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Experiments in Natural Ventilation for Passive Cooling

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SYNOPSIS

A naturally ventilated three level office building has been used to study basic stack ventilation configurations and the interaction between ventilation and the subsequent cooling of the building structure in summer. The research was performed in the framework of a European project on passive cooling of buildings and the objective was to validate simple ventilation algorithms and to give an experimental basis to design guidelines for night cooling techniques. The multilevel office allowed the studying of the influence of openings (size and position) on the neutral pressure level (NPL) and on airflow rates. Various cross-ventilation situations have been studied. A single flow path configuration was obtained by closing all windows and doors in the building envelope with the exception of the roof exhaust and one office window as the ventilation air inlet. Air flow patterns were traced with smoke and tracer gas.

In a first set of experiments, where the only driving force is stack pressure, air velocities and the position of the NPL have been measured, and contraction and velocity coefficients as used in the Bernoulli model have been observed. In a second set of experiments, the resulting effective area of a combination of two openings in series was studied.

Air flow rates derived from velocity measurements in the open doorways were found to be in agreement with the flow rates obtained with a constant injection tracer gas technique, with an uncertainty of ±20%. Overall agreement was found between the velocity measurements and simplified models based on the Bernoulli equation. In order to cool multiple levels of a building with outside air, the position of the neutral pressure level should be controlled. The restrictions on opening size and position are discussed.

LIST OF SYMBOLS

A	Surface area	[m^2]
C_d	Discharge coefficient	[-]
g	Acceleration of gravity	[m/s^2]
H	Distance between opening centres	[m]
L	Leakage flow rate	[kg/s]
$\dot{m}$	Mass flow rate	[kg/s]
N	Kinetic energy (Coriolis) coefficient	[-]
p	Pressure	[Pa]
T	Temperature	[K, °C]
u	Air velocity	[m/s]
$\dot{v}$	Volume flow rate	[m^3/s]
W	Opening width	[m]

z	Height	[m]
Δp	Pressure difference	[Pa]
ε	Jet contraction coefficient	[-]
ζ	Frictional pressure drop coeff.	[-]
ξ	Local pressure drop coefficient	[-]
ρ	Air density	[kg/m^3]
φ	Velocity coefficient	[-]

SUFFIXES

b	Bottom	t	top
e	External	i	Internal
eff	Effective	int	Intermediate opening

1. INTRODUCTION

Reality is infinitely complex. Our knowledge of the world is always finite and therefore always incomplete. The marvel is that we function quite well in the world in spite of never fully understanding it. Our tool to deal with incomplete knowledge is modelling. A model is a small finite (incomplete) description of an infinitely complex reality for the purpose of answering particular questions. The complexity of a model depends on the kind of questions we are seeking to answer [1].

Ventilation in buildings is a complex phenomenon. A key question is what variables should be taken into account to answer a particular question. For summer natural ventilation, engineers and architects are interested to know if the ventilation rate is sufficient to extract pollutants or heat from a given space. A dominant parameter to answer this question is the opening position and size. Simple ventilation models in the pre-design phase of a project are often found to be sufficient to determine the effect of these parameters [2,3]. Moreover, in a comparison of detailed and simple models of air infiltration it was found that more complex models do not generally increase the accuracy of the result [4,5].

The well-known Bernoulli model offers valuable information on the air flow path, flow rate and both inlet and outlet velocities [6,7,8]. More recently, detailed ventilation models have been coupled with building thermal models, in order to evaluate the effect of cooling by natural ventilation [9,10], but the effect of cooling by natural ventilation can also be described by using simple models [11,12].

In all these modelling efforts, an important source of uncertainty, affecting similarly both detailed and simple models, is related to the hydraulic resistance of airflow networks. Which value to attribute to discharge coefficients and velocity coefficients? While a large compilation of coefficients can be found in the reference work of Idelchik [13], few data are available which have been measured on real buildings. Indeed, a large number of sources deal with the *coefficient* [2,3,6,8], but not so much with the factors determining its value. In the absence of better information, a general value for the discharge coefficient of a large opening of $C_d = (0.6 \pm 0.2)$ can be used [8].

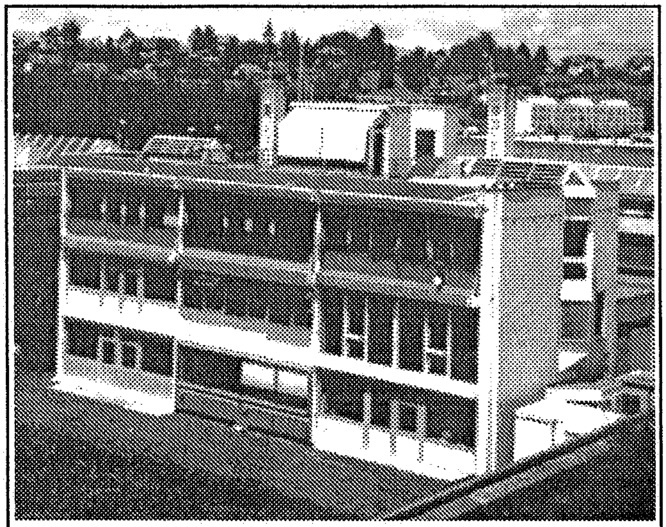

Figure 1. Outside view of the LESO building.

