Council on Tall Buildings and Urban Habitat Korea

International Journal of
High-Rise Buildings
www.ctbuh-korea.org/ijhrb/index.php

International Journal of High-Rise Buildings
March 2025, Vol 14, No 1, 43-57
https://doi.org/10.21022/IJHRB.2025.14.1.43

The Influence of Stack Effect and Other Pressure Forces on Infiltration Heating and Cooling Loads

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Abstract The calculation of the heating and cooling energy demands for mega-tall buildings is a critical issue, especially when considering the impact of energy usage on the building and the resultant CO2 emissions from the building and its systems. Infiltration is one of the forms of energy demand in a building, but it does not receive much detailed in building design. This paper presents an alternate thought on how to assess infiltration/exfiltration on supertall (300+ m) and mega tall (600+ m) buildings. It proposes a quick method of determining the neutral pressure level for tall buildings which is required to assess infiltration rates. This paper takes then previous work and quantifies the energy consequences of infiltration and exfiltration on an example building and compares to a common rule of thumb. By identifying the true heating and cooling loads required to operate a tall building's HVAC systems, a proper estimate of the overall demand can be made and the systems right-sized and correctly operated. This approach has the potential to provide cost and energy benefits long term.

Keywords Stack Effect, Neutral Pressure Level, Infiltration, Heating and Cooling loads

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1. Introduction

There are many elements that contribute to a tall building's overall energy demand. These include environmental loads, both heating and cooling, as well as internal loads. One parasitic load that does not get much attention is infiltration. Infiltration is caused by a negative pressure difference ($P_{in} - P_{out}$) acting across an envelope to drive air in. That envelope is inevitably not perfectly sealed and hence the inward pressure forces air to enter the building through cracks and gaps. The analogous phenomenon to infiltration for positive pressure differences across the façade is exfiltration where air is driven outwards.

When the infiltrating air is colder than the heating setpoint or hotter than the cooling setpoint it represents a load to the system. Under natural ventilation or economizer operations, that infiltration can be useful if T_{out} is less than $T_{setpoint}$, but not at an outdoor temperature that is too far from the setpoint temperature.

The rate of infiltration through any particular area of a building envelope is governed by two parameters: the pressure difference across the envelope, and the leakage rate of that façade element. However, both of those parameters are dependent on a variety of factors. The façade leakage rate will depend on the façade type, the number of operable components, its age and construction quality. The pressure difference will depend on wind speed coupled to the building's wind exposure, as well as stack effect and HVAC pressurization. For tall buildings, these factors can weigh more heavily because the driving forces of stack effect and wind are greater than those for shorter buildings.

In general, only infiltration adds to a building load. While exfiltrating conditioned air represents an energy loss, it in itself does not constitute a load: only the incoming air does. Each floor in a building can have either infiltration, exfiltration, a combination of both due to wind differential pressures, or be effectively neutral to ambient conditions – in the absence of wind. The location where the indoor /outdoor pressure difference is zero, for a calm wind scenario, is referred to as the Neutral Plane Level or Neutral Pressure Level (NPL). The terms are synonymous and, in this paper, we shall use the term Neutral Pressure Level. The NPL is discussed below. As one moves further away from the NPL, the stack effect driven pressure difference, and hence rate of infiltration/exfiltration, increases. Floors with higher infiltration would typically see a higher load to the system. In reality floors can also have both infiltration and exfiltration: this is usually caused by differential wind pressures where the windward side experiences a greater inward wind pressure and the leeward side of the building experiences an outward pressure.

Complicating the calculation of loads to the system is the fact that the ambient temperature is a function of altitude, and for tall buildings (e.g. greater than 300m), the T(z) relationship can become important to the overall heat gain or loss to any particular space up the building.

The complications above are discussed in Simmonds (2020). As should be clear, one of the uncertainties facing building designers is understanding the overall impacts of the stack effect and the loads it can cause. Not much material exists on the subject of infiltration loads for tall, supertall, and mega tall buildings. The purpose of this paper is to show, analytically, the loads to the system that the stack effect can impose on a building and how wind and pressurization from HVAC systems modify those loads. Part of this discussion will include the importance of the NPL, how it is determined, and how it moves based on wind, HVAC pressurization and outdoor temperature.

2. Background

Stack effect is a phenomenon known to many but its nuances are often misunderstood. Descriptions that include the word buoyancy and recommended solutions involving single-floor pressurization are symptoms of this misunderstanding. The work presented in this paper builds further upon the CTBUH publication, Stack Effect in Tall Buildings (Jalayerian and Jensen, 2023).

Stack effect is caused by the hydrostatic pressure difference indoors vs. outdoors that is caused by an air density difference indoors vs. outdoors. That density difference is temperature-driven. Ultimately the weight of the column of air outside is different from that inside. In heating/winter conditions, the outdoor air is denser and in summer it is less so. It is the temperature in the vertical shafts that is important, not the temperature on any single occupied level. That said, it is common to assume that the temperature in the shafts is the same as the setpoint on an occupied floor, however, this is not always true as an elevator shaft has internal heat gains, or the shafts might be vented to outdoors.

The density difference for winter conditions (heating season) results in the weight of the column of air inside being lighter than that outside. The weight difference creates an indoor/outdoor hydrostatic pressure difference and this results in inward flows at lower levels in winter and flows out at the top. For calm wind conditions, somewhere up the height of the building, the inward flows transition to being outward. This transition is typically where the indoor-outdoor pressure difference is zero, also known as the Neutral Pressure Level (NPL). A method of estimating the location of the NPL is described in more detail below.

During cooling months (e.g., summer) the outdoor air is less dense than inside and as a result the pressure differences are reversed with flows being driven in the opposite directions (e.g., in at the top and out at the bottom). Since the temperature difference is typically smaller in summer compared to winter, the pressure difference is also and therefore, the flows are not as severe as those under winter conditions.

Publications on stack effect in North America can be traced back to the 1960s. Tamura and Wilson (1967) measured a pressure distribution in high-rise office buildings, and they examined the effect of the airtightness of exterior walls and interior architectural elements on airflow via numerical simulation. Tamblyn (1993), and Lovatt (1994) reported the influence of the stack effect on the opening and closing of an elevator, and ventilation system performance.

As construction practices have evolved, so too have the infiltration characteristics of buildings (Liddament, 1986). Several models and algorithms have been developed for evaluating infiltration. Among those are Jackman (1974), Reeves et al. (1979), Warren (1982), Crall (1983) and Walton (1984). The inclusion of infiltration calculations is essential in estimating a building's thermal performance and hence should contribute to the design process.

As noted in the introduction, for all buildings, under calm wind conditions, there exists a point where the interior and exterior pressures are equal. This point is known as the "neutral pressure level" or "NPL". The location of the NPL is an important parameter in calculating the pressure distribution. For a single-zone building of any height, with no internal flow resistance, and a uniform envelope and floor to floor leakage distribution, the NPL would be located at mid-height, halfway up the building.

For real buildings, determining the location of the NPL is more complex. There are multiple factors contributing to this including: i) a non-uniform envelope leakage distribution, ii) varying internal flow resistances, and iii) building occupants who open and close doors and windows which change the parameters in i) and ii). Finally, the presence of HVAC pressurization and wind can also change the location of the NPL because they change the pressure distribution of the static / neutral building that does not have these phenomena acting on it.

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). While the NPL of a static building is independent of outdoor temperature, as will be shown here, it is dependent on outdoor temperature when the building is pressurized by the HVAC system - Phillips (2021). The NPL will move up or down depending on the relative size and location of building openings (e.g., opening doors at the top and bottom can shift the NPL towards the opening). This comes in useful when designing natural ventilation systems. Finally, in winter, mechanical exhaust systems can increase the height of the NPL location if the building is at a lower pressure than outside, and the presence of excess mechanical supply (e.g. pressurization) will lower the NPL. In summer, the reverse is true. Measured data presented in Phillips (2021) shows how this works.

If infiltration is important to the calculation of building energy demands, and stack effect is important to the

prediction of infiltration, then the location of the NPL becomes important to the calculation of energy on a floor-by-floor basis. The floor-by-floor distribution of building energy demand can influence equipment sizing and, in the case of super- and mega-tall buildings, the equipment sizing could be different from one mechanical level to another several hundred meters up or down.

Clearly, estimating the location of the NPL level is important to the overall energy demand calculation. This paper provides a novel way of accurately calculating the NPL specific to the relationship between the building envelope openings and internal openings such as elevator doors and staircases. The method assumes that the major resistance to flow is the envelope itself rather than internal barriers. This assumption is important. Ultimately the location of the NPL depends on the ability of the building to resist airflow. If the internal pressure losses are greater than those at the envelope, then they dominate the analysis.

