Determining the infiltration and exfiltration in Supertall and Mega Tall Buildings

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Abstract. Most traditional heating and cooling load calculations are based on weather conditions measured at a height of 10 m. But how appropriate is this in Super-Tall buildings 300m+ and Mega-Tall Buildings 600m+? This paper will present some specifics of evaluating building designs and performance in Tall Buildings.
From previous designs and research, we know that outdoor conditions vary with height. and the outside climate can have both a positive and a negative effect on the space conditions within the building. This paper illustrates the fluctuation of pressure differentials on the heating and cooling loads of spaces over the height of the building.
Rarely does the design of the upper level of the building capitalize on this phenomenon. Furthermore, wind, temperature, and pressure conditions at the top of a tall building are considerably different, therefore façade leakage rates and the buildings stack effect must be carefully assessed. If sufficient data is known about this difference, it can be incorporated to optimize the overall building design.
This novel paper explores the nuances of the ambient climate on tall buildings and the effects on the performance of the building.

Keywords. Mega Tall Buildings, Stack Effect, Energy Consumption
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1. Introduction

Stack effect is a phenomenon that causes challenges in tall building design and subsequent operation. Temperature and air density differences between the indoors and outdoors cause stack effect driven pressure differences to be created that drive airflows through the building envelope. The pressure differences are created because the density of air inside the building is less than that outside. This results in the weight of the column of air inside being lighter than that outside in winter months. The weight difference results in inward flows at lower levels in winter and flows out at the top. 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. During cooling months (e.g., the summer) the pressure differences are typically less as the temperature difference is not as severe as during winter conditions. This results in a lower pressure differential between the shaft and the outside compared to those under winter temperature differences.

2. Background Information

In most tall buildings there are shafts/risers that run top to bottom in the building. From the floorplate layouts we have been using in this and previous papers we have two emergency exits stairways and two freight elevators. There are also other risers such as plumbing chases and electrical chases, but these are not considered in this exercise.

The dimensions of the stair and elevators shaft openings such as doors and cracks are provided in the NPL calculations provided in previous papers.

3. Calculating Location of Neutral Plane Level (NPL)

To get the sum of the effective crack area openings we use a resistance formula:

$$\mathrm{ECA} = \frac{1}{\frac{1}{\Sigma AF}+\frac{1}{\Sigma S+E}} \qquad (12)$$

Where: ΣAF is the crack opening areas such as:

- Entrance doors
- Exterior wall leakage cracks

And $\Sigma S+E$ is the crack opening areas such as:

- Stair shaft wall
- Stair shaft doors
- Elevator shaft wall
- Elevator doors

The crack opening areas effectively act as a passage for air flow with a 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. create a resistance network. Hence the objective is to calculate an effective crack area on each floor and then calculate a height weighted average and turn that into an estimate of the NPL (Simmonds and Phillips, 2022).

The design engineer will determine the number of elevators, transfer floors, refuge floors and other such elements as shown on the architectural drawings.

The exterior wall leakage rate in this case is 1.96 cm2/m2. The area of the exterior walls is 756 m2. The crack area is 1.96*756 = 1481.76 cm2 or 0.148 m2. This term is called AF, 1/AF = 6.7

The leakage rate of the stair shaft is 0.4 cm2/m2, the area of the stairwell = 62.1 m2 and the crack area =25.5 cm2 or 0.0025 m2

The leakage of the elevator doors = 187.5 cm2 per elevator, there are 6 elevators giving a total crack area of 1125 cm2 or 0.1125 m2.

The leakage rate of the elevator wall is 1.57 cm2/m2, the elevator wall area = 100.8 m2 giving a total crack area of 158.25 cm2 or 0.0158 m2.

The total stairwell and elevator (S+E) area is 0.0025+0.1125+0.0158 = 0.128 m2. This term is called S+E, 1/S+E = 7.792.

