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Ventilation and Energy Flow Through Large Vertical Openings in Buildings

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SYNOPSIS

After a short description of the physical phenomena involved, unified expressions are worked out describing net airflow and net heat flow through large vertical openings between stratified zones. These formulae are based on those of Cockroft for bidirectional flow, but are more general in the sense that they apply to situations of unidirectional flow as well. The expressions are compatible with a pressure network description for multizone modelling of airflow in buildings. The technique has been incorporated in the flows solver of the ESP-r building and plant energy simulation environment.

The relative importance of the governing variables (pressure difference, temperature difference and vertical air temperature gradients) is demonstrated by parametric analysis of energy performance in a typical building context and by comparison with experimental data in the literature. It is concluded that vertical air temperature gradients have a major influence on the heat transferred through large openings in buildings and should be included in building energy simulation models. Finally, it is discussed how the air temperature gradient, an input parameter which depends strongly on the heating and cooling mode, could be predicted.

Symbols

a_i	temperature profile coefficient for zone i (K)	z	height coordinate (m)
b_i	temperature gradient in zone i (K/m)	z_n	height of neutral level (m)
C_d	discharge coefficient (–)	z_0	height of reference level (m)
c_p	specific heat of air (J/kgK)	z_b	height of bottom of aperture (m)
g	acceleration of gravity (m/s^2)	Φ_{ij}	heat flow from zone i to zone j (W)
h	aperture height (m)	ρ	air density (kg/m^3)
M	molecular mass of air $(kg/kgmole)$	ξ	integration variable (m)
$\dot{m}_{ij}$	air mass flow from zone i to zone j (kg/s)	α	$\equiv (z_0 - z_b)/h$ (–)
P	pressure (Pa)	C_a	$\equiv \Delta P(z_b + h)$ (Pa)
$\dot{q}_{ij}$	air volume flow from zone i to zone j (m^3/s)	C_b	$\equiv \Delta P(z_b)$ (Pa)
P_{ref}	reference pressure (Pa)	C_t	$\equiv hgK\left(\frac{1}{T_2(z_0)} - \frac{1}{T_1(z_0)}\right) = C_a - C_b$ (Pa)
R	universal gas constant $(J/kgmole\ K)$	K	$\equiv P_{ref}M/R$ $(Pa\ kgK/J)$
T	temperature (K)	Z_a	$\equiv \frac{2\sqrt{2}}{3}\frac{C_d hW}{C_t} C_a^{3/2}$ $(m^2Pa^{1/2})$
u	horizontal air velocity (m/s)	Z_b	$\equiv \frac{2\sqrt{2}}{3}\frac{C_d hW}{C_t} C_b^{3/2}$ $(m^2Pa^{1/2})$
W	aperture width (m)		

1 INTRODUCTION

Airflow through doorways, windows and other large openings are important paths via which air (including moisture and pollutants) and thermal energy are transferred from one zone of a building to another. In case of large openings, the airflow at the top usually differs from the flow at the bottom of the opening. Under certain conditions this may even result in bidirectional flow through the opening.

In recent times there has been an increased interest in modelling airflow through large openings in buildings (eg Allard et al. 1992). The current publication seeks to be a basic contribution in this area by presenting and demonstrating a general approach for predicting airflow and heat flow through large vertical openings between stratified zones.

2.1 Net Heat Flow when Zero Volume Flow

For the mass and heat transfer through large vertical openings, Balcomb et al. (1984) and others like White et al. (1985) and Boardman et al. (1989) used the so-called *isothermal zone* Bernoulli model.

According to Bernoulli, the maximum velocity $u(z)$ in a large vertical opening between two zones resulting from a static pressure difference (thereby excluding any frictional losses) is given by:

$$u(z)=\sqrt{\frac{2\Delta P}{\rho}}=\sqrt{\frac{2\Delta\rho}{\rho}g(z-z_n)}=\sqrt{\frac{2g}{T}\Delta T(z-z_n)}\quad (m/s) \qquad [1]$$

where z_n indicates the height of the neutral level (ie the level at which the pressure difference $\Delta P\equiv P_1-P_2=0\ Pa$), $\Delta\rho\equiv\rho_1-\rho_2$, and ΔT is the temperature difference between zone 1 and zone 2 ie $\Delta T\equiv T_2-T_1$.

In this expression, it is implicitly assumed that ΔT is independent of the height coordinate z, ie that temperature gradients are equal and not too large. When the top-to-bottom temperature difference over the opening is small compared to the absolute temperature, this approximation is highly accurate.

