Stairwell Flow Pressurization – A New Method

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ABSTRACT: Pressurization is used to prevent smoke spread into a stairwell. The stairwell height is limited by the pressure to open doors, about 80 Pa, the pressure to prevent smoke spread, about 20 Pa and the outdoor–indoor temperature-induced pressure gradient, about 2 Pa/m. This limits the height to 30 m ((80−20)/2). However, this limit can be increased by balancing the temperature-induced pressure gradient with an equal and opposite flow pressure gradient created by a flow passing through the whole stairwell.

KEY WORDS: pressurization, stairwell, high rise buildings, smoke spread, fire safety, fire protection.

INTRODUCTION

STAIRWELLS ARE USED to evacuate a building in case of a fire. Stairwell pressurization is a well-known method to prevent smoke from entering a stairwell in case of a fire. Using conventional methods, the stairwell overpressure is limited to a rather small interval, defined by minimum and maximum overpressure limits.

The minimum overpressure limit is mainly determined by the temperature difference across the door. The vertical pressure gradient for air of 300 and 600 K is close to 12 and 6 Pa/m. The vertical pressure difference across a 2 m high door with 300 and 600 K on the two sides is 12 Pa (2(12−6)). Higher fire temperatures than 600 K are possible. The temperature in the room with the fire will vary with the level (elevation). The expansion of the air and combustion products can also create an additional overpressure depending on the airtightness of the fire room. Another uncertainty is the wind

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pressure that can increase or decrease the necessary stairwell overpressure. A reasonable minimum overpressure limit with some safety margin could be 20 Pa.

The maximum overpressure limit can be based on a maximum door opening force of 130 N according to [1] and reduced by a 50 N door friction. The remaining force of 80 N can be applied at the door handle close to the door edge and overcome twice as large a force, 160 N, applied in the door center. The maximum overpressure limit is then 80 Pa for a door area of 2 m^2.

The chosen overpressure limits of 20 and 80 Pa are not unconditional fixed values, but rather possible examples. The total overpressure variation is then limited to about 60 Pa. The overpressure variation in a stairwell without any flow is created by the temperature-induced pressure gradient, which can be about 2 Pa/m during severe winter conditions. The stairwell flow at the bottom floor, equal to the total leakage flow, creates an opposite average flow pressure drop less than 0.1 Pa/m and is neglected. This means that the height is limited to about 30 m with the values mentioned above. Higher stairwells have to be sectioned.

However, it is not necessary to be restricted by the preceding conventional methodology. This paper presents a new method to increase the stairwell height limit considerably. The new method has been documented by the author in [2,3].

The vertical temperature-induced pressure gradient in a stairwell can be balanced by a flow that creates an equal and opposite pressure gradient. One important condition is that the staircase has to be rather compact with the horizontal cross section almost covered by solid landings and stairs. Such a compact stairwell will have the sufficient flow pressure drop at reasonable flows and velocities.

Another important condition is that the pressurization and inlet air have the same temperature as the stairwell surfaces and its air. This assumption makes the analysis simpler to follow and to understand. However, outdoor air is used as pressurization air, but this will change the air temperature in the lower part of the stairwell. This minor change in stairwell air temperature is due to the fact that the surface heat transfer capacity for a tall stairwell is larger than that of a balancing airflow.

A third condition is that the normal ventilation system of the stairwell is not considered in the study.

Normal static pressurization can be improved by creating a substantial flow in the stairwell, which in turn creates the desired pressure drop. This can be done by increasing the leakage flow to a desired value or even better by adding a large leakage outlet at the top floor of the stairwell. This leakage outlet can be opened when necessary. A third possibility is to allow a doubled overpressure and to use lobbies between the building and the

Table 1. Summary of pressurization methods.

Pressurization Method	Temperature Pressure Gradient	Flow Pressure Gradient	Inlet Flow
Normal static	Large	Small	Leakage flow
Increased leakage	Large	Increased	Increased leakage flow
Fixed bleed off area	Large	Increased	Bleed off flow
Lobby	Large	Small	Leakage flow
Flow	Large	Large	Balancing flow

stairwell. The stairwell overpressure is split evenly over the two doors by adding two bypass areas larger than the nominal door leakage area. The leakage areas for two lobby doors can differ so much that the overpressure becomes too large or too small over a single lobby door due to minor production differences. The added bypass areas at each lobby door will increase the leakage, which is also desirable. Another possibility is to have lobby doors with bypass areas activated by the door handle. All these pressurization methods for stairwells are summarized in Table 1. Only the flow pressurization method will be treated in this paper. The three modified static pressurization methods will be treated in a future study.

Pressurization of elevator shafts is a difficult task because there is hardly any pressure drop. The hydraulic diameter is several meters for elevator shafts. Large flows with extreme vertical velocities, about 20 m/s, are needed to create the necessary flow pressure gradient. However, large outdoor air flows of modest vertical air velocity, about 2 m/s, will decrease the temperature difference and consequently the temperature-induced pressure gradient. Such a pressurization method using the temperature effect could be named the temperature pressurization method.

The paper starts to derive simple expressions for necessary balancing flow, inlet flow, and maximum stairwell height for both the winter and summer case. The necessary stairwell flow pressure loss is derived from the stairwell walking line looked upon as a rectangular duct. The paper ends with a description and use of a simulation model. Seven simulated cases show different properties and possibilities with flow pressurization.

Stairwell Temperature-induced Pressure Gradient

The temperature dependent pressure gradient Δp_t that has to be balanced is calculated as follows:

$$\Delta p_t = (\rho_o - \rho_i)g \qquad \text{(Pa/m)} \tag{1}$$

where, Δp_t is the vertical temperature-induced pressure gradient, Pa/m; ρ_o is the outdoor air density, kg/m^3; ρ_i is the indoor air density, kg/m^3; g is the gravity, 9.81 m/s^2.

Stairwell Flow Pressure Gradient

The stairwell flow pressure gradient Δp_q is assumed to be turbulent and thereby a quadratic function of the flow and is given by the following expression:

$$\Delta p_q = -Rq^2 \quad q > 0 \quad (\text{Pa/m}) \tag{2}$$

where, Δp_q is the vertical flow pressure gradient, Pa/m; R is the specific flow pressure loss, Pa/(m(m^3/s)^2); q is the stairwell air flow upwards, m^3/s.

The stairwell flow pressure drop consists mainly of local single losses. A stairwell can be regarded as a rectangular duct with a rectangular cross section following the walking line. However, local single losses are averaged out on each story and are handled as friction losses for a fictitious vertical duct.

