Explicit and Implicit Methods in Natural Ventilation Design

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Abstract

I Natural ventilation, also called free convection, is rather necessary to provide sufficient fresh air and thermal comfort for occupants in the building. It is usually caused by either buoyancy or wind or both of them, which leading to various formulas and methods during design process. The report is firstly to implement explicit method for peak designs in summer and winter and implicit method for off-peak designs, then to compare them and estimate the differences by the result tables and graphs to acquire an understanding of their relations.

Keywords

Natural ventilation, explicit method, implicit method.

1. Explicit Method (Sizing of Air Vents)

Explicit method mainly uses the obtained ventilation rate which matches the worst condition to determine the air inlet or outlet areas in each room. In this case, some property numbers are supposed to remain constants in whether summer condition or winter condition. They are listed below.

Table 1. constants in the design process

Name	Symbol	Value
Specific heat of air	C_p	1005J/lg K
Gravitational acceleration	g	$9.8m/s^2$
Reference density of air	ρ_0	$1.2kg/m^3$
Discharge coefficient	C_{di}	0.61

Since we consider this is uniform air density condition, ρ is assumed as same as ρ0.

1.1 Summer design

Sizing of air vents in summer condition aims at minimizing overheating. In order to satisfy with any day requirement during the warm season, the extreme case with buoyancy alone (i.e. wind speed equals zero) should be raised to estimate maximum opening areas.

Within the known statistics, TE=25℃, TI=28℃ and Cp1=0.20, take opening 1 as an example to present the calculation process.

Use formula $\frac{\Delta\rho_0}{\rho_0} = \frac{T_I - T_E}{T_E + 273}$ … (1).

Δρ0 = $\frac{\rho_0(T_I - T_E)}{T_E + 273} = \frac{1.2*(28-25)}{28+273}$ =0.01196kg/m3.