The heat flow Φ_{21} from the warmer zone (2) to the colder zone (1) is carried by air flowing from 2 to 1 *above* the *neutral level.* The heat flow Φ_{12} from the colder zone (1) to the warmer zone (2) takes place *below* the *neutral level.* These contributions are given by:

$$\Phi_{21}=c_pC_dW\int_{z_n}^{z_b+h}\rho_2(z)u(z)T_2(z)dz\quad (W) \qquad [2a]$$

$$\Phi_{12}=c_pC_dW\int_{z_b}^{z_n}\rho_1(z)u(z)T_1(z)dz\quad (W) \qquad [2b]$$

Balcomb's expression for the *net heat flow* through the aperture is obtained by inserting the expression for $u(z)$ into the expressions for Φ_{21} and Φ_{12}, thereby assuming that the temperature profiles in both zones are linear, ie $T_i(z)=a_i+b_iz$, and assuming that the *net volume flow* is zero, ie that the neutral level is located in the middle of the aperture. The expression reads:

$$\Phi_{12}+\Phi_{21}=\frac{C_d\rho c_pW}{3}\sqrt{\frac{g}{T}}h^{3/2}\Delta T^{1/2}*\left[\Delta T+0.3h(b_1+b_2)\right]\quad (W) \qquad [3]$$

and is good approximation when the thermal gradients in both zones are equal, and not too large.

From Eq. [3] it is seen that by including the temperature gradients b_1 and b_2 the heat flow is increased by the factor

$$\left[1+\frac{0.3\,h(b_1+b_2)}{\Delta T}\right] \qquad [3b]$$

In practice b_1 and b_2 are not well known, but the importance of this correction factor for small ΔT shows the need to include the effect of stratification in building energy simulation environments like ESP-r.

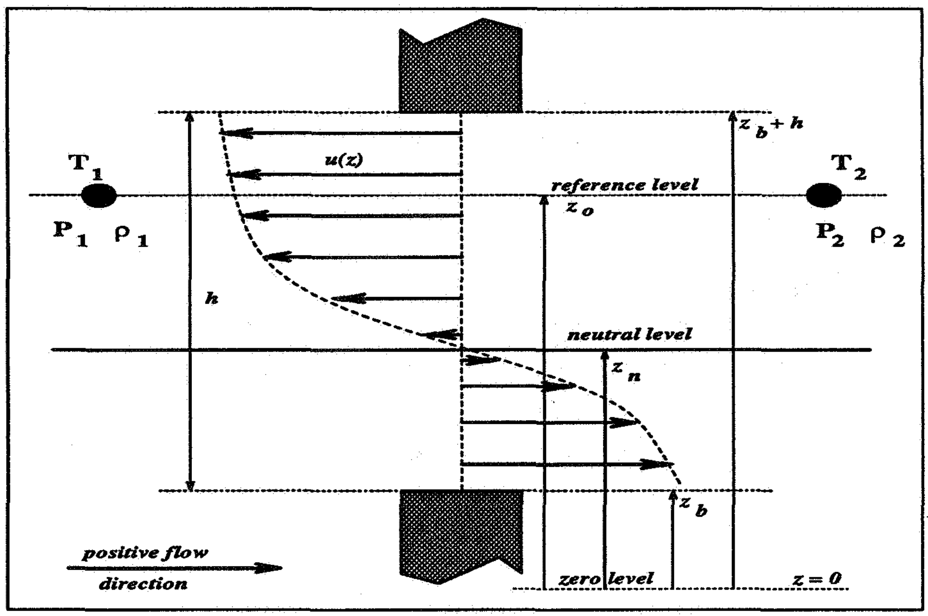

Figure 1 Definition of various parameters

2.2 Mass Flow between Stratified Zones

In the following, an expression for the mass flow through a large opening separating two zones of different temperature and pressure is derived. The general case is considered, ie there is a static pressure difference at reference level z_0 between zone 1 and 2, and different vertical temperature profiles occur in the two zones. These temperature profiles are assumed linear, though the temperature gradients can be different. The situation is depicted in Figure 1.

First we assume that conditions are such that the neutral level, ie the level at which the pressure is equal in zones 1 and 2, is located in the opening, so that *bidirectional* air flow occurs.

The *stack pressure difference* between a point at height z and a point at reference height z_0 is calculated from:

$$\Delta P(z) - \Delta P(z_0) = \int_{z_0}^{z} g\left[\rho_2(\xi) - \rho_1(\xi)\right] d\xi \quad (Pa) \qquad [4]$$

Although density variations due to pressure variations are negligible small, those resulting from temperature differences should be taken into account, especially when temperature gradients are large. The air density in zone i is inversely proportional to the temperature, namely:

$$\rho_i = \frac{P_{ref} M}{R T_i} \quad (kg/m^3)$$

where P_{ref} is some reference pressure, eg the atmospheric pressure, M is the molecular weight of air, and R is the universal gas constant. To a very good approximation one may write:

$$\rho_i = \frac{K}{T_i} \quad (kg/m^3)$$

with K constant. The expression for $\Delta P(z)$ now reads:

$$\Delta P(z) - \Delta P(z_0) = \int_{z_0}^{z} gK\left[\frac{1}{T_2(\xi)} - \frac{1}{T_1(\xi)}\right]d\xi \quad (Pa) \qquad [5]$$

