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Stack Effect Guidelines for Tall, Mega Tall and Super Tall Buildings

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Abstract

The ASHRAE Technical Committee for Tall Buildings, TC 9.12, has defined a tall building as one whose height is greater than 300 feet (91m). Since the publication of the HVAC Design Guide for Tall Commercial Buildings in 2004, there were only about 300 buildings taller than 200 meters; this number has risen to 600 in 2010 and the prediction 765 buildings taller than 200 meters in 2012. There has also been an introduction of two new classes of tall buildings:

- Mega tall, which are buildings taller than 300 m, and
- Super tall, which are buildings taller than 600 m.

The effect of ambient air temperature over the height of buildings, especially Mega tall and Super tall buildings. The ambient climatic conditions vary with altitude and these changes in ambient conditions can seriously affect load calculations and performance of super and mega tall buildings. This paper presents revised calculations for stack effect for Tall, Mega Tall and Super tall Buildings.

Keywords: Tall buildings, Load calculations, Air infiltration, Natural ventilation

1. Introduction

Stack effect is a result of pressure differences between the environment and tall buildings (over 300 feet tall) and has a large impact on the functionality of these buildings, even in parts that would not be in direct contact with the exterior walls. This causes engineers and architects to carefully design and inspect every aspect of a skyscraper to make sure it doesn't cause problems for its occupants. Reverse stack effect is the same concept, just opposite for the top and bottom of a building.

Stack effect can be troublesome for occupants when it is strong within the building. It can cause doors to fail at opening, prevent elevator doors from closing, and heating of the building can have minimized effects because of the strong pressure within the building. This problem is usually maximized in very cold climates and very tall buildings.

Luckily, there are ways to minimize, or even prevent, stack effect from occurring in tall buildings, especially in cold weather cities like Chicago or New York City. The sealing of all possible ways of entry and exit for air maintain the pressure difference between the building and the environment. Revolving doors must be used for the entry and exit of people because they have an even weight distribution at any point from the pivot. Well-sealed doors between stairs, especially fire stairs, minimize vertical airflow between the top and bottom floors.

The neutral pressure level (NPL) is the vertical location in the building where the indoor and outdoor air pressure are in equilibrium. Parts of the building that remove air from inside the building raise the NPL, while parts of the building that supply air into the building lower the NPL. Any large openings relative to a building's leakage move the NPL closer to the opening. There can be buildings that do not have a NPL because there are no locations on the building envelope that have zero pressure difference between the environment and building. The most common vertical location for a NPL on a building is 0.3 to 0.7 of the height of the building.

The taller the building and the smaller its internal resistance to airflow the stronger the stack effect. Ventilation flows, however, can complicate the pressure difference on different floors of a building. Pressurizing the ground floor of tall buildings during the winter in cold climates reduces negative air pressures across entryways.

Compartmentalization of a building also affects the NPL location. If a building has no internal partitions between each floor, then the thermal draft coefficient, which is the sum of the actual pressure differences at the top and bottom divided by the sum of external wall pressure differences at the top and bottom, approaches a value of one. For a building with airtight partitions between each floor, the thermal draft coefficient approaches a value of zero and each story has its own NPL because of its independence

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from other floors' conditions. Almost all buildings are not completely airtight or open between floors. If a building has twice the vertical shaft leakage as it does building envelope leakage, then the thermal draft coefficient approaches one for exit stairwells and can cause stack effect that becomes apparent during emergencies, as well as leads to poor ventilation of floors. This means buildings are more airtight between floors than they are open.

2. Stack Effect

2.1. Definition

Stack effect occurs in tall buildings when the outdoor temperature is lower than the temperature of the spaces inside. A tall building acts like a chimney in cold weather, with natural convection of air entering at the lower floors, flowing through the building, and exiting from the upper floors. It results from the difference in density between the cold, denser air outside the building and the warm, less dense air inside the building. The pressure differential created by stack effect is directly proportional to building height as well as to the difference between the warm inside and cold outdoor temperatures.

When the temperature outside the building is warmer than the temperature inside the building, the stack effect phenomenon is reversed. This means that, in very warm climates, air enters the building at the upper floors, flows through the building, and exits at the lower floors. The cause of reverse stack effect is the same in that it is caused by the differences in density between the air in the building and the air outside the building, but in this case the heavier, denser air is inside the building.

