Stack Effect and Mechanical Exhaust System Impacts on Building Pressures and Envelope Air Leakage

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ABSTRACT

Air leakage through building enclosures is driven by air pressure differentials between the interior and exterior of a building. In a typical low-rise building, pressure differentials are primarily driven by transient wind effects – air is "pushed" in at the windward side and "pulled" out on the leeward side. On a calm day, even a relatively leaky building enclosure will experience only minimal air leakage due to low pressure differential. Conversely, many of the features of mid- and high-rise buildings, including height, can impact pressure differentials and thus air leakage. Stack pressure in tall buildings can lead to significant and relatively constant pressure differentials throughout the height of the building during cold weather, exacerbating air infiltration on the lower floors and exfiltration on the upper floors. Often more significant, however, is the impact of mechanical ventilation and exhaust systems, such as unit-by-unit ventilation, constant bathroom exhaust fans, and intermittent clothes dryer and kitchen exhausts. These systems can generate sustained pressure differentials with much greater impact than wind or stack pressure alone; they create internal airflows between units/spaces and floors, and constant (year-round) driving force for air leakage through the building enclosure. This paper discusses the physical phenomena that drive pressure differentials and air leakage in mid- and high-rise buildings, uses case studies and investigative examples to illustrate both the magnitude and impact of these phenomena, and provides guidelines for designing mechanical systems to control air pressure and minimize air leakage in these types of buildings.

KEYWORDS

Infiltration, Ventilation, Stack Effect, Exhaust, Air Leakage

1. INTRODUCTION

Air leakage in buildings can have many undesirable effects, including condensation, increased heating and cooling costs, noise, transfer of air-borne contaminants, and reduced occupant comfort. It follows that reducing air leakage has many benefits, hence the development of continuous air barrier industry guidelines, such as specifications from the Air Barrier Association of America, and local and national energy code requirements, including ASHRAE 90.1-2010: Energy Standard for Buildings Except Low-rise Residential Buildings and state-wide energy codes in Massachusetts, New York, Maryland, Washington, and others. While airtightness is important in all buildings, it is especially important in mid- and high-rise buildings due to the potential impact of leakage through the large enclosure areas, and the presence of mechanical ventilation and exhaust systems which can significantly impact building pressures – the driving force behind air leakage through building enclosures. Air leakage rates through building enclosures in low-rise buildings are relatively well understood, and these buildings are typically the most common subject of studies on the topic. In taller buildings, however, the magnitude of air leakage in "tight" buildings may still be much greater than that of a "leaky" low-rise building due to the effects of mechanically-induced pressure differentials. This paper reviews the driving forces behind air leakage in tall buildings, compares leakage in low-rise buildings to leakage in mid- and high-rise buildings, and discusses strategies for minimizing mechanically-induced pressure differentials as a means of controlling air leakage.

2. SUMMARY OF DRIVING FORCES

The driving force behind air leakage is a difference in air pressure between the interior and exterior of a building. Air will naturally flow from regions of high pressure to regions of low pressure. Just as a building with no roof covering will never leak if it never rains, a "leaky" building enclosure will only experience air leakage if a pressure differential exists.

Pressure differentials in buildings can be caused by three different phenomena. The most common, and the primary driver for air leakage in low-rise buildings, is wind. Wind creates a positive pressure on the windward side of a building, negative pressure on the leeward side, and varying pressures over surfaces parallel to the direction of flow, such as roofs and side walls. The effects of wind are intermittent and highly variable, as buildings rarely see constant, sustained winds for extended periods of time.