The sum of the crack areas = 1/ (1/AF +1/S+E) =0.0687 (at the highest level)

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

Stack Effects

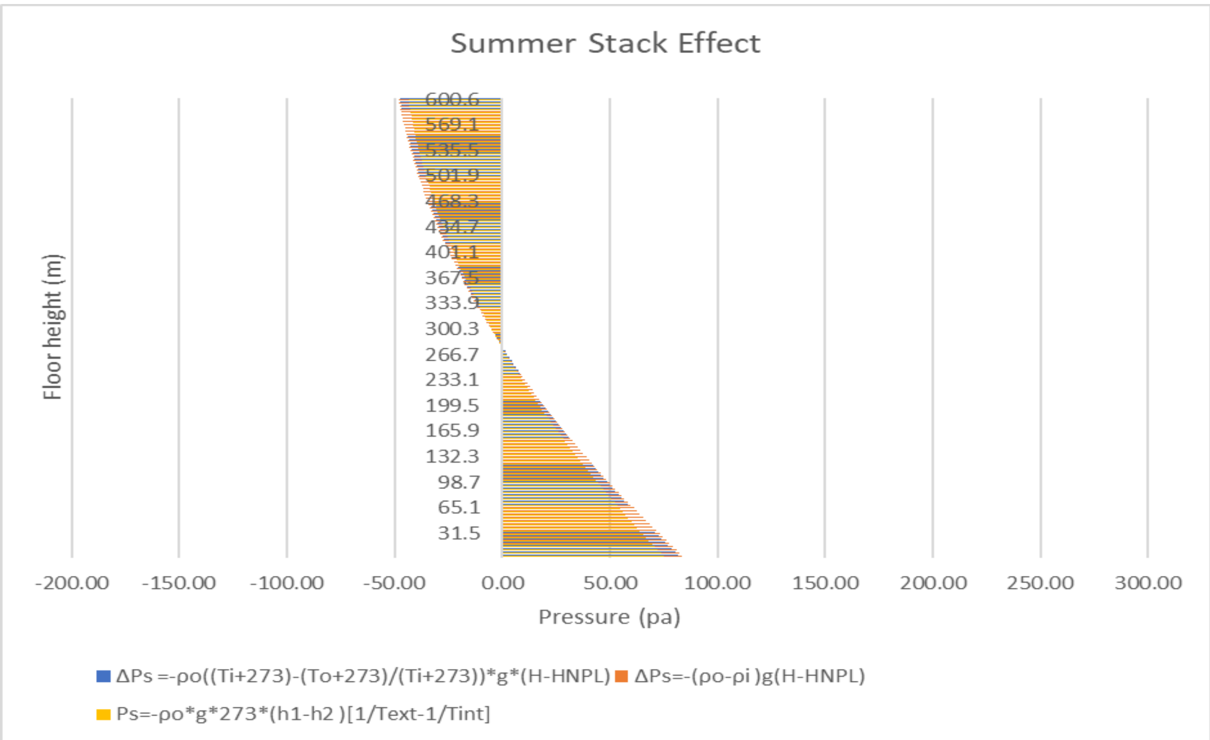

Figure 1 Stack effect driven indoor-outdoor pressure difference as a function of height in summer given the position of the neutral plane assuming the building is a single zone.

Figure 1 presents the indoor / outdoor pressure difference for the reference building for summer conditions with the outside temperature 32°C and the indoor temperature 24°C. This pressure difference is created exclusively because of the temperature difference between the indoors and outdoors.

