# Air and Heat Flow through Large Vertical Openings

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*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. 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.*

## Symbols

| | |
|---|---|
| $a_i$ | temperature profile coefficient for zone $i$ $(K)$ |
| $b_i$ | temperature gradient in zone $i$ $(K/m)$ |
| $C_d$ | discharge coefficient $(-)$ |
| $c_p$ | specific heat of air $(J/kgK)$ |
| $g$ | acceleration of gravity $(m/s^2)$ |
| $h$ | aperture height $(m)$ |
| $M$ | molecular mass of air $(kg/kgmole)$ |
| $\dot{m}_{ij}$ | air mass flow from zone $i$ to zone $j$ $(kg/s)$ |
| $P$ | pressure $(Pa)$ |
| $\dot{q}_{ij}$ | air volume flow from zone $i$ to zone $j$ $(m^3/s)$ |
| $P_{ref}$ | reference pressure $(Pa)$ |
| $R$ | universal gas constant $(J/kgmole\,K)$ |
| $T$ | temperature $(K)$ |
| $u$ | horizontal air velocity $(m/s)$ |
| $W$ | aperture width $(m)$ |
| $z$ | height coordinate $(m)$ |
| $z_n$ | height of neutral level $(m)$ |
| $z_0$ | height of reference level $(m)$ |
| $z_b$ | height of bottom of aperture $(m)$ |
| $\Phi_{ij}$ | heat flow from zone $i$ to zone $j$ $(W)$ |
| $\rho$ | air density $(kg/m^3)$ |
| $\xi$ | integration variable $(m)$ |
| $\alpha$ | $\equiv (z_0 - z_b)/h$ $(-)$ |

$$C_a \equiv \Delta P(z_b + h)\ (Pa)$$

$$C_b \equiv \Delta P(z_b)\ (Pa)$$

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

$$K \equiv P_{ref}\,M/R\ (Pa\,kgK/J)$$

$$Z_a \equiv \frac{2\sqrt{2}}{3}\frac{C_d hW}{C_t}\,C_a^{3/2}\ (m^2 Pa^{1/2})$$

$$Z_b \equiv \frac{2\sqrt{2}}{3}\frac{C_d hW}{C_t}\,C_b^{3/2}\ (m^2 Pa^{1/2})$$

## INTRODUCTION

Airflows 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

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approach for predicting airflow and heat flow through large vertical openings between stratified zones.

**Net Heat Flow when Zero Volume Flow**

For the mass and heat transfer through large vertical openings, Balcomb et al. (1984) and others like 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 $\Delta T$ 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 $\Delta T$ is independent of the height coordinate $z$, ie that temperature gradients 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 $\Phi_{21}$ 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 $\Phi_{12}$ from the colder zone (1) to the warmer zone (2) takes place *below* the *neutral level*. These contributions are given by:

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

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

Balcomb's expression for the *net heat flow* through the aperture is obtained by inserting the expression for $u(z)$ into the expressions for $\Phi_{21}$ and $\Phi_{12}$, thereby assuming that the temperature profiles in both zones are linear, ie $T_i(z) = a_i + b_i z$, 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:

$$\Phi_{12} + \Phi_{21} = \frac{C_d \rho c_p W}{3} \sqrt{\frac{g}{T}} h^{3/2}\Delta T^{1/2} *$$