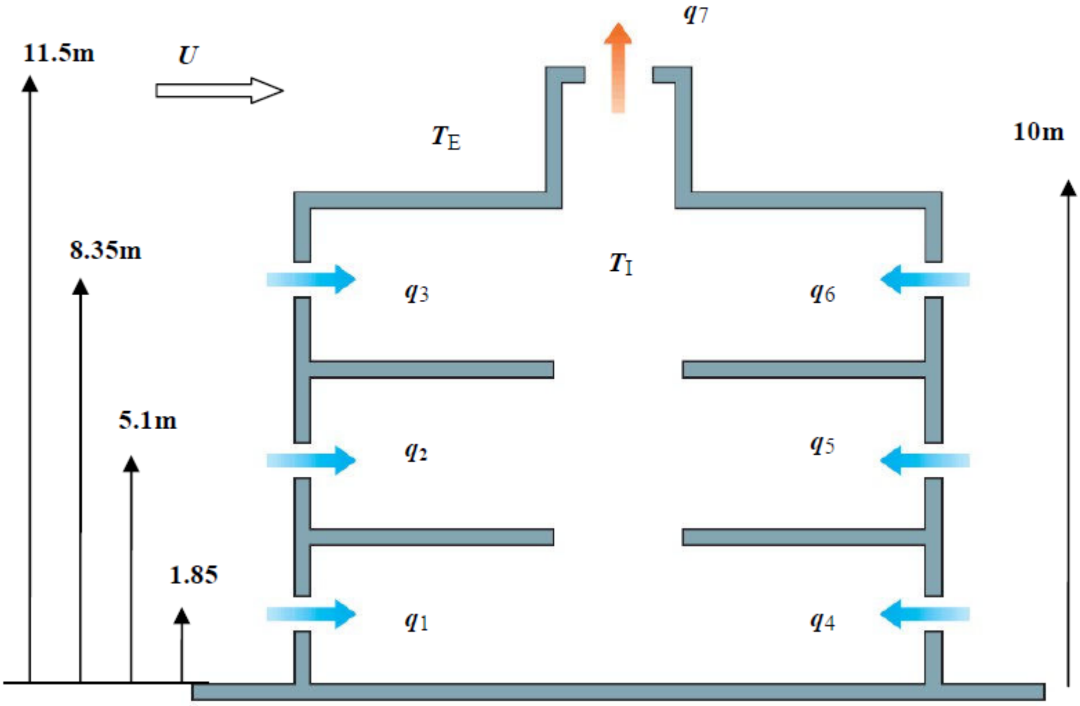

Figure 1: flow pattern of the office building

See the flow pattern in Figure 1, opening 1, 2, 3, 4, 5 and 6 are inlet vent and opening 7 is outlet vent. Thus a feasible approach to specifying Δp0 is based on the assumption Δp3= -Δp7, using Δpi=Δp0 – Δρ0gzi … (2) to indicate Δp3 and Δp7.

$\Delta p0 - \Delta\rho0gz3 = \Delta p0 - \Delta\rho0gz7$

$\Delta p0 = 0.5\Delta\rho0g(z3+z7) = 0.5*0.01196*9.8*(8.35+11.5) = 1.163Pa$

Then use equation (2) again to gain the value of Δp1.

$\Delta p1 = \Delta p0 - \Delta\rho0gz1 = 1.163-0.01196*9.8*1.85 = 0.9462Pa$

(Note: apparently the magnitude by hand calculation is a little different from the number in the following table, which is because the accuracy in the example is not same with the ones by Excel software. Same reason for following differences.)

According to the constraints, the office floor area is dependent on the length and width of each office. Meanwhile, it demands to limit heat gain to 30W/m2. Therefore the heat gain for each office=15*25*30=11250W. Combined this with another formula which also presents heat loss H=ρCp qiΔT… (3) to determine ventilation rate of each office.

$q1 = H/(\rho Cp\Delta T) = 11250/(1.2*1005*3) = 3.11m3/s$

(Note: Office 1 to 6 have the same inlet flow rate and the sum is the outlet flow rate of the central atrium, 3.11*6=18.66m3/s.)

Applying equation CdiAi= $\frac{q_i}{S_i}\sqrt{\frac{\rho}{2|\Delta p_i|}}$ … (4).

$$Cd1A1 = \frac{q_1}{S_1}\sqrt{\frac{\rho}{2|\Delta p_1|}} = \frac{3.11}{1}\sqrt{\frac{1.2}{2*0.9462}} = 2.4765m2$$

A1=2.4765/0.61=4.060m2.

Repeat the same procedure to know area of each opening and the result is shown in Table 1 below.

Table 2. Buoyancy alone in summer

Opening	z_i [m]	C_{pi}	q_i [m^3s^{-1}]	Flow pattern	S_i	Δp_i [Pa]	$C_{di}A_i$ [m^2]	C_{di}	A_i [m^2]
1	1.85	0.2	3.11	Inward	+1	0.9465	2.4762	0.61	4.059
2	5.1	0.35	3.11	Inward	+1	0.5655	3.2034	0.61	5.251
3	8.35	0.25	3.11	Inward	+1	0.1846	5.6068	0.61	9.192
4	1.85	-0.1	3.11	Inward	+1	0.9465	2.4762	0.61	4.059
5	5.1	-0.1	3.11	Inward	+1	0.5655	3.2034	0.61	5.251
6	8.35	-0.1	3.11	Inward	+1	0.1846	5.6068	0.61	9.192
7	11.5	-0.45	-18.66	Outward	-1	-0.1846	33.6410	0.61	55.149

1.2 Winter design

In this case, the worst condition should be the combination of wind and buoyancy, since that it would lead to the maximum heat loss. Within new environmental conditions, some data should be changed.

Opening 1 for instance, use equation (1) to compute

$\Delta\rho 0 = \frac{\rho_0(T_I - T_E)}{T_E + 273} = \frac{1.2*(20-0)}{0+273}$ =0.08791kg/m3.

Use equation (2) to determine Δp0, the method introduced before still works here, which means Δp3 and Δp7 achieve the identical absolute value but opposite signs. However expression for Δpi is altered because of the existence of wind,

$\Delta p_i = \Delta p_0 - \Delta\rho_0\, g\, z_i + 0.5\, \rho_0\, U^2\, C_{pi}$… (5).