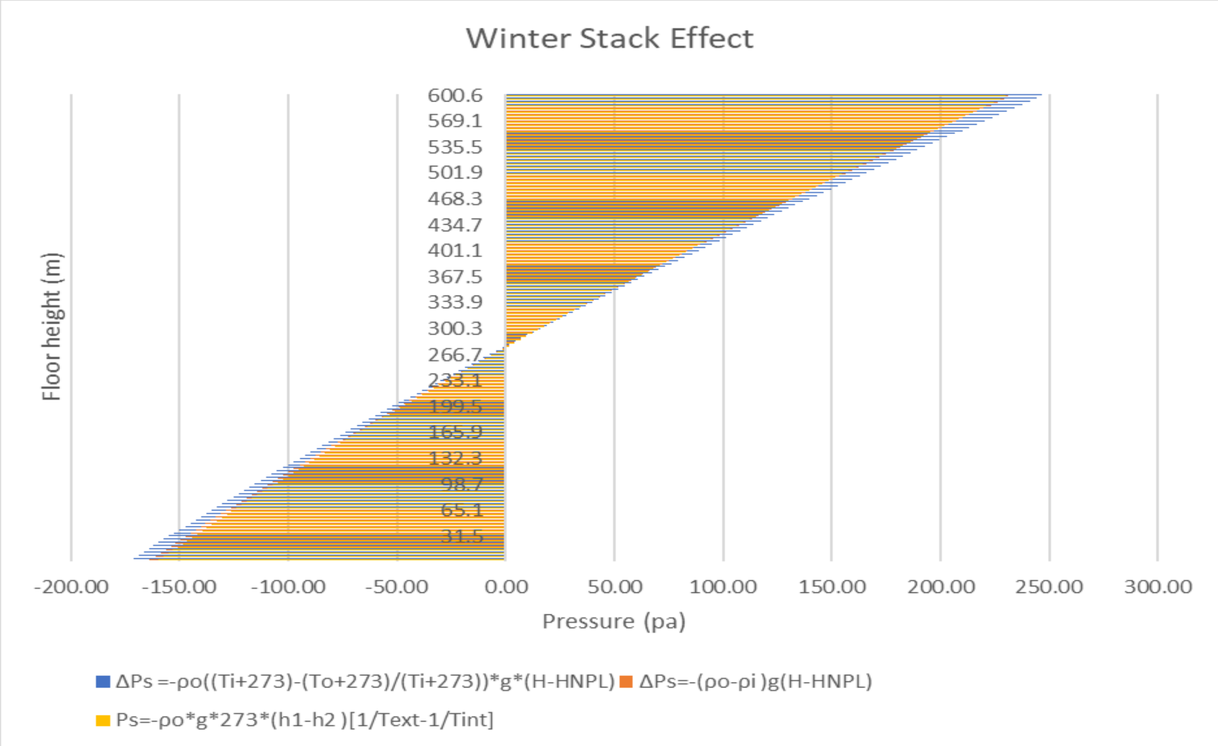

Figure 2 Stack effect driven indoor-outdoor pressure difference as a function of height in winter given the position of the neutral plane assuming the building is a single zone.

Figure 2 presents the indoor / outdoor pressure difference for winter conditions: the outdoor temperature is 6°C and the indoor temperature 20°C. The total delta P for the building is approximately 330 Pa. Clearly the slope here is less steep indicating a higher temperature difference: a vertical plot would mean zero temperature difference and a more horizontal slope would reflect a very high temperature difference.

4. Static air pressure in the shafts.

Static pressure, or hydrostatic pressure as it is sometimes called, is the pressure exerted by a fluid at rest. A fluid is any substance that does not conform to a fixed shape. This can be a liquid or a gas. Since the fluid is not moving, static pressure is the result of the fluid's weight or the force of gravity acting on the particles in the fluid.

Static pressure is the weight of the fluid above the point being examined. The pressure difference between two elevations can be calculated using the following equation:

$P = \rho * g * \Delta h$

Where:

P = the hydrostatic pressure (Pa)

ρ= the density of the air at height h

Δh = the height difference between the two points being examined

For this paper we are assuming the building to be 600m tall, we calculate the hydrostatic pressure at each floor starting at the top of the building. As we go down the building the pressure of the air at the floor above is integrated with the hydrostatic pressure at the floor being considered. At the bottom of the building there is a height of 600m creating the hydrostatic pressure difference.