In order to improve our insight into the actual values of flow resistance coefficients in networks describing air flows in buildings, this paper presents new experimental results. The data have been obtained on a naturally ventilated three level office building (Figure 1) which was available for the study of basic stack ventilation configurations. The research was performed in the framework of a European research project on passive cooling of buildings [14,15] and the objective was to validate simple ventilation algorithms and to give an experimental basis to design guidelines for night cooling techniques [16,17,18].

The multilevel office allowed the studying the influence of openings (size and position) on the neutral pressure level and on airflow rates. Single sided and cross-ventilation situations have been studied. A single flow path configuration was obtained by closing all windows and doors in the building envelope with the exception of the roof exhaust and one office window as the ventilation air inlet. Air flow patterns were traced with smoke and tracer gas. Air flow rates derived from velocity measurements in the open doorways were found to be in agreement with the flow rates obtained with a constant injection tracer gas technique, with an uncertainty of ±20%. Overall agreement was found between the velocity measurements and simplified models based on the Bernoulli equation.

The simple Bernoulli model is used to determine the influence of the size and position of openings on the natural ventilation of buildings. The position of the openings in relation to the NPL to achieve efficient cooling is also discussed.

In the experiments, air velocities and the position of the NPL have been measured, and contraction and velocity coefficients as used in the Bernoulli model have been observed, where the only driving force is stack pressure. In a second set of experiments, the resulting effective area of a combination of two openings in series was studied.

2. VENTILATION MODELLING

2.1 Stack pressure

Temperature differences between outdoors and indoors cause density differences and therefore pressure differences. When the inside temperature is higher than the outside temperature, the pressure distribution over the building height qualitatively takes the form shown in Figure 2. In this case, incoming air flows through the openings below the NPL and outlet air through the openings above it. The height at which the interior and exterior pressures are equal is called the neutral pressure level (NPL) [3]. z_{npl} is the distance of the NPL from the reference level.

In a closed airtight building the NPL is at midheight of the building. The size and position of the openings determine the location of the NPL (Figure 2 b,c,d). According to the mass conservation principle the air mass flow rate through the openings below the NPL equals the air mass flow rate through the openings above it.

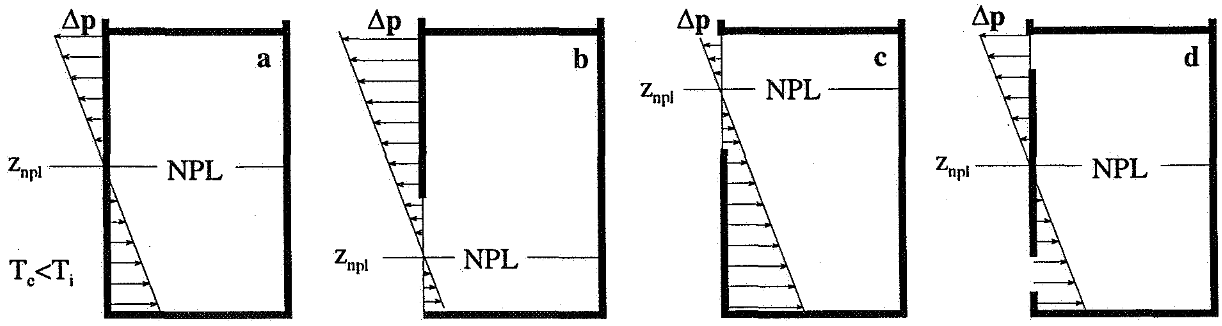

Figure 2. In-out stack pressure difference for different opening configurations.

The indoor outdoor pressure difference in an enclosure where the air is supposed to be ideal gas, frictionless, incompressible and with a homogeneous density is:

$$\Delta P_s(z) = \left(\rho_e - \rho_i\right) g \left(z - z_{npl}\right) = \rho_i g (z - z_{npl}) \frac{(T_i - T_e)}{T_e} \qquad (1)$$

2.2 Bernoulli's equation

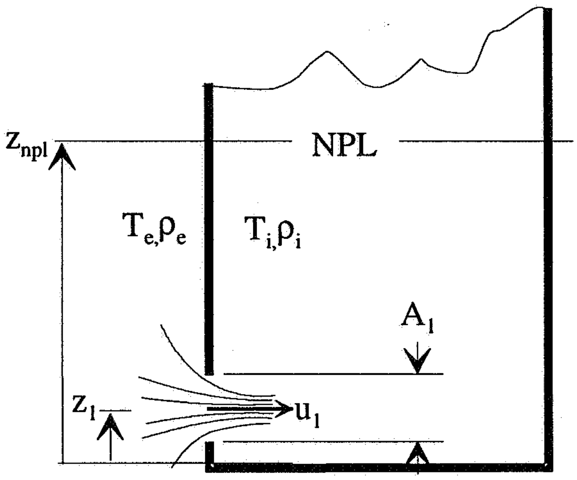

Figure 3: Air flow through an opening due to stack pressure when $T_i > T_e$.