Stairwell Temperature-induced Pressure Gradient Balancing Flow

When it is colder outside than inside, a positive temperature-induced pressure gradient can be balanced with a negative flow pressure gradient created by an upwards flow in the stairwell. This flow is named the balancing flow and denoted q_b. The opposite case with a negative temperature-induced pressure gradient (colder inside than outside) can also be balanced with a positive flow pressure gradient from a downwards flow in the stairwell. This flow is a negative balancing flow q_b. The balancing flow can be calculated from (1) and (2) depending on the outdoor temperature T_o and the indoor temperature T_i as follows:

$$q_b = ((\rho_o - \rho_i)g/R)^{0.5} \quad T_o < T_i \quad (\text{m}^3/\text{s}) \tag{3}$$

$$q_b = -((\rho_i - \rho_o)g/R)^{0.5} \quad T_o > T_i \quad (\text{m}^3/\text{s}) \tag{4}$$

Note that the balancing flow q_b is independent of the stairwell height. This ideal balancing flow implies that the stairwell overpressures at the bottom Δp_i and at the top Δp_o are equal. A more general case for different overpressures Δp_i and Δp_o can be developed. The overpressure at the top can be written as the overpressure at the bottom plus the total temperature pressure change minus the total flow pressure change for a flow moving upwards. The third term is positive if the flow moves downwards. The expression is:

$$\Delta p_o = \Delta p_i + (\rho_o - \rho_i)gh - Rq_b^2h \qquad q_b > 0 \quad \text{(Pa)} \tag{5}$$

This more general balancing flow can be solved from (5) and written as follows.

$$q_b = \begin{cases} (f)^{0.5} & f \geq 0 \\ -(-f)^{0.5} & f \leq 0 \end{cases} \qquad (\text{m}^3/\text{s}) \tag{6}$$

where the term f stands for:

$$f = (\Delta p_i - \Delta p_o)/hR + (\rho_o - \rho_i)g/R \quad (\text{m}^6/\text{s}^2) \tag{7}$$

Stairwell Inlet and Outlet Flow

The stairwell inlet flow is equal to the balancing flow if no leakage is present. However with leakage present the stairwell inlet flow has to be adjusted for the total leakage flow. The average stairwell flow has to be close to the balancing flow from (5) to (7). A good approximation is to calculate the stairwell inlet flow q_i as the sum of the balancing flow plus half the leakage flow q_x at the nominal overpressure Δp_x. This makes the bleed off or outlet flow q_o at the top of the stairwell equal to the balancing flow minus half the leakage flow.

$$q_i = q_b + q_x/2 \quad q_i \geq q_x \quad (\text{m}^3/\text{s}) \tag{8}$$

$$q_o = q_b - q_x/2 \quad q_o \geq 0 \quad (\text{m}^3/\text{s}) \tag{9}$$

The above expressions set a limit for the total leakage flow versus the balancing flow. The outlet flow cannot be negative. Such a case would have required a second pressurization fan at the top of the stairwell. It follows from (9) and a nonnegative outlet flow that the total leakage flow cannot be larger than twice the balancing flow.

Stairwell Maximal Height – Winter Case

The variation in stairwell overpressure limits the stairwell height. The stairwell overpressure has to be larger than the minimum limit $\Delta p_{\min}$ and smaller than the maximum limit $\Delta p_{\max}$. The variation in overpressure is caused by the fact that the stairwell flow is not constant. The stairwell flow decreases more or less linearly from inlet to outlet. The difference is the leakage flow.

If the inlet and outlet overpressures are equal, then the overpressure will have a minimum close to the vertical center of the stairwell. The stairwell flow is equal to the balancing flow at the overpressure minima. For the sake of simplicity, the minimum overpressure is assumed to occur at the vertical center of the stairwell. The maximal stairwell height for flow pressurization, denoted as h_f, is then limited by the following three relations.

$$\Delta p(0) = \Delta p_{\max} \quad \text{(Pa)} \tag{10}$$

$$\Delta p(h_f) = \Delta p_{\max} \quad \text{(Pa)} \tag{11}$$

$$\Delta p(h_f/2) = \Delta p_{\min} \quad \text{(Pa)} \tag{12}$$

The actual overpressure variation can be calculated from the flow pressure loss only as the difference between the flow pressure drop for the first half of the stairwell and half of the total flow pressure drop. This overpressure variation should then be less than or equal to $\Delta p_{\max} - \Delta p_{\min}$. The temperature pressure change is constant throughout the stairwell and does not contribute to the overpressure variation.

The stairwell overpressure variation can be estimated by assuming that the stairwell flow decreases linearly from inlet to outlet as a function of the stairwell level denoted z as follows:

$$q(z) = q_b + q_x/2 - q_x z/h_f \quad (\text{m}^3/\text{s}) \tag{13}$$

The flow pressure loss for the first half of the stairwell can be calculated by simple integration of $Rq(z)^2$ over the first half of the stairwell height, which gives:

$$\int_0^{h_f/2} Rq(z)^2 dz = R(q_b^2 + q_b q_x/2 + q_x^2/12)h_f/2 \quad \text{(Pa)} \tag{14}$$

The total flow pressure loss can be calculated in the same way, which gives:

$$\int_0^{h_f} Rq(z)^2 dz = R(q_b^2 + q_x^2/12)h_f \quad \text{(Pa)} \tag{15}$$

Note that without leakage the result of (15) would have been $Rq_b{}^2h_f$. The flow pressure variation is now calculated as the right-hand side of (14) minus half of the right-hand side of (15). This pressure variation is in the limit case equal to the allowable overpressure variation. This gives the height limiting relation stated below.

$$\Delta p_{\max} - \Delta p_{\min} = Rq_b q_x h_f/4 \quad \text{(Pa)} \tag{16}$$

Note that the balancing flow q_b is independent of the stairwell height, but the total leakage flow q_x is directly proportional to the height. The above expression should also be compared with the height limit for the static pressurization with its maximal height denoted h_s as shown below. The small flow pressure loss is neglected in this case.

$$\Delta p_{\max} - \Delta p_{\min} = (\rho_o - \rho_i)gh_s \quad \text{(Pa)} \tag{17}$$

Now it is possible to derive a simple relation between the static pressurization height h_s and the possible stairwell height denoted h_f for the flow pressurization method by elimination of the overpressure difference in (16) and (17) and by the use of Expression (3) or (4) which gives:

$$h_f/h_s = 4q_b/q_x \qquad (-) \tag{18}$$

An important remark is that the above expression is based on some simple assumptions. Another remark is that the flow pressurized stairwell can be four times higher than the static pressurized stairwell if the balancing flow q_b is equal to the leakage flow q_x.