Reverse stack effect is not as significant a problem in tall buildings in warm climates because the difference in temperature between inside and outside the building is significantly less than the temperatures difference in very cold climates. Accordingly, this section focuses on the problems caused by stack effect in cold climates.

2.2. Practical considerations of stack effect

Stack effect in tall buildings often presents major problems. Elevator doors may fail to close properly because of the pressure differential across the doors, which cause the door to bind in its guide way enough that the closing mechanism does not generate sufficient force to overcome it. Manual doors may be difficult to open and close because of strong pressure created by stack effect. Smoke and odor propagation through the air path of stack effect can also occur. Heating problems can occur in lower areas of the building may be difficult to heat because of a substantial influx of cold air through entrances and across the building's outside wall (caused by higher-than-anticipated wall permeability). Heating problems can be so severe as to freeze water in sprinkler system piping, cooling coils, and other water systems on lower floors. The National Association of Architectural Metal Manufacturers (NAAMM) specifies a maximum leakage per unit of exterior wall area of 0.00003 cm^3/m^2 at a pressure difference of 75 Pa exclusive of leakage through operable windows. In reality, tall buildings in cold climates can exceed this pressure difference through a combination of stack, wind, and HVAC system pressure. Even when leakage similar to the NAAMM criterion is included in project specification, it is not always met in actual construction, thereby causing potential operational problems.

Two actual examples, although extreme, illustrate the degree to which stack effect can cause major problems in building in cold climates.

A very tall commercial building in Chicago was partially occupied in September: the lower 30% of the building was occupied, and the top of the building was still under construction and open to atmosphere. There were few operating problems as the construction of the top portion of the building continued into the fall. Major problems only

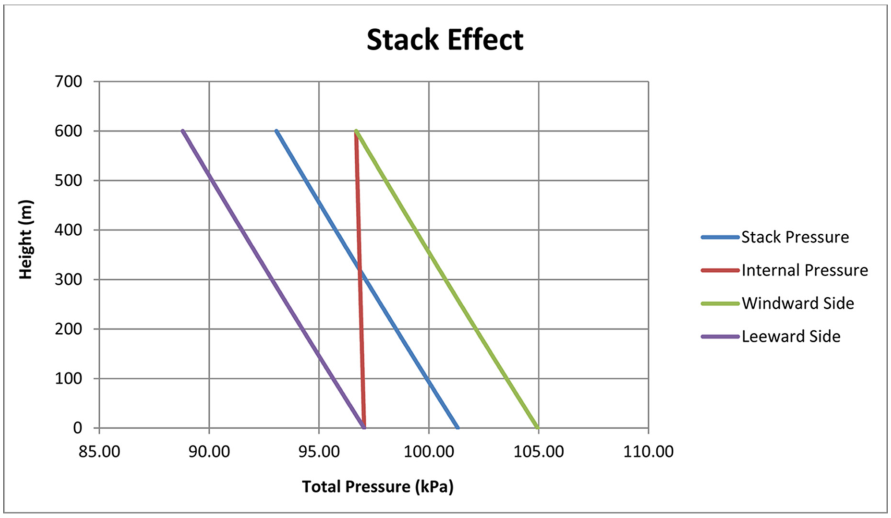


Figure 1. shows the stack effect and internal pressure for building heights up to 600 m.

occurred when winter hit the area and temperatures -7°C and below were experienced. At this time, because of the building's open top, its neutral pressure level was raised substantially above the midpoint. (In a practical sense, the neutral pressure level was at the roof and the entire theoretical pressure differential was experienced at the entrance level.) The result was the collapse of revolving doors, an inability to close elevator doors, and inability to adequately heat the entrance levels of the building. Additional heated outdoor air was introduced at the entrance level, stairs at the point where occupancy stopped were sealed, and construction at the top of the building was expedited to close that portion of the building. By midwinter, these efforts minimized the problems and allowed more conventional use of the occupied lower floors.

