Selection Considerations of Exterior Wall Leakage Values for Smoke Control Systems Design

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Abstract

Smoke control in buildings is crucial for ensuring occupant safety during fire incidents. The design analysis of smoke control systems requires several input parameters. Included among those inputs are the leakage characteristics of building components, most notably exterior walls, stairwell enclosing walls and stairwell doors. A lack of adequate data for the leakage of these and other building components results in uncertainty in calculations of fan capacities needed for stairwell pressurization systems. Leakage rates that are commonly used for smoke control design analyses using hand calculations or software such as Ventus or CONTAM are selected based on experience or arbitrarily.

Introduction

The design analysis of smoke control systems requires several input parameters. Included among those inputs are the leakage characteristics of building components, most notably exterior walls, stairwell enclosing walls and stairwell doors. For the design of stairwell pressurization systems, selecting accurate estimates of the magnitude of the leakage associated with building components as inputs can be challenging. Klote, et al. [2012] provide tables of leakage characteristics of these building components. For exterior walls, the leakage is characterized in terms of a leakage ratio, defined as the ratio of the effective area of the leak to the total surface area of the component. Four categories of exterior wall leakage provided by Klote, et al. are presented in Table 1. The magnitudes of the leakage rates included in the table vary by two orders of magnitude with no guidance being available on which one to select.

Table 1. Leakage Characteristics of Exterior Walls

Leakage Category	Leakage Ratio (m^2/m^2)
Tight	5.0×10^{-5}
Average	1.7×10^{-4}
Loose	3.5×10^{-4}
Very Loose	1.2×10^{-3}

As a means of describing the magnitude of these leakage ratios, in section C402.5.1.3 in the International Energy Conservation Code (IERC) [2021] for commercial buildings, the air permeability of air barriers is limited to a maximum of 0.004 cfm/ft^2 given a pressure difference of 0.3 in. w.g. (0.02 L/sec-m^2 at pressure difference of 75 Pa). This relates to a leakage ratio of 1.27×10^{-4} and is comparable to the entry in Table 1 for the “average” category.

There are two challenges with the use of this table. First, no description is available to identify what type of wall construction is associated with these categories. Second, the surveys conducted to develop these values in the table were completed 30 to 60 years ago.

Hence, design engineers are left to make choices of leakage factors based on intuition or experience, or in some cases, they make choices arbitrarily. With the values for exterior wall leakage included in Table 1 varying by two orders of magnitude, differences in resulting fan sizes in pressurized stairwell systems obtained in engineering analyses can vary appreciably, depending on the choice of the leakage rate of the exterior walls. This review paper investigates the relationship between various building parameters and exterior wall leakage, aiming to enhance selection guidance for building leakage assumptions used by designers for smoke control design.

Building Survey Data

The earliest study on the leakage characteristics of exterior walls was conducted in the 1970's by Tamura and Shaw of the National Research Council (NRC) of Canada [1976]. Their experiments were conducted in eight office buildings ranging in height from 11 to 22 stories. These buildings were all built during the 1960s to early 1970s and all included curtain walls. Three of the eleven buildings had metal panels as the exterior façade and the other eight had concrete panels. The leakage rates determined by Tamura and Shaw are those included in Table 1. Shaw [1993] conducted a follow up of the 1970's study to examine the changes in air leakage levels of six Canadian office buildings. The author stated that the subjects tested in this study were some of the same buildings that were tested in the 1970's. Shaw found that there was an improvement in air tightness of the five buildings that had undergone renovations, including items such as adding a new vapor barrier, resealing windows, sealing vertical columns from inside, installing a new curtain wall system, re-caulking joints, and adding a new roof. The extent of the reduction in leakage rate in these buildings ranged from 0 to 43%. For the one building that had not been renovated, its leakage rate increased by 23% in the 20 years since it was last tested.

Reported exterior leakage rates did not significantly change from the 1960s to the 1990s [Emmerich and Persily, 2011]. Strege and Ferreira [3] measured differential pressures in fifteen (15) high-rise buildings in four (4) different cities (Cleveland, Baltimore, Minneapolis, and Philadelphia) during the winter months of January to March 2013. The buildings included in their study had exterior walls with either fixed glass curtain walls or masonry with fixed windows. Their analysis found the leakage of the exterior walls to be in the "loose" category of the values presented in Table 1.