The Expression (18) can be transformed further by introducing the specific nominal leakage flow per meter stairwell q_m and the balancing flow leakage height h_b defined as:

$$q_m = q_x/h_f \quad ((\text{m}^3/\text{s})/\text{m}) \tag{19}$$

$$h_b = q_b/q_m \quad \text{(m)} \tag{20}$$

The maximal stairwell height can now be stated as twice the geometric mean of the balancing flow leakage height h_b and the static height h_s using (18)–(20) which gives:

$$h_f = 2(h_b h_s)^{0.5} \quad \text{(m)} \tag{21}$$

The maximal stairwell height can be estimated and calculated from (16) after elimination of the balancing flow q_b with (3) and the leakage flow q_x with (19). A correction factor k is also introduced which corrects the leakage flow by taking into account the actual overpressure conditions compared with the nominal overpressure. The maximal stairwell height h_f can then be calculated as follows:

$$h_f = 2((\Delta p_{\max} - \Delta p_{\min})/kq_m(R(\rho_o - \rho_i)g)^{0.5})^{0.5} \quad \text{(m)} \tag{22}$$

Note that, according to (22), the possible stairwell height will be doubled if the overpressure interval is increased by a factor of 4 or if the leakage is decreased by a factor of 4 or if the pressure loss or the temperature difference is decreased by a factor of 16. The correction factor k can be estimated and calculated from the actual average overpressure Δp_m and the nominal leakage overpressure Δp_x as follows:

$$k = (\Delta p_m/\Delta p_x)^{0.5} \qquad (-) \tag{23}$$

Note that the correction factor k defined and calculated as in (23) is an approximation because it should have been calculated with the average of the square root of the actual overpressure that influences the leakage and not as above with the square root of the average overpressure. However, it turns out that this error is rather small in comparison with other errors due to different assumptions.

The actual average overpressure Δp_m can be estimated from the maximum overpressure $\Delta p_{\max}$ and the minimum overpressure $\Delta p_{\min}$ with simple interpolation with the parameter b as follows:

$$\Delta p_m = b\Delta p_{\max} + (1 - b)\Delta p_{\min} \quad \text{(Pa)} \tag{24}$$

It can be shown that the parameter b should be equal to 1/3 if the overpressure varies as a quadratic function between $\Delta p_{\max}$ and $\Delta p_{\min}$. A simulation model has been used to calibrate parameter b. The model is described later in the paper with (26) to (27).

Ninety combinations have been made between three outdoor air temperatures of −20, −10, and 0°C (−4, 14, and 32°F), five specific leakage rates of 0.01, 0.02, 0.03, 0.04, and 0.05 m^3/sm and six possible overpressure intervals based on the values 20, 40, 60, and 80 Pa. The indoor air temperature has been 20°C and the specific pressure loss 0.1 Pa/(m(m^3/s)^2). The simulated stairwell heights have been larger than 100 m in 61 cases and larger than 200 m in 11 cases.

Table 2. Stairwell height error for 90 winter cases.

	Relative Stairwell Height Error			Stairwell Height Error m		
b	**Minimum**	**Mean**	**Maximum**	**Minimum**	**Mean**	**Maximum**
0.16	−0.06	−0.02	0.01	−10.8	−2.2	0.5
0.25	−0.09	−0.03	0.00	−19.0	−4.7	0.0
0.33	−0.12	−0.05	−0.01	−31.6	−7.8	−0.7

The errors and relative errors in stairwell height have been calculated with (22)–(24) for several values of parameter b. The stairwell height error is defined as the difference between the stairwell height calculated with (22)–(24) minus the stairwell height obtained by simulation. The relative stairwell height error is defined as the stairwell error divided by the stairwell height obtained by simulation. The result is shown in Table 2 for three values of parameter b, 0.16, 0.25, and 0.33. The value 0.16 seems to be a good choice if a minor overestimation of the stairwell height can be allowed.

Stairwell Maximal Height – Summer Case

The stairwell overpressure with an inlet at the bottom floor will in the summer design case decrease from the maximum limit $\Delta p_{\max}$ at level 0 m to the minimum limit $\Delta p_{\min}$ at the design height. There will be no outlet flow or bleed-off flow at the top floor. The inlet flow is equal to the total leakage flow.

The stairwell overpressure variation is equal to the sum of the total temperature pressure drop and the total flow pressure drop, which is derived from (15) by putting $q_b = q_x/2$. The stairwell flow goes from the assumed leakage and inlet flow q_x to zero at the top of the stairwell, which gives the pressure loss of $Rq_x^2 h/3$. The leakage flow q_x is equal to the product of q_m and h_f. The temperature pressure drop is a linear function of the stairwell height. This gives the following third order equation for the summer design stairwell height denoted as h_s.

$$\Delta p_{\min} = \Delta p_{\max} + (\rho_o - \rho_i) g h_s - Rk^2 q_m^2 h_s^3/3 \quad \text{(Pa)} \tag{25}$$

The correction factor k can be estimated with the Expressions (23)–(24). The parameter b should be 0.5 for temperature pressure changes only and 0.25 for flow pressure losses only.

The best choice for parameter b has been investigated in the same way as in the winter case. Only the three outdoor air temperatures differ and are 25, 30, and 35°C (77, 86, and 95°F). The calculated stairwell heights have been larger than 50 m in 62 cases and larger than 100 m in 11 cases.

Table 3. Stairwell height error for 90 summer cases.

	Relative Stairwell Height Error			Stairwell Height Error m		
b	Minimum	Mean	Maximum	Minimum	Mean	Maximum
0.250	−0.04	0.00	0.01	−3.4	0.2	1.7
0.375	−0.09	−0.01	0.00	−8.9	−1.2	0.1
0.500	−0.13	−0.03	0.00	−14.5	−2.4	0.0

The errors and relative errors in stairwell height have been calculated with (23)–(25) for several values of parameter b. The result is shown in Table 3 for three values of b, 0.25, 0.375, and 0.5. The value 0.25 seems to be a good choice if a minor overestimation of the stairwell height can be allowed.

Modeled and Measured Stairwell Flow Pressure Loss

The stairwell flow pressure loss can be neglected when static pressurization is used. However, this does not mean that the flow pressure loss is zero. The proposed flow pressurization method is based on the stairwell flow pressure loss.