The application of the energy conservation principle [13] between the horizontal cross section of the building at the NPL level and the vertical cross section of the opening A_l (Figure 3) gives the Bernoulli equation. The surface area of the building cross section compared to the opening surface area is large, so velocity in this section is low. Kinetic energy on the section NPL can be neglected.

The pressure drop between the two sections is the sum of the local pressure drop in the opening and the pressure drop due to friction in the air path from A_l at NPL. They can be normalised to the air velocity u_l as:

$$\Delta p_{local} = \frac{1}{2} \xi \rho_e u_1^2, \quad \Delta p_{frictional} = \frac{1}{2} \zeta \rho_e u_1^2 \qquad (2, 3)$$

Under these conditions Bernoulli's equation becomes:

$$\Delta p_s(z_1) - \frac{1}{2} \rho_e \zeta u_1^2 - \frac{1}{2} \rho_e \xi u_1^2 - \frac{1}{2} \rho_e N_1 u_1^2 = 0 \qquad (4)$$

Air velocity in the opening can be expressed as:

$$u_1 = \varphi \sqrt{2g\left(z - z_{npl}\right)\frac{\Delta T}{T_e}} \qquad (5)$$

φ is the velocity coefficient:

$$\varphi = \frac{1}{\sqrt{\zeta + \xi + N_1}}) \qquad (6)$$

N_l is the kinetic energy coefficient depending on the uniformity of the velocity distribution in the opening section, ξ is the local pressure drop coefficient for the opening and ζ is the friction pressure drop coefficient [13]. In a real building ζ includes also the effects of the pressure drop due to obstacles and direction changes in the air flow path.

φ is determined experimentally and depends on the Reynolds number, on the opening nature as well as on the obstacles in the air flow path. It is difficult to distinguish the effect of each parameter included in φ, but an overall value can be found.

2.3 *Neutral Pressure Level*

z_{npl} is the distance of the NPL from the reference level. The mass conservation principle leads to equation (7) for an air tight enclosure with two openings, one at the top and one at the bottom.

$$z_{npl} - z_1 = \frac{H}{1 + \left[\left({}^{A_{bot.}}\!/\!{}_{A_{top}} \right)^2 \left({}^{T_{in}}\!/\!{}_{T_{out}} \right) \right]} \tag{7}$$

H is the vertical distance between the centres of gravity of the two openings.

z_l is the vertical distance between the centre of gravity of the bottom opening and the reference level. For convenience the reference level could be chosen such that z_l=0

For enclosures with a single opening, the NPL is situated in the middle of the opening height. Applying the mass conservation principle strictly, the NPL is not exactly in the middle due to the density difference of the inlet and outlet air but the error is less than 0.3% for a ΔT of 10K [8]. For more than two openings the neutral level cannot be calculated by an explicit equation and numerical resolution should be used. The software LESOCOOL [18] offers a tool to determine the NPL for an enclosure with multiple large openings. The algorithm used combines the basic principle of AIDA [7] with the full large opening algorithm [19].

2.4 *Jet forming in the opening*

The air passing through an opening forms a jet. The air path lines are curved on the opening edge and the air flow does not fill the whole opening section. The effective area of the opening is smaller than the geometrical one due to the contraction of the flow path lines. In section 3.2 the jet forming through an external opening is visualised using smoke (Figure 6). The jet contraction depends on the Reynolds number, on the kind of opening boards, as well as on the ratio of the section area of the opening and the section area of the space through which the air passes. In the case of outside openings this ratio is infinite [13].

The effective area of the opening depends on how the jet fills the opening section. ε is the coefficient of jet contraction (or coefficient of filling the section) and it is defined as:

$$\varepsilon = \frac{A_{effective}}{A_{geometrical}} \tag{8}$$

2.5 *Air flow rate*

Integration over the opening height gives the airflow rate though the opening

$$\dot{v} = \int_{z1}^{z2} W u \, dz \tag{9}$$

For a single opening this integration gives:

$$\dot{v} = \frac{1}{3} \varepsilon \varphi A \sqrt{gH \frac{\Delta T}{T}} = \frac{1}{3} C_d A \sqrt{gH \frac{\Delta T}{T}} \tag{10}$$

For two openings the air velocity can be considered constant all over the opening height if the opening is far from the NPL. The mean air velocity can be taken equal to the velocity in the centre of the opening. In this case the airflow rate is:

$$\dot{v} = AC_d\sqrt{2g(z - z_{npl})\frac{\Delta T}{T}} \tag{11}$$

C_d is the discharge coefficient. It is the product of the velocity coefficient φ and the contraction coefficient ε.

$$C_d = \varepsilon\,\varphi \tag{12}$$

The discharge coefficient can be determined experimentally only if the air flow rate is directly measured. This can be done by tracer gas methods [20]. The velocity coefficient can be determined by measuring the air velocities.