The resistance of the envelope includes the summed contribution of the fixed façade, operable windows and doors, louvres, vents, etc. Flow can enter through gaps in the fixed components, as well as the window and door openings, HVAC louvres and other dampened openings. The internal flow passages include hallways, ceiling plenums, vertical chases, stairwells and elevator shafts. The internal resistances along these internal flow paths include swing doors as well as the elevator doors, cracks, and air transfer louvres.

For details of areas and leakage rates see ASHRAE Fundamentals (2021) Chapters 16 and 24, also ASHRAE Applications Handbook (2019) Chapter 4 and Chapter 54.

One way to view the flow resistances is to see them in a manner analogous to electrical circuits; the flow network established by the passages within the building (hallways, chases, shafts), driven by pressures imposed from stack effect (e.g. voltage) and the resistances across doors, walls, facades, and louvers, etc. creates a resistance network. The means to use this thought process is discussed below.

3. Methodology

This paper estimates the pressure difference between the core of a mega-tall building and ambient conditions using different outside weather conditions (e.g. temperature and wind) and then demonstrates the impact on infiltration and energy demand. For this study, we assumed two elevators and two emergency egress stairs arranged in the core, such as that shown in Figure 1. To simplify calculations for this paper we have assumed the two elevators and emergency stair shafts behave as a single shaft. This is reasonable as they act in parallel across the height of the building but is not true of all buildings. The leakage area calculations of the façade and those of the interior shafts include both crack leakage and that of doors at ground level for the façade and all levels for the shaft.

4. Theoretical Calculation of Stack Effect Strength and Neutral Plane

4.1. Stack Effect

The magnitude of the stack effect-driven pressure difference (ΔP_s) at any height (h) is related to the location of the NPL and the indoor (T_i) and outdoor (T_O) temperatures as shown in Equations 1, 2 and 3). These equations are from different sources. Equations (1) and (2) are from ASHRAE Fundamentals (2021) Equation 16.24, while Equation (3) is from Liddament (1986). Equations (2) and (3) can be derived from (1). That said the derivation of (2) from (1) requires that one assume that the ratio of outside and inside static pressures is 1 when substituting for indoor and outdoor density. This is not quite true, but introduces only an approximate 1% error depending on the building height and temperature difference. The derivation of (3) requires not only that assumption but also that the external temperature is 273K. This is clearly a variable that can change but at temperatures close to 0°C, the error introduced is small. The error is larger when outside conditions are hot: for an outdoor temperature of 40°C, the error introduced is approximately 15%. Equation 1 is the preferred equation.

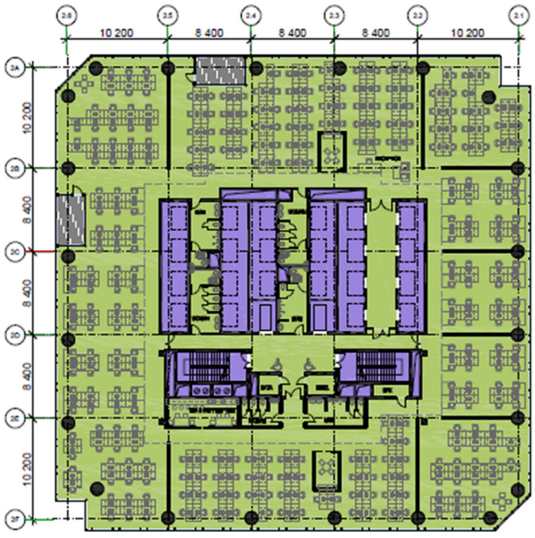


Figure 1. Typical floorplan of the building under consideration. Includes Two Emergency Staircases and Two Freight Elevators – Courtesy of Jahn Architects.

$$\Delta P_S(h) = -(\rho_o - \rho_i) g (H_{NPL} - h) \quad (1)$$

$$\Delta P_S(h) = -\rho_o \left(\frac{T_i - T_o}{T_i} \right) g (H_{NPL} - h) \quad (2)$$

$$\Delta Ps(h) = \rho_o \; g \; 273 (h - H_{NPL}) [1/T_o - 1/T_i] \quad (3)$$

Where:
$\Delta P_s(h)$ = the stack effect driven pressure difference [Pa];
H_{NPL} = the height above grade of the neutral pressure level (NPL) without any other driving forces (e.g. wind) [m];
h = height above the NPL [m];
T_o = absolute outdoor temperature [K];
T_i = absolute indoor temperature [K];
ρ_o = outdoor air density [kg/m^3];
ρ_i = indoor air density [kg/m^3]; and,
g = gravitational acceleration [m/s^2].

The negative sign at the front of Equations 1 and 2 was added by the authors and will be updated in the upcoming ASHRAE handbook. Fundamental 2025 This is to acknowledge the standard convention on the signs of the pressures. ASHRAE Handbook, Fundamentals (2021), Chapter 16, page 6 states

"By convention, stack pressure differences are positive when the building is pressurized relative to outdoors, which causes flow out of the building. Therefore, absent other driving forces and assuming no stack effect within the flow elements themselves, when indoor air is warmer than outdoors, the base of the building is depressurized and the top is pressurized relative to outdoors; when indoor air is cooler than outdoors, the reverse is true. At some elevation in the building, with such conditions, the pressure indoors is equal to the outdoors: this height is the neutral pressure level".

The version of the equations above ensures this result.

Figure 2 shows a plot of Equations 1, 2 and 3 under winter conditions for a 600 m tall building ($T_{outside}$ = –10°C, T_{inside} = 22°C, H_{NPL} = 277 m). The results for each of the three equations are similar, but not identical. Equations 1 and 2 effectively lie on top of one another – as noted above the error is only approximately 1%. Equation 3 presents a different line that has a slightly reduced slope indicating a higher predicted stack effect strength.

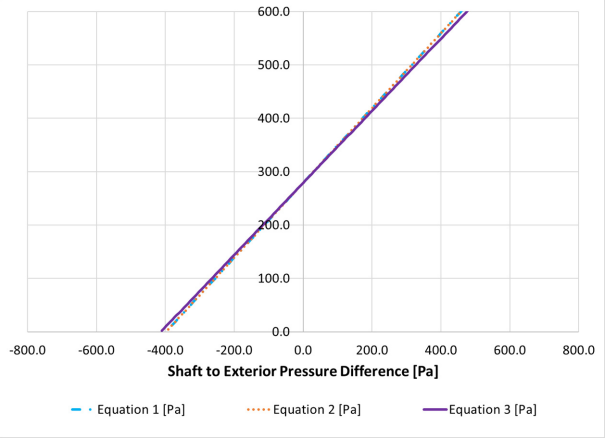


Figure 2. Stack Effect Pressures Predicted Through Equations 1, 2 and 3 in a 600 m Tall Building Under Winter Conditions.

As noted earlier, absent wind and HVAC influences, and assuming the internal resistance to flow is small relative to that at the façade, the location of the NPL is driven by the leakage distribution of the building. If the interior compartmentalization is tight, that reduced ability to conduct flow influences the overall flow capacity on that floor, or between floors and can influence the location of the NPL. When one includes the different leakage rates associated with operable components (e.g. windows and doors) as well as different façade elements (e.g. louvers, punched windows, etc.) the NPL is not likely to be at the mid-height of the building. The imposition of HVAC pressurization can also influence the NPL. Positive pressurization has a different impact in the summer versus that in winter. Further, internal vertical compartmentalization, or HVAC zones, can result in each zone have its own individual NPL. Finally, wind-driven pressures will result in different total pressure differences on the upwind and downwind sides of the building: hence there will be different neutral planes under windy conditions.

In most tall buildings there are some shafts/risers that run from top to bottom in the building (e.g. fire fighter lift) while others are segmented (e.g. shuttle lifts to lobby floors with lifts providing local transport). The floorplate layout we will demonstrate this analysis for in this paper we have two emergency exit stairways and two freight elevators (per Figure 1). Real buildings also have other risers such as plumbing chases and electrical chases, but these are not considered in this exercise.

4.2. Simplified Calculation of The Neutral Pressure Level

As noted earlier, the location of the neutral plane/ pressure level (NPL) is often assumed to be half of the building height; however, this is not always true, and the NPL should be calculated. This has benefits for tall building design as well as the design of natural ventilation systems in shorter buildings. A quick method of calculating the neutral plane of a building is as follows:

$$NPL = \frac{\Sigma_{i=1}^{n} h_i A_i^{openings}}{\Sigma_{i=1}^{n} A_i^{openings}} \quad (4)$$

Where:
A_i = the total area of façade openings on floor i [m^2];
h_i = the representative height of the façade openings at floor i [m]; and,n = the number of levels in the building.