Assuming a linear temperature profile $T_i(z) = a_i + b_i z$ one obtains:

$$\Delta P(z) - \Delta P(z_0) = gK\int_{z_0}^{z}\left[\frac{1}{a_2 + b_2\xi} - \frac{1}{a_1 + b_1\xi}\right]d\xi$$

$$= \dots\dots\dots\dots\dots$$

$$= gK\left[\frac{1}{b_2}\ln\frac{T_2(z)}{T_2(z_0)} - \frac{1}{b_1}\ln\frac{T_1(z)}{T_1(z_0)}\right] \quad (Pa) \qquad [6]$$

If the temperature gradient in both zones is not too large, we have to a very good approximation:

$$\ln\frac{T_i(z)}{T_i(z_0)} \approx \frac{T_i(z) - T_i(z_0)}{T_i(z_0)} \quad (-),$$

ie the *first order approximation* is highly accurate. Inserting the linear temperature profile gives:

$$\ln\frac{T_i(z)}{T_i(z_0)} \approx b_i\frac{z - z_0}{T_i(z_0)} \quad (-)$$

so that in first order approximation:

$$\Delta P(z) - \Delta P(z_0) \approx gK\left(\frac{1}{T_2(z_0)} - \frac{1}{T_1(z_0)}\right)(z - z_0) \quad (Pa) \qquad [7]$$

This means that $\Delta P(z)$ changes linearly with the height coordinate z when temperatures in both zones differ at the reference height z_0. Note that the first order approximation results in Eq. [7] which is independent of the temperature gradients in both zones, b_1 and b_2. Inserting the *second order approximation*, ie

$$\ln\frac{T_i(z)}{T_i(z_0)} \approx \frac{T_i(z) - T_i(z_0)}{T_i(z_0)} - \frac{1}{2}\left(\frac{T_i(z) - T_i(z_0)}{T_i(z_0)}\right)^2 \quad (-)$$

in Eq. [6] gives:

$$\Delta P(z) - \Delta P(z_0) \approx gK\left(\frac{1}{T_2(z_0)} - \frac{1}{T_1(z_0)}\right)(z - z_0) - \frac{1}{2}gK\left(\frac{b_2}{T_2^2(z_0)} - \frac{b_1}{T_1^2(z_0)}\right)(z - z_0)^2 \quad (Pa),$$

showing that the temperature gradients give only a second order contribution to $\Delta P(z)$. The *relative error* made by assuming that

$$\ln\frac{T_i(z)}{T_i(z_0)} \approx \frac{T_i(z) - T_i(z_0)}{T_i(z_0)} \quad (-)$$

is of the order of $(T_i(z) - T_i(z_0))/2T_i(z_0)$. Even for a ceiling-to-floor temperature difference of 6 K, this relative error will be $\approx 1\%$ at most. As in the mass flow calculation the square root of $\Delta P(z)$ is integrated over the height of the opening, the resulting error will even be smaller. In the following, this error will therefore be neglected.

If the opening through which the air flows extends from z_b to $z_b + h$, the pressure difference between the two zones at bottom level z_b will be equal to:

$$\Delta P(z_b) = \Delta P(z_0) + gK\left(\frac{1}{T_2(z_0)} - \frac{1}{T_1(z_0)}\right)(z_b - z_0) \quad (Pa) \qquad [7a]$$

and at the top of the opening:

$$\Delta P(z_b + h) = \Delta P(z_0) + gK\left(\frac{1}{T_2(z_0)} - \frac{1}{T_1(z_0)}\right)(z_b + h - z_0) \quad (Pa) \qquad [7b]$$

Now, if EITHER $\Delta P(z_b) > 0$ *and* $\Delta P(z_b + h) < 0$ OR $\Delta P(z_b) < 0$ *and* $\Delta P(z_b + h) > 0$ then the neutral level z_n is located inside the opening and *bidirectional* airflow occurs. If $\Delta P(z_b)$ and $\Delta P(z_b + h)$ have the same sign, or if one of them is zero, only *unidirectional* flow takes place.

According to Bernoulli's Law, a pressure difference $\Delta P(z)$ results in a local air velocity $u(z)$ proportional to the square root of $\Delta P(z)$. Therefore, an infinitesimal volume flow $d\dot{q}$ through an element of height dz in the opening can be written as:

$$d\dot{q} = W\,u(z)\,dz \quad (m^3/s) \qquad [8]$$

If we consider the case where $T_2 > T_1$ and where the pressures at reference level z_0 in both zones are such that the neutral level is located inside the opening (so bidirectional airflow will occur), then the mass flow from 2 to 1 is equal to:

$$\dot{m}_{21} = \int_{z_n}^{z_b+h} \rho_2 d\dot{q} = C_d W\sqrt{2\rho_2}\int_{z_n}^{z_b+h} \Delta P(z)^{1/2} dz \quad (kg/s) \qquad [8a]$$

and the mass flow from 1 to 2 is equal to:

$$\dot{m}_{12} = \int_{z_b}^{z_n} \rho_1 d\dot{q} = C_d W\sqrt{2\rho_1}\int_{z_b}^{z_n} \Delta P(z)^{1/2} dz \quad (kg/s) \qquad [8b]$$

where C_d is an empirical constant.