5. Calculating Static Pressure Differences

Using the data shown in tables 1 through 4 above we can calculate the static pressure of the air in a shaft.

summer temp ©	summer density (kg/m3)
18	1.212

Table 1: Summer conditions in the stair shaft

Winter temp ©	Winter density (kg/m3)
14	1.229

Table 2: Winter conditions in the stair shaft

summer temp ©	summer density (kg/m3)
28	1.172

Table 3: Summer conditions in the elevator shaft

Winter temp ©	Winter density (kg/m3)
18	1.212

Table 4: Winter conditions in the elevator shaft

Using the above temperatures and resultant densities we calculate the pressures in the shafts

6.Calculating Flow Driven by Predicted Pressure Differential on Each Level

To calculate the air movement either from the shaft to the outside or vice versa we use the following formula:

$$Q = C_p A\sqrt{2\,\Delta P_{tot}/\rho} \qquad (1)$$

Where:

Q = airflow, m3/s

Cp =flow coefficient (0.61 was used for these calculations)

A = cross-sectional area of opening (e.g., the cracks in the case of infiltration), m2

ΔP_{tot} = total pressure difference between the vertical shaft and outdoors at the elevation of interest {Pa}

ρ = air density, kg/m3

The following formula is used to express the total pressure differential between a shaft and the outside.

$$\frac{1}{C_p^2}\left(\frac{Q}{A}\right)^2\frac{\rho}{2} = \Delta P_{tot} \qquad (2)$$

If we work with just the elevator shafts and assume the stair shafts are not participating in the stack effect:

$$\Delta P_{tot} = \Delta P_F + \Delta P_E \qquad (3)$$

The total pressure from is the pressure differential across the façade and the pressure differential across the elevator doors.

$$\Delta P = \frac{\rho}{2}\frac{1}{C_p^2}\left(\frac{Q_F}{A_F}\right)^2 + \frac{\rho}{2}\frac{1}{C_p^2}\left(\frac{Q_E}{A_E}\right)^2 \qquad (4)$$

Where:

Q_F = air flow through the façade

Q_E = the air flow through doors and cracks

A_F = the area of the façade

A_E = the area of doors and cracks

Formula 4 is derived from expanding formula 3 with formula 2.

Simplifying formula 4 we get,

$$\Delta P = \frac{\rho}{2C_p^2}\left(\frac{Q_F}{A_F} + \frac{Q_E}{A_E}\right)^2 \qquad (5)$$

As the air flows through the two sets of cracks (e.g. elevator and façade) are equal, we get,

$$Q_F = Q_E \qquad (6)$$

The next step is to assess the infiltration or exfiltration through the elevator shaft and the infiltration or exfiltration through the façade,

$$\Delta P = \frac{\rho}{2C_p^2}\left(Q_F A_E + Q_E A_F / A_F A_E\right)^2 \qquad (7)$$

Simplifying formula 7 we get

$$\Delta P = \frac{\rho}{2C_p^2}\left(2Q(A_E + A_F)/A_F A_E\right)^2 \qquad (8)$$

Further simplifying formula 8, we get

$$Q = \sqrt{2\,\Delta P/\rho}\;\frac{C_D}{2}\;(A_E A_F)/(A_E + A_F) \qquad (9)$$

To identify the pressure differential across the façade we get

$$\Delta P_F = \Delta P_{tot} - \frac{\rho}{2C_p^2}\left(\frac{Q}{A_E}\right)^2 \qquad (10)$$

This equation permits one to split the total pressure difference at any elevation into that across the façade and elevator doors based on the relative leakiness of the elements. To use this approach, the designer needs to acquire the following information:

- Equivalent façade leakage areas (at a known pressure difference) over the height of the building.

- Emergency exit stair shafts (these are usually the height of the building).
- Openings in stair shafts that lead to leakage including gaps underneath the doors.
- All elevator shafts, including goods and firefighter's elevators as well as the height of each elevator shaft.
- Openings in elevator shafts that lead to leakage including the gaps around the elevator doors; and,
- Any required building sections such as refuge floors.