2.6 *Two openings in series*

For a number of openings in series the mass flow is constant but there is a partial pressure drop over each opening. Because the velocities vary inversely with the opening area (continuity equation) the pressure drop over successive openings varies inversely with the square of the area [6,12].

$$\Delta p = \sum_{i=1}^{n}\Delta p_i = \sum_{i=1}^{n}\frac{\rho}{2}\left(\frac{u}{\varphi}\right)_i^2 = \frac{\dot{m}}{2\rho}\sum_{i=1}^{n}\left(\frac{1}{\varphi\varepsilon A}\right)_i^2 = \frac{\dot{m}}{2\rho}\sum_{i=1}^{n}\left(\frac{1}{C_d A}\right)_i^2 \tag{13}$$

When two openings on the same height z are placed in series an effective opening area, A_{eff}, can be defined as:

$$\left(\frac{1}{A_{eff}}\right)^2 = \left(\frac{1}{C_{d1}A_1}\right)^2 + \left(\frac{1}{C_{d2}A_2}\right)^2 \tag{14}$$

If $A_2 >> A_1$ the pressure drop in the second opening can be neglected. If $A_2 > 1.5A_1$ the error of neglecting A_2 is less than 11%, while if $A_2 > 2A_1$, this error is less than 6%.

3. EXPERIMENTS

The naturally ventilated LESO office building (Figure 1) offers many possibilities for real scale experimental work. Its structure is ideal for ventilation experiments. It has three storeys plus a basement and a sunspace as extension of the central staircase through which the building is ventilated (Figure 7). It is 11 m high with openings available on all levels offering several opening combinations.

3.1 *Velocity coefficient φ for large openings*

For all experiments the building was kept closed. All internal doors towards the staircase were closed as well in order to limit the effect of leakage. The sunspace door at the top of the building was kept open (0.9m×1.98m). The bottom opening on ground level was varied. For the experiments "b" to "f", an office window of fixed height (1.5m) and variable width (0.95m-0.2m) and for the experiment "a" the entrance door (0.8m×2.3m) were used as the bottom opening.

The experiments were performed at three different dates and the in-out temperature differences varied between 8.6 and 11.8 °C. The wind velocity was less than 0.6 m/s.

T_i is the average of four temperatures measured on every storey. The thermal stratification along the air flow path varies from 2.5 to 5.5 °C. Notice that the effects of the thermal stratification are ignored by the Bernoulli model.

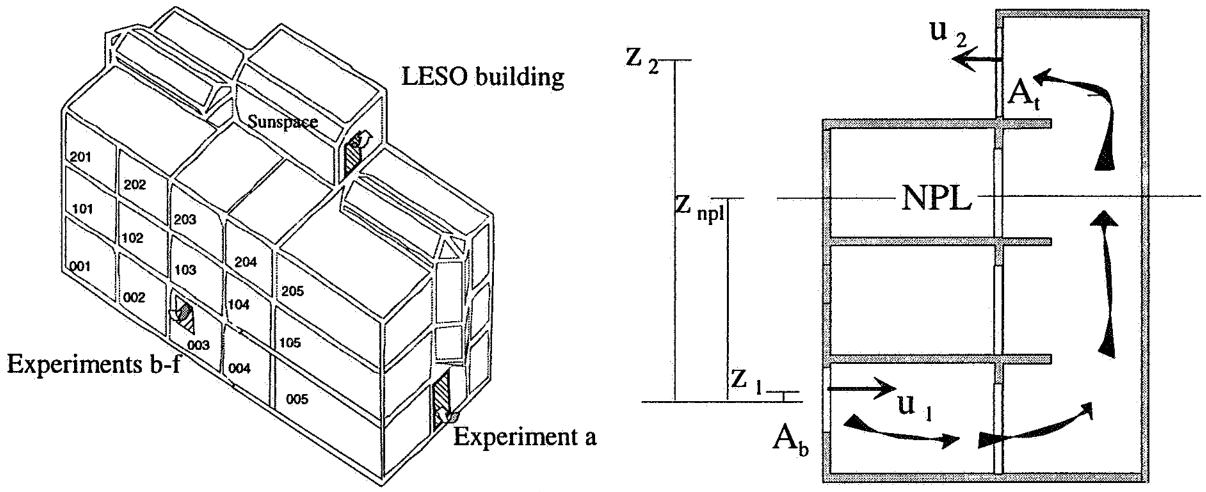

Figure 4: Openings used for the experiments of section 3.1

Figure 5 shows the measured velocity coefficients in the experiments a to f. Within the domain the experiments have been performed, no significant correlation was found between φ and the opening dimension or air velocity. Table 1 gives more details on each experiment.