The second driver is a phenomenon known as "stack effect". Warmer air is naturally less dense than cooler air, so in a heated building in a cold climate, the air within will tend to rise. This effect is a function of interior/exterior temperature differentials and building height, so low-rise buildings rarely experience noticeable stack pressure effects. In a mid or high-rise building, especially in colder climates, stack pressure can be significant, often creating higher pressure differentials than wind, and for greater lengths of time. Rising air within the building "column" will create a negative pressure at the base of the building, where air is drawn in, and a positive pressure at the top, where air is forced out. The reverse is also true during warm weather, as cooler interior air tends to sink and create a negative building pressure at the top and positive pressure at the bottom. This effect is usually less pronounced due to the lower temperature differentials present during the cooling season (usually about 5 to 10ºC, as opposed to 25 to 35ºC during the heating season). For all buildings, there exists a point where the interior and exterior pressures are balanced. This point is known as the "neutral pressure level" or "NPL". For a single-zone building of any height, with no internal flow resistance, the NPL would be located at mid-height, halfway up the building. Real buildings contain interior components such as walls and floor partitions, as well as full-height shafts for utilities, elevators, and stairwells, which can significantly affect the location of the NPL. Data on the location of the NPL in tall buildings is sparse, but the available data suggest that the NPL is typically between 0.3 and 0.7 of the total building height (Tamura and Wilson 1966, 1967b).

The last, and potentially most significant driver of building pressure, is mechanical pressurization/depressurization. There are a wide variety of mechanical systems in modern (as well as many older) buildings that can influence building pressure by forcing air in or drawing air out of the space. These include ventilation systems (either dedicated outside air systems or smaller air handlers with outside air capacity), kitchen and bathroom exhausts, dryer and other equipment exhausts, and economizer systems on air handling equipment. Unlike wind, and to a lesser extent, stack effect, which are both transient phenomena, mechanical systems often run 24 hours per day and 365 days per year, creating a constant pressure differential between the interior and exterior and greatly exacerbating air leakage as a result. Mechanical systems are also the only one of the three phenomena that a designer can modify substantially to control air flow and leakage, and are the focus of this paper.

For reference, the three phenomena that impact building pressure and air leakage are shown graphically in Figure 1.

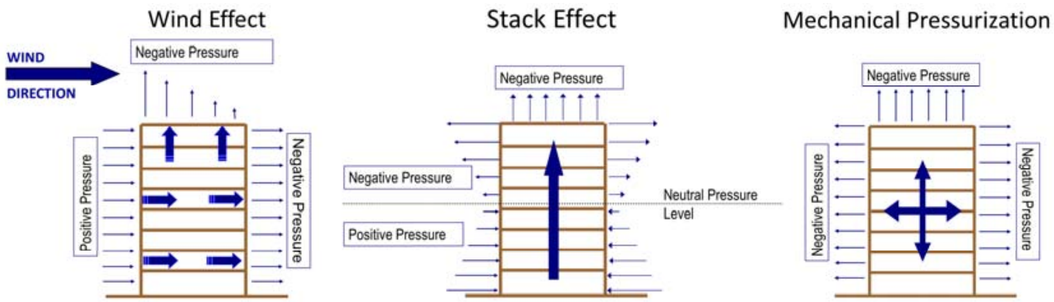

Figure 1 – Primary drivers of air leakage in buildings

3. STACK EFFECT

Stack effect in tall buildings is typically only a problem where mechanical systems (discussed in more detail below) fail to provide sufficient control over building pressures. In these cases, or in isolated cases within otherwise well-controlled buildings, stack effect can lead to significant air leakage into and out of buildings. Take the worst-case scenario of a 30m tall mid-rise building in Washington, DC, where the winter design temperature is approximately -10ºC. In a completely open building without floor or area separations, heating the building space to 21ºC during the winter results in a total potential stack pressure of nearly 40 Pa. That potential represents the greatest possible pressure differential that could occur due to stack effect within the building. If the pressure at the ground floor is neutral with respect to the exterior, this would mean a positive pressure of 40 Pa would be possible at the roof level. For an NPL at the mid-height of the building, the result would be a pressure of -20 Pa at the ground floor and +20 Pa at the roof (infiltration on the lower half of the building followed by exfiltration at the top).

It is important to note that for simple openings ("leaks") in building enclosures, air leakage is relatively unaffected by the direction of airflow. This means that a hole in the building's air barrier will generally allow the same amount of air leakage regardless of whether air is flowing into or out of the building. However, components such as windows and doors often rely on gasket compression for air and water sealing, and may experience different amounts of air leakage depending on the direction of flow. For example, under positive interior pressure the sash of an outswing casement window will be pushed away from the perimeter gaskets, reducing their air sealing effectiveness. Conversely, negative pressure will pull the sash in and provide greater compression of the gaskets, which may actually improve airtightness. The net result is that for tall buildings, stack effect may exacerbate air leakage in some areas while reducing it in others, depending on the specific enclosure systems being used on the building as well as their specific location.