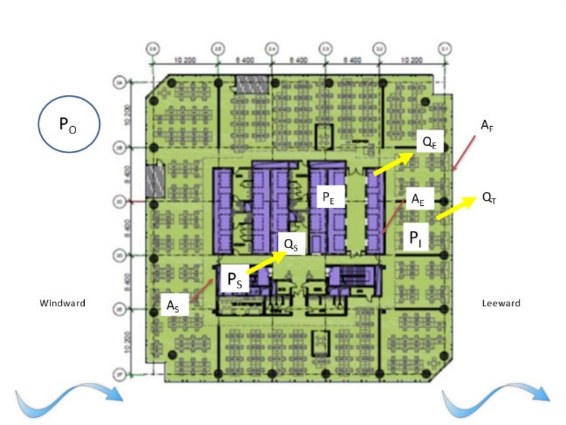

Figure 3:Typical floorplan of the building under consideration. There are two emergency staircases and two freight elevators

Leakage performance data is sometimes specified as a flow at a given pressure difference – this 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. Finally, leakage area could be specified per unit (e.g., per door). To perform the calculation, the equivalent leakage areas should be calculated for all components which removes the pressure-based relationship of flow vs. pressure difference.

7. Pressure Predictions

Due to the dynamics of the interaction between outside conditions and temperatures in unconditioned spaces the study was conducted using three steps. The first step was to assume the outside temperature was constant over the height of the building, the second step was to assume a variable temperature over the height of the building and the third step was to assume a variable temperature and pressure over the height of the building.

The pressure in the stair shaft and elevator shaft were calculated for each floor and then the pressure in the floor above is integrated with the pressure from the floor below to provide a pressure head at that point.

The following figures show the results of comparing the pressure differential between the stair shaft and outside and the pressure differential between the elevator shaft and the outside.

From figures 1 and 2 we can see the building has a different characteristic fir the Summer and for the Winter. During the summer the flow of pressure is from the outside to the inside above the neutral plane. This means outside air will infiltrate the building and will add an extra cooling load to the conditioning system. In the winter the flow of pressure is from the outside to the inside below the neutral plane. This results in outside air infiltrating the building and will increase the heating load.

The goal of this research is to quantify the energy effects of the outside air infiltration due to the pressure differential between shafts and the outside.

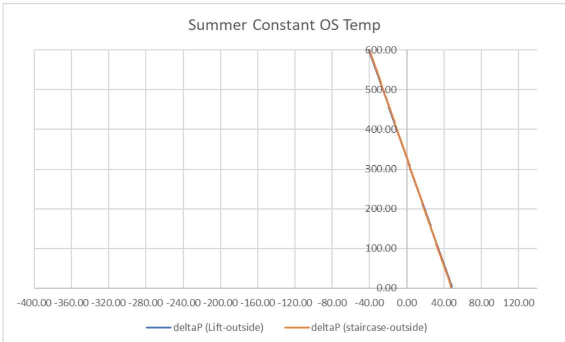

Figure 4 shows the pressure differential between the shafts and the outside when the outside temperature is assumed to be constant over the height of the building.

The pressure differential is from -40 Pa at the top of the building to +40 Pa at the bottom of the building. As the temperature differentials between shafts and outside are relatively small, 80 Pa.

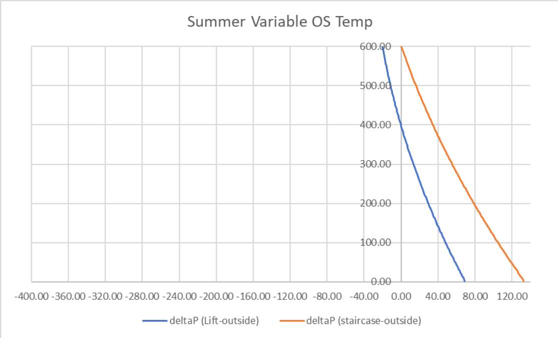

Figure 5 shows the pressure differential between the shafts and the outside when the outside temperature is assumed to be variable over the height of the building

Figure 5 shows a curved relationship this is due to the temperatures in the shafts being constant, but the outside temperature reduces over the height of the building. The pressure differential between the elevator shaft and outside is from -- 40 Pa at the top of the building to +80 Pa at the bottom of the building. The pressure differential between the Stair shaft and outside is from 0 Pa at the top of the building to +130 Pa at the bottom of the building.

