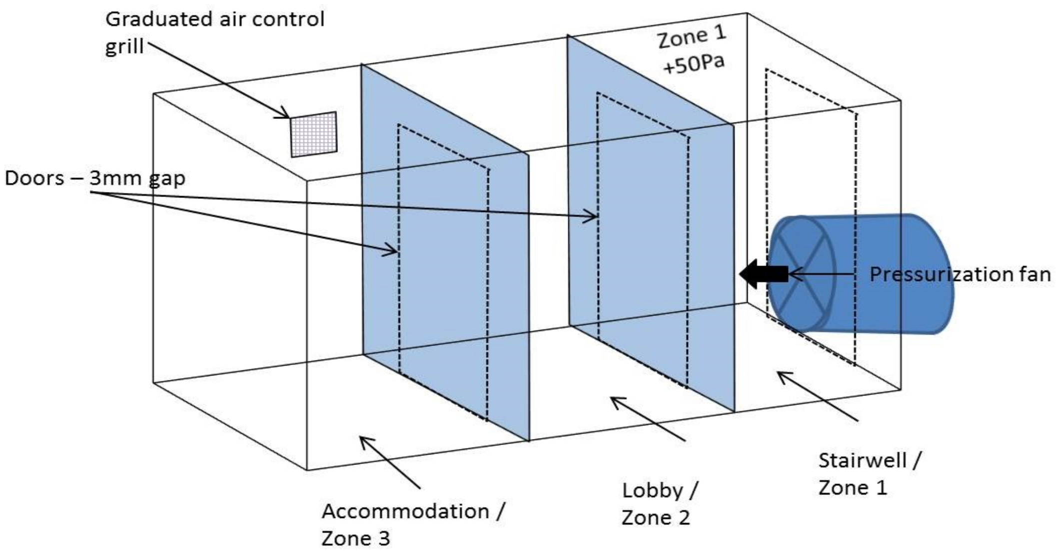

Figure 2 - Schematic of Experimental Rig

Table 1 – Probe Locations

Equipment	Location			
Bi-directional probes	Probes 5, 6, 9 & 10 form necklace at fan outlet	Probe 12 located outside graduated grill	Probe 7 located in the lobby zone at junction of door and frame	Probe 8 located in the accommodation zone at junction of door and frame
Pressure differential probes	Probe 4 fixed to external frame of test rig	Probe 2 located in the stair zone	Probe 1 located in the lobby zone	Probe 3 located in the accommodation zone

The primary objective of the experiments was to determine under test conditions the pressure difference from a pressurized stairwell to the lobby and to the accommodation space under varying levels of airtightness. The setup was effectively a tunnel test with flow paths created to move from areas of high pressure (stairwell) to areas of low pressure (lobby to accommodation). The aim was for the experimentation to take place with doors both open and closed representing the escape and rescue stage during an outbreak of fire.

The experimental rig allowed the investigation and identification of the consequences of varying the pressure and leakage paths by comparing the pressure difference across the different 'spaces' (stair to lobby to accommodation).

TESTING RATIO

The level of airtightness achieved in buildings in the UK is measured as air permeability, $m^3/h.m^2$ at 50 Pa. This is determined by measuring the volume of air that leaks out of a building in an hour (m^3) divided by the internal 'envelope' area, measured when the area is pressurized to 50 Pa. A lower value indicates a building that is more airtight. To assess the impact of reduced airflows tests were undertaken at four different levels of airtightness; these were $4m^3/h/m^2$, 5m3/h/m2, $7m^3/h/m^2$, and $14m^3/h/m^2$ to measure the pressure differential in each of the three spaces .

In total there were 6 tests carried out at each level of airtightness. This allowed the robustness of the various design guides to be interrogated with regards to airtight buildings or refurbished buildings which have improved levels of airtightness.

Observation and recorded data indicated that at an airtightness level of $7m^3/h/m^2$ the pressurization system should operate as designed and keep smoke flow away from the escape stair. The experiments indicate however, that the pressure levels and flow velocity in the areas adjoining the stairwell were impacted by changes in the airtightness of the test rig (see figure 3 below). The data collected from the probes during the series of experiments at 50Pa show that for each improvement in the airtightness of the test rig the pressure increases in each adjacent zone. When the rig reaches an airtightness level of $4m^3/h/m^2$ the pressure in the lobby zone breaches the recommended pressure differences as recommended in the research by Butcher and Parnell [18].

