HEAT TRANSFER THROUGH A HORIZONTAL APERTURE CONNECTING TWO NON ISOTHERMAL ROOMS

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ABSTRACT

This paper deals with the convective flow through a horizontal aperture connecting two superimposed large enclosures which are kept at different temperatures. The lower room is warmer than the upper room and this unstable thermal configuration generates a natural thermosyphon flow, between both volumes. This type of flow can occur inside buildings : stairwell flows or natural ventilation flows through horizontal openings.

In the literature, very little information is available concerning this domain of applications. We carried out a full-scale experimental study in order to determine the heat transfer rate and to point out the influence of the aperture area, the aperture location, the aperture thickness and the presence of a stairwell.

KEYWORDS

Natural ventilation, natural convection, convective heat transfer, full-scale experiment.

INTRODUCTION

We investigate the natural turbulent convective flow between two rooms separated by a horizontal partition with a square opening ; the lower room is kept warmer than the upper room.This type of flow can occur inside buildings : stairwell flows or natural ventilation flows through horizontal openings.

Literature is rather poor on this subject. Previous works are due to Brown (1961) and Epstein (1988). Their studies were achieved using scale models for high values of the aspect ratio, e/D ; in this case the flow is mainly governed by viscous forces along the walls of the partition aperture. Blay (1994), carried out experiments for smaller values of e/D in a water scale model. Flow visualizations pointed out the complexity and the unstability of the flow in the aperture where both cold and warm fluids fully interpenetrate each other. More globally, the flow appears to look like two symmetrical plumes issuing from the partition aperture acting itself as a virtual reservoir maintained at the average temperature of both rooms. In a more recent work, Blay (1998) carried out experiments and direct numerical simulations in the case of a 1m high air filled cavity partitioned into two compartments communicating through a square opening (Rayleigh number comprised between 10^9 and 4.10^9). These last two works showed that, for small values of e/D (which is the case for the present applications), the thermosyphon flow is controlled by buoyancy effects rather than friction forces along the aperture walls. Consequently, the main governing parameters are the ΔT between both rooms and the room height but not the partition thickness as assumed by Brown (1961).

In order to complete the studies achieved on scale models, a full-scale experiment was carried out. We present in this paper some results which confirm the previous analysis and precise the influence of the dimensions and the position of the aperture as well as the influence of a stairwell.

THEORETICAL ANALYSIS

Considering that the flow is similar to a plume flow, we assume that the mean velocity, V, through the aperture can be written as :

$$V = k\sqrt{g\beta \Delta T H} \qquad (1)$$

In a dimensionless form, this velocity is equal to Reynolds number :

$$Re = \frac{H.V}{\nu} = kGr^{1/2} \qquad (2)$$

Introducing the Froude number, $Fr = \frac{Re}{Gr^{1/2}}$, we obtain :

$$Fr = k \qquad (3)$$

The heat transfer through the aperture is given by the Nusselt number :

$$Nu = \frac{h.H}{\lambda} \quad (4)$$

$$h = \frac{Q}{A.\Delta T} = \rho c_p V \quad (5)$$

From equations (1), (4), (5), it follows that:

$$Nu = k\,(Ra.Pr)^{1/2} \quad (6)$$

The objective of the present study is to determine the influence of the aperture geometry *(D/H, e/H)* on the coefficient *k*..

EXPERIMENTS

Test apparatus

Experiments were performed on an experimental set-up composed of two superimposed square rooms (2.75m high, 4m side) separated by a horizontal partition with a rectangular aperture of variable area ($0.09m^2 < A < 0.86m^2$), as shown in figure 1. The lower room was thermally insulated and warmed using an electrical heater located on the floor, along a wall. The upper room was naturally cooled and maintained at a constant but lower temperature.

24 K-thermocouples were used to measure temperature in both rooms. Characteristic vertical temperature profiles obtained at steady state conditions are given in figure 2. Plume temperatures were measured along the room axis ; room temperature vertical profiles were determined at mid-distance between the aperture and the wall facing the heater.