More recent studies have been conducted, being motivated principally by an interest in energy conservation. Emmerish and Persily [2011][2014] compiled a database of leakage data in two stages. The first one completed in 2011 included surveys of 228 U.S. commercial and institutional buildings. The second stage was completed in 2014 and included data from an additional 159 buildings. Some of the data was collected by Emmerish and Persily from the National Institute of Standards and Technology team, with other data provided from other sources. It should be noted that Emmerich and Persily determined the leakage by considering either a 5- or 6-sided surface envelope. When data was not available for both conditions, they used a conversion factor of 1.5 to convert data from 5-sided envelope surfaces to values for a 6-sided envelope surface based on the average value for other buildings in the database. That conversions factor was used in some of the Figures 1-5 included in this paper.

The information on leakage compiled by Emmerish and Persily is presented in Table 2. The data shown in the table has been converted to the expressions of leakage ratio included in Klote, et al. [2012] by the following expression:

$$\frac{\dot{V}}{A_w} = C\frac{A_L}{A_w}\sqrt{\frac{2\Delta p}{\rho}}$$

Where:

$\dot{V}/A_w$ = reported leakage flow per unit wall area in Emmerish and Persily [2011][2014] ($m^3/s\text{-}m^2$)

C = coefficient of discharge, assumed to be 0.65

A_L/A_W = leakage ratio as expressed in Table 1 (A_L = area of leak, A_w = total wall area)

Δp = Pressure difference across exterior building surface, given as 75 Pa by Emmerish and Persily [2011][2014]

ρ = density of air, assumed to be 1.2 kg/m^3 (associated with air at 20 °C)

The average leakage of 7.45×10^{-4} for all 387 buildings is in the "loose" to "very loose" categories noted in Table 1. Except for the data collected in Washington and as part of the ASHRAE RP 1478 study [Anis, et al., 2013], the maximum leakage values included in Table 2 are all greater than the value associated with the "very loose" category noted in Table 1.

Table 2. Leakage Ratios determined from Emmerish and Persily Surveys [2014]

Dataset	Qty	Mean	Standard Deviation	Minimum	Maximum
2011 Database					
Source 1	9	5.77E-04	4.40E-04	1.49E-04	1.66E-03
Source 2	89	1.29E-03	8.87E-04	1.53E-04	4.74E-03
Source 3	39	7.57E-04	6.96E-04	1.03E-04	3.08E-03
Source 4	88	7.38E-04	3.94E-04	1.30E-04	2.42E-03
Source 5	3	3.33E-04	7.64E-05	2.45E-04	3.86E-04
2014 Database					
Efficiency VT	36	3.67E-04	3.94E-04	2.68E-05	1.85E-03
ASHRAE RP 1478	16	2.68E-04	1.91E-04	5.35E-05	7.80E-04
Washington	18	4.01E-04	1.57E-04	1.15E-04	6.69E-04
Other VT/NH	79	5.66E-04	4.13E-04	5.35E-05	1.75E-03
Other VT/NH	10	3.17E-04	2.45E-04	9.94E-05	8.68E-04
Summary					
Total-2011	228	9.52E-04	7.30E-04	1.03E-04	4.74E-03

Total-2014	159	3.78E-04	3.25E-04	2.68E-05	1.85E-03
Total-all	387	7.45E-04	6.57E-04	2.68E-05	4.74E-03

It is noteworthy that the original study in 2011 included a total of 41 buildings built or renovated under the Efficiency Vermont program. This program incentivized households and businesses to reduce their energy costs. In the more recent study, data from another 36 buildings from that initiative were included in the database. Anis, et al., [2013] obtained data in 16 recently built mid- and high-rise buildings as part of an ASHRAE research project. The new data reported in 2014 also included data from 18 buildings in Washington state where there is a non-mandatory target airtightness level included in a local code. Overall, the leakage rate noted from buildings included in the 2014 update was about 50% less than that in the 2011 version of the database.

Influence of Building Characteristics

In the database compiled by Emmerich and Persily, they also identified some characteristics of the building which permit an assessment of whether there is a relationship between these characteristics and the leakage rate of the exterior wall. These characteristics include:

- building height
- building floor area
- wall construction
- climate in the location of the building
- year of construction

It should be noted that these factors do not directly dictate the leakage characteristics of a building. For example, a tall building is not inherently more or less leaky than a short building. The differences that are reflected in the following figures and tables is that there may be different material choices or construction practices for buildings with a particular characteristic, e.g. short vs. tall or small floor area vs. large floor area and these differences affect the leakage rate for the building.