A second problem developed in a 64-story building in New York City that was built, in part, over a major transportation hub with a direct open connection from the building to the hub itself. The transportation center, with train tunnels entering and leaving the hub and multiple doors that open and close as passengers enter the hub, is effectively open to atmosphere. With large volumes of outdoor air entering the train hub and able to pass directly to the connected office building, the result on cold winter days was such that the elevator doors would not close and comfort conditions could not be maintained in the lobby areas of the office building.

This problem was solved by providing a glass enclosure with revolving doors between the office building lobby and the escalators that allowed individuals to enter the train station. The practical closure of the openings to the train station solved the elevator door and heating problems, and the glass enclosure maintained the desired sense of openness.

2.3. Minimizing stack effect

During design, the architect and HVAC design engineer should take steps to minimize air leakage into or out of (and vertically within) the building. Although it is not possible to completely seal any building, this approach can help mitigate potential problems that could be caused by stack effect.

Outdoor air infiltration points include building entry doors, doors that open to truck docks, outside air intake or exhaust louvers, construction overhangs with light fixtures that are located immediately above the ground level and are not properly sealed against leakage or provided with heat, and any small fissures in the exterior wall itself. Internally, the building allows air passage through fire stairs, elevator shafts, mechanical shafts for ducts and piping, and any other vertical penetrations for piping or conduit or at the edge of the floor slab at the exterior wall. All these are candidates for careful review to ensure, as much as possible, that the exterior wall is tight, all shafts are closed, and all penetrations sealed. Vestibules or airlocks can be provided for loading docks with good door seals on the doors to and from the loading dock. Entrances for tall buildings in cold climates should be revolving doors. Doors of this type are balanced, with equal pressure in opposite directions on the panels on either side of the central pivot, making operation relatively simple and requiring no special effort to turn. Their gasketing also provides closure at all times.

Two-door vestibules are acceptable for the loading dock, assuming the doors are properly spaced to allow them to be operated independently and with one door to the vestibule always closed, and sufficient heat is provided in the space between the doors. If properly spaced, the simultaneous opening of both doors on either side of the vestibule can be controlled. However, two-door vestibules in cold climates are inadequate for personnel entry because, with large numbers of people entering the building at various times, both doors will be open simultaneously and major quantities of air can enter the building. In cold climates, it is strongly recommended that revolving doors be used at all points of personnel entry.

To control airflow into the elevator shaft, consider adding doors at the entry to the elevator banks. This creates an elevator vestibule on each floor that minimizes flow through open elevator doors. Elevator shafts are also a problem because an air opening may be required at the top of the shaft. All shafts, however, can be sealed in their vertical faces to minimize inflow that would travel vertically in the shaft to the openings at its top.

It can be helpful to interrupt stairs with well-sealed doors to minimize vertical airflow through buildings. This is particularly useful for fire stairs that run the height of the building. Entrances to fire stairs should be provided with good door and sill gaskets.

The last key item is to ensure a tight exterior wall through specification, proper testing, and hiring a contractor to erect the wall.