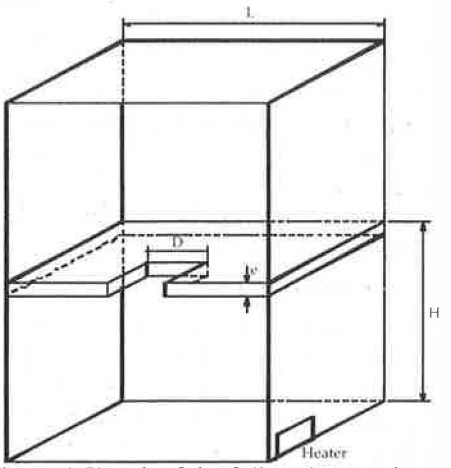

Figure 1 Sketch of the full-scale experiment (half part)

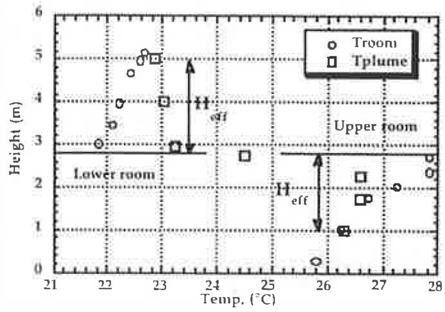

Figure 2 Vertical temperature profiles. Electrical input = 400 W.

These temperature profiles show that the driving temperature difference between the plume axis and the room vanishes at an intermediary height, H_{eff}. This means that the physical height which as to be considered as the characteristic length in the determination of the velocity is H_{eff}. Actually, equation 1) should be written as :

$$V = k_1 \sqrt{g\beta \Delta T H_{eff}}$$

But considering that the efficient height, H_{eff}, is a function which is dependent on the problem parameters :

$$\frac{H_{eff}}{H} = f(Ra, Pr, \frac{D}{H}, \frac{e}{H}, \frac{L}{H}) = k_2^2$$

We obtain $V = k\sqrt{g\beta \Delta T H}$

with $k = k_1 k_2$.

$k = k\,(Ra, Pr, D/H, e/H, L/H)$.

Experimental procedure

The procedure which was used to determine this velocity coefficient, *k*, lies on a thermal balance. For symmetry reasons the thermal balance was only established in the lower room. For a given set of parameters, two series of measurements were performed.

1) First step, the aperture is closed with insulating materials. For a given heater input, it is waited for steady state conditions. Air and wall temperatures are then measured. At equilibrium, the electrical input balances the heat losses through the walls. This allows to determine the room heat loss coefficient.

2) Second step, the aperture is opened and it is waited for the new steady state conditions for the same value of the heater input. New steady room temperatures are measured.

From the thermal balance, we can derive the convective heat transfer through the aperture:

$$Q_{conv} = Q_{in} - Q_{cond} - Q_{rad}$$

Q_{in} is the electrical input measured with a wattmeter,

Q_{cond} is the conductive heat loss calculated using the heat loss coefficient determined in step 1 and the new steady temperatures,

Q_{rad} is the net radiative loss through the aperture. It is calculated using measured wall temperatures and view factors.

$$Q_{conv} = \rho c_p A V \Delta T \qquad (7)$$

Using equations 1 and 7 allows to determine the coefficient k :

$$k = \frac{Q_{conv}}{\rho c_p A (g\beta H)^{1/2} \Delta T^{3/2}} \qquad (8)$$

RESULTS

Influence of temperature difference

We first pointed out the influence of the average temperature difference between both rooms on the convective heat flow. This experiment was conducted in the case of a centered square aperture with an area of 0.86 m^2. The parameter values were the following :

D = 0.927 m
e = 0.355m
H = 2.75m
L =4m
D/H = 0.337 e/H = 0.129 L/H = 1.454
$10^{12} < Ra < 3.0^{12}$

Results are given in table 1 and figure 3. They show that the convective heat transfer is proportional to $\Delta T^{1/2}$ as assumed in equation 1, $V = k\sqrt{g\beta\Delta TH}$.

The value of the velocity coefficient, k, is :
k = 0.076± 16%

Electrical input (W)	ΔT (°C)	Total heat losses (W)	Conv. heat transfer (W)
200	**2,6**	110	**90**
302	**3,7**	149	**150**
400	**3,6**	233	**167**
710	**6,6**	331	**379**

Table 1 Convective heat transfer vs ΔT

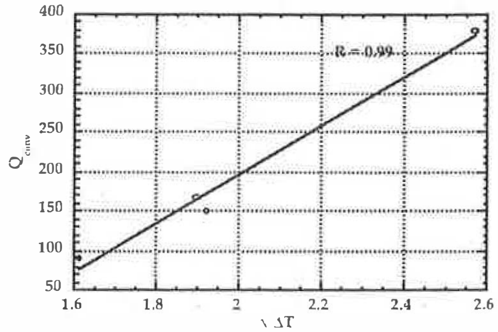

Figure 3 Convective heat transfer vs temperature

Influence of aperture area

We investigated the influence of the aperture area on this velocity coefficient for two positions of the aperture : case 1 , the aperture is located in the middle of the partition ; case 2, the aperture is located in a corner of the partition as shown in figure 4.