$$* \left[ \Delta T + 0.3h(b_1 + b_2) \right] \quad (W) \qquad [3]$$

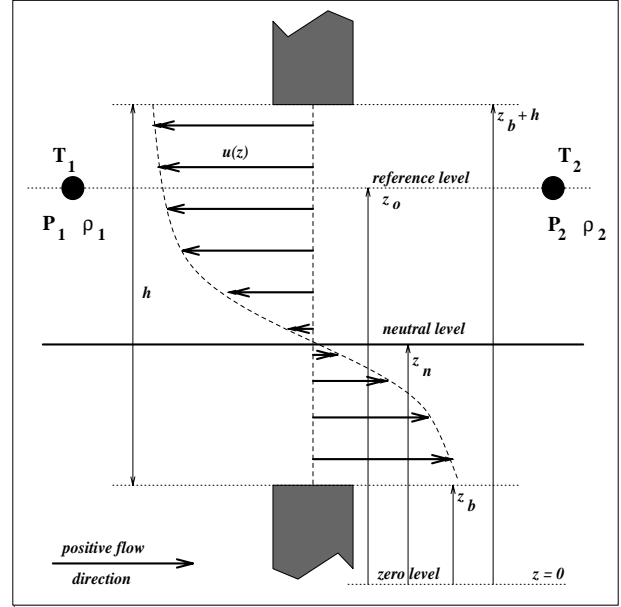and is good approximation when the thermal gradients in both zones are equal, and not too large.



Figure 1 Definition of various parameters

From equation [3] it is seen that by including the temperature gradients $b_1$ and $b_2$ the heat flow is increased by the factor $\left[ 1 + \dfrac{0.3 \, h(b_1 + b_2)}{\Delta T} \right]$. In practice $b_1$ and $b_2$ are not well known, but the importance of this correction factor for small $\Delta T$ shows the need to include the effect of stratification in building energy simulation environments like ESP-r.

**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:

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

Although density variations due to pressure variations are negligibly 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:

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

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:

$$\Delta P(z) - \Delta P(z_0) =$$

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

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

$$\Delta P(z) - \Delta P(z_0) =$$

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

$$= \cdots\cdots\cdots\cdots$$

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

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:

$$\Delta P(z) - \Delta P(z_0) \approx$$

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

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 equation [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 equation [6] gives:

$$\Delta P(z) - \Delta P(z_0) \approx$$

$$\approx gK\left(\frac{1}{T_2(z_0)} - \frac{1}{T_1(z_0)}\right)(z - z_0)$$

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

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 $(T_i(z) - T_i(z_0))/2\,T_i(z_0)$. 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:

$$\Delta P(z_b) = \Delta P(z_0) + \quad\quad\quad [7a]$$

$$+ gK\left(\frac{1}{T_2(z_0)} - \frac{1}{T_1(z_0)}\right)(z_b - z_0) \quad (Pa)$$

and at the top of the opening:

$$\Delta P(z_b + h) = \Delta P(z_0) + \quad\quad [7b]$$

$$gK\left(\frac{1}{T_2(z_0)} - \frac{1}{T_1(z_0)}\right)(z_b + h - z_0) \quad (Pa)$$

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:

$$\dot{m}_{21} = \int_{z_n}^{z_b+h} \rho_2 d\dot{q} =$$

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

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

$$\dot{m}_{12} = \int_{z_b}^{z_n} \rho_1 d\dot{q} =$$

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

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:

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

$$C_a \equiv \Delta P(z_b + h) \quad (Pa)$$

$$C_b \equiv \Delta P(z_b) \quad (Pa)$$

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:

1st 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.

2nd 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:

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

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

As the direction $1 \to 2$ 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 quantites $Z_a$ 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 $1 \to 2$), on the positive imaginary axis (when there is a unidirectional flow $2 \to 1$), 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.

**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 $\Phi_{12}$ and $\Phi_{21}$ 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 calculated by evaluating integrals of the type:

$$\int c_p T_i(z) \rho_i(z) d\dot{q} =$$

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

in an analogous way.

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 (we will gladly provide the full derivation to readers wishing to obtain this material). 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 $\Phi_{12}$ and $\Phi_{21}$, namely:

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

$$\Phi_{12} = c_p \sqrt{\rho_1} * \qquad\qquad\qquad [12a]$$

$$* \, \mathrm{Re}\,(\tilde{T}_{1a}(z_0) Z_a - \tilde{T}_{1b}(z_0) Z_b) \quad \geq 0 \quad (W)$$

$$\Phi_{21} = - c_p \sqrt{\rho_2} * \qquad\qquad\qquad [12b]$$

$$* \, \mathrm{Im}\,(\tilde{T}_{2a}(z_0) Z_a - \tilde{T}_{2b}(z_0) Z_b) \quad \leq 0 \quad (W)$$

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 $\alpha$ is a dimensionless reference height ($\alpha \equiv (z_0 - z_b)/h$), and the densities $\rho_1$, respectively $\rho_2$, are evaluated at the reference level $z_0$.