4. MECHANICAL SYSTEMS IN TALLER BUILDINGS

Mid and high rise buildings often contain significantly more mechanical equipment than smaller, low-rise buildings. This is due to the sheer size of the buildings and the need for common equipment to handle bathroom exhaust, kitchen exhaust, and other air systems. Moving air over large vertical distances requires carefully designed ductwork, fans, and controls capable of providing balanced airflows to the spaces that the equipment serves. Unfortunately, these systems are often subject to generic design approaches that may be inadequate or inappropriate for specific building configurations and layouts. Well thought out designs are often considered excessive or unnecessary and end up being "value engineered" down to much less effective systems. Poor design and installation seem to be more common in residential-use buildings (including mid and high rise construction), which typically produce a greater number of problems related to air flow and air leakage. This paper will focus on multi-family residential buildings which have a large number of bathrooms, kitchens, and other features that result in much greater mechanical system airflows than similarly sized office and general commercial buildings.

4.1 Code Provisions

The 2009 International Mechanical Code (the "Code"), which forms the basis for many state and local codes, contains provisions for outside air supply and exhaust air systems. The Code requires all occupied spaces to be ventilated, but it allows ventilation to be provided by either natural or mechanical means. Mechanical ventilation requires specific flow rates for specific applications, and will generally result in more even and consistent ventilation of spaces as the systems can all be adjusted and balanced to provide the desired flows.   Natural ventilation simply requires providing a certain percentage of the occupied floor space as "openable area to the outdoors" (currently 4%), and provides highly variable and inconsistent airflow. In many cases, areas such as interior (windowless) bathrooms must be mechanically exhausted, but are allowed under the Code to draw makeup air from the adjacent spaces – which may be naturally ventilated using operable windows. This "hybrid" ventilation scheme, which is very common in tall residential buildings, can lead to a wide range of problems as discussed further in the following sections.

4.2 Outside Air Systems

A distinguishing feature of tall residential occupancy buildings is the typical reliance on operable windows to provide ventilation air to the spaces, as opposed to office and commercial spaces which are almost exclusively mechanically ventilated. The driver behind this difference is simple economics – adding mechanical ventilation to a commercial building with 5 to 10 air handlers is relatively simple, requiring localized components in the air handlers to control the flow of outside air into the recirculating airstream within the ducts. In contrast, a large residential tower may contain 50 to 100 units, each of which has its own air handling system (or other space conditioning equipment). The cost and logistics of providing dedicated outside air to each of those air handlers are often prohibitive, and almost always ends up being less than the cost of using operable windows, which may be in the design already, to meet code requirements for ventilation air. An additional contributing factor is the difficulty of accommodating large numbers of outside air intakes within the architecture of the building, especially for buildings with large glazed areas or monolithic facades.

4.3 Exhaust Systems

"Ventilation" for areas such as bathrooms is typically provided by exhausting air from the bathrooms and allowing makeup air to enter from the surrounding spaces. The Code allows either constant or intermittent exhaust to be used, with the intermittent requirements being 2-1/2 times higher than the constant requirements. However, as with the outside air systems, residential buildings rarely include dedicated (intermittent) exhaust for bathrooms as that option requires an independent, controllable fan in each unit as opposed to constant exhaust where a single fan at the roof level will accomplish the same end.

Other major exhaust systems include kitchen clothes dryer exhaust. The amount of exhaust for these systems is not specifically noted in the code, although for single installations, no make-up air is required for dryers exhausting less than 95 L/s or kitchen devices exhausting less than 190 L/s (less of a problem for kitchen systems that operate intermittently, but dryer systems with longer run times may be a bigger issue). Dedicated makeup air supply is required above those levels to prevent pressure imbalances, but typical residences will not have exhaust flows exceeding those limits. The Code does require makeup air for common dryer exhaust risers in multi-story structures, but individual dryers attached to the riser will still be drawing air out of the occupied spaces in their respective units even if the main riser has an opening to the exterior.