As a consequence, $\Delta p0 - \Delta\rho 0\ g\ z3 + 0.5\rho 0\ U2\ Cp3 = -(\Delta p0 - \Delta\rho 0\ g\ z7 + 0.5\ \rho 0\ U2\ Cp7)$.

$\Delta p0 = 0.5\Delta\rho 0\ g(z3 + z7) - 0.5*0.5\rho 0\ U2(Cp3 + Cp7)$

$= 0.5*0.08791*9.8*(8.35+11.5) - 0.5*0.5*1.2*52*(0.25-0.45) = 10.051$Pa

Next find Δp1 from equation (5) as wind speed is 5m/s

$\Delta p1 = \Delta p0 - \Delta\rho 0gz1 + 0.5\rho 0U2Cp1$

$= 10.051 - 0.08791*9.8*1.85 + 0.5*1.2*52*0.2 = 11.4572$Pa

The maximum number of people is 40 in each room and at least ventilation rate per person 8l/s is necessarily needed. Accordingly, flow rate is 8*40=320l/s=0.32m3/s.

(Note: Office 1 to 6 have the same inlet flow rate and the sum is the outlet flow rate of the central atrium, 0.32*6=1.92m3/s.)

By equation (4) $Cd1A1 = \frac{q_1}{S_1}\sqrt{\frac{\rho}{2|\Delta p_1|}} = \frac{0.32}{1}\sqrt{\frac{1.2}{2*11.4572}} = 0.0732$m2

A1=0.0732/0.61=0.120m2.

Repeat the same procedure and the result is shown in Table 2 below.

Table 3. Wind and buoyancy combined in winter

Opening	z_i [m]	C_{pi}	q_i [m^3s^{-1}]	Flow pattern	S_i	Δp_i [Pa]	$C_{di}A_i$ [m^2]	C_{di}	A_i [m^2]
1	1.85	0.2	0.32	Inward	+1	11.4564	0.0732	0.61	0.120
2	5.1	0.35	0.32	Inward	+1	10.9068	0.0751	0.61	0.123
3	8.35	0.25	0.32	Inward	+1	6.6071	0.0964	0.61	0.158
4	1.85	-0.1	0.32	Inward	+1	6.9564	0.0940	0.61	0.154
5	5.1	-0.1	0.32	Inward	+1	4.1568	0.1216	0.61	0.199
6	8.35	-0.1	0.32	Inward	+1	1.3571	0.2128	0.61	0.349
7	11.5	-0.45	-1.92	Outward	-1	-6.6063	0.5786	0.61	0.949

2. Implicit Method (Off-design Calculations)

Implicit method with given opening areas and weather information is implemented through iteration process to find out flow rates. Air vent size acquired from explicit method above is regarded as known data, as well as the constaents in List 1. The only way is to input correct numbers and start the simple Excel program of implicit method. After it cease, collect the statistics needed.

3. Off-peak summer design

Input area size, Cpi and zi of opening 1 to 7, TE, TI and U. Also type 10Pa as the initial value for Δp0, permeability 0.001m3/h/m2 instead of zero, the step size for each iteration -0.002Pa and the convergence criterion 0.2%. Run the program and obtain the new numbers of qi, then compare them with the original values in buoyancy alone condition. See Table 3, obviously, the magnitude of flow rates with wind speed at 3m/s are all much larger than the ones with buoyancy alone respectively. The extra air ventilation perhaps causes draughts and discomfort, which is not expected.

Table 4. With the same A7, qi at the distinct situations.

Same A_7 (55.149m^2)	q_1 [m^3/s]	q_2 [m^3/s]	q_3 [m^3/s]	q_4 [m^3/s]	q_5 [m^3/s]	q_6 [m^3/s]	q_7 [m^3/s]
Wind speed 3m/s	6.05	8.28	12.72	4.47	5.19	7.92	-45.02
Buoyancy alone	3.11	3.11	3.11	3.11	3.11	3.11	-18.66

Hence, to regulate qi in each office by altering A7 from 10m2 to 60m2, select 5 as the number of interval, list the results in Table 4 and create Graph 1 to illustrate the correlation.