This calculation is effectively a façade crack area weighted height calculation. The opening areas at each floor include the open doors and windows as well as the cracks / minor leakage paths in the façade. When calculating the NPL of a "static" or neutral building, one would just use the crack areas. If trying to determine the NPL of a "living" building, or one using natural ventilation, the open façade areas would include the other openings.

It should be obvious that the equation could be used to calculate the NPL using each individual opening. For a natural ventilation calculation, where the leakage areas are very small relative to the natural ventilation openings, the crack areas can be effectively ignored and just the areas of the natural ventilation opening included.

With this neutral plane estimate, the distribution of pressures, and potential flow rates, throughout the building can be evaluated. Note the equation intuitively shows that opening a door at the bottom of the building will pull the NPL downwards.

4.3. Detailed Method to Calculate the Neutral Pressure Level (NPL)

The method above is tied to façade crack area alone and assumes that the internal resistances are small relative to those at the building envelope. Given that a building includes multiple paths from the core to the exterior, the floor opening area calculation should really be an effective area calculation using the flow passages on each floor calculated as an equivalent flow conductance. This more detailed approach would allow unusual floors, such as a refuge or amenity floors, to influence the NPL differently from office and residential apartment floors.

Thinking this way then turns the calculation of the neutral plane into an estimate of the capacity of the network to carry flow. If one assumes the internal resistance is negligible, or small relative to that at the facade, and the conductance for flow to leak through the façade is effectively linear on flow area, then the NPL can be estimated as the crack area weighted height of each of the façade openings as shown above. However, in reality the resistance across the façade may not be the dominant constraint. Apartment buildings that are naturally ventilated may have relatively porous facades but tight unit door. Hence the more complete approach is to calculate an effective conductance on each floor, based on the sum of crack areas in series and parallel on each floor and then calculate a height-weighted average and turn that into an estimate of the NPL (Simmonds and Phillips, 2021). That all said, if the internal resistance is low, then the façade resistance dominates and the calculation is simpler as show in Equation 4.The discussion above notes that an effective crack area calculation looks a lot like the calculation of resistances in an electrical network which means that a lot more information is required to perform this calculation. This list includes:

- The openings in the façade, such as doors and loading docks.
- The equivalent façade leakage areas (at a known pressure difference) over the height of the building.
- A count of all stair shafts (these are usually over the height of the building).
- The doorway and other openings into the stair shafts, their leakage sizes and information on whether the stairs are directly connected to outdoors. This last item complicates the calculation greatly.
- A count of all elevator shafts, including the goods and firefighter elevators and the floors to which these connect. The doors and their leakage rates need to be known. If the elevator is vented to outdoors, this information is required as well. This last item complicates the calculation greatly.
- A count of all risers and chases along with their connection type to the floor space and the leakage characteristics of the connection type.
- To refine the calculation, the cross-sectional area on each floor, of all shafts on that floor as well as the leakage characteristics of the construction type; and,
- Any required building locations such as refuge floors.

The list above presumes that the HVAC system does not contribute to the NPL calculation which implies the HVAC system is sealed from outdoors. However, if some of the floors are passively vented (e.g., the air intake is a passive duct to connected to outdoors, or the stairwell is used to naturally ventilate the hallway) then these can influence the NPL,

Leakage performance data is sometimes specified as a flow at a given pressure difference – this is typically for the façade. For other components, for example operable windows, the leakage performance data is specified as a leakage area per linear distance of component perimeter. Finally, the leakage area could be specified per unit (e.g., per door). To perform the calculation, the leakage data should be converted to an equivalent leakage area for all components. This will among other things, remove the pressure-based relationship of flow vs. pressure difference.

For a building with a consistent floorplate, that includes stairwell and elevator shafts that access each floor, and no other internal partitions, one can use resistance in series / parallel equation to calculate the effective crack area (ECA):

$$ECA = \frac{1}{\frac{1}{\Sigma AF} + \frac{1}{\Sigma(S+E)}} \tag{5}$$

ΣAF = the sum of the façade crack opening areas [m^2] such as, the entrance doors and exterior wall leakage cracks; and,

$\Sigma(S+E)$ is the sum of the crack opening areas [m^2] on each floor such as the elevator and stair doors as well as the shaft walls.

The crack opening areas effectively act as a passage for airflow with resistance in place. In a manner analogous to electrical circuits, the flow network established by these resistances across doors, through walls, facades, up and down ducts, etc. creates a resistance network. Hence the objective is to calculate an effective crack area on each floor and then calculate an area weighted height and turn that into an estimate of the NPL. The use of Equation 5 substituting ECA for $A^{openings}$ for each

floor makes the NPL calculated by Equation 4 more universal. Note however that Equation 4 assumes that the stairs and elevators run the same height of the building and they are effectively parallel vertical flow passages.

Façade (per floor)

Exterior wall combined leakage	2.19	[cm^2/m^2]
Exterior wall area	766.0	[m^2]
Total crack area = AF	0.168	[m^2]

Elevator (per floor)

Leakage rate of elevator doors	0.042	[m^2/elevator]
Number of elevators	4	[-]
Total crack area of elevator doors = E	0.168	[m^2]
Leakage rate of elevator wall	0.000118	[m^2/m^2]
Area of all elevator walls	142.8	[m^2]
Total crack area of elevator wall	0.0257	[m^2]

Total leakage area associated with elevators per floor = 0.194 m^2

Stairs (per floor)

Leakage rate of stairwell doors (crack area)	0.03044	[m^2/elevator]
Number of Stairwells	2	[-]
Total crack area of stairwell doors	0.06088	[m^2]
Leakage rate of stairwell wall	0.0001	[m^2/m^2]
Area of stairwell wall	140.28	[m^2]
Total crack area of stairwell wall = S	0.0309	[m^2]

Total Leakage area associated with stairwells per floor = 0.092 m^2

Total leakage area associated with elevators and stairs per floor = E = 0.286 m^2.

Use of equations (4) and (5) with the data in the table results in a NPL at 277 m.

5. Results of Pressure Distribution Predictions

5.1. Pressure Distribution for a Neutral Building

Figrue 3. presents the hydrostatic pressures for outdoor and indoor conditions for a 600 m building in winter. The indoor and outdoor temperatures are –10°C and 22°C respectively. The gauge pressure is set at grade for both the indoor and outdoor conditions: they are assumed to be independent of one another at this point. For the discussion here, the lapse rate (the change in temperature as a function of altitude) is assumed to be zero.

The difference between the two curves in Figure 3 results in the data shown Figure 4 in as a bar graph. The data has been corrected to acknowledge the location of the Neutral Pressure Level (NPL) as discussed above for winter. Figure 5 presents the same information for summer.

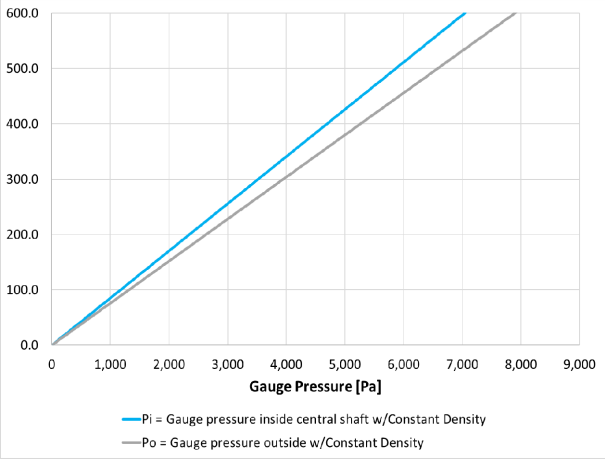


Figure 3. Hydrostatic Pressures [Pa] for Indoor (Blue) and Outdoor (Grey) Conditions with Constant Exterior Temperature as a Function of Height [m]

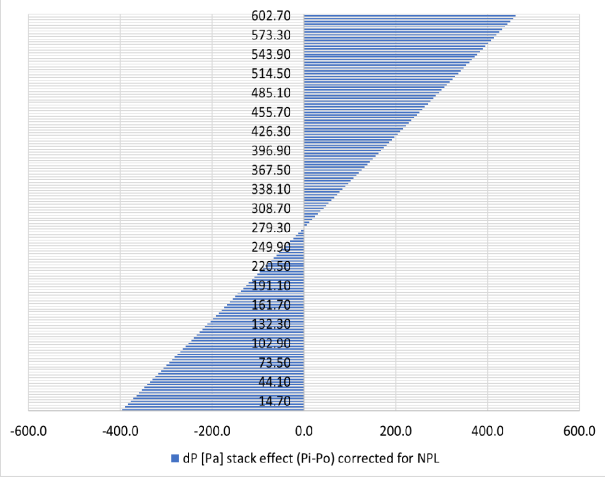


Figure 4. Indoor - Outdoor Pressure Difference [Pa] Driven by Stack Effect as a Function of Height [m] in Winter.