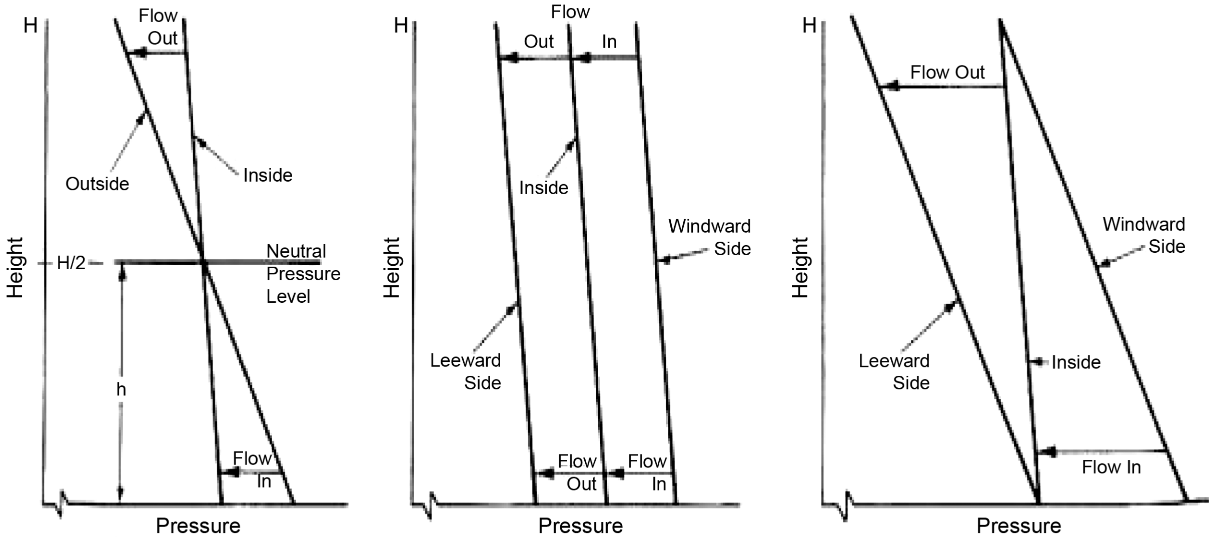
The preceding precautions involve the architect and allied trades. The HVAC designer primarily must ensure that mechanical air conditioning and ventilation systems supply more outdoor air than they exhaust, to pressurize the building above atmospheric pressure. This is true of all systems where a full air balance should be used for the entire building; with a minimum of 5% more outdoor air than the combination of spill and exhaust air provided at all operating conditions, to ensure pressurization. In addition, it is good design, and often required by code for smoke control, to have a separate system for the entrance lobby. Although not always required, this system can be designed to operate in extreme winter outside air conditions with 100% outdoor air. This air is used to pressurize the building lobby, which is a point of extreme vulnerability in minimizing stack effect.

2.4. Neutral pressure level

The neutral pressure level (NPL) is that location or locations in the building envelope where there is no indoor-to-outdoor pressure difference. Internal partitions, stairwells, elevator shafts, utility ducts, chimneys, vents, operable windows, and mechanical supply and exhaust systems complicate the prediction of NPL location. An opening with a large area relative to the total building leakage causes the NPL to shift toward the opening. In particular, chimneys and openings at or above roof height raise the NPL in small buildings. Exhaust systems increase the height of the NPL; outdoor air supply systems lower it.

Fig. 2 qualitatively shows the addition of driving forces for a building with uniform openings above and below mid-height and without significant internal resistance to airflow. The slopes of the pressure lines are a function of the densities of the indoor and outdoor air. In Fig. 2A, with indoor air warmer than outdoor air and pressure differences caused solely by thermal forces, the NPL is set at mid-height, with inflow through lower openings and outflow through higher openings. Direction of flow is always from the higher to the lower-pressure region.

Fig. 2B presents qualitative uniform pressure differences caused by wind alone, with opposing effects on the windward and leeward sides. When temperature difference and wind effects both exist, the pressures caused by each are added together to determine the total pressure difference across the building envelope. In Fig. 2B, there is no NPL because no locations on the building envelope have zero pressure difference. Fig. 2C show the combination, where the wind force of Fig. 2B has just balanced the thermal force of Fig. 6A, causing no pressure difference at the top windward or bottom leeward side. The relative importance of wind and stack pressures in a building depends on building height, internal resistance to vertical airflow, location and flow resistance characteristics of envelope openings, local terrain, and the immediate shielding of the building. The taller the building and the smaller its internal resistance to airflow, the stronger the stack effect. The more exposed a building is, the more susceptible it is to wind. For any building, there are ranges of wind speed and temperature difference for which the building's infiltration is dominated by stack effect, wind, or the driving pressures of both (Sinden, 1978b). These building and terrain factors determine, for specific values of temperature difference and wind speed, in which regime the building's infiltration lies. The effect of mechanical ventilation on envelope pressure differences is more complex and depends on both the direction of ventilation flow (exhaust or supply) and the differences in these ventilation flows among the zones of the building. If mechanically supplied outdoor air is provided uniformly to each story, the change in the exterior wall pressure difference pattern is uniform. With a non-uniform supply of outdoor air (for example, to one story only), the extent of pressurization varies from story to story and depends on internal airflow resistance. Pressurizing all levels uniformly has little effect on pressure differences across all floors and vertical shaft enclosures, but pressurizing individual stories increases the pressure drop across these internal separations. Pressurizing the ground level is often used in tall buildings in winter to reduce negative air pressures across entries. Available data on the NPL in various kinds of buildings are limited. The NPL in tall buildings varies from 0.3 to 0.7 of total building height (Tamura and Wilson, 1966, 1967b). For houses, especially houses with chimneys, the NPL is usually above mid-height. Operating a combustion heat source