Figure 1 provides data of air leakage for buildings ranging from 1 to 15 stories. As presented in the graph, there is appreciable scatter in the data, especially for 1- to 3-story tall buildings. Overall, there is a notable trend in the data that indicates that taller buildings have less leakage than short buildings. Furthermore, the data demonstrates that operable openings, such as exterior doors located on the ground floor, can notably increase exterior wall leakage for a given floor. Strege and Ferreira [3] highlight the importance of accounting for these variations in exterior wall leakage from floor-to-floor when modeling buildings for smoke control design.

The data of air leakage versus floor area is presented in Figure 2. Here, the greatest scatter is evident for buildings with small floor areas (less than 10,000 ft^2). The overall trend noted in the figure is for larger buildings to have less leakage than smaller buildings.

The leakage for buildings with a variety of wall construction materials for exterior walls is presented in Figure 3. The buildings with masonry walls have the smallest average leakage value, while those with concrete panels have the greatest average leakage value (along with the greatest range in reported values).

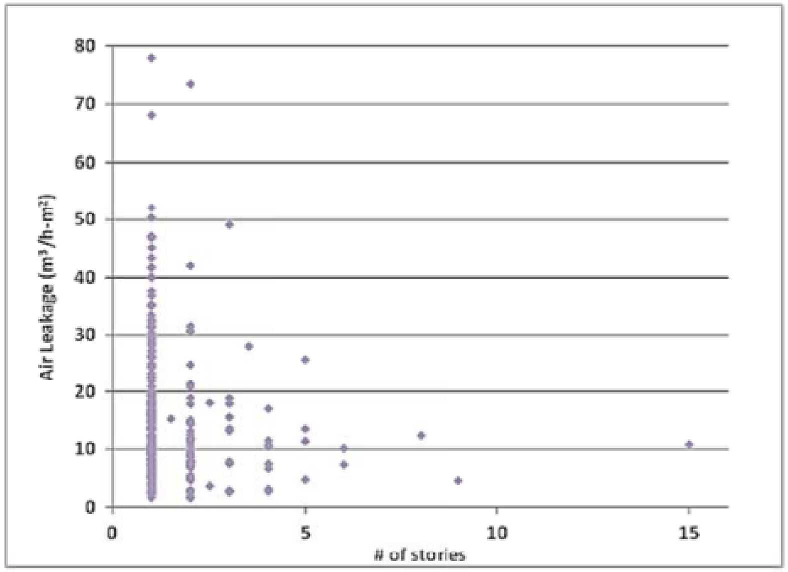

Figure 1. Building Air Leakage Rate vs. Height of Building [Emmerish and Persily, 2014]

Note: air leakage of 1 $m^3/hr\text{-}m^2$ = leakage rate of $3.82x10^{-5}$

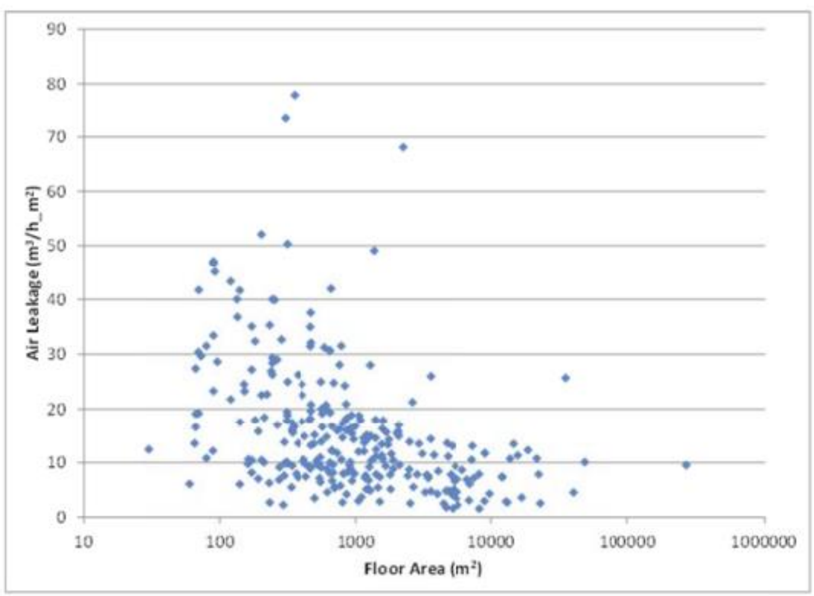

Figure 2. Building Air Leakage Rate vs. Floor Area of Building [Emmerish and Persily, 2014]