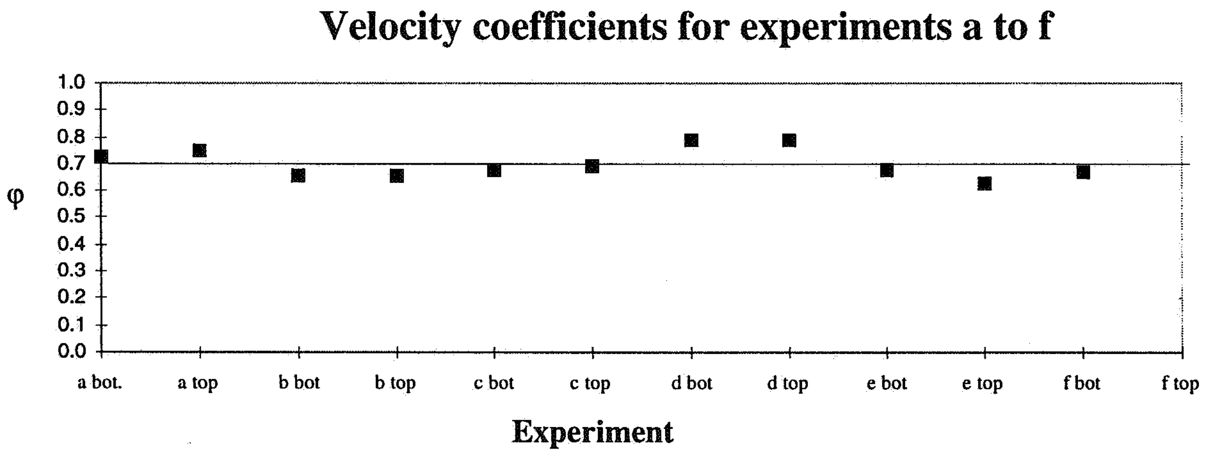

Figure 5. Top and bottom velocity coefficients measured in six experiments. The experiments are sorted according to the bottom opening dimension (Table 1)

Experiment		a	b	c	d	e	f	σ*
A_b (bottom)	m²	1.9	1.4	1.4	1.4	0.9	0.3	0.06
A_t (top)	m²	1.8	1.8	1.8	1.8	1.8	1.8	0.06
T_i (internal temp.)	°C	16.2	22.1	18.9	16.7	22.1	22.1	0.3
T_e (external temp.)	°C	6.0	13.0	9.1	4.9	13.0	13.5	0.3
z_{npl}* (NPL height)	m	4.4	6.4	6.1	6.2	8.7	10.2	0.3
u_1 (measured velocity)	m/s	1.3	1.3	1.4	1.8	1.6	1.6	0.04
u_2 (measured velocity)	m/s	1.4	1.0	1.1	1.3	0.6		0.04
φ_1 (top velocity coefficient)	-	0.73	0.66	0.68	0.79	0.68	0.67	0.09*
φ_2 (bott. velocity coefficient)	-	0.75	0.66	0.69	0.79	0.63		0.09*

Table 1. Results of the experiments a to f to determine velocity coefficient φ

* The mean value of the calculated velocity coefficient is 0.7. Using the standard deviations indicated in the last column of Table 1 the theoretical standard deviation for φ is 0.09 The standard deviation of the twelve experimental values of φ is 0.06 showing that the theoretical σ is pessimistic and the differences in the experimental values are due to random errors.

** Equation (7) for the NPL is an application of the mass conservation principle assuming that the building is air tight. In reality there is no absolutely air tight building. The leakage with natural ventilation depends not only on the size of the cracks but also on their location in relation to the NPL. As the second parameter changes for every experiment it is impossible to take into account a fixed leakage. For every experiment the leakage is evaluated applying

$$\varepsilon_1 A_b \rho_e u_1 - \varepsilon_2 A_t \rho_i u_2 + L = 0 \qquad (15)$$

L is the leakage mass flow rate.

Taking the experimental values of u_1 and u_2 equation (15) gives the leakage, whereas the theoretical values of u_1 and u_2 give an implicit equation to calculate z_{npl}:

$$C_d A_b \rho_e \sqrt{2gZ_{npl}\frac{T_e - T_i}{T_i}} - C_d A_t \rho_i \sqrt{2g(Z_2 - Z_{npl})\frac{T_e - T_i}{T_i}} + L = 0 \qquad (16)$$

The same experimental procedure was applied to two more buildings satisfying the following conditions:

- Internal restrictions > 2 times the smaller opening
- Temperature stratification < 1 K/m
- Wind < 0.5 m/s
- Building height > 3 times opening height

The measured φ was also found equal to 0.7 ±0.1 showing that this value is not specific to a particular building.