A. Stack Action Only with Neutral Pressure Level at Mid-Height

B. Wind Action Only with Pressure of Equal Magnitude on Windward and Leeward Sides

C. Wind and Stack Action Combined

Figure 2. qualitatively shows the addition of driving forces for a building with uniform openings above and below mid-height and without significant internal resistance to airflow. The slopes of the pressure lines are a function of the densities of the indoor and outdoor air.

Table 1. Conditions for building heights use in the calculations for constant parameters

Height (m)	0	100	200	300	400	500	600
Outside Air Temperature (°C)	37.78	36.30	34.82	33.34	31.86	30.37	28.89
Air Pressure (kPa)	101.33	99.97	98.63	97.30	95.99	94.70	93.41
Air Density (kg/m^3)	1.14	1.13	1.12	1.11	1.10	1.09	1.08
Stack Pressure Difference (kPa)	0.00	-0.06	-0.13	-0.19	-0.25	-0.31	-0.36
Wind Pressure (kPa)	9.15E-04	5.29E-03	8.10E-03	1.06E-02	1.30E-02	1.52E-02	1.73E-02
Total Pressure (kPa)	101.32	99.90	98.50	97.12	95.75	94.40	93.06
Airflow Rate (m^3/s)	23.56	23.49	23.43	23.37	23.30	23.24	23.17
Internal Pressure (kPa)	97.05	96.99	96.93	96.87	96.81	96.75	96.69
Wind Speed (km/hr)	8.05	19.43	24.15	27.76	30.82	33.50	35.93
Windward Side (kPa)	104.95	103.54	102.14	100.75	99.39	98.03	96.69
Leeward Side (kPa)	97.05	95.64	94.24	92.86	91.49	90.13	88.80

with a flue raises the NPL further, sometimes above the ceiling (Shaw and Brown, 1982).

2.5. Thermal draft coefficient

Compartmentalization of a building also affects the NPL location. The sum of pressure differences across the exterior wall at the bottom and top of the building equals the total theoretical draft for the building. The sum of actual top and bottom pressure differences, divided by the total theoretical draft pressure difference, equals the thermal draft coefficient. The value of the thermal draft coefficient depends on the airflow resistance of exterior walls relative to the airflow resistance between floors. For a building without internal partitions, the total theoretical draft is achieved across the exterior walls, and the thermal draft coefficient equals 1. In a building with airtight separations on each floor, each story acts independently, its own stack effect being unaffected by that of any other floor. The theoretical draft is minimized in this case, and each story has an NPL.

Real multistory buildings are neither open inside, nor airtight between stories. Vertical air passages, stairwells, elevators, and service shafts allow airflow between floors. Some of the pressure difference between floors maintains flow through openings in the floors and vertical shafts. As a result, the pressure difference across the exterior wall at any level is less than it would be with no internal flow resistance.

Maintaining airtightness between floors and from floors to vertical shafts is a way to control indoor/outdoor pressure differences because of the stack effect and, therefore, infiltration. Good separation is also conducive to proper operation of mechanical ventilation and smoke management systems. However, care is needed to avoid pressure differences that could prevent door opening in an emergency. Tamura and Wilson (1967a) showed that when vertical shaft leakage is at least two times envelope leakage, the thermal draft coefficient is almost one and the effect of compartmentalization is negligible. Measurements of pressure differences in three tall office buildings by Tamura and Wilson (1967b) indicated that the thermal draft coefficient ranged from 0.8 to 0.9 with ventilation systems off.