Note: air leakage of 1 $m^3/hr\text{-}m^2$ = leakage rate of $3.82x10^{-5}$

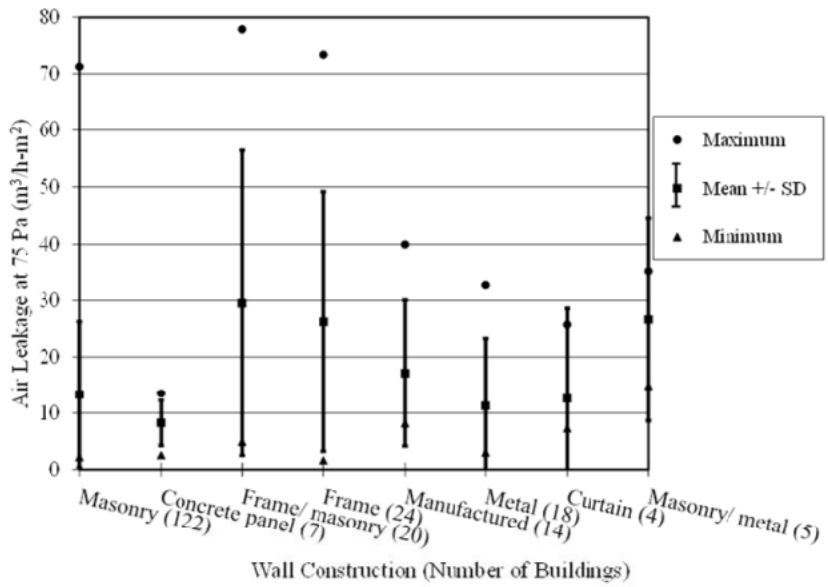

Figure 3. Building Air Leakage Rate vs. Composition of Exterior Wall [Emmerish and Persily, 2014]

Note: air leakage of 1 $m^3/hr\text{-}m^2$ = leakage rate of 3.82×10^{-5}

In Figure 4, the influence of building location on leakage factor is indicated. While the trend is not as evident here as in the previous figures due to the scatter in the data, there does appear to be a tendency that buildings in areas with a greater number of heating degree days have reduced leakage.

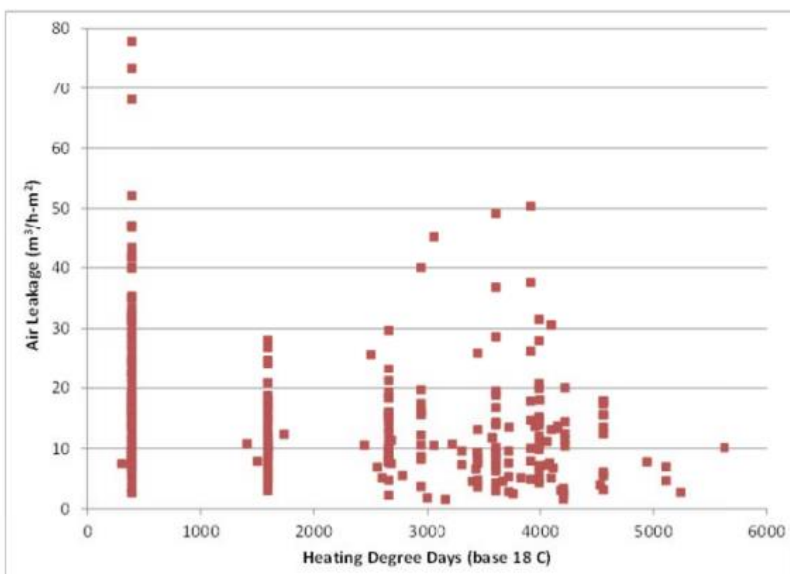

Figure 4. Building Air Leakage Rate vs. Climatic Conditions for Building Location [Emmerish and Persily, 2014]

Note: air leakage of 1 $m^3/hr\text{-}m^2$ = leakage rate of 3.82×10^{-5}

Lastly, the variation of the leakage rate in buildings for the year of construction is presented in Figure 5. As in the previous figures, the amount of scatter is appreciable. In this case, a trend is difficult to discern, though a low leakage rate is indicated for the relatively small number of samples for buildings constructed after 2000.