Table 5. Changes of qi against different A7

A_7 [m^2]	q_1 [m^3/s]	q_2 [m^3/s]	q_3 [m^3/s]	q_4 [m^3/s]	q_5 [m^3/s]	q_6 [m^3/s]
55.149	3.11	3.11	3.11	3.11	3.11	3.11
10	4.32	6.21	8.35	1.44	-1.75	-5.44
15	4.58	6.51	9.03	2.09	0.90	-4.20
20	4.84	6.82	9.71	2.62	2.23	-2.20
25	4.98	6.99	10.07	2.88	2.71	1.56
30	5.20	7.25	10.61	3.23	3.31	3.69
35	5.41	7.51	11.16	3.57	3.85	5.05
40	5.61	7.75	11.64	3.86	4.30	6.05
45	5.78	7.95	12.06	4.11	4.66	6.82
50	5.92	8.13	12.41	4.31	4.95	7.42
55	6.04	8.27	12.71	4.47	5.19	7.90
60	6.15	8.40	12.96	4.61	5.38	8.30

According to Graph 1 below, generally the raise of outlet vent area would bring in the increasing of flow rates of q1, q2, q3, q4, q5 and q6 individually. Some enhance steadily with a roughly identical gradient, acting more like linear growth, such as q1, q2, q3 and q4. While the others q5 and q6 involving a sudden rapid ascent are displayed more like curvilinear growth.

Furthermore from the graph, the points of q1, q2, q3 and q4 are all above x axis but some points at the start stage of q5 and q6 are below x axis (negative value), which means their flow pattern is outward, different from the original ones in explicit section. By logical analysis, this occurrence is probable because outlet vent area in the atrium begin at 10m2, much less than previous value 55.149m2, leading to the reduction of outward ventilation which need to distribute to other openings. And the openings in higher floor at the leeward side would be undertake the responsibility of outflow with higher possibility, for example, q6 in the second floor at the leeward side plays as the major role for outward ventilation when A7 is rather small, except q7.