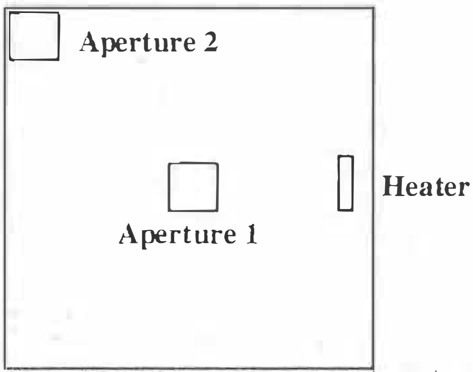

Figure 4 Location of the apertures in the partition plane *(the heater is placed on the floor)*

Several experiments were performed for an area varying from 0.09m^2 up to 0.86 m^2 in the case of aperture 1, and for an area varying from 0.18m^2 up to 0.43 m^2 in the case of aperture 2. Results are given in table 2a and 2b and figure 5.

A (m^2)	D/H	k
0.09	0.109	0.025
0.21	0.167	0.043
0.42	0.236	0.066
0.70	0.304	0.070
0.86	0.337	0.077

Table 2a Velocity coefficient vs aperture area. Centered aperture

A (m^2)	*D/H*	*k*
0.18	0.154	0.049
0.27	0.189	0.054
0.43	0.24	0.074

Table 2b Velocity coefficient vs aperture area. Aperture located in the corner.

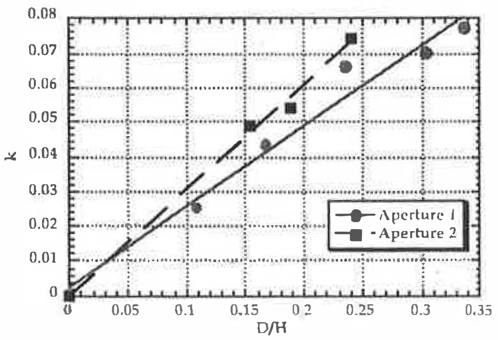

Fig. 5 Velocity coefficient vs aperture area

It appears that the velocity coefficient is about 30 % greater in the case of a lateral opening. This is due to the structurating influence of the walls which was also noticed during flow vizualisations.
In both cases, results show that the velocity coefficient is a linear function of the aperture aspect ratio D/H :

Centered aperture : $k = 0.234\frac{D}{H}$

Lateral aperture : $k = 0.303\frac{D}{H}$

Influence of the aperture thickness

In order to point out the influence of the aperture thickness several experiments were carried out for different types of apertures as shown in figure 6 (A=0.70m^2). Results are given in table 3.
Taking into account measurement errors, (about 15%), we may conclude that the partition thickness has no major influence on the velocity coefficient *k*.

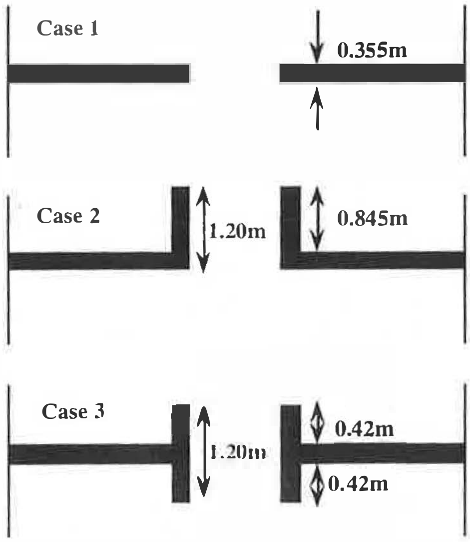

Figure 6 Sketch of the different apertures

	e/H	*k*
Case1	0.129	0.0700 ± 0.01
Case 2	0.436	0.0563 ± 0.01
Case 3	0.436	0.0657 ± 0.01

Table 3 Velocity coefficient vs aperture thickness

Influence of a stairwell

In order to point out the influence of a stairwell on the flow through the aperture, a complementary experiment was carried out in the case of the aperture located in the corner of the partition (A=0.46m^2). The stairwell was located along the vertical wall as shown in figure 7. It was made of a smooth inclined plane (no steps).
From results (table 4a et 4b, figure 8), the following velocity coefficients were found :

No stairwell : k = 0.074± 15%

With stairwell : k = 0.051± 15%

This shows that in spite of its structurating effect on the flow, the stairwell induces a supplementary pressure drop which slows down the flow by about 30%.