3.2 *Contraction coefficient ε*

The purpose of this experiment is to visualise the jet forming in the opening. The experimental set up is identical to the experiments of section 3.1. The smoke is released outside the opening 003. A video camera is placed on the opening edge, recording the air-smoke flow. A graph paper placed vertically on the window edge allows an estimation of the contraction and effective area (1 graduation = 1cm). Some digitised images for air velocities from 0.4 to 0.9 m/s are shown in Figure 6.

Figure 6 Digitised video images of the incoming air through a window of a LESO office.

The jet contraction in the opening section oscillates continually between 2 and 4 cm in the range of air velocities 0.3 to 1 m/s independently of it. Considering a contraction of 3 ±1 cm, the coefficient ε for a rectangular opening of dimensions 1×1.5 m is 0.90 ± 0.03

3.3 Openings in series

In the first set of experiments, it was supposed that there was no particular resistance (restriction or considerable obstacles) between the two openings. In this second set of experiments, the windows at first floor are used, varying the area of intermediate opening (office door) in order to test the validity of equation (14).

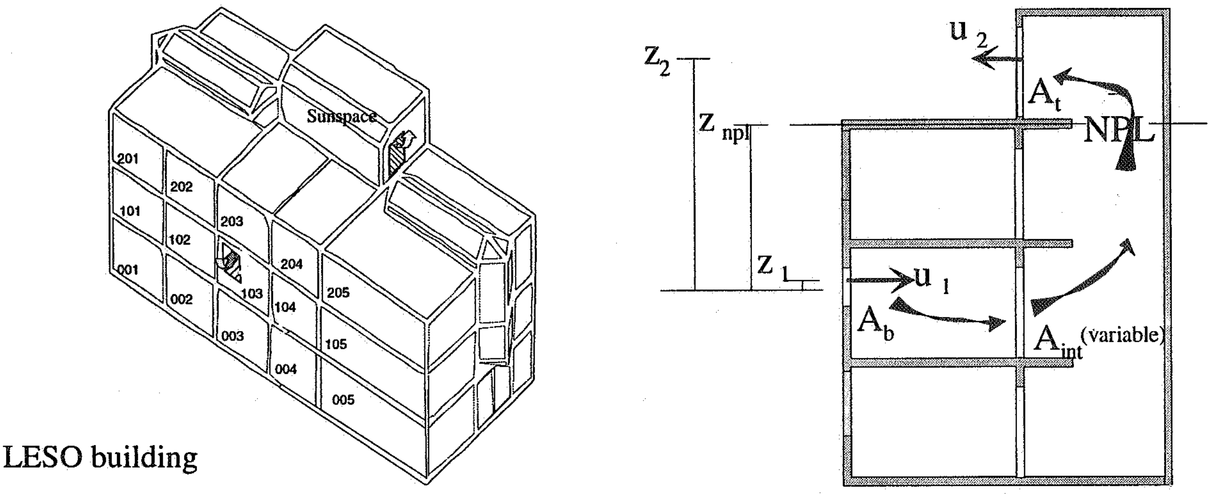

Figure 7: Openings used for the experiments of the section 3.3

The effective surface area A_{eff} could be normalised to A_b as $A_{eff} = \varepsilon_b\ \varphi_{eff} A_b$, where φ_{eff} is the new velocity coefficient after combining the two openings in series A_b and A_{int}

From equation (14) φ_{eff} could be derived as:

$$\frac{1}{\varphi_{eff}^2} = \frac{1}{\varphi_b^2} + \frac{1}{\varphi_{\text{int}}^2}\left(\frac{\varepsilon_b A_b}{\varepsilon_{\text{int}} A_{\text{int}}}\right)^2 \qquad (17)$$

The contraction coefficients have been evaluated by visualising the air path streams with cold smoke. For the outside opening A_b the distance between the jet and the opening edge was 3 cm ±1 (Figure 6) on the 4 sides of the perimeter. This gives a contraction coefficient of

0.85±0.05. For the intermediate opening, A_{int}, the ε_{int} is higher (ε_{int}=0.95) because only two edges are sharp (the sides near the floor and near the wall do not modify the air stream lines).

The results in Table 2 show good agreement between the measured velocity coefficients and those estimated using equation (17). The velocity coefficients for the top opening are the same as those of the first set of experiments.