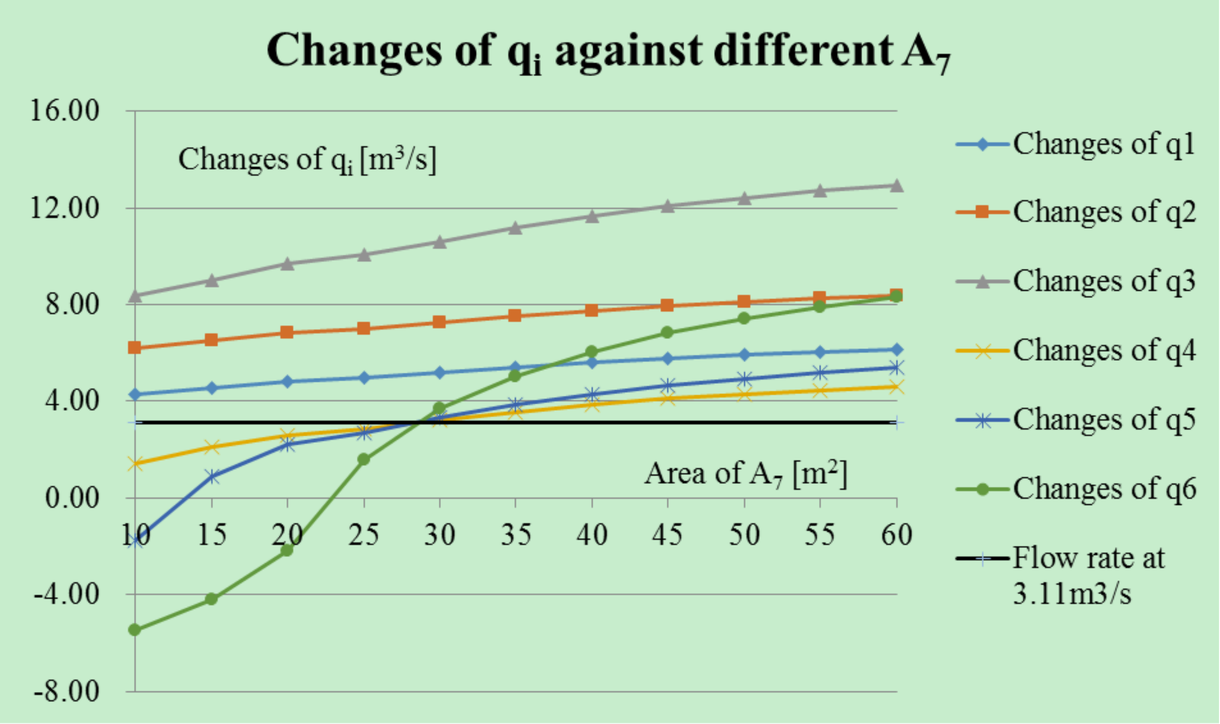

Figure 2. Changes of qi against different A7

To ensure fresh air into each office, q1, q2, q3, q4, q5 and q6 should all be positive. The intersection point of changes of q6 and x axis is located in the range of 20m2 to 25m2. Input the approximate numbers, 23 in this case, into the blank of A7 in the Implicit program to gain more accurate number until q6 is positive and closest to zero. Finally, A7 turns out to be 23.451m2 and q6 0.45013m3/s. Calculate the percentage change in area required by formula: %=(original A7 – new A7)/original A7=(55.149-23.451)/55.149=57.48%.

Then to ensure that the flow rates in 6 offices are more than 3.11m3/s individually as demanded, find out new A7 in this situation by the method mentioned before using the black line of flow rate at 3.11m3/s instead of x axis. Moreover, also check q7 to ensure it is larger than 18.66m3/s. A7 is 28.334m2 at last and the others are listed below in Table 5 to provide evidence that it matches the requirement.

Table 6. Qi when A7 is 28.334m2

q_1 [m^3/s]	q_2 [m^3/s]	q_3 [m^3/s]	q_4 [m^3/s]	q_5 [m^3/s]	q_6 [m^3/s]	q_7 [m^3/s]
5.12191	7.15786	10.42709	3.11152	3.11165	3.11270	-32.30078

Percentage change = (55.149-28.334)/55.149=48.62%.

A quantity of environmental elements could influence the outlet flow rate, such as temperature and wind speed. Other impacts mainly come from the building itself, such as the structure (affect discharge coefficient) and number of occupants (affect the internal temperature).

Despite all these variables, the easiest control method of outlet ventilation rates is changing the size of openings by either manual operation or mechanical equipment or both of them. The outflow rate is changed while inward flow rate alters. People can flexibly open windows in proper size or close them according to their heat sensation. Installation which is sensitive to the temperature and humidity can act automatically to provide thermal comfort inside by adjust the degree of opening for windows.

Mechanical ventilation is aid for natural ventilation. Some extraction-only system is highly practical in controlling the outlet ventilation.

3.1 Adventitious leakage at winter design

Change TE, TI, U and Ai, Adjust Δp0 by rising from 10Pa until the convergence criterion can be finished with positive sign and set permeability from 0.001m3/h m2 (regarded as zero leakage condition) to 30m3/h m2 with an appropriate interval 3. Record the statistics, shown in Table 6 below and Graph 2.