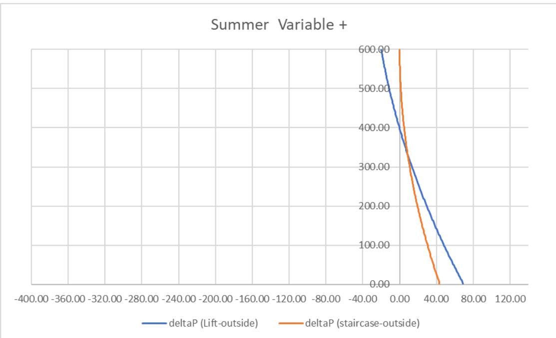

Figure 6 shows the pressure differential between the shafts and the outside when the outside temperature and pressure is assumed to be variable over the height of the building

Figure 6 shows the sensitivity of the pressure relationships. The pressure differential between the elevator shaft and outside is from -- 20 Pa at the top of the building to +70 Pa at the bottom of the building. The pressure differential between the Stair shaft and outside is from 0 Pa at the top of the building to +40 Pa at the bottom of the building.

Both stair and elevator shafts to outside pressure differentials are lower than the pressure differentials shown in figure 5.

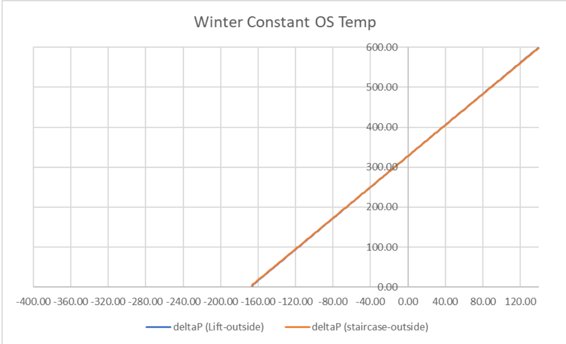

Figure 7 shows the pressure differential between the shafts and the outside when the outside temperature is assumed to be constant over the height of the building.

The pressure differential is from +130 Pa at the top of the building to -160 Pa at the bottom of the building. As the temperature differentials between shafts and outside are large, 290 Pa.

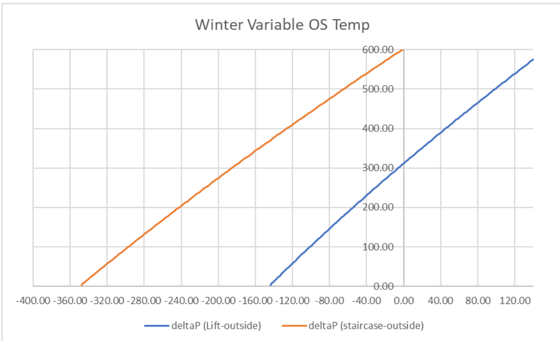

Figure 8 shows the pressure differential between the shafts and the outside when the outside temperature is assumed to be variable over the height of the building

Figure 8 shows a curved relationship this is due to the temperatures in the shafts being constant, but the outside temperature reduces over the height of the building. The pressure differential between the elevator shaft and outside is from +130 Pa at the top of the building to -140 Pa at the bottom of the building. The pressure differential between the Stair shaft and outside is from 0 Pa at the top of the building to -350 Pa at the bottom of the building. Both pressure differentials are much higher than the summer calculation and this is due to the larger temperature differential between the shafts and the outside.

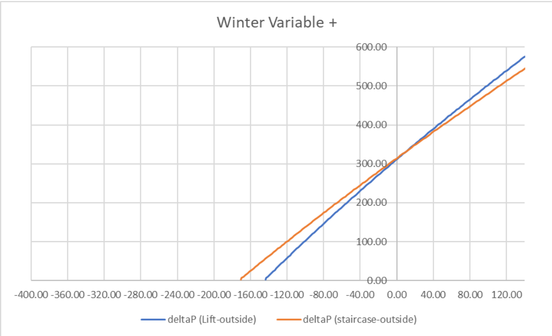

Figure 9 shows the pressure differential between the shafts and the outside when the outside temperature and pressure is assumed to be variable over the height of the building

Figure 9 shows the sensitivity of the pressure relationships. The pressure differential between the elevator shaft and outside is from +130 Pa at the top of the building to -140 Pa at the bottom of the building, which is 270 Pa. The pressure differential between the Stair shaft and outside is from +130 Pa at the top of the building to -170 Pa at the bottom of the building, which is 300 Pa.