5. TYPICAL PROBLEMS

5.1 Design

The design of exhaust systems in tall buildings is fairly complex, as designers must account for moving air over large vertical distances, maintaining consistent flow through multiple inlets at different elevations, and accounting for stack pressures that vary from month to month and can upset airflow balances between floors. The American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) provides guidance for designing vertical duct runs to achieve balanced flow, but unfortunately these guidelines seem to be ignored more than they are implemented. In many of the buildings that the authors have investigated, exhaust risers consist of a straight, constant cross-section ductwork extending from the roof-mounted fan all the way to the ground level. In cases where balancing dampers are not installed at the inlets, the result is a disproportionate amount of airflow through the upper inlets, nearest to the fan, and little to no flow near the bottom of the shaft. This effect is magnified where the exhaust fan is oversized and produces greater-than-code-minimum exhaust flows, also a common occurrence. This produces strong negative pressures near the top of the stack, the opposite of what one would expect in a tall building where stack effect typically produces positive pressure in that location. Variable cross section duct and/or the use of balancing dampers are necessary to prevent these flow imbalances and generate a consistent exhaust flow at all levels.

In order to prevent excessive stack pressures from developing, buildings need to have relatively continuous horizontal partitions (at floor levels) to "compartmentalize" the interior space. In most cases, this happens by default rather than design, since floors often require fire and smoke seals at penetrations, etc. which also function as air barriers. Vertical shafts such as elevators, stairs, and duct/utility chases must be effectively isolated from the occupied spaces of the building using seals, gaskets, and fire doors to minimize their impact on building pressures. It is more common for unbalanced mechanical systems (supply or exhaust) to contribute to poor control over stack pressure more than the physical design of the building. Stack pressure is typically more of a localized effect, for example leading to moderate air leakage at the top of elevator shafts, which are often (by code) vented directly to the exterior. These shafts basically function as chimneys, drawing in warm building air from all areas and exhausting it to the exterior above the roof level.

We recently investigated a large, 20+ story condominium building in the mid-Atlantic region that exhibited strong negative pressures on the upper floors. The occupants on the upper floors complained of drafts, loud "whistling" noises near doors, and difficulty opening doors. We measured negative pressures, relative to both the corridors and the exterior, of 60 to 80 Pa on the upper floors, with pressures approaching neutral near the ground floor. The bathroom exhaust risers were constant cross section ducts for the full height of the building, with no balancing dampers or other provisions for adjusting airflows from the units. The corridors were supplied with dedicated outside air but did not have return or relief ducts, increasing the pressure differential to the units. The high negative pressures we observed were creating forces of over 100N on doors, making both interior (to the corridor) and exterior (to balcony) doors difficult to operate. Whistling was being caused by high speed airflows around the entry doors, which were fairly well-sealed due to the need for fire/smoke resistance but not completely airtight. Due to the high negative pressures, air leakage was significant in some areas of the enclosure despite the wall systems being relatively airtight.

This building was a classic case of imbalanced airflows leading to building-wide problems. In the case of the corridors, this was apparently intentional since there was no exhaust or return air to compensate for the supply. Although larger residential buildings often use the strategy of supplying ventilation air to the corridors which then supplies the individual units via door undercuts (which is oddly enough prohibited by most building and fire codes), this was not the design intent here as the units had sealed entry doors and specifically included operable windows to provide ventilation directly to the units. In the case of the bathroom exhaust risers, it was simply poor design which resulted in unacceptable pressure differentials. Remediation of these problems involved a combination of new balancing dampers at the bathroom inlets and removing sweeps from the unit entry doors (with building department approval) to allow the excess fresh air from the hallway into the units, helping to minimize pressure differentials by balancing out the bathroom exhaust flows.