Table 7. Qi and QFT at different permeability in winter

Permeability $[m^3/h\ m^2]$	0.001	3	6	9	12	15	18	21	24	27	30
Q_{FT} $[m^3/s]$	1.855	1.962	2.049	2.135	2.316	2.462	2.590	2.705	2.808	2.903	2.991

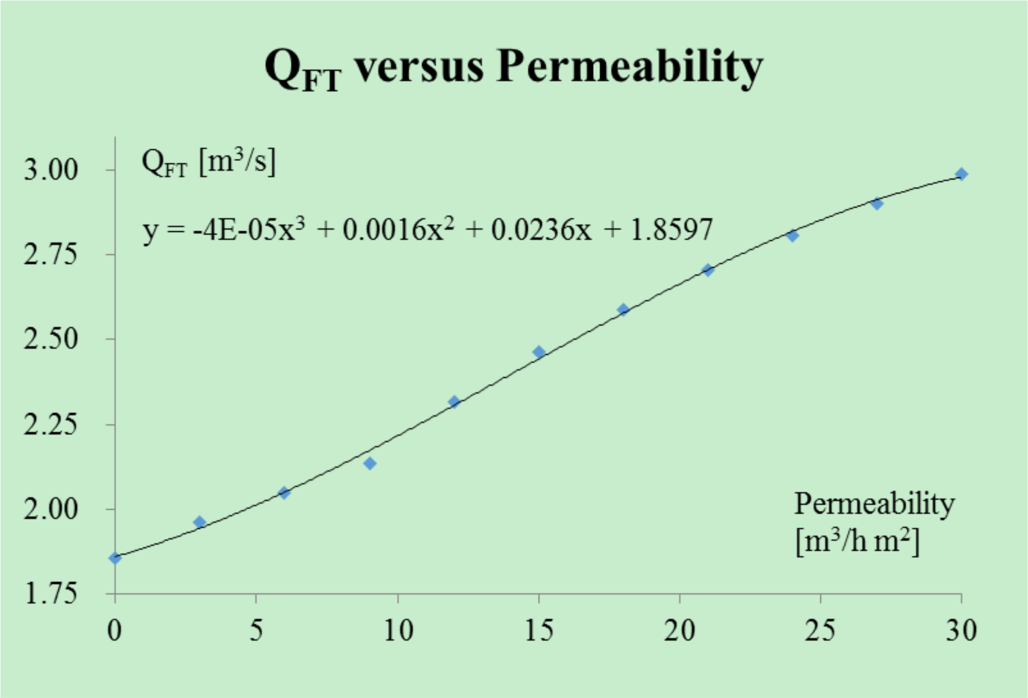

Figure 3. QFT versus permeability

The function y = -4E-05x3 + 0.0016x2 + 0.0236x + 1.8597 is the trend line of these scattered points, worked out by Excel program automatically.

When permeability is 7m3/h m2, QFT= -4*10-5*73+0.0016*72+0.0236*7+1.8597=2.090m3/s, and the percentage increase = (2.090-1.92)/1.92=8.85%.

When permeability is 3m3/h m2, QFT= -4*10-5*33+0.0016*32+0.0236*3+1.8597=1.944m3/s.

Use implicit method again to get the heat loss at permeability of 3m3/h m2 and 7m3/h m2, which are 50.6433kW and 53.5348kW correspondingly.

Thus percentage change of heat loss = (53.5348-50.6433)/53.5348=5.40%. It estimates that the less adventitious leakage, the lower heat loss it would have.

If use Equation (3) to compare heat loss instead the values gained from Excel,

$$\frac{H_7 - H_8}{H_7} = \frac{\rho Cp\ q_7 \Delta T - \rho Cp\ q_8 \Delta T}{\rho Cp\ q_7 \Delta T} = \frac{q_7 - q_8}{q_7} = \frac{2.090 - 1.944}{2.090} = 6.98\%$$

Very near to 5.4%. So both methods are feasible for computation.

3.2 Off-design calculations

Put 0.001 in the permeability blank, change the external temperature form 0℃ to 10℃ with 1℃ as the interval, and run the program to know the QF and to create graph QF versus ΔT (i.e. TI-TE). Table 7 and Graph 3 are the consequences.

Table 8. QFT against different TE (or different ΔT)

T_E [℃]	0	1	2	3	4	5	6	7	8	9	10
ΔT [℃]	20	19	18	17	16	15	14	13	12	11	10
Q_{FT} [m^3/s]	1.433	1.413	1.392	1.370	1.349	1.326	1.304	1.280	1.256	1.231	1.205

With the function y = 0.0227x + 0.9825, when ΔT is 17℃, QF=0.0227*17 + 0.9825=1.3684 m3/s, which equivalent to the outlet air flow rate. The original air outlet flow obtained by explicit method at ΔT 20℃ is 1.92m3/s.