A simple way to estimate the pressure loss is to describe a stairwell walking line as a rectangular duct which the air flow has to follow. No shortcuts are assumed to be possible. The duct for a single story consists of two horizontal $90 + 90^\circ$ square bends, two partly vertical 37° bends between staircases and landings (four if double return) and one contraction for the stair clearance (two if double return). The angle 37° is based on the normal staircase slope of 3 : 4.

The air flow will be turbulent with a Reynolds number of 10^5 based on an air velocity of 1 m/s, a kinematic viscosity of $15 \times 10^{-6}\,m^2/s$ and a hydraulic diameter of 1.5 m based on a width of 1 m and a height of 3 m. The pressure losses will be a quadratic function of the flow.

Data from [4] states that a 90° square bend has a local loss coefficient or a single loss of 1.1. The local loss coefficient and the single loss are defined as the actual pressure loss divided by the dynamic pressure for the air velocity in the cross section. The system reduction coefficient is 0.6 when two bends are added immediately after one another. This gives a single loss of 1.3 for a 180° bend and 2.6 for two 180° bends. The stair clearance reduces the flow cross section and causes an estimated single loss of 0.1. Each change between a landing and a staircase can also be treated as a 37° bend (if slope 3 : 4) with a single loss of 0.1. The total expected single loss is estimated to 3.2 for the double return case and 2.9 for the single return case with one straight flight of stairs between the stories.

The single loss is about 3 per story and 1 per meter, if the story height is 3 m. The pressure loss will be about 0.6 Pa/m for a velocity of 1 m/s in the walking line cross section. The corresponding dynamic pressure is 0.6 Pa for an air density of 1.2 kg/m^3 valid for an air temperature of 20°C. A double velocity and a double flow will result in a pressure loss of 2.4 Pa/m. This corresponds to an indoor and outdoor temperature of 20 and −30°C.

Note that a stairwell with another walking line width will have the same single losses. A double width will only mean that the flow has to be doubled in order to have the same pressure drop as before. However, if the height per story is doubled, then the single loss per meter is halved because the single losses per story are still unchanged. The number of bends and contractions are unchanged but the staircase length is doubled. This means that the air velocity has to be increased by a factor of $2^{0.5}$ to result in the same pressure drop Pa/m + as before.

Stairwell flow pressure loss expressions, based on measurements, can be found in [5] and also refer to [6,7]. These references show that a flow smaller than 3 m^3/s creates a pressure loss of 1 Pa/m and the specific pressure loss for a flow of 1 m^3/s is larger than 0.12 Pa/m for a stairwell with a horizontal cross section of 10 m^2.

Our own model experiments at the scale 1 : 100 documented in [2] gave similar results. Single and double return staircases were tested with a slope of 3 : 4 and a walking line width of 1 m and a height of 3.0 m. Both staircases were open on one side. The horizontal stairwell cross sections were 12 and 8 m^2 , respectively. The specific pressure loss was at least 0.08 Pa/m for a flow of 1 m^3/s. The flow to create a pressure loss of 1 Pa/m varied between 3 and 4 m^3/s and the air velocity was less than 1.5 m/s. These stairwells could also be looked upon as vertical circular ducts with a diameter smaller than 800 mm.

Design By Simulation

Simulation is a simple method to find the necessary design flow that will eliminate the thermal pressure change with the flow pressure loss. The simulation model is based on two differential equations with the level z as an independent variable; one for the stairwell overpressure $\Delta p(z)$ and one for the stairwell flow $q(z)$. The stairwell overpressure differential Equation (26) is based on (1) and (2) and becomes:

$$\frac{d\Delta p(z)}{dz} = (\rho_o - \rho_i)g - R\left|q(z)\right|q(z) \quad \text{(Pa/m)} \tag{26}$$

The stairwell flow differential is equal to the local leakage flow. This flow is equal to the effective leakage slot width of w times the local slot air velocity $v(z)$.

$$\frac{dq(z)}{dz} = -wv(z) \quad ((\mathrm{m}^3/\mathrm{s})/\mathrm{m}) \tag{27}$$

The slot velocity is a function of the overpressure. The slot pressure loss is equal to the overpressure $\Delta p(z)$ and the dynamic pressure $\rho_i v^2/2$ for the slot velocity. The slot velocity can be written as follows:

$$v(z) = (2\Delta p(z)/\rho_i)^{0.5} \quad \Delta p(z) > 0 \quad (\mathrm{m/s}) \tag{28}$$

The effective slot width w can be calculated from the nominal leakage velocity v_x together with the stairwell height h and the nominal leakage flow q_x or the specific leakage flow $q_{m,}$ which gives:

$$w = q_x/hv_x = q_m/v_x \quad (\mathrm{m}) \tag{29}$$

The nominal leakage velocity v_x is calculated according to (28) and results in the following expression.

$$v_x = (2\Delta p_x/\rho_i)^{0.5} \quad \Delta p_x > 0 \quad (\mathrm{m}^3/\mathrm{s}) \tag{30}$$

Notice that both differential Equations (26) and (27) allow both positive and negative stairwell overpressure and stairwell flow. It is not sufficient to only check the inlet and outlet conditions at level 0 and h m. A check must also be made that the stairwell overpressure fulfils the overpressure interval for the entire stairwell height. The stairwell overpressure can even become negative about halfway up in the stairwell.

The two coupled differential Equations (26) and (27), can be integrated over the entire stairwell height using two known values at known levels. The solution is obtained directly when the stairwell overpressure and stairwell flow are known at the same level. The other case with known values at different levels can be solved by a simple search for a solution that fulfils the boundary conditions. Such an example is to have the same overpressure at the bottom floor and the top floor. Another example is a fixed overpressure at the bottom floor and no stairwell flow or bleed-off flow at the top floor.

The effective bleed off area A_o is calculated from the simulated stairwell flow q_o at outlet level h m and the bleed off velocity v_o as follows:

$$A_o = q_o/v_o \quad (\mathrm{m}^2) \tag{31}$$

The bleed off pressure loss is assumed to be equal to the stairwell overpressure. The bleed off velocity v_o is calculated with the overpressure Δp_o at level h m according to (28) and results in the following expression.

$$v_o = (2\Delta p_o/\rho_i)^{0.5} \quad \Delta p_o > 0 \quad (\mathrm{m/s}) \tag{32}$$

Stairwell Simulation Example

A stairwell with the height $h = 100$ m, nominal leakage flow $q_x = 1\,\mathrm{m^3/s}$ at nominal leakage overpressure $\Delta p_x = 50$ Pa and specific flow pressure loss $R = 0.1\,\mathrm{Pa/(m(m^3/s)^2)}$ will be studied in a number of simulations covering different inlet flows, overpressures and climates.