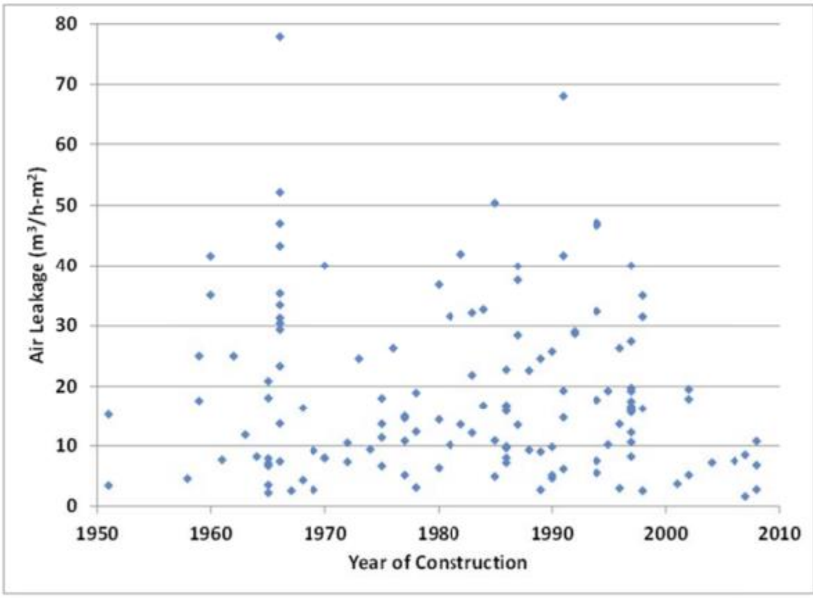

Figure 5. Building Air Leakage Rate vs. Year of Construction [Emmerish and Persily [2014]

Note: air leakage of 1 $m^3/hr\text{-}m^2$ = leakage rate of $3.82x10^{-5}$

Effect of Exterior Wall Leakage on Fan Capacity for Stairwell Pressurization

The following example is presented to provide an illustration of the influence of exterior wall leakage on the fan capacity needed for a stairwell pressurization system. The building considered in this example is presented in Figure 6. The building selected for analysis is a simple, 12-story building, with each floor being 3.6 m. The building has 2 stairways, each being 3.5 m by 9 m in size. The shaft wall, stair wall, floors, and roof have “loose” leakage characteristics. All doors have a width of 0.9 m and height of 2.13 m; the air gaps around the door leaf are 2.03 mm at the top and sides, 6.4 mm gap at the bottom. The shaft is 3 m by 4.5 m in size. The elevator door has a width of 1.22 m and height of 2.4 m and is characterized as having “loose” tightness. The interior temperature is set to be 20 ℃, and the exterior temperature is −10.6 ℃ which is the winter design temperature of Baltimore, MD.