In these expressions, the error made by placing $\sqrt{2\rho_i}$ in front of the integral sign is negligible because density variations are very small over the integration interval when compared to variations in $\Delta P(z)$. Inserting the linear expression for $\Delta P(z)$ into the integrals gives for $\dot{m}_{21}$ and $\dot{m}_{12}$ the following expressions:

$$\dot{m}_{21} = \frac{2}{3} C_d W\sqrt{2\rho_2}\,\frac{h}{C_t}\,C_a^{3/2} \quad (kg/m^3) \qquad [9a]$$

$$\dot{m}_{12} = \frac{2}{3} C_d W\sqrt{2\rho_1}\,\frac{h}{C_t}\,(-C_b^{3/2}) \quad (kg/m^3) \qquad [9b]$$

where:

$$C_t \equiv hgK\left(\frac{1}{T_2(z_0)} - \frac{1}{T_1(z_0)}\right) = C_a - C_b \quad (Pa)$$

$$C_a \equiv \Delta P(z_b + h) \quad (Pa) \quad \text{and} \quad C_b \equiv \Delta P(z_b) \quad (Pa)$$

Note that in the situation in figure 1, the pressure difference at the top level of the opening, $C_a \equiv \Delta P(z_b + h)$ is *negative*, so that $C_a^{3/2}$ is an *imaginary* number. To keep the value of $\dot{m}_{21}$ real, the absolute value of C_a should be taken.

It is convenient, however, to write the *net mass flow* of air through the opening as a complex quantity, ie:

$$\dot{m}_{net} = \dot{m}_{21} + \dot{m}_{12} = \frac{2\sqrt{2}}{3} C_d W \frac{h}{C_t} * \left(\sqrt{\rho_2} C_a^{3/2} - \sqrt{\rho_1} C_b^{3/2}\right) \quad (kg/s) \qquad [10]$$

This expression was first derived by Cockroft (1979). The net mass flow is a *complex number*, of which the *real* part gives the flow from 1 to 2 and the *imaginary* part gives the flow from 2 to 1.

It must be emphasized that the Cockroft formula for $\dot{m}_{net}$ in the form given above only holds for the special case depicted in Figure 1! There are two reasons why it is necessary to modify the expression:

i If zone 1 on the left were the *warmer zone* instead of the cooler one, $\dot{m}_{12}$ would take place *above* the neutral level, and $\dot{m}_{21}$ *below* it. The integration interval for both contributions would be interchanged, so that in Cockroft's expression, the term containing C_a is now $\dot{m}_{12}$ and the term containing C_b is now $\dot{m}_{21}$. The formula now reads:

$$\dot{m}_{net} = \dot{m}_{12} + \dot{m}_{21} = \frac{2\sqrt{2}}{3} C_d W \frac{h}{C_t} * \left(\sqrt{\rho_1} C_a^{3/2} - \sqrt{\rho_2} C_b^{3/2}\right) \quad (kg/s) \qquad [10a]$$

However, the *real* part still gives the flow from 1 to 2 and the *imaginary* part still gives the flow from 2 to 1.

ii If the external pressures in both zones differ considerably, the neutral level will shift to a height *below or above* (ie outside) the opening, so that the airflow becomes *unidirectional*. In this situation, one of the flow terms results from an integration over the *entire* opening, ie from z_b to $z_b + h$, while the other term is canceled. In the situation of unidirectional flow, the pressure differences at the bottom and top of the opening, C_b and C_a, have the *same sign* (unless one of them vanishes), so that $C_a^{3/2} - C_b^{3/2}$ is either a *real* or a *pure imaginary* number.

By carefully comparing the expressions for $\dot{m}_{net}$ which can be established for the different cases of unidirectional and bidirectional flow, ie by "tuning" the temperature difference and the pressure difference between zone 1 (left) and zone 2 (right), the following very convenient formula for $\dot{m}_{net}$ which holds in *all cases* can be obtained:

$$\dot{m}_{net} = \dot{m}_{12} + \dot{m}_{21} \quad (kg/s) \qquad [11]$$

$$\dot{m}_{12} = \sqrt{\rho_1}\,\mathrm{Re}(Z_a - Z_b) \quad \geq 0 \quad (kg/s) \qquad [11a]$$

$$\dot{m}_{21} = -\sqrt{\rho_2}\,\mathrm{Im}(Z_a - Z_b) \quad \leq 0 \quad (kg/s) \qquad [11b]$$

where:

$$Z_a \equiv \frac{2\sqrt{2}}{3}\frac{C_d h W}{C_t} C_a^{3/2} \quad (m^2 Pa^{1/2}) \qquad Z_b \equiv \frac{2\sqrt{2}}{3}\frac{C_d h W}{C_t} C_b^{3/2} \quad (m^2 Pa^{1/2})$$

As the direction $1 \rightarrow 2$ is, by definition, the *positive* direction, the contribution $\dot{m}_{21}$ should be *non-positive*, which explains the minus sign appearing in it. The artificial complex quantities Z_a and Z_b are introduced for convenience and have no physical meaning. In the complex plane, $Z_a - Z_b$ is located either on the positive real axis (when there is a unidirectional flow 1 $\rightarrow$ 2), on the positive imaginary axis (when there is a unidirectional flow 2 $\rightarrow$ 1), or in the first quadrant of the complex plane (when the flow is bidirectional). When for a given temperature difference between zone 1 and 2 the external pressure difference $\Delta P(z_0)$ is continuously increased from highly negative to highly positive, $Z_a - Z_b$ describes a smooth continuous curve.