The selected specific pressure drop corresponds to a small stairwell with a horizontal cross section area of $10\,\mathrm{m^2}$ and a walking line width of 1 m and a story height of 3 m. However, the simulated stairwell can also be looked upon on as a part of a stairwell with another walking width than 1 m. All flows have only to be scaled with the width. The local single losses and pressures are unchanged. However, notice that the leakage is also scaled with the width. A doubled walking line width could also mean two doors per story.

The inlet and stairwell air temperatures are 20°C (68°F). The lowest outdoor temperature used is −20°C (−4°F) which gives a temperature-induced pressure gradient of 1.86 Pa/m using (1) and a corresponding balancing flow of $4.31\,\mathrm{m^3/s}$ using (3).

The specific leakage flow is q_m $0.01\,\mathrm{m^3/sm}$. The leakage data corresponds to an effective vertical leakage width close to 1 mm. The leakage width can be interpreted as an average leakage per story created by one door per story with a perimeter of 6 m with an average effective leakage width of 0.5 mm.

The actual chosen stairwell height of 100 m is far from the possible stairwell height for the severe winter case. An overpressure interval (20,80) Pa allows a stairwell height of 269 m calculated from (22)–(24) with the interpolation parameter b equal to 0.16. The intervals (30,70), (40,60) and (45,55) Pa give the stairwell heights 208, 141, and 98 m, respectively. These heights using flow pressurization should also be compared with the normal static pressurization height of 32 m ((80−20)/1.86) using (17) and disregarding any flow pressure losses.

The highest outdoor temperature used is 30°C (95°F), which gives a temperature-induced pressure gradient of −0.39 Pa/m and a corresponding balancing flow of $-1.97\,\mathrm{m^3/s}$ using (4). A negative balancing flow means that the stairwell flow has to go from the top floor to the bottom floor. The total temperature pressure change is −39 Pa, which can be handled within the allowable overpressure interval (20,80) Pa and normal static pressurization. The maximal stairwell height is in the severe summer case 138.5 m using (25) which includes flow pressure losses, and 154.4 m without flow losses using (17).

Seven different studies have been made to show different properties with the same climate in Figures 1–4 and different pressurization methods and climates in Figures 5–7. All cases are set out in Table 4 with outdoor temperature, nominal leakage flow and the simulated stairwell overpressure and flow both at inlet level 0 m and at outlet level 100 m. The calculated inlet flow based on (5) and (8) and the calculated effective bleed-off area based on (31) and (32) are also included in Table 4.

The maximal stairwell height Expressions (22)–(24) have been checked for all cases in Table 4 with equal overpressure at inlet and outlet using the actual simulated minimum stairwell overpressure $\Delta p_{\min}$ as input data. The calculated maximal stairwell height h_f and the actual simulated minimum stairwell overpressure $\Delta p_{\min}$ are also given in Table 4. The errors from the expected simulated stairwell height of 100 m are rather small. All calculated stairwell heights are underestimated.

Different Inlet Flows and Same Nominal Leakage – Figure 1

The influence of inlet flow is studied with a 50 Pa inlet overpressure. The outdoor temperature is −20°C (−4°F). The first case is without leakage and

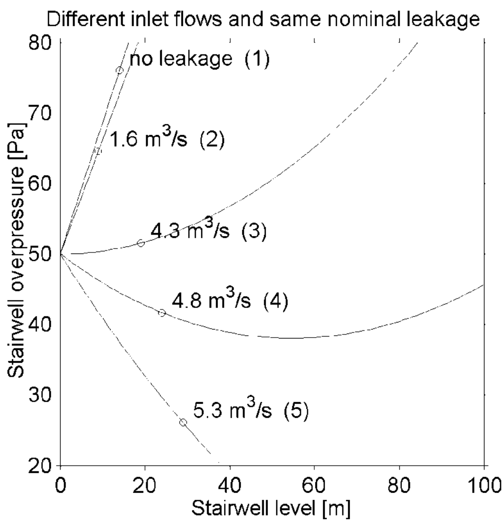

__Figure 1.__ Stairwell overpressure Δp(z) as a function of the stairwell level z for five cases with different inlet flows and same nominal leakage except case 1 without leakage from Table 4.

Table 4. Stairwell simulation cases in Figures 1–7.

Figure	Curve	T_o °C	q_x m^3/s	$q_{i(5,8)}$ m^3/s	Δp_i Pa	Δp_o Pa	q_i m^3/s	q_o m^3/s	A_o m^2	Δp_{min} Pa	h_f m
1	1	−20	0	0.00	50	236.1	0.00	0.00	0.00		
1	2	−20	1	1.00	50	225.8	1.62	0.00	0.00		
1	3	−20	1	4.81	50	92.1	4.31	3.19	0.26		
1	4	−20	1	4.81	50	45.7	4.81	3.91	0.45		
1	5	−20	1	4.81	50	−13.7	5.31	4.94	–		
2	1	−20	1	4.81	70	70	4.86	3.75	0.36	58.2	99.9
2	2	−20	1	4.81	60	60	4.82	3.79	0.38	49.1	99.9
2	3	−20	1	4.81	50	50	4.77	3.84	0.42	40.2	99.9
2	4	−20	1	4.81	40	40	4.72	3.89	0.48	31.3	99.9
2	5	−20	1	4.81	30	30	4.66	3.96	0.56	22.6	100.0
3	1	−20	1	4.81	50	50	4.77	3.84	0.42	40.2	99.9
3	2	−20	2	5.31	50	50	5.15	3.42	0.37	32.1	99.7
3	3	−20	3	5.81	50	50	5.48	3.04	0.33	25.3	99.3
3	4	−20	4	6.31	50	50	5.75	2.69	0.29	20.2	98.7
3	5	−20	5	6.81	50	50	5.99	2.38	0.26	16.0	98.2
4	1	−20	5	6.81	70	70	6.36	1.87	0.17	27.3	97.9
4	2	−20	4	6.31	60	60	5.91	2.48	0.25	26.4	98.7
4	3	−20	3	5.81	50	50	5.48	3.04	0.33	25.5	99.3
4	4	−20	2	5.31	40	40	5.06	3.53	0.43	24.3	99.7
4	5	−20	1	4.81	30	30	4.66	3.96	0.56	22.6	100.0
5	1	30	1	1.00	72.1	30.3	1.00	0.00	0.00		
5	2	20	1	1.00	52.9	49.6	1.00	0.00	0.00		
5	3	10	1	2.54	50	50	2.50	1.54	0.17	45.15	99.6
5	4	0	1	3.44	50	50	3.40	2.45	0.27	43.12	99.8
5	5	−10	1	4.16	50	50	4.12	3.18	0.35	41.54	99.8
5	6	−20	1	4.81	50	50	4.77	3.84	0.42	40.16	99.9
6	1	30	1	1.95	80	20	1.96	1.00	0.17		
6	2	20	1	2.95	80	20	2.96	2.01	0.35		
6	3	10	1	3.69	80	20	3.69	2.76	0.48		
6	4	0	1	4.32	80	20	4.33	3.41	0.59		
6	5	−10	1	4.91	80	20	4.91	4.00	0.69		
6	6	−20	1	5.46	80	20	5.46	4.56	0.79		
7	1	30	1	1.00	61.1	20	0.88	0.00	0.00		
7	2	20	1	1.00	21.3	20	0.64	0.00	0.00		
7	3	10	1	1.00	20	58.7	0.87	0.00	0.00		
7	4	0	1	2.12	20	80	2.02	1.06	0.09		
7	5	−10	1	3.23	20	80	3.13	2.19	0.19		
7	6	−20	1	4.05	20	80	3.95	3.03	0.26		