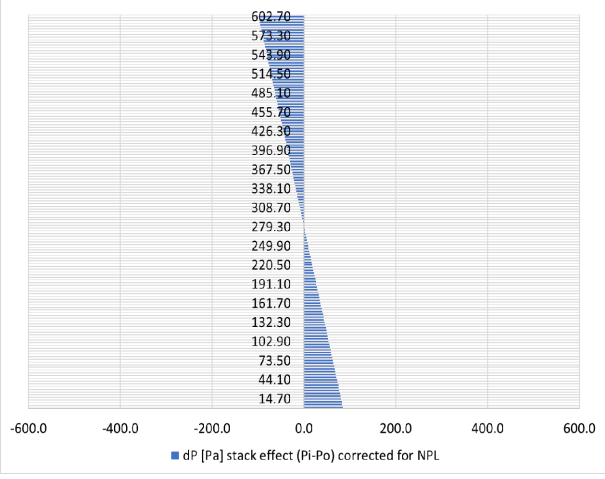


Figure 5. Indoor - Outdoor Pressure Difference [Pa] Driven by Stack Effect as a Function of Height [m] in Summer.

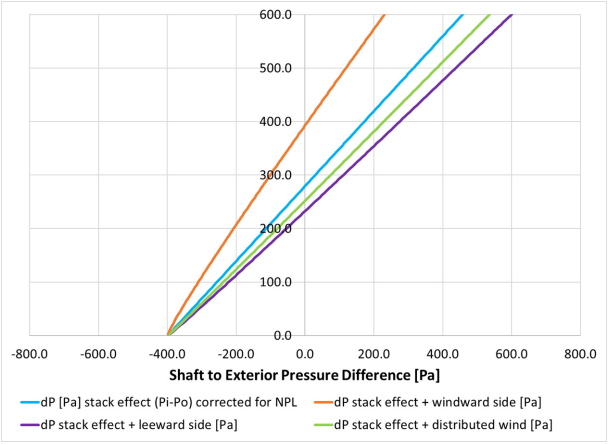


Figure 6. Indoor - Outdoor Pressure Difference [Pa] Driven by Stack Effect With and Without Wind Influences as Functions of Height [m].

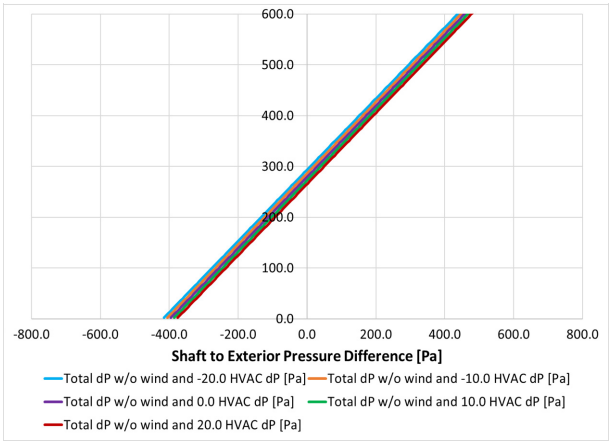


Figure 7. Indoor - Outdoor Pressure Difference [Pa] Driven by Winter Stack Effect With Different HVAC Pressurization Imposed as Functions of Height [m]. Note how the NPL drops in height with an HVAC imposed internal positive pressure and raises with a negative pressure.

Figure 6 shows the pressure difference between the indoor and outdoor conditions shown in Figure 3 ($P_{in} - P_{out}$) along with the impacts of wind. The cyan straight line presents the pressure difference under calm wind conditions. The orange and purple lines represent the pressure differences on the windward and leeward sides of the building respectively with an assumed wind speed of 4.0 m/s referenced to 10m above grade and power law profile on wind speed with an alpha of 0.4 (urban). Finally, the green line represents the average pressure difference around the perimeter of the building, including the sides parallel to the wind direction. Here the impact of wind on the overall pressure difference is clear. On some floors, there are both positive and negative pressure differences predicted. This would result in both inflow and outflow respectively.

5.2. The Influence of Net Ventilation System Over or Under Pressure on NPL

The pressure distribution within the building is also influenced by the ventilation system. Mechanical systems often deliver an oversupply of outdoor air into the building to create a positive pressure with respect to outside conditions. In a low-rise building, this might result in the entire building being positive with respect to outdoors, in a high-rise building, this is not so clear as the stack effect pressure might overwhelm that created by the ventilation system.

For buildings in winter/heating conditions, the ventilation (HVAC) system can move the neutral plane down (positive pressurization) or up (negative pressurization) relative to the position under neutral (static or zero) HVAC pressurization. Conservation of mass requires that the interior static pressure adjusts so that the sum of all airflows through openings in the building envelope, plus the net HVAC equipment-induced airflows, balance to zero. To predict these changes in pressure differences and airflow rates caused by mechanical equipment, the location of each opening in the envelope and the relation-ship between pressure difference and airflow rate for each opening need to be known.

Figure 7 presents the same baseline pressure difference for the calm condition scenario along with 5 plots of varying HVAC pressurization plots. As can be seen, positive pressurization moves the NPL downwards while net negative pressurization moves it upward. Clearly, this will have an impact on the overall infiltration/exfiltration. This impact will be discussed later.

The interaction between mechanical ventilation system operation and envelope airtightness has been discussed for many years for low-rise buildings (Nylund 1980) and for office buildings (Persily and Grot 1985a; Tamura and Wilson 1966, 1967a). There is less published experience for high-rise (meant here to imply tall, super-tall and mega-tall) buildings. In a high-rise, HVAC pressurization will change the pressure but might not result in the full building being positive the outside at all levels. This will depend on the degree of pressurization applied by the building systems and the outdoor temperature. This is where the location of the neutral plane does depend on outside temperature which is different from that for a neutral HVAC-pressured building.

Figure 8 uses the +20 Pa HVAC pressure difference example from above, under calm wind conditions, and shows how changes in the external temperature revise the location of the NPL. Under a net zero HVAC pressure difference, the location of the NPL is fixed – it is a function of the building leakage distribution only. However, for a building with either positive or negative pressurization, the NPL moves if the outdoor temperature changes.

Figure 9 presents the same information as that in for the summer scenario with $T_{outside}$ at 32°C and T at 24°C. Here the roles of positive and negative net pressurization are reversed in that positive pressure pushes the NP

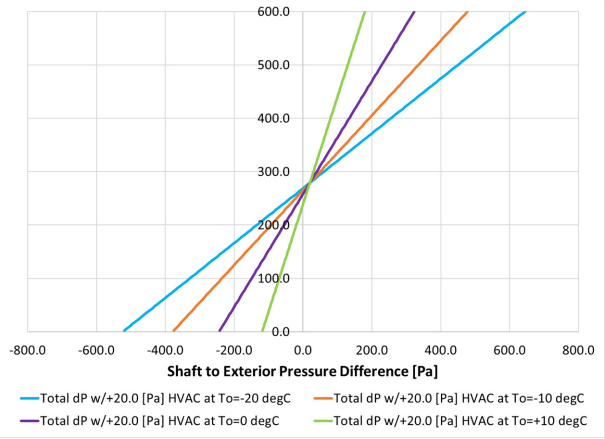


Figure 8. Indoor - Outdoor Pressure Difference [Pa] Driven by Stack Effect With 20 Pa HVAC Pressurization at Different Ambient Temperatures as Functions of Height [m]. With no pressurization, the NPL does not change with outdoor temperature. However if there is an internal pressurization, the NPL does depend on outdoor temperature.