2.3 Heat Flow between Stratified Zones

Just as for the mass flow, a convenient expression for the bidirectional heat flow through a large opening between stratified zones can be derived, giving Φ_{12} and Φ_{21} as real and imaginary parts of complex quantities.

Whereas mass flows are calculated by evaluating integrals of the type:

$$\int \rho_i(z) d\dot{q} \quad (kg/s)$$

heat flows are analogously calculated by evaluating integrals of the type:

$$\int c_p T_i(z) \rho_i(z) d\dot{q} = c_p C_d W \int \sqrt{2\rho_i(z)} T_i(z) \sqrt{\Delta P(z)} dz \quad (W)$$

To be able to evaluate these integrals analytically for linear temperature profiles $T_i(z) = T_i(z_0) + b_i(z - z_0)$, the integrand $\sqrt{2\rho_i(z)} T_i(z) \sqrt{\Delta P(z)}$ above, should be of the form $[polynomial] \cdot \sqrt{\Delta P(z)}$, which means that $\sqrt{2\rho_i(z)} T_i(z)$ should be approximated by its "best linear fit", which is (as can be checked easily):

$$\sqrt{2\rho_i(z_0)} \cdot [T_i(z_0) + 1/2 b_i(z - z_0)] \quad (\sqrt{kg/m^3} K)$$

Evaluation of the integrals is a rather laborious task, which will not be documented here due to space constraints. However, when these integrals are worked out in the same way as was done for the mass flows, we obtain convenient expressions for the heat flows Φ_{12} and Φ_{21}, namely:

$$\Phi_{net} = \Phi_{12} + \Phi_{21} \quad (W) \qquad [12]$$

$$\Phi_{12} = c_p \sqrt{\rho_1} * \mathrm{Re}\,(\tilde{T}_{1a}(z_0) Z_a - \tilde{T}_{1b}(z_0) Z_b) \ \geq 0 \quad (W) \qquad [12a]$$

$$\Phi_{21} = -c_p \sqrt{\rho_2} * \mathrm{Im}\,(\tilde{T}_{2a}(z_0) Z_a - \tilde{T}_{2b}(z_0) Z_b) \ \leq 0 \quad (W) \qquad [12b]$$

where:

$$\tilde{T}_{ia}(z_0) \equiv T_i(z_0) - b_i h \left[\frac{C_a}{5 C_t} + \frac{\alpha - 1}{2} \right] \quad (K) \ \text{ for } i = 1,2$$

$$\tilde{T}_{ib}(z_0) \equiv T_i(z_0) - b_i h \left[\frac{C_b}{5 C_t} + \frac{\alpha}{2} \right] \quad (K) \ \text{ for } i = 1,2$$

in which α is a dimensionless reference height ($\alpha \equiv (z_0 - z_b)/h$), and the densities ρ_1, respectively ρ_2, are evaluated at the reference level z_0.

3 APPLICATION

Eq. [11] and Eq. [12] have been incorporated into the *large vertical openings* component of the flows solver (Hensen 1991) of the ESP-r building and plant energy simulation environment (Aasem et al. 1993). This particular solver is based on a nodal network mass balance approach, and can be used - amongst others - for multizone modelling of airflow in buildings.

In the following some calculation results are given, which demonstrate the relative importance of the flow governing variables by means of parametric analysis.

For this we started from a base-case involving two building zones connected by a door opening with width $W = 1.0\ m$, height $h = 2.0\ m$, and reference height $\alpha = 0.5$. The discharge coefficient C_d was assumed to be 0.50. Various combinations of pressure difference, temperature difference, and vertical air temperature gradients were considered.