just shows the temperature-induced pressure gradient. The second case has an inlet flow that balances the leakage flow and no outlet flow at the top floor. Both these cases result in large overpressures. The possible stairwell height for normal static pressurization is only 32 m. There is only a minor difference in overpressure at the top floor between the two cases due to the flow pressure loss in the second case.

The Cases 3–5 have inlet flows equal to q_b, $q_b + q_x/2$ and $q_b + q_x$. Case 4 is equal to the simple design case and gives the best result. The overpressure at level 100 m becomes rather close to the expected overpressure equal to the overpressure at level 0 m. Case 3 has too small an inlet flow and Case 5 too large a flow. These three cases show that the stairwell overpressure changes a lot as a function of the inlet flow.

Different Overpressures and Same Nominal Leakage – Figure 2

All inlet and outlet overpressures are equal for each case and have been 70, 60, 50, 40, and 30 Pa. The corresponding inlet flows vary much less. The outdoor temperature is −20°C. The balancing flow is equal to 4.31 m^3/s and to the fixed and large part of the inlet flow. The inlet flow variations are due to different leakage flows. The leakage flows can be calculated from the inlet and outlet flows in Table 4, which gives 1.11, 1.03, 0.93, 0.83, and 0.70 m^3/s. A simple estimation of the leakage flows is made using the correction factor defined by (23). The result is 1.18, 1.10, 1.00, 0.89, and 0.77 m^3/s, which is rather close to the simulated result. These leakage flows are overestimated

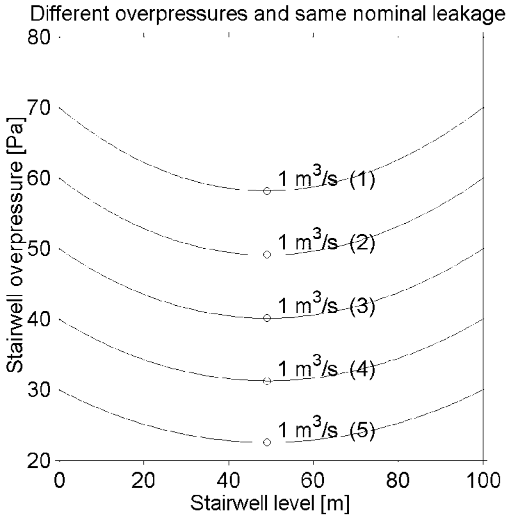

Figure 2. Stairwell overpressure Δp(z) as a function of the stairwell level z for five cases with different overpressures and same nominal leakage from Table 4.

because the stairwell overpressure is overestimated. The stairwell overpressure is assumed to be constant. The inlet flows can be estimated with (8) which gives 4.90, 4.86, 4.81, 4.75, and 4.69 m^3/s. These values are close to the simulated ones 4.86, 4.82, 4.77, 4.72, and 4.66 m^3/s.

None of the five cases drop below the minimum overpressure limit of 20 Pa. The maximum stairwell height must be larger than 100 m in all five cases. The possible stairwell height can be calculated with (22)–(24) for the actual inlet and outlet overpressures and the overpressure minimum limit of 20 Pa. The heights are 233, 213, 189, 159, and 117 m for the corresponding inlet/outlet overpressures of 70, 60, 50, 40, and 30 Pa, respectively.

Different Nominal Leakages and Same Overpressure – Figure 3

The nominal leakage flows at an overpressure of 50 Pa have been 1, 2, 3, 4, and 5 m^3/s. All inlet and outlet overpressures are equal to 50 Pa. The outdoor temperature is −20°C. The curves in Figure 3 show that a relatively large leakage flow can limit the stairwell height. The curves also show that the overpressure minima are slightly below the stairwell height of 50 m.

Case 5 goes below the 20 Pa limit. The nominal leakage flow of 5 m^3/s is larger than the balancing flow of 4.31 m^3/s. Using the Expressions (22)–(24) to calculate the maximum stairwell height with the overpressure limits

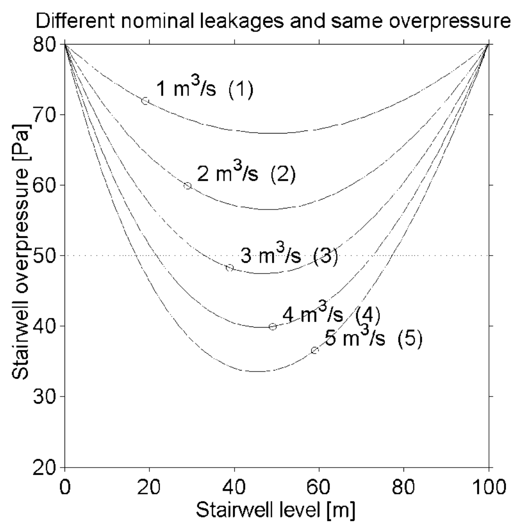

Figure 3. *Stairwell overpressure Δp(z) as a function of the stairwell level z for five cases with different nominal leakages and same overpressure from Table 4.*

of 20 and 50 Pa as in Figure 3, gives the heights 199, 140, 115, 99, and 89 m for the leakage flows of 1, 2, 3, 4, and 5 m^3/s. The calculated height for Case 5 agrees with the simulated result. The calculated case 4 does not seem to agree with the simulated case. The explanation is that the calculation underestimates the possible stairwell height of 100 m. The simulated minimum overpressure for Case 4 is equal to 20.2 Pa, which is close to the limit of 20 Pa.