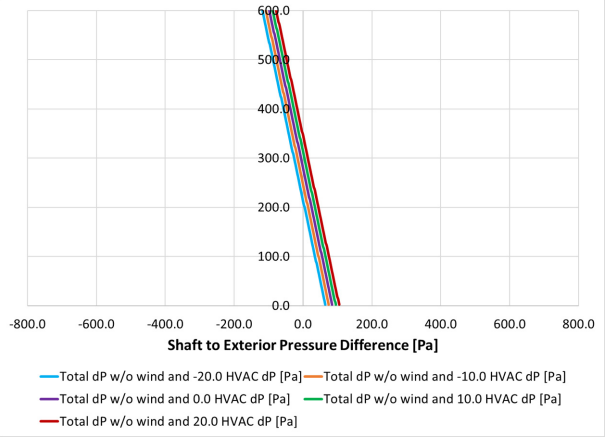


Figure 9. - Indoor - Outdoor Pressure Difference [Pa] Driven by Summer Stack Effect With Different HVAC Pressurization Imposed as Functions of Height [m]. Note how the NPL increases in height with an HVAC imposed internal positive pressure and drops with a negative pressure. This is opposite to that for the heating (winter) season.

upwards while a negative pressure pulls it down.

Clearly, the location of the neutral plane has shifted based on the HVAC pressurization for both winter and summer conditions. However, the amount of shift varies for summer and winter conditions as the temperature difference is not the same. This corroborates the earlier comment communicated in Phillips (2021).

Finally, Figure 10 presents the combined pressure differences for the building with a 4.0 m/s wind at 10 m, +22°C/-10°C indoor/outdoor temperatures, and the same five different HVAC pressures. This plot can be compared to Figure 7. Figure 11 presents the same atmospheric conditions but the pressure difference on the leeward side of the building. Note here that the DP at the top of the building

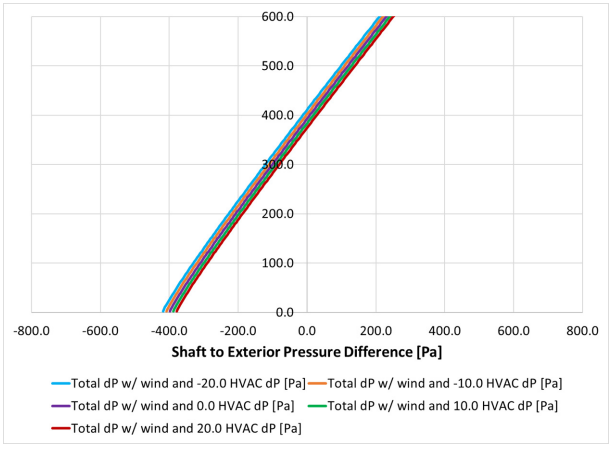


Figure 10. Indoor - Outdoor Pressure Difference [Pa] Driven by Winter Stack Effect With Different HVAC Pressurization Imposed and a 10 m/s Wind Acting on the Windward Side of the Building as Functions of Height [m]

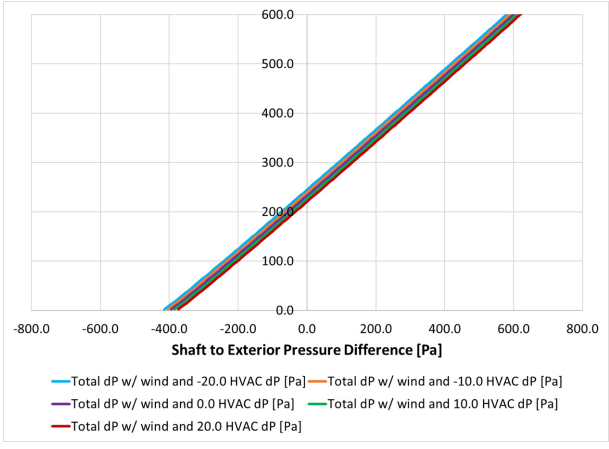


Figure 11. Indoor - Outdoor Pressure Difference [Pa] Driven by Winter Stack Effect With Different HVAC Pressurization Imposed and a 10 m/s Wind Acting on the Leeward Side of the Building as Functions of Height [m]. There is a slight curve to the building and it is shifted relative to the no-wind case.

on the windward side has moved from 475 Pa to 250 Pa for the no-wind and windward side respectively. However, on the leeward side of the building, the pressure difference is 625 Pa all for the +20 Pa HVAC pressurization. Clearly, wind plays an important role and further, the role of pressurization adds nuance to the effects.

6. Influence of Variable Density on Predictions

As described earlier, stack effect pressure is the difference in the indoor / outdoor hydrostatic pressures caused by the difference in the weight of the columns of air located inside and outside a building. The pressure difference depends on the density and the height of interest above a reference point which is usually the neutral pressure level (NPL). Air density is a function of local barometric pressure,

temperature, and humidity ratio. As a result, the use of standard conditions to calculate density, and the assumption of constant outdoor temperature, can result in deviations in the actual value of the stack effect pressure.

If one assumes an adiabatic lapse rate of -0.0065C °C/m, and adjusts pressure as a function of height using standard equations from ASHRAE (2021), the results in Figure 6, which presents the stack effect pressure difference in winter with wind overlaid, changes and becomes the form shown in Figure 12.

Doing the same calculation for summer results in the data presented in Figure 13 below. An important aspect of Figure 13 is that near the top of the building, the pressure difference on the upper levels has started to shift back to a winter-mode (e.g. a positive slope). This is because the temperature difference, shown in Figure 14 dropped as ones moves up the building. The imposition of wind pressures has changed the overall pressure distribution to behave more like a winter scenario. If the building were taller, the indoor - outdoor temperature difference would become positive higher up.

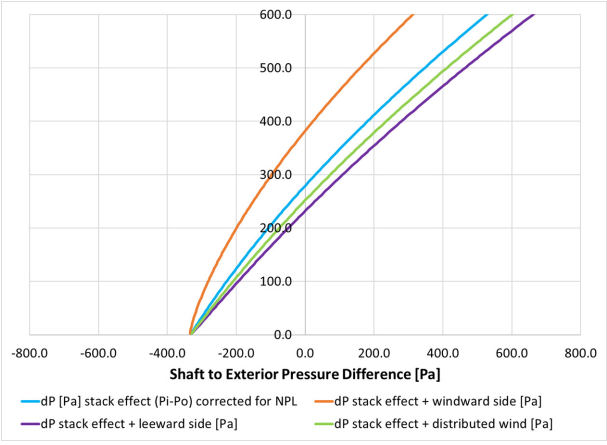


Figure 12. Indoor - Outdoor Pressure Difference [Pa] Driven by Stack Effect in Winter With and Without Wind Influences With Temperature and Density as Functions of Height [m]

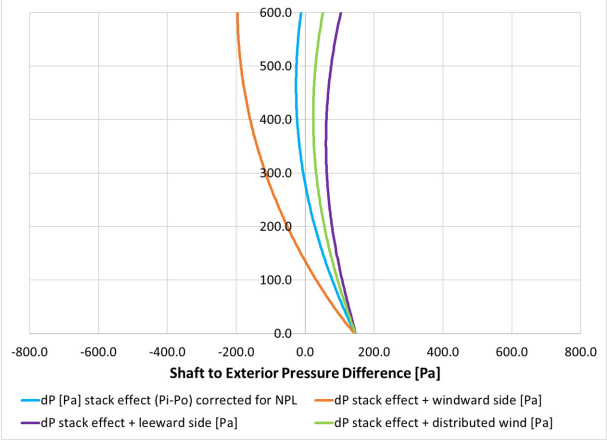


Figure 13. Indoor - Outdoor Pressure Difference [Pa] Driven by Stack Effect in Summer With and Without Wind Influences With Temperature and Density as Functions of Height [m]

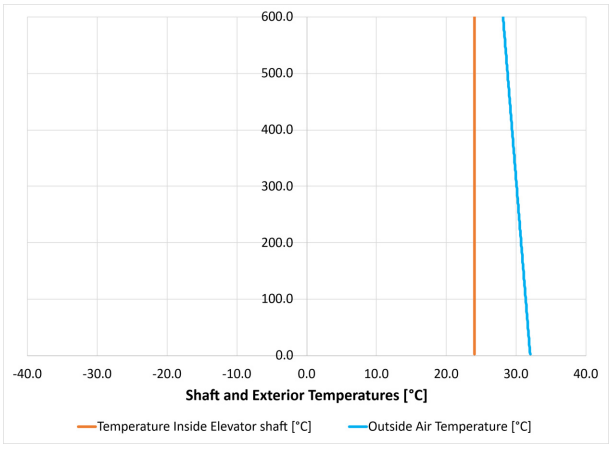


Figure 14. Indoor and Outdoor Temperatures Assuming an Adiabatic Lapse Rate Outdoors and a Constant Indoor Condition as Functions of Height [m] in Summer.