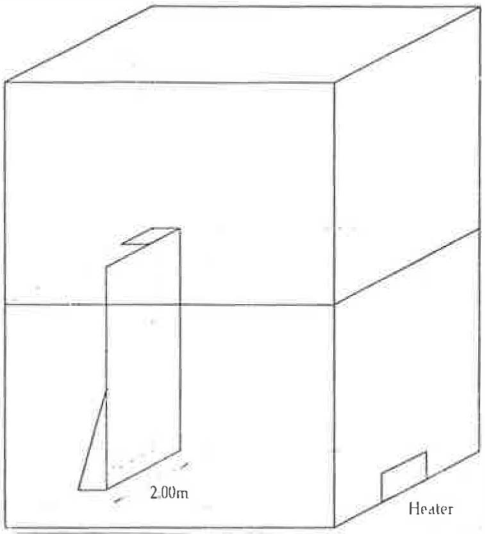

Figure 7 Sketch of the experiment with the stairwell.

Electrical input (W)	$\Delta T(°C)$	Conv. heat transfer (W)
405	**5.6**	**133**
600	**7.6**	**228**
820	**9.5**	**330**

Table 4a Convective heat transfer vs ΔT. Case without a stairwell

Electrical input (W)	$\Delta T\,(°C)$	Conv. heat transfer (W)
405	**6.55**	**105**
615	**9.7**	**219**
820	**11.6**	**302**

Table 4b Convective heat transfer vs ΔT. Case with a stairwell

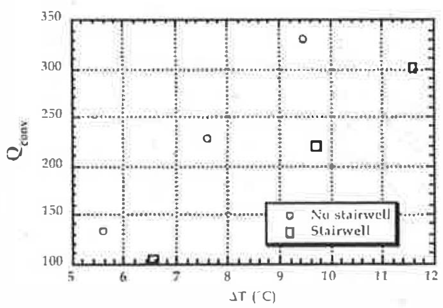

Figure 8 Convective heat transfer vs ΔT

CONCLUSION

Full-scale experiments were carried out in order to get a better understanding of the natural thermosyphon flow between two rooms at different temperatures communicating through a horizontal aperture.

We first pointed out that the flow was governed by buoyancy forces and that the flow structure corresponds to two symmetrical plumes issuing from the aperture. Flowrate and heat transfer rate through the horizontal aperture are defined by Froude and Nusselt numbers :

$$Fr = k$$

$$Nu = k\,(Ra.\,Pr)^{1/2}$$

where k is a coefficient depending mainly on the aperture geometry and location.

Second, we determined this velocity coefficient k. for different values of the room temperature difference of the aperture size and of the aperture location. It was found that :

- the convective heat transfer rate is proportional to the square root of the room temperature difference

- the mean velocity in the aperture is given by :

$$V = k\sqrt{g\beta \Delta T H}$$

- the velocity coefficient k depends on the aperture size :

Centered aperture ($0.11 < D/H < 0.34$)

$$k = 0.234\frac{D}{H}$$

Corner aperture ($0.15 < D/H < 0.24$)

$$k = 0.303\frac{D}{H}$$

- the partition thickness (in the range $0.13 < e/H < 0.44$) has no signigficant influence on the velocity coefficient k,

- the presence of a stairwell reduces the flowrate through the aperture by 30%.

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SYMBOLS

A	aperture area
D	partition side length
e	partition thickness
g	gravity acceleration
Fr	Froude number, $Fr = \frac{Re}{Gr^{1/2}}$
Gr	Grashof number, $Gr = \frac{g\beta\Delta TH^3}{\nu^2}$
H	room height
h	heat transfer coefficient
L	room length
Pr	Prandtl number, $Pr = \frac{\mu c_p}{\lambda}$
Q_{conv}	convective heat transfer rate through the aperture
Ra	Rayleigh number, $Ra = \frac{g\beta\Delta TH^3}{\nu\alpha}$
Re	Reynolds number, $Re = \frac{H.V}{\nu}$
T_c	temperature of the cold room
T_h	temperature of the warm room
V	average velocity in the aperture
β	expansion coefficient
ΔT	room temperature difference, $\Delta T = T_h - T_c$

REFERENCES

Brown W. (1961) Natural convection through rectangular openings in partitions. *Int. J. Heat & Mass Trans.* vol.5,pp.869-878.

Epstein M. (1988) Buoyancy driven exchange flow through small openings in horizontal partitions. *Journal of Heat Transfer*, vol.110, pp885-893.

Reynolds A.J., Mokhtarzadeh M.R., Zohrabian A.S. (1988) The modelling of stairwell flows. *Building and Environment*, vol.23, n°1, pp. 63-66.

Blay D., Gautier B. (1994) Fluid flow through a horizontal aperture between two enclosures at different temperatures. *Roomvent'94*, Cracovie, Poland.

Blay D., Le Quéré P. (1998) Fluid flow through a horizontal aperture between two enclosures at different temperatures. *Int. Turbulent Heat Transfer Conference*, Manchester, UK.