Experiment		g	h	i	j
A_t (top opening surface area)	m²	1.8	1.8	1.8	1.8
A_b (bottom opening surface area)	m²	0.7	0.7	0.7	1.4
A_{int} (intermediate opening surface	m²	1.9	0.9	0.72	1.9
u_2 (measured)	m/s	0.72	0.64	0.64	1.00
u_1 (measured)	m/s	1.32	1.10	1.01	0.98
φ_2 (top velocity coefficient)	-	0.74	0.64	0.62	0.69
φ_1 (measured bott. Velocity coef.)	-	0.66	0.54	0.50	0.62
φ_{eff} (calculated from eq. (17))	-	0.66	0.57	0.53	0.58
% difference		-1%	-6%	-5%	6%

Table 2. Measured velocity coefficient compared to the calculated one from equation (17)

3.4 Tracer gas measurements

The experimental set up is the same as in section 3.1 (Figure 4) with a bottom opening of 1.4 m² and a top opening of 1.35 m². In-out ΔT is 3.5°C with no detectable outside wind. In the intermediate door between the office 003 and the staircase a constant flow rate of 4.17 ml/s of SF6 gas is mixed naturally with the incoming air. The concentration of SF6 measured at the top opening gives the air flow rate through the building and therefore the discharge coefficient C_d. The tracer gas apparatus CESAR and tracer gas measuring techniques are explained in ref. [20].

Point velocity measurements at different heights of the openings give the velocity coefficient φ. Multiplied with the contraction coefficient ε calculated in section 3.2 they give a second discharge coefficient. Figure 1 shows good agreement of the discharge coefficients evaluated by the two methods. The generally accepted value of C_d = 0.6±0.1 is confirmed once again.

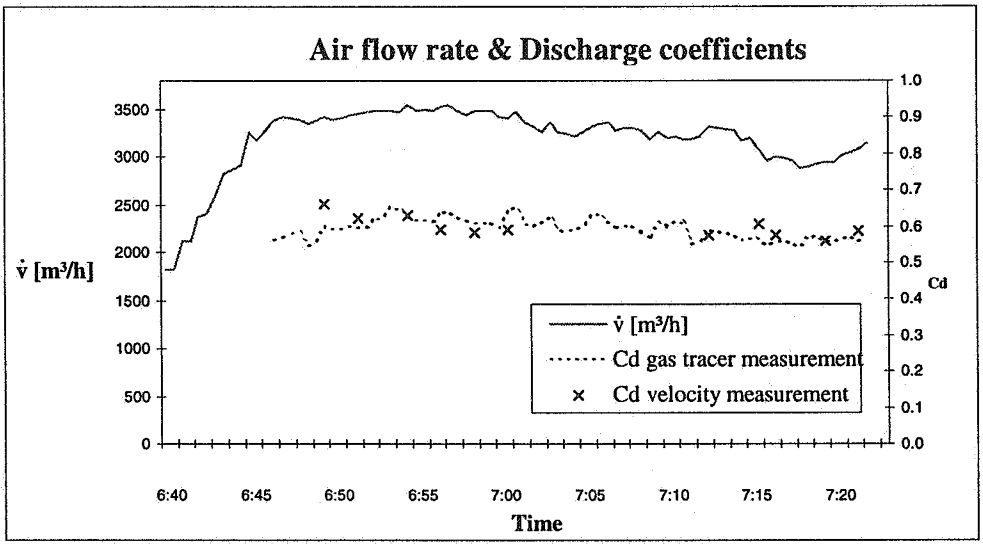

Figure 8. Comparison of the discharge coefficient measured by tracer gas and by velocity measurements.

4. DESIGN GUIDELINES

The NPL is a very important concept for the correct design of natural ventilation. When purely stack driven ventilation is used to cool high buildings, it is impossible to pass fresh air through the openings above the NPL. Opening a window in a high building implies a modification of NPL location and the air path in the whole building can be radically changed with an inversion of the flow direction in some openings.

The top opening should be as large and as high as possible. It should be placed in the low pressure facade of the building so that wind and stack pressure work in the same direction.

If the stack pressure at highest storeys is low, special arrangements may correct the situation (Figure 9). If these arrangements are impossible, mechanical ventilation could be considered for these storeys.