7. Estimated Stack effect Driven Infiltration / Exfiltration

The flow rate passing through an opening is a function of the pressure difference and the pressure loss characteristics of the opening. In the case of the fixed elements of the envelope, the opening is a crack or gap through which infiltration or exfiltration occurs. That flow rate can be calculated using the equation:

$$Q = C_D A \sqrt{2\Delta P_{tot}/\rho} \quad (6)$$

Where:
Q = airflow [m^3/s];
C_D = flow coefficient (0.65 is commonly assumed for stack effect calculations) [unitless];
A = cross-sectional area of opening (e.g., the equivalent crack area in the case of infiltration)[m^2];
ΔP_{tot} = total pressure difference between the indoor vertical shaft and outdoors at the elevation of interest [Pa]; and,
ρ = air density [kg/m^3].

This equation provides the flow rate through an opening with a particular pressure loss characteristic. Note that it is linear on the opening area, hence one can calculate the flow rate through the entire envelope if the full crack area is known for the various elements of the envelope (e.g. façade, louvers, operable components, etc.) along with the pressure difference distribution assumed by those different elements.

Herein lies the challenge, in a typical building, there are a number of building components between the exterior

conditions and the elevator or stair shafts. The stack effect pressure difference is in fact the interior shaft to outdoor condition. Hence any other obstructions between the exterior and the interior shaft needs to be acknowledged when calculating the flow infiltrating into the building. A second complication is that there are typically multiple shafts within a building – whether that be elevator or stairwell or riser. This too needs to be included in any detailed calculations as a relatively leaky elevator door will accommodate more flow than a tight stairwell door.

This is where the analogy to an electrical resistor network is useful for building design. It permits one to calculate the overall network flow resistance and then the flows passing through each element within the resistor network. This can be derived as follows:

- If one rearranges Equation (6), the pressure difference across an element (ΔP) can be expressed in terms of the flow rate (Q), opening area (A) and pressure resistance characteristics (C_D)

$$\Delta P = \frac{1}{C_D^2}\left(\frac{Q}{A}\right)^2 \frac{\rho}{2} \tag{7}$$

- Assuming for now that the stairwell doors are much better sealed than the elevator doors (e.g., $A_{stairs} \gg 0$), then the total flow resulting from the pressure difference (ΔP_{tot}) passes through the façade and elevator doors which are the elements in the pressure path that can leak. If the stairwell doors have similar leakage characteristics to that of the elevator doors, then the elevator and stair doors would act in parallel to one another. The tight stair door assumption is reflected in Equation (8) below. In this we are also assuming that the shaft wall is well sealed and there are no other partitions between the façade and core that are able to take up a pressure difference.

$$\Delta P_{tot} = \Delta P_{FACADE} + \Delta P_{ELEVATOR} \tag{8}$$

- Substituting Equation (ii) in for both the elevator and façade, one arrives at:

$$\Delta P_{tot} = \frac{\rho}{2}\frac{1}{C_D^2}\left(\frac{Q_F}{A_F}\right)^2 + \frac{\rho}{2}\frac{1}{C_D^2}\left(\frac{Q_E}{A_E}\right)^2 \tag{9}$$

Where:
DP_{tot} = total pressure difference [Pa];
DP_{FACADE} = pressure difference across the full envelope (e.g. façade, louvers, etc.) [Pa];
$DP_{ELEVATOR}$ = pressure difference across the elevator doors [Pa];
Q_F = air flow through the façade [m^3/s];
Q_E = the air flow through the elevator door cracks [m^3/s];
A_F = the area of the façade cracks [m^2]; and,
A_E = the area of the elevator door cracks [m^2].

- Note that the areas in the equation above are flexible and based on a definition we choose. For example, the façade area (A_F) can be the crack area of the fixed façade along with that for the doors and windows etc. If a door is opened, that can be included too in the total area. The caveat here is that all of the flow openings must have the same crack flow resistance characteristic (e.g. C_d). This is a common assumption that ideally needs testing, but for the moment it is a helpful assumption.
- Since mass is conserved, the flow through the façade and the elevator doors is the same.

$$Q_{tot} = Q_{FACADE} = Q_{ELEVATOR} \tag{10}$$

Where:
Q_{tot} = total flow rate [m^3/s];
Q_{FACADE} = total flow rate through the full envelope (e.g. façade, louvers, etc.) [m^3/s]; and,
$Q_{ELEVATOR}$ = pressure difference across the elevator doors [m^3/s].

- Rearranging equation (15) and assuming for now that density is similar, the total flow rate becomes:

$$Q_{tot} = \sqrt{\frac{2\Delta P_{tot}}{\rho}} C_D \left(\frac{(A_E^2 A_F^2)}{(A_E^2 + A_F^2)}\right)^{1/2} \tag{11}$$

- Rearranging to extract the component of the total pressure accommodated by the façade:

$$\Delta P_F = \Delta P_{tot} - \frac{\rho}{2C_{D^2}}\left(\frac{Q}{A_E}\right)^2 \tag{12}$$

This equation permits one to assign the total pressure difference accommodated by different elements, at any elevation, into that accommodated by the façade and the internal elements, here represented by the elevator doors, based on the relative leakiness of these elements.

The assumptions offer some limitations to this calculation. A similar air density at the façade and elevator door implies the air temperature leaking through is the same. This is reasonable for exfiltration, but less so for infiltration. The limitation to just the internal elevator shaft implies other shafts are well sealed. Finally, when summing up the overall flows into and out of the building, the netflow is not necessarily zero. This is a result of the current spreadsheet calculations not coupling the predictions from floor to floor. This limitation, and the previous assumption on well-sealed shafts can be relaxed with a more detailed resistance network calculation. The influence of multiple shafts can also be assembled into an equivalent single shaft through the use of parallel circuit theory per electrical circuits.

7.1. Flow Predictions

Equation (11) is useful because it permits one to estimate the infiltration or exfiltration flow rate on any floor based on the total indoor / outdoor pressure difference at that floor and the leakage areas. It is important to note that when the outside pressure is higher than the pressure

in an elevator or stair shafts the flow is negative: outside air will infiltrate the building, (e.g. winter conditions below the NPL). When the pressure difference is positive, flow will leave / exfiltrate the building (e.g., above the NPL in winter). In the winter the infiltration of outside air will increase the space heating load below the NPL and in summer the infiltration of air will increase the space cooling load above the NPL.

Using equation (11), and assumptions on façade leakage areas and elevator door leakage performance, the infiltration / exfiltration characteristics for the 600 m building described earlier is shown in Figure 15 and Figure 16 for winter and summer scenarios respectively. For these estimates, the pressure distributions for the calm wind conditions for winter and summer were used along with façade leakage characteristics of 2.19 cm^2/m^2 acting over 766.0 m^2 of façade and a total elevator leakage area, including doors and walls, of 0.7 m^2 per floor.

The plots above are based on a no-wind and no-HVAC scenario. This is not how buildings typically operate. Figure 17 (HVAC pressurization off) and Figure 18 (HVAC pressurization on) present the infiltration predictions for the same building as Figure 15 for different wind exposure (Figure 18). The infiltration sum assumes the entire façade is exposed to the windward / leeward and parallel facades. As is clearly seen, the neutral plane shifts significantly depending on the face of the building being considered. On some floors, there is both infiltration and exfiltration.

We should note here that the calculation has been simplified to assume that the internal pressure is unaffected by the different pressures around the building. This is a reasonable assumption provided that the facade is a lot tighter than the elevator doors – the façade will take up most of the pressure.