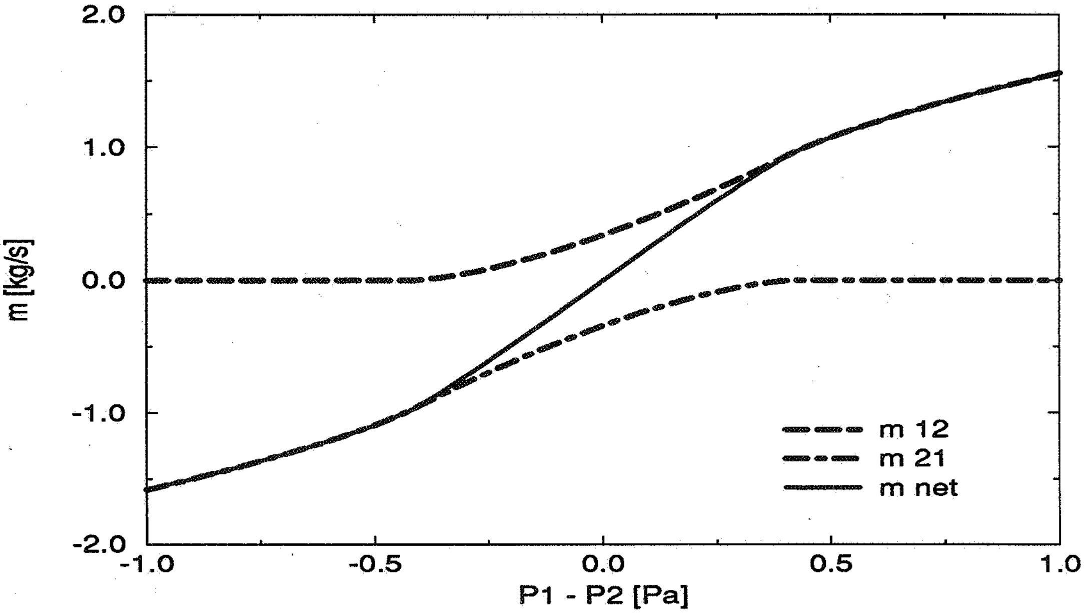

Figure 2 Mass flow rate $\dot{m}$ (kg/s) vs pressure difference $P_1 - P_2$ (Pa) for $|T_1(z_0) - T_2(z_0)| = 10\ K$

Figure 2. shows the mass flow results as a function of the pressure difference between zone 1 and zone 2, for an absolute temperature difference of 10 K. From Eq. [11] follows that the temperature gradients do not influence the mass flows. Flow $\dot{m}_{12}$ will be above the neutral level when zone 1 is the warmer zone, otherwise it will be below neutral level. From the results it is clear that there is only a small band in ΔP for which bidirectional flow occurs. It should be noted however that the corresponding airflows are quite large; eg for $\Delta P = 0.25\ Pa$ $\dot{m}_{12}$ is $\approx 0.75\ kg/s$ or $\approx 2250\ m^3/h$. This implies that there will also be a large heat flow associated with that. If we would make graphs for the heat flows Φ (and assuming that there are no vertical temperature gradients), then the shapes would be quite similar to the ones in Figure 2. Obviously the y-axis values will be different and would range from -600 kW to 600 kW for the range of pressure and temperature differences in Figure 2.

Figure 3. shows the net mass flow results for various absolute temperature differences. At very low or zero temperature difference there will only be uni-directional flow and the airflow will be similar to the flow through a large orifice. Figure 3. indicates that an

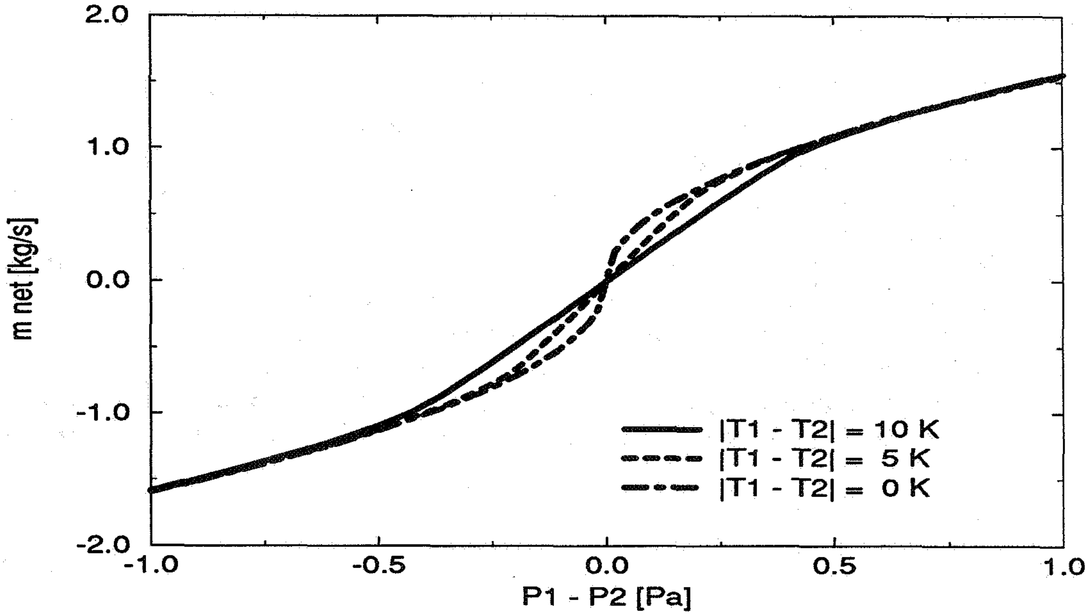

Figure 3 Net mass flow rate $\dot{m}_{net}$ (kg/s) vs pressure difference $P_1 - P_2$ (Pa) as a function of absolute temperature difference $|T_1(z_0) - T_2(z_0)|$ (K)

increase in temperature difference "smoothes" the transition from flow in the direction of $1 \rightarrow 2$ to the direction of $2 \rightarrow 1$ when ΔP changes from positive to negative.