2.6. Data

The following conditions were made constant for Table

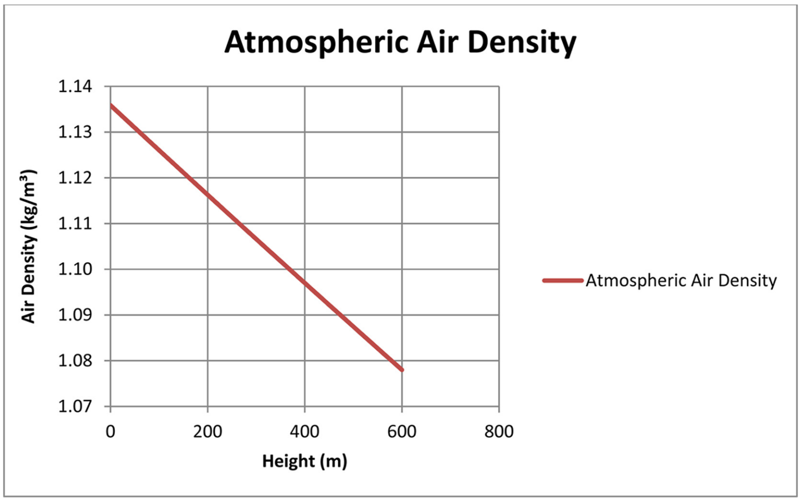


Figure 3. Air density change over 609 m (2000 ft), starting at sea level.

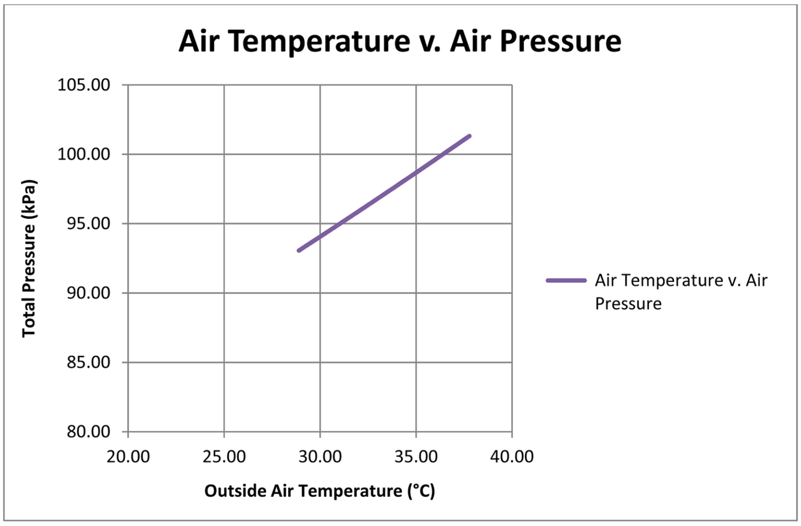


Figure 4. Change in total pressure with outside air temperature, starting at sea level to 609 m (2000 ft).

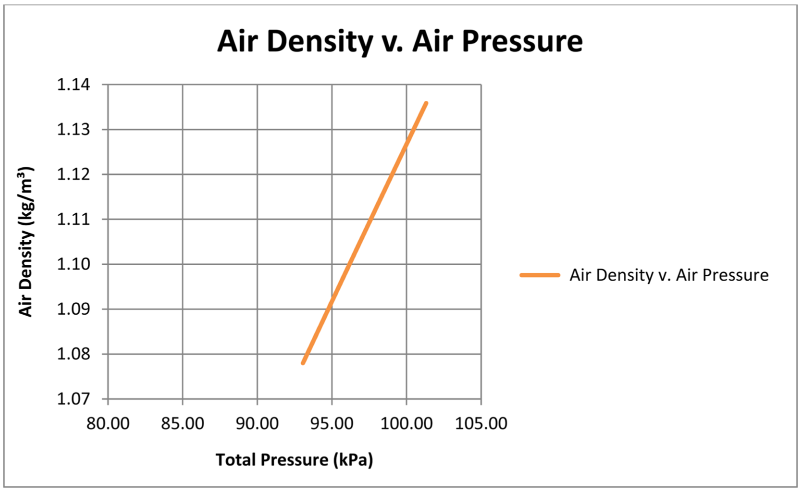


Figure 5. Change in air density with total pressure, starting at sea level to 609 m (2000 ft).