The calculated inlet flows are somewhat larger than the simulated inlet flows. The deviation increases with the nominal leakage flow.

Different Combined Overpressures and Nominal Leakages – Figure 4

Five suitable combinations of the cases in Figure 2 with different overpressure levels and in Figure 3 with different nominal leakage flows have been made. Increasing overpressure levels have been combined with increasing nominal leakage flows. Using the Expressions (22)–(24) once more to calculate the maximum stairwell height with the overpressures limits as in Figure 4, gives 119, 117, 115, 113, and 111 m for the leakage flows of 1, 2, 3, 4, and 5 m^3/s, respectively. The overpressure curves show that the overpressure minima are slightly below the stairwell height of 50 m and above 20 Pa.

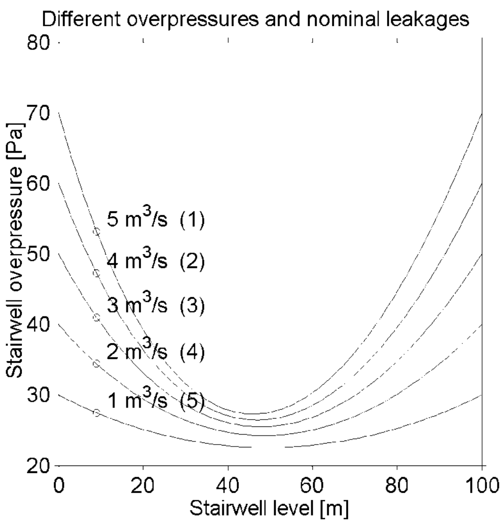

Figure 4. *Stairwell overpressure $\Delta p(z)$ as a function of the stairwell level z for five cases with different combined overpressures and nominal leakages from Table 4.*

The calculated inlet flows are somewhat larger than the simulated inlet flows. The deviation increases with the nominal leakage flow.

Different Climates and Normal Inlet Flow – Figure 5

The climate or the outdoor temperature has been 30, 20, 10, 0, −10, and −20°C (86, 68, 50, 32, 14, and −4°F). The inlet and outlet overpressures have been equal to 50 Pa. The 30 and 20°C cases cannot fulfill this overpressure condition. The outlet flow is fixed to zero and the overpressure condition is changed to keep the overpressure to 50 Pa at the middle of the stairwell at the level of 50 m. The inlet and outlet flows set out in Table 4 show that the ventilation of the stairwell increases with decreasing outdoor temperature.

Notice that the overpressure profile for Case 1 with 30°C outdoor temperature is dominated by the negative temperature gradient of −0.39 Pa/m, which becomes −39 Pa for the entire stairwell. The total change in overpressure is −41.8 Pa and the difference of 2.8 Pa is the flow pressure loss. Notice that the overpressure change for Case 2 with no temperature-induced pressure gradient is 3.3 Pa which is just equal to the estimated pressure loss for flow linearly decreasing from 1 to 0 m^3/s. This pressure loss is equal to one third of the pressure loss for a constant flow of 1 m^3/s, which becomes 10 Pa ($100 \cdot 0.1 \cdot 1^2$).

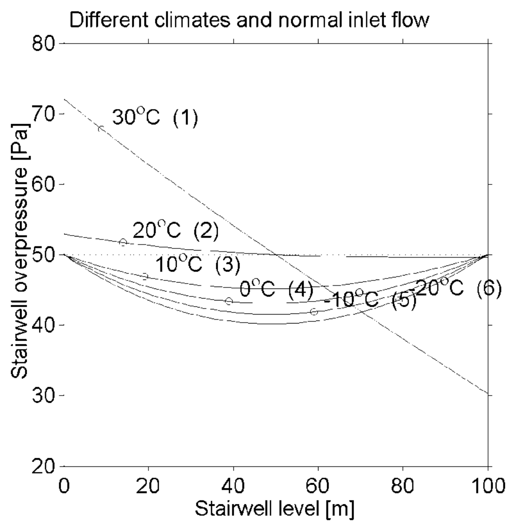

***Figure 5.** Stairwell overpressure Δp(z) as a function of the stairwell level z for six cases with different climates and normal inlet flow from Table 4.*

The actual inlet flows for Cases 3–6 can be estimated with the Expressions (5)–(8) to 2.54, 3.44, 4.16, and 4.81 m^3/s which are close to the simulated values of 2.50, 3.40, 4.12, and 4.77 m^3/s. The good agreement is explained by the relatively small leakage flow.

Different Climates and Maximum Inlet Flow – Figure 6

The flow pressurization design presented so far in this article aims to keep the stairwell overpressure constant as shown earlier in Figure 5. This design will result in stairwell ventilation that depends on the indoor–outdoor temperature difference according to the balancing flow calculated with (3) or (4).

The ventilation flow will only be equal to the leakage flow when the indoor air temperature is equal to the outdoor air temperature. It is, however, possible to increase the ventilation of the stairwell and to pressurize the stairwell within the allowable overpressure interval. This means that the pressure at the bottom floor should be equal to the maximum overpressure and at the top floor equal to the minimum overpressure. The balancing flow can now be calculated by the more general Expressions (5)–(7).

The difference between inlet and outlet overpressure increases the stairwell ventilation as seen from the values in Table 4 and as intended. The inlet flows have increased compared with the constant overpressure

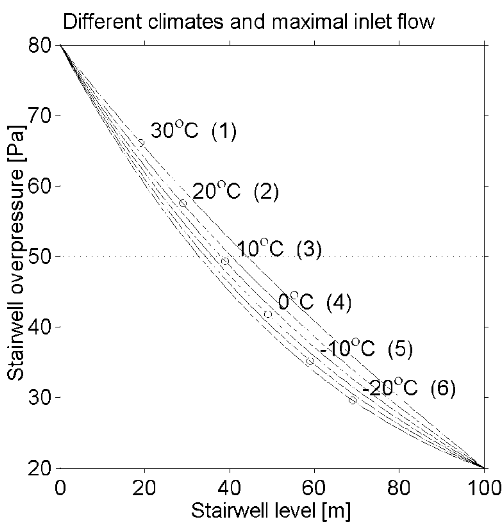

Figure 6. *Stairwell overpressure Δp(z) as a function of the stairwell level z for six cases with different climates and maximum inlet flow from Table 4.*

cases by a factor of 1.96, 2.96, 1.48, 1.27, 1.19, and 1.14 for 30, 20, 10, 0, −10, and −20°C, respectively. The ventilation is almost tripled for the 20°C case.