Note that one difference between Figure 17 and Figure

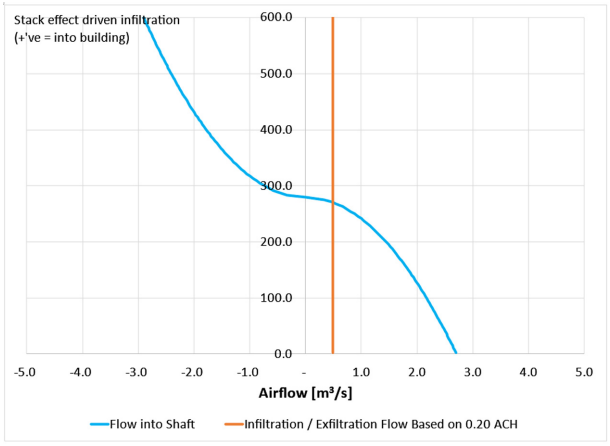


Figure 15. Infiltration (+) / Exfiltration (–) Flows into the Building (Blue) as a Function of Floor Height [m] in Winter Compared to a Simple Assumed 0.2 ACH (Orange)

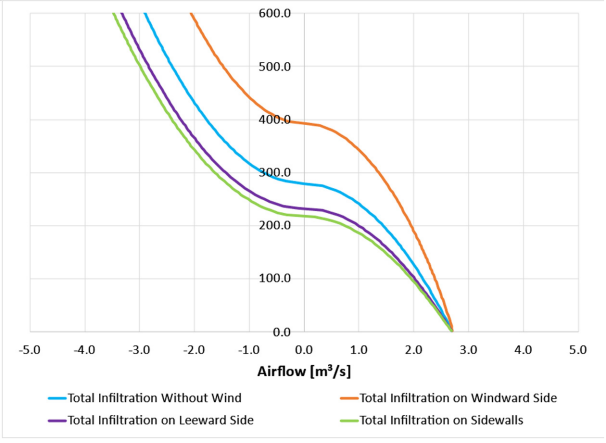


Figure 17. Infiltration (+) / Exfiltration (–) Flows into the Building as a Function of Floor Height [m] in Winter with Wind Impacts Alone

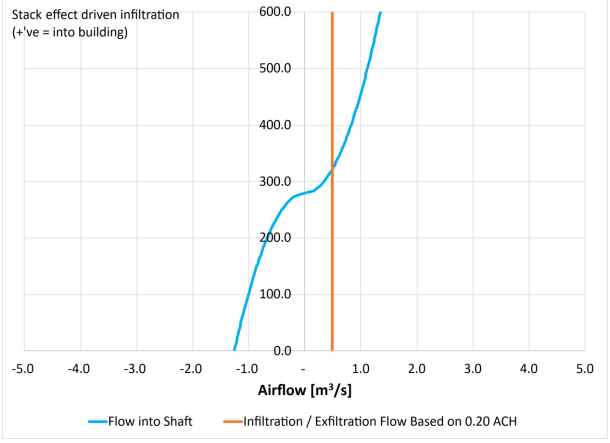


Figure 16. Infiltration (+) / Exfiltration (–) Flows into the Building (Blue) as a Function of Floor Height [m] in Summer Compared to a Simple Assumed 0.2 ACH (Orange)

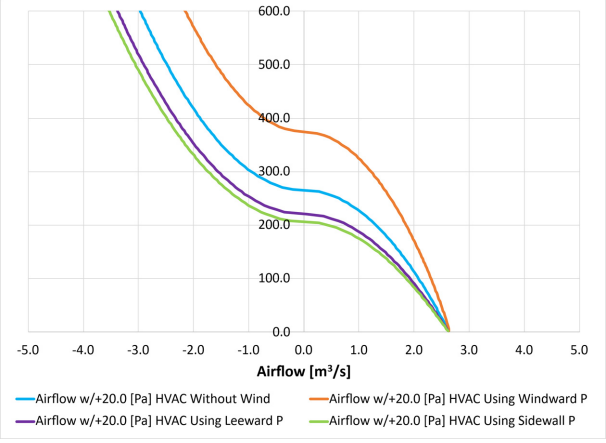


Figure 18. Infiltration (+) / Exfiltration (–) Flows into the Building as a Function of Floor Height [m] in Winter with Wind and HVAC Impacts

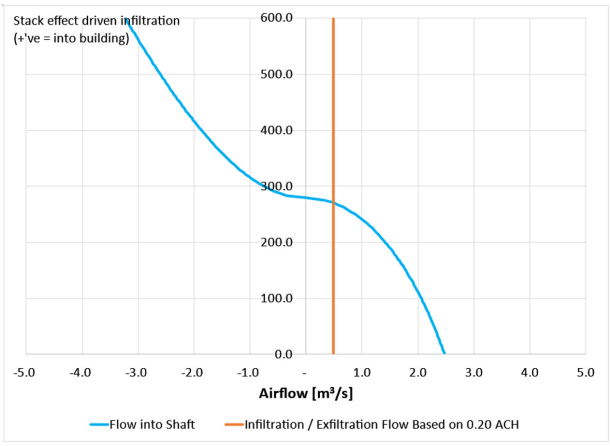


Figure 19. Infiltration (+) / Exfiltration (–) Flows into the Building as a Function of Floor Height [m] in Winter with An Adiabatic Lapse Rate and Standard Atmospheric Calculation on Pressure.

18 is the location of the NPL. Once again, this is the action of the HVAC pressurization.

Comparing Figure 17 and Figure 18 there is not much difference in the plots. This is because the HVAC pressurization of +20Pa is small relative to the wind pressures for this example.

Finally, the calculations above have assumed a constant outdoor temperature and simple hydrostatic pressure calculation used in the calculation of density as a function of height. This is not always true. Applying a standard adiabatic lapse rate and standard atmospheric estimate of pressure as a function of height, the predicted infiltration is as shown in Figure 19. The results in this image show that the infiltration plot is pushed to the left compared to the prediction without the variable temperature and pressure shown in Figure 15. Meaning that the change from a constant to a more complex calculation on outdoor density generates a net increase in indoor to outdoor pressure difference.

8. Energy Analysis

With an estimate of the infiltration on each floor, the heating or cooling demand associated with that outside air infiltrating into the building can be calculated. The energy demand predictions in Figure below are based on a simple equation:

$$E = Q\rho\Delta TC_P \quad (18)$$

Where;

E = Energy [KJ/s = kW];

Q = the infiltration flow into the building [m^3/s];

C_p = the specific heat capacity of air [kJ/kg. k]; and

r = the density of air at the temperature and height for the calculation [Kg/m^3].

The summer version of this plot is presented in Figure 21. A negative value here means that cold winter air is infiltration into the building and a positive value means hot summer air is infiltrating. Also, above the NPL for the winter scenario, and below the neutral plane for the summer case, the load to the system has been set to zero. This is because outflowing air does not cause a load to the system. It does represent an energy loss in the building, but the impact on the systems is with the incoming air.

The difference in values of the two lines at any given height in Figure 20 and Figure 21 (e.g. orange line – blue line at 100 m) can be considered as the "missing" infiltration load if one uses a rule of thumb approach. In many 'standard' energy analyses, an assumption is made whereby the outside air infiltration rate is assumed to be 0.2 ACH. This assumption is incorporated in heating and cooling load calculations in energy calculation software. For the prototypical building used in this paper. an ACH

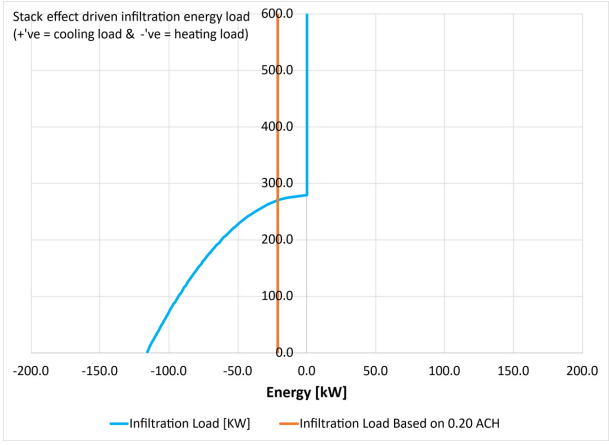


Figure 20. Energy Demand on Each Floor by Height [m] in Winter Associated (Blue) with Infiltration Assumption of 0.2 ACH (Orange) in Energy Calculations. Exfiltration (above the NPL) does not cause a load to the system and is set to zero.

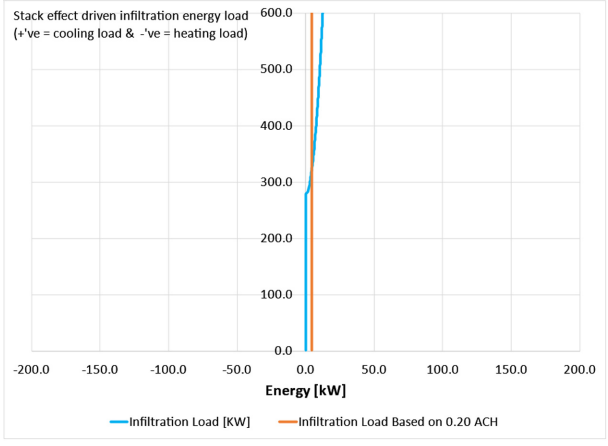


Figure 21. Energy Demand on Each Floor by Height [m] in Summer Associated (Blue) with Infiltration Assumption of 0.2 ACH (Orange) in Energy Calculations. Exfiltration (below the NPL in summer) does not cause a load to the system and is set to zero.

of 0.2 air changes is approximately 0.5 m^3/s for each floor and is shown by the orange lines. The energy demand presented in Figure 20 and Figure21 by the blue lines is actually based on the flow rates presented in Figure 7 and Figure 9 for winter and summer respectively. The difference in the lines is the missing information. For the winter case, Figure 20, the estimated heating load to the system using the more detailed calculations (blue line) results in a greater energy demand value than the rule of thumb (orange line) for floors below approximately 275 m. Above 275 m to the NPL, the rule of thumb approach is slightly conservatives.