With each improvement in airtightness the difference in pressure levels in the three zones reduced until an airtightness level of $4m^3/h/m^2$ had been achieved when there was equilibrium in the pressure in the three zones throughout the test period (10 minutes). If this were to occur in a real fire situation the system would not be able to keep smoke out of the stairwell.

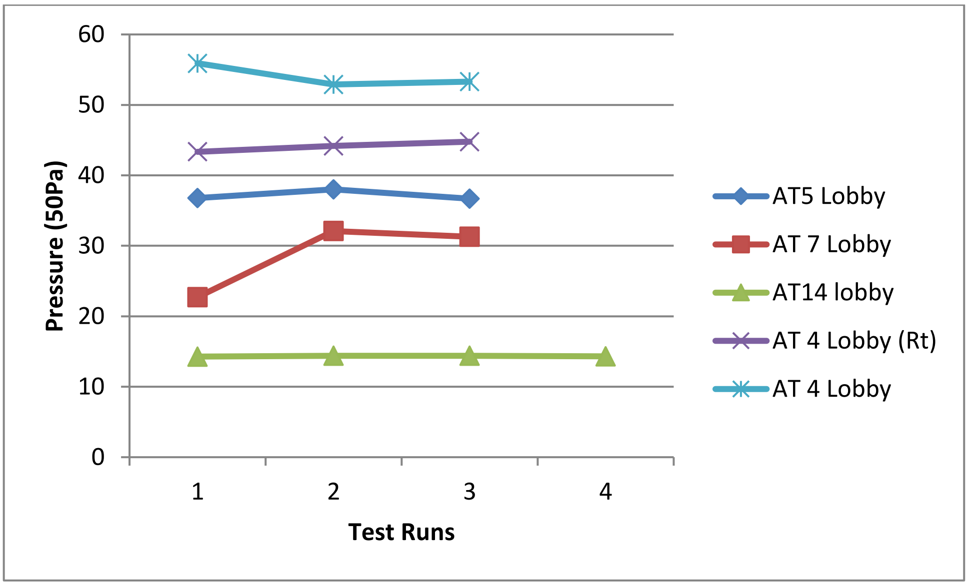

Figure 3 – Pressure Readings in Lobby at Airtightness Level of $14\text{-}4m^3/h/m^2$

With the stair zone pressurized to 25Pa the tests were repeated the data from these tests across the airtightness rates of 4, 5 and $7m^3/h/m^2$ was analysed, this is shown in figure 3. It again demonstrates that as the test rig becomes more airtight the pressure difference across the three zones reduces. The reduction while significant is not as marked as for those tests carried out at 50Pa.

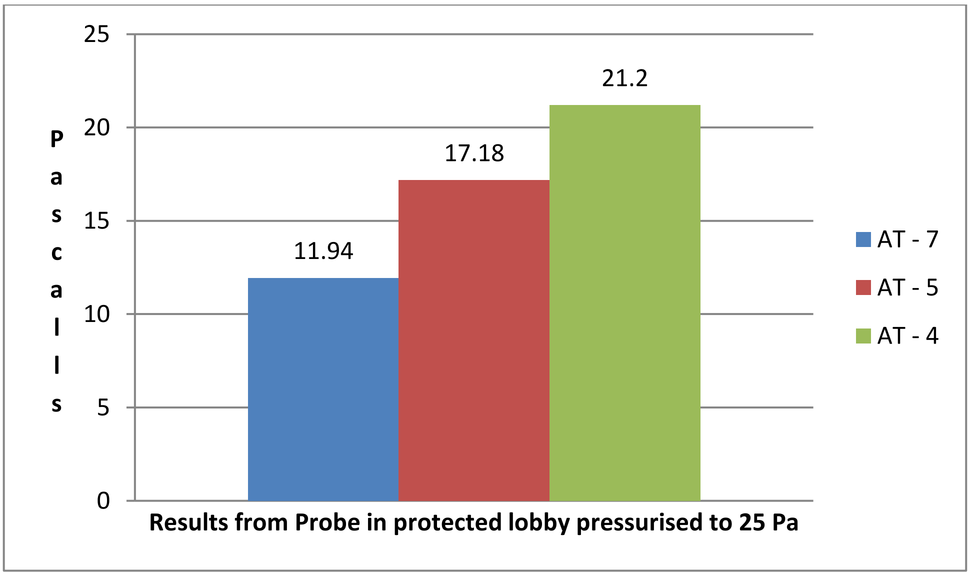

Figure 3 – Probe Outputs at 25 Pascals

CALCULATION METHODOLOGY

The methodology for calculating volume of air required to maintain the necessary pressure can be found using the following equation from BS EN 12101 [5]