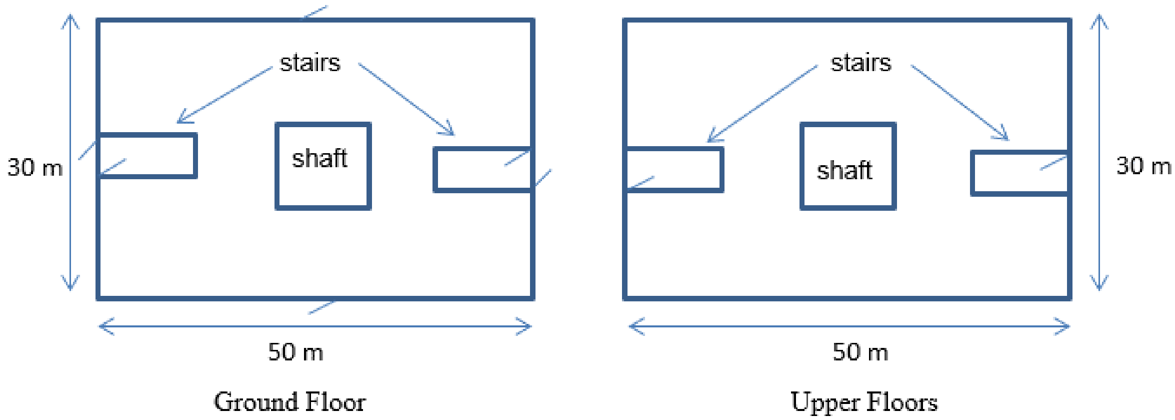

Figure 6. Floor Plan of Example Building

The analysis of the minimum required stairwell pressurization fan capacities was conducted using the network model CONTAM.[1] The minimum pressure difference for stairwell pressurization was selected as 12.4 Pa, based on the requirements in NFPA 92 [2018]. The resulting minimum required fan capacity for the example building with respect to leakage characteristics of the exterior wall are presented in Table 3 and Figure 7. The observation of the results of this analysis is that the minimum required fan capacity to adequately pressurize the stairwell approximately doubles over the range of leakage rates noted in Table 1.

Table 3. Fan Capacity for Stairwell Pressurization vs. Leakage Rate of Exterior wall

Leakage Category	**Area Ratio (A_L/A_w)**	**Fan Capacity (m^3/s)**
Tight	5.0×10^{-5}	1.7
Average	1.7×10^{-4}	2.05
Loose	3.5×10^{-4}	2.46
Very Loose	1.2×10^{-3}	3.61

[1] Appreciation is extended to Sofia Braddock for conducting the stairwell pressurization system analysis. This analysis was conducted in 2020 while she was a student majoring in Fire Protection Engineering at the University of Maryland.

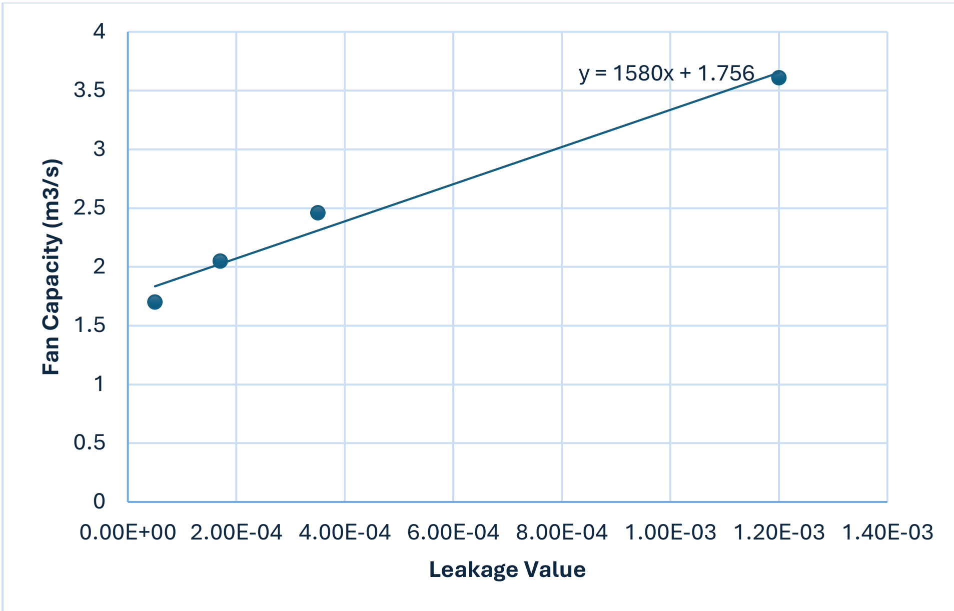

Figure 7. Stairwell Pressurization Fan Capacity vs. Leakage Rate for Exterior Wall

Summary

Previous studies have found that building envelope leakages were either "loose" or "very loose". An identification of trends in the database by Emmerish and Persily of the leakage rate of exterior walls for buildings using five characteristics of the building can be an aid to design engineers when making estimates of the leakage rates for exterior walls. The five building characteristics are a building's 1) height, 2) floor area, 3) age, 4) composition of exterior wall, and (5) climatic condition.

While there is not a direct cause-effect type of relationship between these characteristics and the leakage rate for the exterior wall, the leakage rate measured in buildings varied with these characteristics. Recognizing these trends can assist the design engineers in making informed assumptions about leakage rates rather than making those assumptions arbitrarily, thereby yielding improved fan capacity selections and reducing the potential for fans and ductwork overdesign.

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