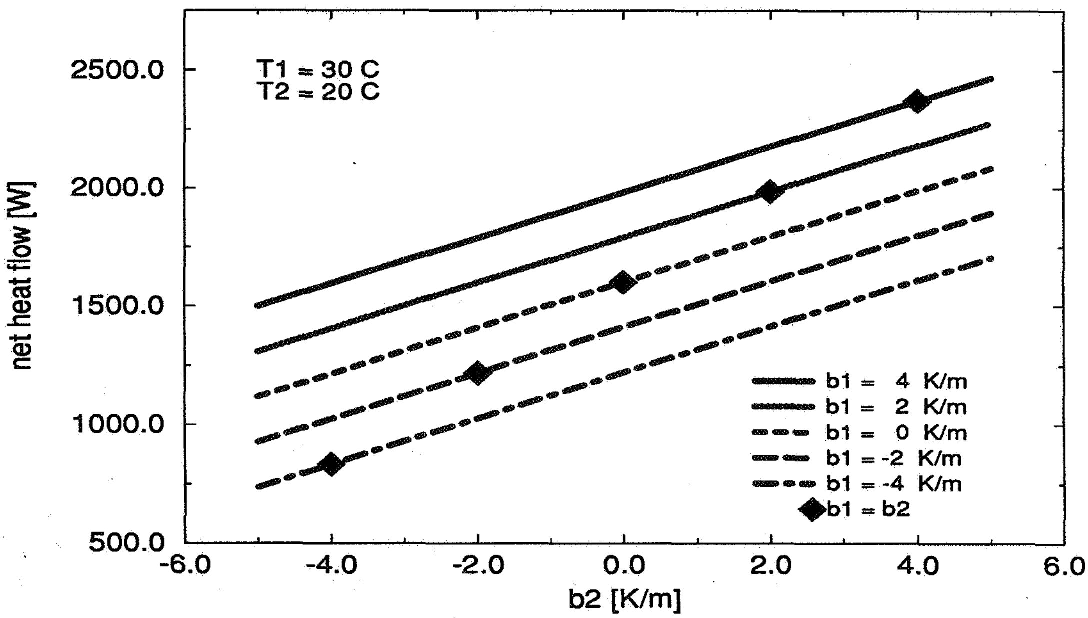

Figure 4 Net heat flow Φ_{net} (W) vs vertical temperature gradient b_2 (K/m) for zone 2 as a function of gradient b_1 (K/m) for zone 1; $\Delta P(z_0) = 0$ (Pa)

As indicated above, the mass flows are not influenced by the vertical temperature gradients. This is clearly not the case for the heat flows as can be seen in Figure 4. This figure shows the net heat flow (ie $\Phi_{net} = \Phi_{12} + \Phi_{21}$) between zone 1 and zone 2, assuming that the reference temperature in zone 1 is 30 $°C$ and is 20 $°C$ in zone 2. For this case there is no pressure difference at reference height; ie $\Delta P(z_0) = 0$ Pa. From Figure 4 follows that net heat flow for this case would be $\approx 1600\ W$ when the temperature gradients would not be taken into account (ie $b_1 = b_2 = 0\ K/m$). If there would only be a gradient in one of the zones (eg $b_1 = 0$ and $b_2 \neq 0$) then (for this particular case) the change in net heat flow is about $100\ W$ for each unit change in vertical temperature gradient. If both gradients are non-zero then the changes can even be bigger as can be seen in Figure 4. For instance for a common case where there are vertical temperature gradients of $\approx 1\ K/m$ in each zone, then the net heat flow would be $\approx 1800\ W$ instead of $1600\ W$, which is a difference of 12%.

5 DISCUSSION

In the literature a number of natural convection configurations are presented where air temperature stratification was observed to be important (Allard et al. 1992, Ch2 and 3). To handle these situations it is important to know when temperature stratification in buildings occurs and how its magnitude could be estimated or predicted. Some examples are therefore briefly discussed. However, all these situations concern zero net flow because other configurations have not been studied in detail in the literature.

Balcomb (1984 and White et al. 1985) studied the heat distribution in more than ten full scale passive solar buildings. He recognized that the heat flow through internal doors (for example to a sunspace) is proportional to the difference in the mixed mean temperatures of the upper and the lower air streams in the opening, T_d, rather then to T, which is the difference between the mean temperatures of the connected zones. He found invariably that in these buildings the ratio T_d/T was large and typically 1.3 (and as high as 1.6) during the day, for a T ranging between 3 and 12 K. Assuming linear air temperature gradients in the zones (typically 1 to 2 K/m) Eq. [3] was used (White et al. 1985) to calculate the heat flow from the measured temperatures and velocities. It was suggested that the degree of stratification will depend on the rate of heat exchange but no method was proposed to predict stratification.