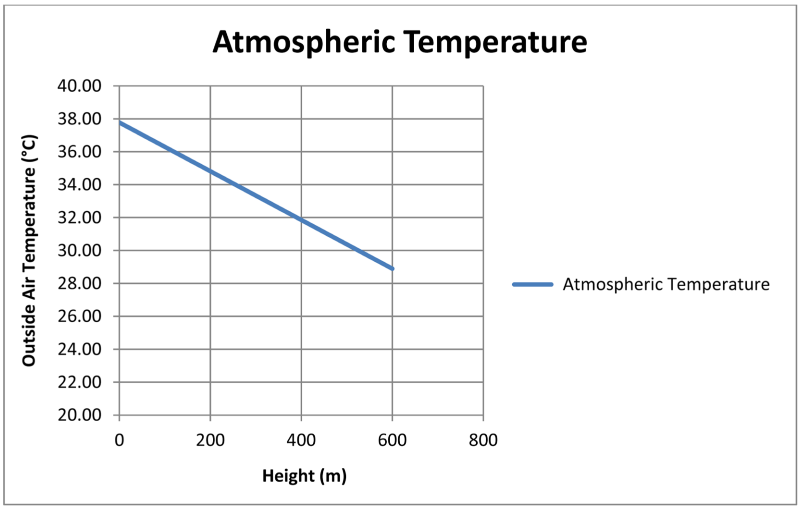


Figure 6. Air temperature change over 609 m (2000 ft), starting at sea level.

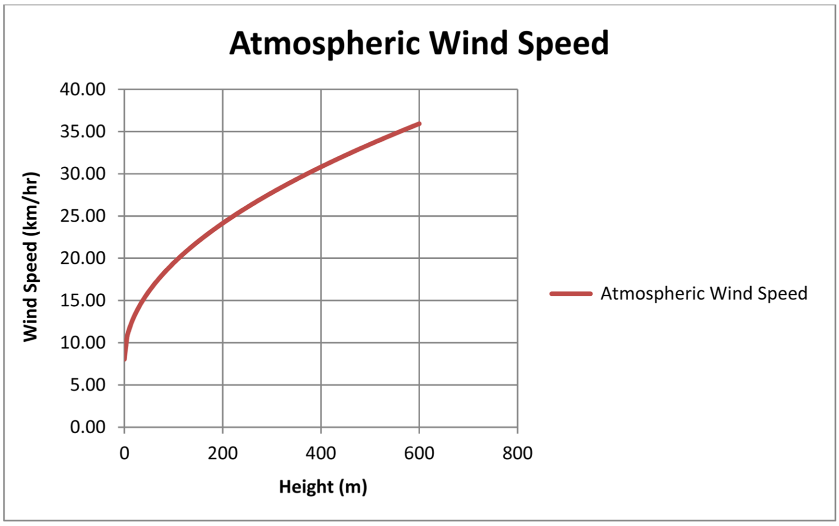


Figure 7. Wind speed change over 609 m (2000 ft), starting at sea level.

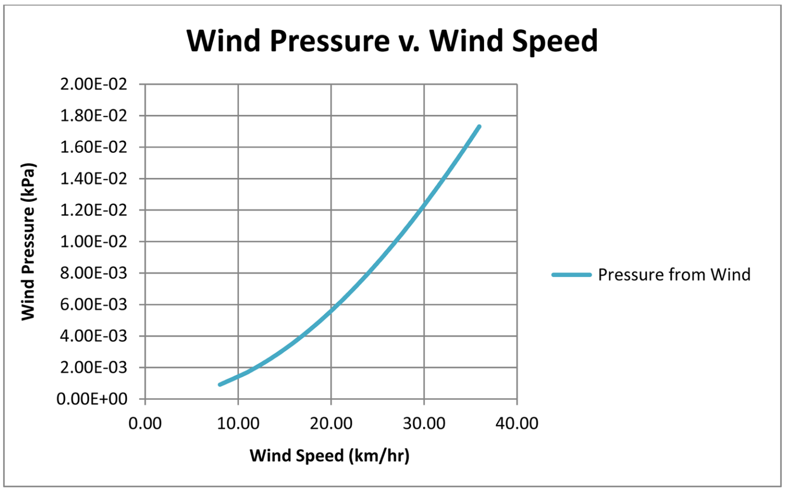


Figure 8. Change in wind pressure with wind speed.