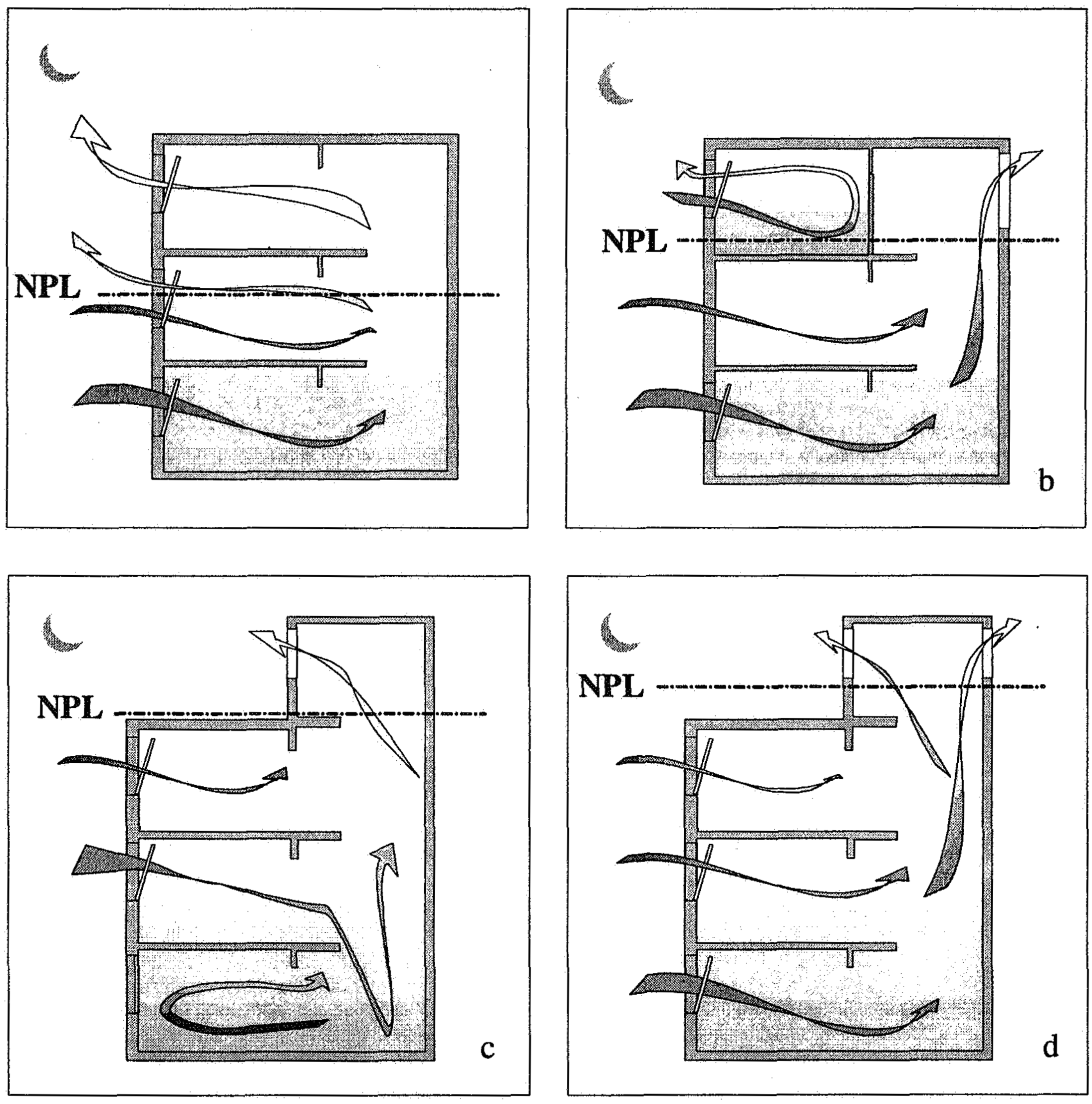

Figure 9. The four drawings show how the opening dimension and position can be manipulated to obtain night cooling of all the storeys of a three storey building.
a): poor cooling of upper level. b) to d): various ways to improve cooling.

The NPL also plays a very important role for the air tightness of the building. Cracks far from the NPL loose more than cracks near to it (see the Δp in Figure 2).

5. CONCLUSIONS

Purely stack driven ventilation can efficiently be used in buildings with more than one storey for night cooling natural ventilation. The outlet opening should be at the highest point of the building and it should have a large opening area. The outlet opening surface area on the top should be calculated so that the NPL be above the highest level to be cooled.

The experiment performed on site in a real building confirm laboratory experiments found in the literature. The air velocity and the tracer gas air flow rate measurements conducted to determine the discharge coefficient give the same results with the same uncertainty. The velocity coefficients $\varphi = 0.7 \pm 0.1$ and jet contraction coefficients $\varepsilon = 0.85 \pm 0.1$ found in the experiments are in agreement with the generally accepted value of the discharge coefficient $C_d = \varphi\,\varepsilon = 0.6 \pm 0.1$.

The nature of the phenomenon of natural ventilation makes the validation of models difficult (impossible?) whether they are simple or complex [4, 5, 7]. The precision in the experiments of this paper is of the order of 20% to 25%.

Depending on the problem to be solved, simple models for natural ventilation can give more valuable information to the designer. The imprecision of the model might be a minor issue if the model gives a qualitatively correct answer, especially when account is taken of the uncertainty of input data [4]. Future research should explore the possibilities of using qualitative modelling and qualitative simulation techniques to model natural ventilation.

6. ACKNOWLEDGEMENTS

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