5.2 Construction

The best-designed building will still fail to perform if that design is not properly implemented by the builders. In the same building discussed above, we observed a variety of construction errors that contributed to the pressure issues and in some cases made them more difficult to diagnose. The typical exhaust risers were enclosed in gypsum wallboard shafts, with branch ducts running to bathrooms on each floor. In the majority of these cases, the ductwork was stopped short of the surface-mounted intake grilles, resulting in large gaps between the duct and the inlet (Figure 2).

Figure 2 – Gaps between exhaust ductwork and surface mounted grilles (removed in this photograph)

In these cases, air was drawn through and around the gypsum wallboard shafts in addition to through the actual duct. When bathroom doors were closed, these gaps often presented the path of least resistance for air, as the bathroom doors were fairly tight and did not allow for makeup air to enter those areas (as is required by the Code). The net effect of these gaps was that exhaust shafts in one vertical "stack" of the building were affecting pressures in adjacent stacks of units as well. In one case, the only way we were able to reduce pressure differentials in a test unit (for diagnostic purposes) was to shut down exhaust fans in that stack as well as in the stacks of units on either side. Shutting down the stack in question produced a slight difference in pressure, but because adjacent, poorly sealed exhaust risers were still drawing air from the adjacent areas, moderate to significant negative pressure persisted.

Although not specifically a construction issue, mechanical contractors are often required to retain independent testing, adjusting, and balancing (TAB) firms to determine if the installed systems are functioning as intended. The design team needs to pay very close attention to this work and carefully review the resulting reports, as the TAB report will contain valuable information on the operation of the building. It also represents the "last chance" for designers to identify problems and make changes before the building is occupied. On most of the buildings that the authors have investigated, at least some of the problems that we were asked to solve were clearly identifiable in the TAB report but were never addressed by the design team.

5.3 Operation

Despite being allowed by the mechanical code, reliance on operable windows for ventilation is generally a poor strategy in terms of airflow control, pressure balancing, and air leakage. The primary reason for this is that there is no way to regulate the amount of ventilation air entering a space (i.e., the makeup air required to balance out exhaust flows) since the occupants of the unit have complete control over opening and closing windows.

With windows open and relatively mild exterior temperatures, the concept works well as the windows allow makeup air to enter the space and supply the various exhaust flows from the occupied space, all without increasing space conditioning loads or affecting occupant comfort.

In reality, conditions in most areas of the United States, especially the Northeast, are only conducive to natural ventilation for a limited amount of time – it is typically either too cold or too humid for naturally-ventilated spaces to meet the often-discerning preferences of occupants, especially in residential buildings. Even if comfort were not an issue, opening a window in January in a building in New York or Boston to provide makeup air for exhaust systems will introduce significant quantities of unconditioned outside air to the occupied spaces – increasing heating loads and reducing energy performance. In this one-sided approach, where air is exhausted but not specifically replaced using mechanical systems, there is no practical way to incorporate heat exchangers or heat recovery systems which are commonly used in fully mechanically ventilated buildings to reduce the inefficiencies associated with providing simultaneous fresh air and exhaust.

6. MAGNITUDE OF AIR LEAKAGE

As discussed previously, even at low pressure differentials, the constant nature of mechanically-induced pressure differentials creates significantly higher potential for air leakage as compared to transient or seasonal effects such as wind and stack pressure. To demonstrate this, we calculated potential air leakage rates for a building on which we recently performed whole-building air leakage testing. The building in question was a 16 story residential tower with approximately 60 individual units, built around 1960. We calculated a pressure-flow curve for the building, which allows us to determine the whole-building leakage rate at any pressure differential within the test results based on the overall area of the building enclosure (in this case, approximately 5,900 m^2). The tested air leakage rate for the building was 3.45 $L/s/m^2$ @ 75 Pa. For reference, current industry guidelines and some state building codes set the target for whole building leakage rate at 2.0 $L/s/m^2$ @ 75 Pa.