Boardman (1989, Scott et al. 1988, Neymark et al. 1989) studied the influence of aperture dimensions on interzonal natural convection in experiments on both an air filled full scale enclosure and a waterscale model. During each run the temperature difference between the hot wall in the hot zone and the cold wall in the cold zone, ΔT_{hc}, was kept constant. In this way heat flow through a door in a solar house was simulated. To describe the experimental results an isothermality factor is defined as $q = \Delta T/\Delta T_{hc}$ where ΔT is the difference between the mean air temperatures in each zone. While the mean zonal temperature difference ΔT was initially close to ΔT_{hc} ($q = 1$), increasing the opening height caused both the temperature gradients b_1 and b_2 to increase and q to approach zero. The temperature drop ΔT_{hc} was finally concentrated in the boundary layers near the hot and cold walls. Using Eq. [3] for the heat flow gave consistent results. From the assumption that stratification scales linearly with the overall length scales and temperature differences, the gradients are written as (Scott et al. 1988):
$b_1 + b_2 = F(\Delta T_{hc}/h)(1 + h/h_r)$ (h is door height and h_r is the room height). Comparing the thermal resistances of the door and the wall boundary layer, the data analysis yielded $F = 0.3$, in other words $(b_1 + b_2)$ was between one and two thirds of $\Delta T_{hc}/h$, the theoretically maximum of the gradient in the opening. Although, the result seems only strictly valid for the configuration of the experiment, it helps to understand how temperature gradients are set up in buildings and what their order of magnitude can be.

Allard et al. (1992) report on test-cell experiments to study mass and heat transfer through open doors under different heating and cooling configurations.

In the first test-cell (Allard et al. 1992, Ch.3.2), the interzone temperature difference is created using heating and cooling plates and the door height is 2 m. The temperature gradients b_1 and b_2 were typically 3 K/m, for a ΔT of about 2 K, and the heat flow increasing factor (Eq. 3b), becomes as high as 2.8. However from the measured velocity profile, it was found that the discharge coefficient is $C_d = 0.3$ rather than 0.6.

In the second test-cell (Allard et al. 1992, Ch.3.3), the interzone temperature difference over the 2 m high door is created using a hot and cold wall, a configuration similar to Boardman's (1989, Scott et al. 1988, Neymark et al. 1989). Varying ΔT_{hc} over the range -5 to 30 °C, the isothermality factor q stayed close to 0.1. The gradient was roughly linear ranging between 0.5 and 4 K/m. Using Boardman's model $b_1 + b_2 = F(\Delta T_{hc}/h)(1 + h/h_r)$ it is noted that in all 5 experiments the gradient scaled with ΔT_{hc}. Forcing over the height of the doorway, a straight line through the data, a factor $F = (0.23 \pm 0.3)$ is obtained with an uncertainty on the fitting procedure of an additional ±0.5 K/m. However from the measured velocity profiles, discharge coefficients between 0.27 and 0.54 were derived without an apparent correlation with the experimental configuration.

These two cases show clearly that for the configuration with hot and cold walls the temperature stratification can be estimated, but that the use of Eq. [3] without detailed knowledge on both b and C_d (Pelletret et al. 1991) imply large uncertainties in the heat flow calculation.

Studies of the temperature stratification in closed rooms and for various heater configurations are quite numerous in the literature (see References in (Inard 1988) and (Inard and Buty 1991). The stratification varies strongly. For example for the case of floor heating it is weakest and for ceiling heating it is strongest. For the case of the convective heater, the gradient in test cells was found to be correlated with the convective heating power (Inard 1988). In addition to this, Allard et al. (1992, Ch.4.5) pointed out that there is an analogy between a convective heater and an open door or window in the sense that the stratification caused by open windows appeared to vary with power as in (Inard 1988) when the ventilative cooling power is used). This idea has not been worked out however. In particular the gradient must be correlated with the floor area and depend on the power density rather than on power.

To cope with these uncertainties and to better understand the dependence of both the discharge coefficient and the stratification on the heating and cooling configuration, Allard et al. (1992, Ch.3.5 and 3.7) proposed that future work should include a systematic comparison between numerical computations (CFD) and simplified models.

Finally, this means that although the use of the new algorithm in ESP-r requires expertise at present in the form of input parameters b and C_d, it can be expected that models will be developed that are able to predict stratification for each particular zonal configuration.

5 CONCLUSION

A general solution is presented for predicting (net) airflow and (net) heat flow through large vertical openings between stratified building zones. The solution proved to be compatible with a nodal network description of leakages for multizone modelling of airflow in buildings. By parametric analyses, the relative importance of the flow governing variables is demonstrated. From the results it is clear that - apart from the other governing variables like pressure and temperature difference - vertical air temperature gradients have a major influence on the heat exchange by inter-zonal airflow.

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