**APPLICATION**

Equations [11] and [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 $W = 1.0 \; m$, heigth $h = 2.0 \; m$, 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.
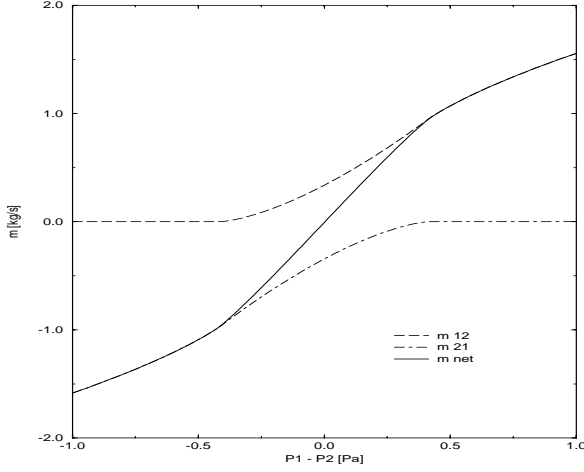


Figure 2 Mass flow rate $\dot{m}$ $(kg/s)$ vs pressure difference $P_1 - P_2$ $(Pa)$ for $|T_1(z_0) - T_2(z_0)| = 10 \; K$

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 equation [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 $\Delta P$ 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 $\Phi$ (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 increase in temperature difference "smooths" the transition from flow in the direction of $1 \to 2$ to the
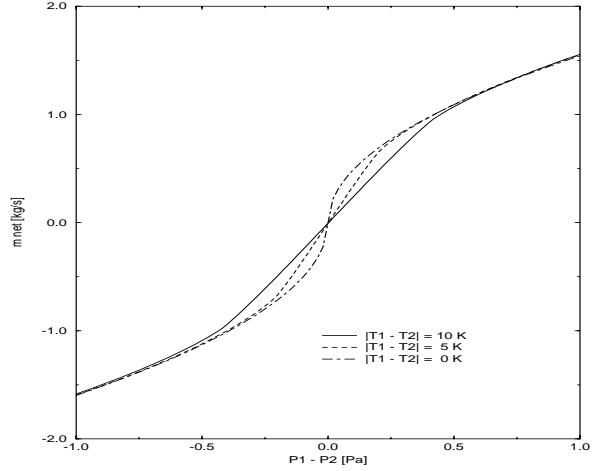


Figure 3 Net mass flow rate $\dot{m}_{net}$ $(kg/s)$ vs pressure difference $P_1 - P_2$ $(Pa)$ as a function of absolute temperature difference $|T_1(z_0) - T_2(z_0)|$ $(K)$

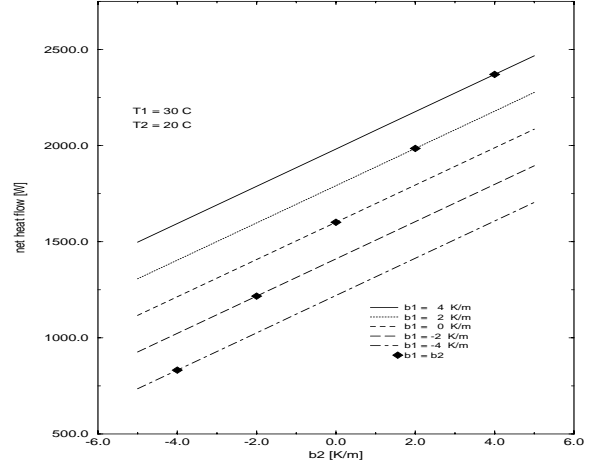direction of $2 \to 1$ when $\Delta P$ changes from positive to negative.



Figure 4 Net heat flow $\Phi_{net}$ $(W)$ 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 $^\circ C$ and is 20 $^\circ C$ 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%.

**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 airflows.

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