We used historical hourly weather data for a mixed Mid-Atlantic climate to calculate hourly wind pressures on the facade, and then used the pressure-flow curve from our testing and the overall area of the building enclosure to convert those into leakage rates. It is important to note that this approach will overestimate wind effects as the reported hourly values for wind speed will rarely be constant for the whole hour and pressure distribution over the façade area will not be uniform; the intent of this exercise was to provide a general comparison, not an exact calculation of air leakage. We used pressure differentials of 10, 20, and 30 Pa (a typical range of pressures for many of the buildings that we have investigated) to calculate leakage rates for the enclosure. The results of this comparison, shown in Figure 3, demonstrate the potentially significant effects of constant mechanically-induced air leakage when compared to intermittent wind pressures. It is important to keep in mind that the relative differences shown on this graph will exist regardless of the airtightness of the building enclosure; although the relative magnitude of leakage will be reduced in a tighter building, leakage due to mechanically induced pressure differential will still be much greater than that induced by wind alone. Similarly, the magnitude of leakage will change based on the exterior climate, but the relative differences between wind- and mechanically-induced air leakage will remain about the same.

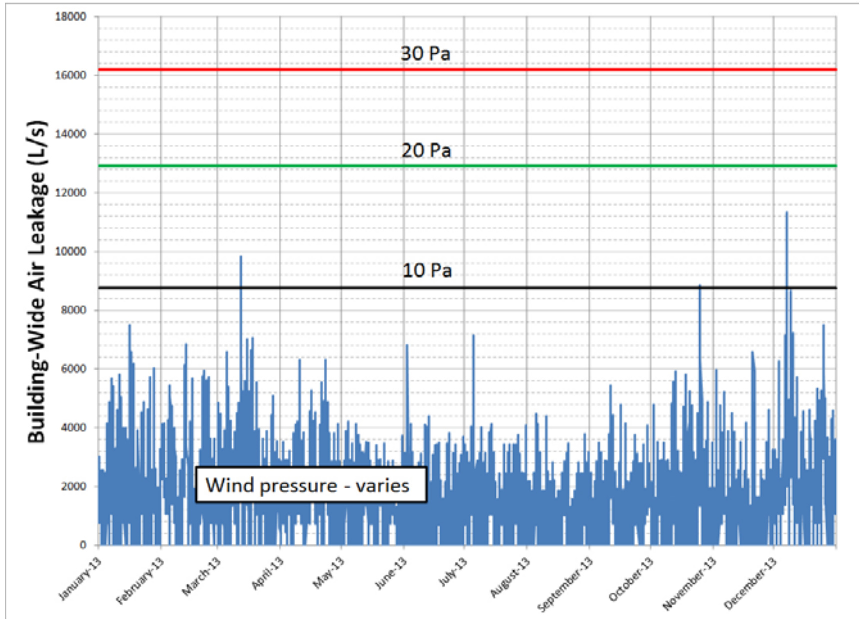

Figure 3 – Comparison of wind vs. mechanically induced air leakage

To further highlight the impact of mechanically induced air leakage, we next calculated the additional heating load on the building resulting from the quantities of air leakage shown in Figure 3, for both the wind-induced and mechanically-induced cases. For comparative purposes, we calculated the conductive heat losses for the building enclosure, using both the existing conditions (minimally insulated walls, single-glazed steel windows) and for an enclosure meeting the basic prescriptive requirements of the 2009 International Energy Conservation Code (IECC), using the maximum allowed value of 40% glazing for the exterior walls. Using the same hourly weather data for Washington, D.C., we calculated the conductive heat loss through the walls, windows, and roofs of the example building on an hourly basis. For an interior temperature of 21ºC, we summed the air leakage-related and conductive heat losses through the enclosure for the month of January. A comparison of these values is shown in Figure 4.