$$Q = 0.83AEP1/n$$

It recommends that for wide cracks such as around doors and large openings, the value of n is 2, while for narrow cracks such as around windows it recommends the value of nlf is 1.6. In fact, it states, "the contribution from window leakage is likely to be small" and as such $n_{lf} = 2$ can be used as an estimate for windows on the leakage path. Included in BS EN 12101 [5] is table A.2 which utilises the air flow equation with $n_{lf} = 2$ and Ae is 1 m^2 to provide a quick methodology for determining the leakage rates and pressure differentials around door gaps and large openings (see table 2).

Table 2 – Airflow Velocities Through Gaps and Large Openings where $n_{lf} = 2$

Pressure differential, Pa	Airflow velocity, m/s
50	5.9
25	4.2

The figures from the test rig experiments do not however, reflect these flow velocities and for these outcomes a better match is achieved where nlf = 1.6. Table 3 show the results from table 2 adjusted to represent the results where nlf = 1.6

Table 3 – Airflow Velocities Through Gaps and Large Openings where $n_{lf} = 1.6$

Pressure differential, Pa	Airflow velocity, m/s
50	9.57
25	6.2

In the examples provided in the BS EN 12101 [5] the various leakage paths are added together to give the total air leakage. The change to n_{lf}=1.6 will therefore have a significant impact on the flow.

The flows achieved through these leakage paths are not dynamic and have a low Reynolds number. As such, it is viscosity that is the main force, therefore, the research would indicate that in airtight buildings (< $5m^3.h/m^2$) it is pressure not velocity that should be the design focus.

SUMMARY

The experiments have indicated that the more airtight a building then greater consideration should be given to ensuring there are adequate leakage paths to the external air.

The tests were carried out at various levels of airtightness to reflect those found in modern buildings. In changing this variable throughout the experiments, it has indicated the following:

- Pressure levels increase as the test rig becomes more airtight
- A positive flow away from the stairwell was achieved in all experiments
- As the test rig becomes more airtight the viscous force is the main force impacting on flow.

It would appear that providing sufficient leakage paths as recommended in BS EN 12101 [5] should keep stairwell free from smoke up to airtightness levels $5m^3/h/m^3$ The experiments indicate however that for buildings designed with even tighter standards of airtightness there may be smoke leakage into the stairwell.

It must be noted that these results do not consider the impact of wind and stack effect which as identified in the research by Stewart and Hobson (Table 4.2) [18] are a fundamental consideration in arriving at an overall design pressure level.

FURTHER WORK

Further international research of PDS as a discipline would be valuable to determine what impact the above outcomes will have on PDS. Initial research should focus on the following:

- The need for research into the leakage rates in the various design codes such as BS EN 12101 PART 6 [5] and NFPA 92 [19]. The current leakage rates are based on very old research and not relevant to modern construction standards
- The need for research into the difference between design and installation and how much they differ, and what can be done to reduce this differential.
- The need for research to identify areas of best practice as well as areas for improvement which could inform future legislative processes in the promotion of better regulation.

CONCLUSION

The literature review has shown that the basis of the calculations for designing smoke control pressurization systems is the Ideal Gas Laws and Bernoulli's principle. Various research projects were carried out in the 1960s and 1970s which demonstrated that pressurization helped clear smoke from the affected area and prevented entry of smoke into the stairs. Empirical formulae were developed and incorporated in smoke control design codes.

The survey of design professionals identified a professional industry in outlook and approach however, there is a limited awareness in the industry in general as to the impact of airtightness on pressurization systems. Many designers had examples where the system did not function as designed due to a lack of air leakage paths.

This was particularly the case where energy efficiency improvements had been made to existing buildings and the installed pressurization system did not have sufficient tolerances to function as originally designed due to lack of air leakage paths. This anecdotal data on installed systems indicates the original design may not be sufficient to accommodate significant reductions in leakage paths due to improving the air tightness of the building.

The test research has shown that the original experiments were based on buildings with an airtightness ratio greater than $14m^3/h/m^2$ and that as buildings become increasingly airtight the effectiveness of the pressurization system reduces.

BS EN 12101 [5] recognises the need for air release paths from a building this is essential in modern buildings however, the air leakage data is out of date and does not reflect modern products. Following this research, the author believes that if this design code is updated to take account of the reduction in air leakage paths, the pressurization systems can still be an effective means of preventing smoke entry into the stairwell.

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