The actual inlet flows for the six cases can be estimated with the Expressions (5)–(8) to 1.95, 2.95, 3.68, 4.32, 4.91, and 5.46 m^3/s which are close to the simulated values of 1.96, 2.96, 3.69, 4.33, 4.91, and 5.46 m^3/s. The good agreement is explained by the relatively small leakage flow compared with the inlet flow.

Different Climates and Minimum Inlet Flow – Figure 7

A natural step after the calculation of maximum inlet flow is to calculate the minimum inlet flow that fulfills the overpressure interval. The calculated inlet flow for this case sets a minimum flow capacity for the pressurization fan.

The Cases 1–3 with outdoor temperatures of 30, 20, and 10°C all have zero outlet flow or no bleed-off flow. The three other Cases 4–6 have fairly large flows. The inlet flows have decreased compared with constant overpressure cases by a factor of 0.88, 0.64, 0.35, 0.59, 0.76, and 0.83 for 30, 20, 10, 0, −10, and −20°C, respectively.

The simulated inlet flows for the three Cases 4–6 are 2.02, 3.13, and 3.95 m^3/s. The inlet flows calculated with (5)–(8) are 2.12, 3.23, and 4.05 m^3/s.

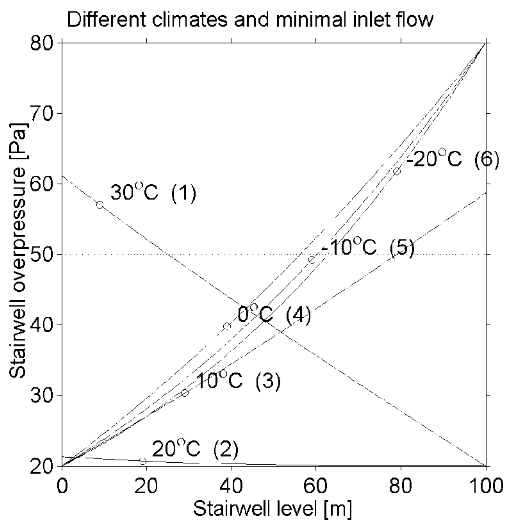

***Figure 7.** Stairwell overpressure Δp(z) as a function of the stairwell level z for six cases with different climates and minimum inlet flow from Table 4.*

The agreement is not so good as before. A possible explanation is that the leakage flow on average travels longer in the stairwell than in the constant overpressure and the maximum inlet flow case.

CONCLUSIONS

This new method can be summarized as follows. Stairwells higher than before can be pressurized and better ventilated. The high inlet flow might also give better protection against smoke spread from an open door. Another advantage is that the single inlet located at ground level might be fairly safe from outdoor smoke and a simpler solution compared with a sectioned stairwell with several inlets on different levels. The main drawback is the need for a fan of high flow capacity at the bottom floor and a damper at the top floor.

The effective bleed-off area needed is rather modest with less than $0.8\,m^2$ for all cases in Table 4 and less than $0.5\,m^2$ if the stairwell overpressure at the outlet is equal to or larger than 50 Pa.

The design inlet flow for constant overpressure can be calculated as the sum of the balancing flow plus half the nominal leakage flow. The balancing flow is independent of the stairwell height and is determined by the temperature-induced pressure gradient and the specific flow pressure loss.

The maximal stairwell height can be calculated with simple expressions calibrated with simulations. The error is fairly small.

Summer conditions with higher outdoor than indoor air temperature may be the limiting case because the temperature-induced pressure gradient and the flow pressure loss gradient coincide if the pressurization fan is connected to the bottom floor. It is possible to use a fan connected to the top floor and thereby eliminate the reversed temperature-induced pressure gradient in the summer case.

A literature study and our own model experiments indicated that the flow pressure loss of a stairwell is a function of the square of the flow. A temperature-induced pressure gradient of 1.5 Pa/m can be balanced by an air flow of about $4\,m^3/s$ for a compact stairwell. This gives a low air velocity in the walking line cross section of the staircase less than 1.5 m/s that does not disturb the evacuation. People in the stairwell will, in fact, increase the flow resistance and reduce the balancing flow needed.

Simulation of a simple model can also be used to test a suitable design inlet flow, to test the effect of an open door and to test different loads due to evacuating persons. The simulation model can also be expanded with an additional equation for the stairwell air temperature to work with outdoor air as inlet air.

NOMENCLATURE

A_o = effective bleed off area (m^2)
b = average overpressure interpolation constant (–)
k = specific stairwell leakage flow correction (–)
g = gravity (9.81 m/s^2)
h = stairwell height (m)
h_b = balancing flow leakage height (m)
h_f = maximal stairwell height for flow pressurization (m)
h_s = maximal stairwell height for normal static pressurization (m)
Δp_q = vertical flow pressure gradient (Pa/m)
Δp_t = vertical temperature-induced pressure gradient (Pa/m)
Δp_i = inlet stairwell overpressure at level 0 m (Pa)
Δp_m = mean stairwell overpressure (Pa)
$\Delta p_{\max}$ = maximal stairwell overpressure (Pa)
$\Delta p_{\min}$ = minimal stairwell overpressure (Pa)
Δp_o = outlet stairwell overpressure at level h m (Pa)
Δp_x = nominal stairwell overpressure (Pa)
$\Delta p(z)$ = stairwell overpressure at level z (Pa)
q = stairwell vertical flow (m^3/s)
q_b = stairwell vertical balancing flow (m^3/s)
q_i = stairwell inlet flow at level 0 m (m^3/s)
q_m = specific stairwell leakage flow at nominal overpressure (m^3/sm)
q_o = stairwell outlet flow at level h m (m^3/s)
$q(z)$ = stairwell vertical flow at level z (m^3/s)
q_x = nominal stairwell leakage flow at nominal overpressure (m^3/s)
R = specific flow pressure loss ($Pa/(m(m^3/s)^2)$)
T_i = indoor air temperature (°C)
T_o = outdoor air temperature (°C)
$\nu(z)$ = leakage slot velocity (m/s)
ν_o = bleed off velocity (m/s)
ν_x = nominal leakage slot velocity at nominal overpressure (m/s)
w = effective stairwell vertical leakage width (m)
z = stairwell level (m)
ρ_o = outdoor air density (kg/m^3)
ρ_i = indoor air density (kg/m^3)

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