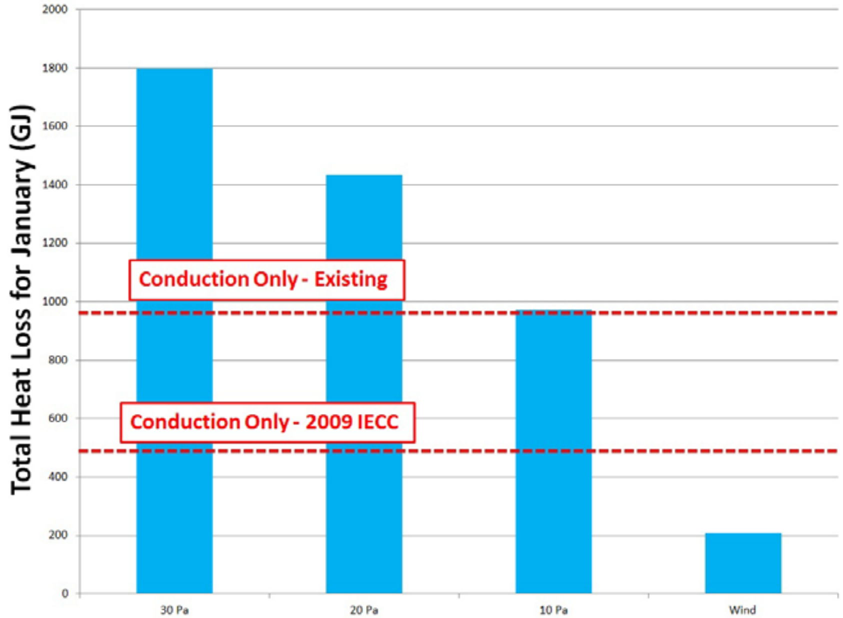

Figure 4 – Comparison of air leakage and conductive heat losses for the example building

This comparison demonstrates that mechanically induced air leakage can form a disproportionately high fraction of the overall heating load for a building, and greatly overshadow the increased heating loads associated with wind-driven air leakage only (as is more typical for low-rise buildings).

7. STRATEGIES TO ADDRESS AIR LEAKAGE AND REDUCE HEAT LOSSES

While improving building airtightness is always one of the first steps in reducing air leakage rates, as the above discussions demonstrate, controlling mechanically-induced pressure differentials is equally important, as it is unreasonable to expect any building to be perfectly airtight. , Some leakage will always occur as long as a pressure differential exists. Understanding the causes of pressure differentials in taller buildings is critical to controlling and reducing the resulting air leakage. Many of the strategies discussed below may be costly in comparison with typical residential building construction standards, but they are sound design guidelines which can significantly improve building performance:

- Provide continuous sealing of vertical shafts (“chimneys”) through the building to prevent stack pressure induced airflows and minimize stack effect over the height of the building. Although this is required by most codes, it is often poorly executed in the field.
- Do not rely on operable windows to provide makeup air for constant-run exhaust systems.
- Consider intermittent bathroom exhaust systems to reduce constant pressure differentials. Some minimal constant exhaust may be necessary to provide sufficient clearing of the exhaust stack, and additional equipment (independent fans in each bathroom) will represent an added project cost.

- For dryer exhausts, consider variable speed fans in the main exhaust riser to prevent the system from operating at full capacity when only a fraction (if any) of the dryers on the stack are active.
- If possible, provide dedicated makeup air, introduced mechanically, to individual units. The specific delivery method (ductwork, door undercuts, etc.) will depend on the details of the project, location of fire separations and rated partitions, and local building and fire code regulations.
- Design constant exhaust risers to provide balanced flow, whether by using variable cross-section ductwork or individual balancing dampers.
- Confirm, through review of field conditions and TAB reports, that the design is properly implemented and that airflows and pressure differentials are within expected limits.

8. SUMMARY

Based on the discussions and calculations discussed above, we conclude as follows:

- The operation of mechanical systems in tall buildings can lead to significantly higher pressure differentials than wind or stack pressure alone.
- Even properly functioning systems will lead to pressure differentials and air leakage; improperly functioning or imbalanced systems will create more significant problems and greater pressure differentials.
- Constant pressure differentials will induce air leakage that can be many times that produced by wind or stack pressure. The increased heat loss associated with this air leakage may far exceed the typical conductive heat losses from a building during cold weather.
- Eliminating excessive constant pressure differentials and using dedicated mechanical ventilation (as opposed to operable windows) are keys to reducing air pressure differentials that result in air leakage in tall buildings.
- Steps to reduce pressure differentials are often more expensive than more common, but less effective, systems and must be included early in the design process.

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