8. Flow Predictions

The following results are for a single stair shaft and a single elevator shaft. For combinations of multiple stair and elevator shafts we refer to a future paper that will include these complicated calculations.

Using the following data from the preliminary analysis:

ρ stair

ρ elevator

ΔP stair to outside

ΔP elevator to outside

AS = Area of the stair openings

AE = Area of the elevator openings

AF= area of the facade

And using formula 9 we get the following results

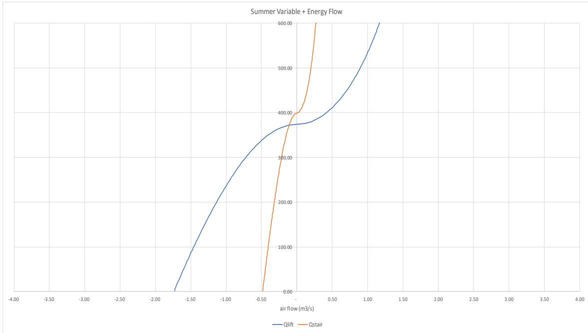

Figure 10 shows the volume of air flow infiltrating and exfiltrating the building in the summer.

When the flow is positive outside air will infiltrate the building. In the summer the infiltration of outside air will increase the space cooling load. The increase in cooling load is estimated at 149*1*1.172*(30-24) = 1,047.7 kW, on the design day.

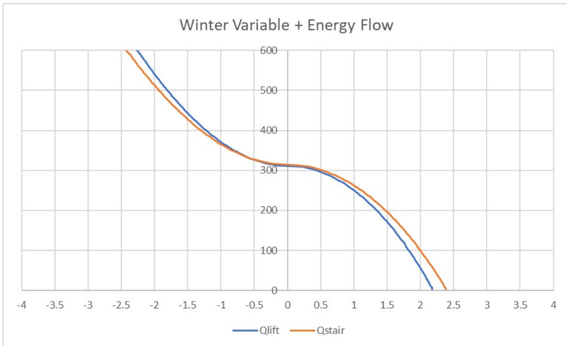

Figure 11 shows the volume of air flow infiltrating and exfiltrating the building in the Winter at 6 C outside temperature.

When the flow is negative outside air will infiltrate the building. In the winter the infiltration of outside air will increase the space cooling load. The increase in cooling load is estimated at 110*1*1.172*(20- 6) = 1,804 kW, on the design day.

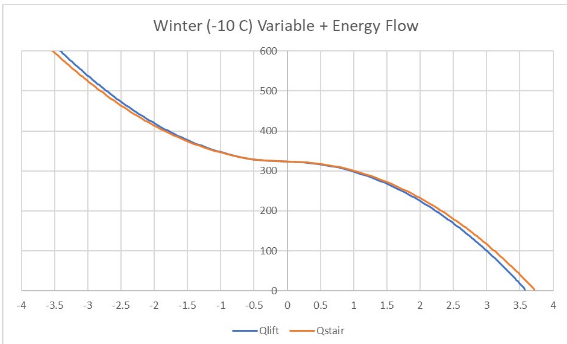

Figure 12 shows the volume of air flow infiltrating and exfiltrating the building in the Winter at -10 C outside temperature.

When the flow is negative outside air will infiltrate the building. In the winter the infiltration of outside air will increase the space cooling load. The increase in cooling load is estimated at 121*1*1.19*(20- -10) = 4,319.7 kW, on the design day.