The calculations presented here are for a standard 'cold' and 'warm' winter and summer's day. They are not extreme values. If one sums the missing energy demand in the two plots (e.g. orange – blue lines for each floor), one can estimate the total infiltration driven building energy demand deficit generated by the rule of thumb approach.

As noted earlier, when the energy demand is negative, cold outside air is infiltrating (119.9 m^3/s) into the building. In the winter, this infiltration will increase the space heating load. On the design day, the increase in total infiltration building heating load is estimated to be 5,148.6 kW using a stack effect driven calculation of infiltration. The total building heating load has been estimated to be 5,317.0 kW excluding infiltration. Infiltration effectively doubles the heating demand. The total energy demand estimate based on the 0.2 ACH assumption, up to the NPL, is approximately 1374.5 kW – 27% of the estimate based on a stack effect calculation.

When the energy demand is positive, hot (and potentially humid) outside air is infiltrating the building. In the summer, the infiltration flow (70.1 m^3/s) of outside air increases the space's cooling load. The increase in cooling load associated with infiltration is estimated at 648.5 kW, on the design day.

When one considers the influence of wind and HVAC pressurization on the energy demand due to infiltration, then the plots above change. Figure 22 presents the infiltrating load during winter when wind is added to the calculation. Note that the cyan line in this figure is the same as that in Figure 20. The infiltration load drops to zero above the NPL as outflow is not considered a load to the system. Figure 23 presents the infiltrating load during winter when both wind and HVAC pressurization are added to the calculations. Since the NPL level drops, there "appears" to be less infiltration load, however this comes at the expense of heating and moving the air that is used to pressurize the building.

Once again, the difference between the with HVAC (Figure 23) and without (Figure 22) is small because the HVAC pressurization of +20Pa is small relative to the wind pressures for this example.

In addition to wind and HVAC pressurization the predicted infiltration, and hence infiltration driven energy demand, is also impacted by the temperature and density

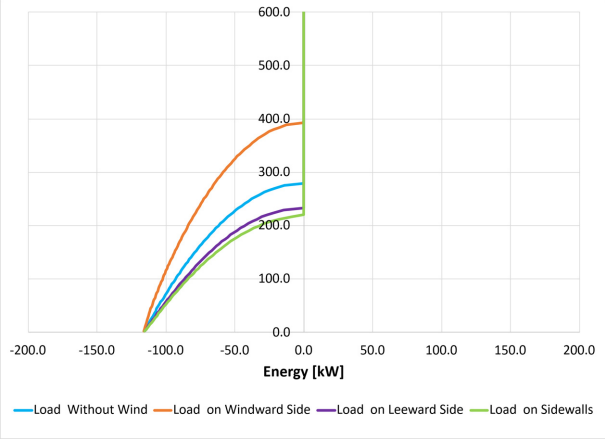


Figure 22. Infiltrating Energy Demand on Each Floor by Height [m] in Winter with Wind Alone.

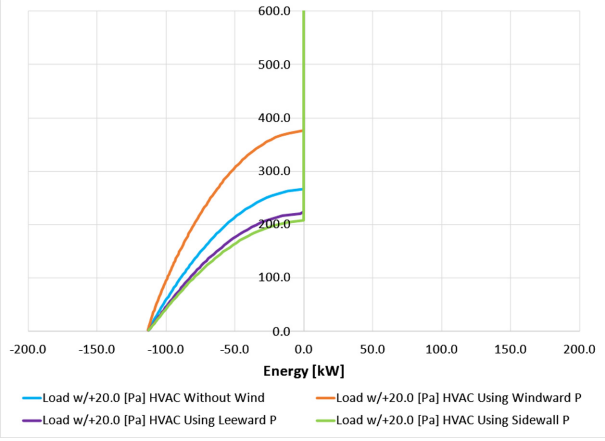


Figure 23. Infiltrating Energy Demand on Each Floor by Height [m] in Winter with Wind and HVAC.

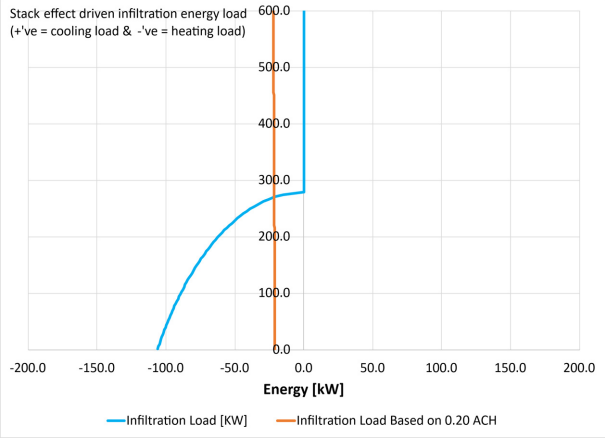


Figure 24. Energy Demand on Each Floor by Height [m] in Winter Associated with Infiltration Based on Variable External Temperature and Density.

assumption. Figure 24 presents the predicted infiltration driven energy flow using a standard adiabatic lapse rate on temperature and assuming a standard atmospheric

relationship for pressure as a function of height. Note that the change in infiltration load to a function of height for the 0.5 ACH assumed infiltration rate (orange line) is associated with the change in temperature as a function of height. The indoor setpoint to outdoor temperature difference increases as one moves up the building – there is a slight slope in the orange line.

8. Highlights

Several important topics were noted through the course of this paper. These are as follows:

- The Neutral Pressure Level (NPL) should be calculated for each project and the estimate of 0.5*h should not be used for important calculations. The NPL is important and its calculation is specific to every building. The discussion above has also shown how the NPL can be influenced by different factors (e.g. wind and HVAC pressurization).
- The leakage rate of the facade must be clearly defined, as any ambiguity could lead to inefficient energy use.
- Wind should be accounted for in infiltration calculations but not as a main driver; the main driver will be stack effect under typical wind condtions.
- It is imperative to give careful attention and consideration to the modification of the internal pressure imposed by ventilation systems. This can significantly impact the NPL height and energy efficiency both directly (the cost to run the fans) and indirectly (the consequence of changing the NPL height).
- The infiltration rate included in load calculations and simulation models must be calculated for each application. The rules of thumb are misleading at best.
- Any default infiltration loads should be ignored above the NPL in the winter and below in the summer. That said, wind can cause both infiltration and exfiltration on the same floor under some conditions (as shown in plots with the windward and leeward wind pressures) which is ample reason to conduct more detailed calculations on important buildings.

10. Conclusions

The discussion and results above lead to the following conclusions:

When calculating heating and cooling loads for tall, supertall, and mega-tall buildings, the actual outside temperature differentials at different building heights must be incorporated into the calculations in order to more accurately reflect the demands on the heating and cooling systems. Commercial software and custom software should reflect this.

The critical period is winter at the bottom of the building and summer at the top, as the temperature and relative humidity differentials between internal setpoints and the outside impact different levels and different parts of the building.

The actual air infiltration under design conditions has been shown to be higher than an assumed 0.2 ACH value. This has clear implications on equipment sizing.

The need for variable outdoor conditions as a function of height for tall buildings implies that ASHRAE or another organization should make these available to designers.Since there are higher pressures across the façade at the top and bottom of a building, there is value in ensuring that the building has suitable leakage control specified for the fixed and operable components of the envelope at these extreme ends of the building.

11. Limitations and Future Work

This paper has used an analytical approach to generate estimates of heating and cooling demand associated with infiltration in a megatall building. These estimates were compared to an approach using rules of thumb for both a building in calm conditions, but also with wind and a non-constant atmosphere applied. That said, there are limitations with this method which are directly related to the simplifications (e.g. combining all shafts into one) based on the assumptions made (e.g. assuming all shafts run throughout the building). The point here was not to present a true building, but discuss how it is important to do these calculations when designing real buildings. Hence the modeling needs to get more sophisticated. Tools such as CONTAM exist for this purpose.

Future work would assess the relative importance of the simplifications made and whether internal partitioning can assist in managing the infiltration energy demands.

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