Use ventilation equation relating to the opening area, flow rate and temperature difference to determine the change in outlet area.

Equations in Case 1 (single-sided, two cents, buoyancy driven) and Case 2 (single-sided, single vent, buoyancy driven) of CIBSE AM10 (2005) both can be used in this condition. Take Case 1 formula as an instance. $A=\frac{q}{C_d}\sqrt{\frac{T_I+273}{\Delta T g h}}$… (6).

(Note: if using Case 2 formula, the result would remain the same.)

Thus compare the outlet vent area by cancelling the same elements. (Subscript o means original data and subscript n means new data).

$$\frac{A_o}{A_n}=\frac{q_o}{q_n}\sqrt{\frac{\Delta T_n}{\Delta T_o}}=\frac{1.92}{1.3684}*\sqrt{\frac{17}{20}}=1.2936$$

The percentage increment in outlet area is 1.2936-1=29.36%. And the new area is An=Ao/1.2936=0.949/1.2936=0.734m2 and the change is 0.949-0.734=0.215m2.

Compute An to the implicit method when outside temperature is 3℃ and permeability is zero. The result is 1.127m3/s, higher but close to 1.3684m3/s and the percentage difference is (1.3684-1.127)/1.3684=17.64%.

Return the outside temperature to 0℃ and raise permeability to 3m3/h m2, run the program again to find total inlet air flow, which is 1.990m3/s, a little higher than 1.92m3/s, the percentage change is (1.92-1.312)/1.92=31.67%.

Alternative approach by using former explicit method by Equation 1, 2, 4 and 5.

$$\Delta\rho 0=\frac{\rho_o(T_I-T_E)}{T_E+273}=\frac{1.2*(20-3)}{3+273}=0.07391\text{kg/m3}$$

Δp0 – Δρ0 g z3 + 0.5ρ0 U2 Cp3 = – (Δp0 – Δρ0 g z7 + 0.5 ρ0 U2 Cp7)

Δp0=0.5Δρ0 g(z3+ z7)-0.5*0.5ρ0 U2(Cp3+ Cp7)

=0.5*0.07391*9.8*(8.35+11.5)-0.5*0.5*1.2*32*(0.25-0.45) =7.729Pa

Δp7=Δp0 – Δρ0gz7+0.5ρ0U2Cp7

=7.729-0.07391*9.8*11.5+0.5*1.2*32*(-0.45) =-3.031Pa

$$\text{Cd7A7}=\frac{q_7}{S_7}\sqrt{\frac{\rho}{2|\Delta p_7|}}=\frac{-1.3684}{-1}\sqrt{\frac{1.2}{2*3.031}}=0.6088\text{m2}$$

A7=0.6088/0.61=0.998m2

So the absolute reduction is 0.998-0.949=0.049m2, and relative reduction is 0.049/0.949=5.16%.

Put the revised A7 into the spreadsheet, outlet flow rate is 1.415m3/s, a little higher than 1.3684m3/s, the percentage change is (1.415-1.3684)/1.3684=3.41%.

Reduce the external temperature to 0℃ and enhance the permeability to 3m3/h m2, the result by implicit method is QF=1.556m3/s, lower than 1.92m3/s. The percentage change is (1.92-1.556)/1.92=18.96%.

Transparently, the results varied by different method, even opposite, one is higher while the other is lower. The first method shows the indirect connection with temperature difference which is more linkable. Despite the advantage, it is less accurate since it neglects the wind change which can influence the ventilation. Method B considers wind speed and the percentage change in the final adjusted air flow rate is further smaller.

In terms of result, window area is Method A is improper since it is even smaller than the minimum value obtained by explicit method. However, both methods proof that the adventitious leakage would have an adverse impact on the ability to control ventilation in the building. In other words, the higher permeability it has, the lower ventilation controllability.

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