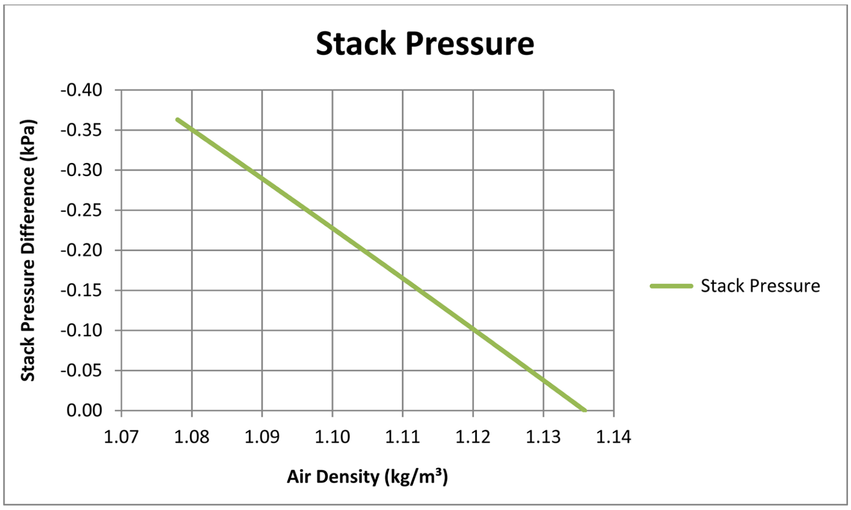


Figure 9. Change in stack pressure with air density, starting at sea level.

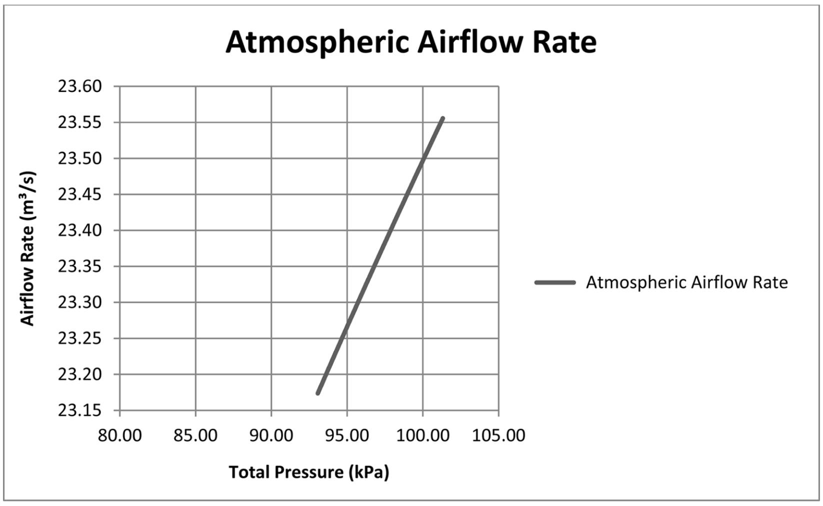


Figure 10. Change in airflow rate with total pressure, starting at sea level to 609 m (2000 ft).

1: outdoor air temperature of 37.78°C (100°F), indoor air temperature of 21.11°C (70°F), 30% humidity, sea level elevation, building height of 609 m (2000 ft), wind speed of 8.05 km/hr (5 mph), and envelope area of 0.09 m^2 (1 ft^2). For Figs. 3-10, a residential building was used in the model for the graphical data.

3. Conclusion

Stack effect has noticeable repercussions on buildings when the temperature and/or pressure difference is high between the ground floor of a building and the environment outside the exterior. The conditions simulate a hot day in a dry climate, which are the perfect conditions for reverse stack effect to occur. The wind speed is almost four times higher at the top of the building than at the ground; this causes the wind pressure to increase with the increasing wind speed. It also means that the stack pressure difference is higher at the top than at the ground floor and causes stack effect to affect occupants at the highest floors. A higher airflow rate at the bottom of the building than at the top signifies that more air is entering the building from the bottom, which could cause vertical shaft leakage to the top of the building as the air cools when gaining altitude. Internal pressure is not uniform throughout the building because of its height and will change slightly with decreasing air pressure and density.

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