9. Conclusions

The results clearly show that when calculation heating and cooling loads for Tall, Supertall and Megatall buildings the actual outside temperature differentials at different building heights need to be incorporated into the calculations.
The critical period is the winter as the temperature differential between internal shafts and the outside are largest, also the infiltration of outside air is at a lower temperature.
The actual outside air infiltration will be much higher than specified and who will be responsible for the increase in infiltration.
What pressure should the façade be tested to? What outside air infiltration rate has been included in the heating and cooling load calculations?
At present, there are no commercially available load calculation programs that use a variable outside temperature in the calculations.
This paper shows how the variable outside temperature can be used when calculating a buildings heating and cooling loads in a spreadsheet. These hand calculations should be recommended for Tall, Supertall and Megatall buildings.
It is, of course, essential that the vertical weather data be made available for such calculations.
The façade air infiltration rate specified by the architect should be appropriate for the overall height of the building.

Data Access

The datasets generated during or analysed during the current study are not publicly available because they are owned by RWDI.

References

ASHRAE. (2019). Standard 62·1-2019. Ventilation for Acceptable Indoor Air Quality, ASHRAE: Atlanta, Ga 30329.

ASHRAE. (2021). Chapter 16 and Chapter 24 Fundamentals Handbook 2021. ASHRAE: Atlanta, Ga 30329.

ASHRAE. (2019). Chapter 4 and Chapter 54, Applications Handbook 2019. ASHRAE: Atlanta, Ga 30329.

Lovatt, J. E. and Wilson, A. G. (1994). Stack effect in tall buildings. ASHRAE Transactions 100(2), pp. 420~431.

Nylund, P.O. 1980. Infiltration and ventilation. Report D22:1980. Swedish Council for Building Research, Stockholm.

Raymond, W. H. (2000). Estimating Moisture Profiles Using a Modified Power Law, Journal of Applied Meteorology 39(7), pp. 1059~1070.

Ross, D. (2004). An HVAC design guide for tall commercial buildings, ASHRAE.

Persily, A.K., and R.A. Grot. 1986. Pressurization testing of federal buildings. In Measured air leakage of buildings, STP 904, p. 184. H.R. Trechsel and P.L. Lagus, eds. American Society for Testing and Materials, West Conshohocken, PA.

Phillips, D, (2014) Personal Correspondence.

Phillips, Duncan A. (2021), Managing Infiltration in Tall Buildings to Control Energy Loss, Minimize Pathogen Transport and Enhance Air Quality, Presented at the ASHRAE January 2021 Conference, Seminar 75.

Simmonds, P., and Zhu, R., Stack Effect Guidelines for Tall, Mega Tall and Super Tall Buildings, International Journal of High-Rise Buildings, December 2013, Vol 2, No 4, 1-8

Simmonds, P., The new ASHRAE Design Guide for Tall, Supertall and Megatall Building Systems, ASHRAE 2015 and second edition 2020

Simmonds, P., and Phillips, D., A unique way to determine the Neutral Plane height in Stack Effect calculations. ASHRAE Journal, 2022

Tamblyn, R. T. (1991). Coping with air pressure problems in tall buildings. ASHRAE Transactions 97(1), pp. 824~827.

Tamura, G.T., and C.Y. Shaw. 1976a. Studies on exterior wall air tightness and air infiltration of tall buildings. ASHRAE Transactions 82(1):122. Paper DA-2388.

Tamura, G.T., and C.Y. Shaw. 1976b. Air leakage data for the design of elevator and stair shaft pressurization system. ASHRAE Transactions 82(2):179. Paper SE-2413.

Tamura, G.T., and A.G. Wilson. 1966. Pressure differences for a nine-story building as a result of chimney effect and ventilation system operation. ASHRAE Transactions 72(1):180.

Tamura, G.T., and A.G. Wilson. 1967a. Pressure differences caused by chimney effect in three high buildings. ASHRAE Transactions 73(2): II.1.1.

Tamura, G.T., and A.G. Wilson. 1967b. Building pressures caused by chimney action and mechanical ventilation. ASHRAE Transactions 73(2): II.2.1.