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EXPERIMENTAL SIMULATIONS OF VENTILATION MODES IN DOUBLE-SKIN ENVELOPES

BY

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An experimental study of a heated vertical plane channel, representative of double-skin envelopes, was undertaken. The study was focused on the dynamics of the natural convection flow resulting from the uniform heating of one of the walls on its central part. Only the convective aspects related to natural ventilation are studied by carrying out the experiments in water in order to neglect radiation. Flow visualization techniques made it possible to show the strongly unsteady and three-dimensional character of the resulting flow and to observe the presence of a reverse flow of variable length on the studied range of modified Rayleigh numbers $10^6 \leq \Re a^* \leq 2 \times 10^7$.

1. Introduction

This experimental work lies within the scope of studies undertaken by the French network of laboratories called AMETH (Amélioration des Echanges THermiques) supported by CNRS. One of the research topics of the network relates to the reduction in overheatings of roofs in summer period, *via* the study of flow patterns within envelopes of double-skin type. Reliable numerical modellings of the thermo-aerodynamic behaviour of such walls require the development of experimental set-ups in order to obtain both thermal and dynamic data necessary to their validation. The study of the natural convection in a heated plane channel, representative of these walls, constitutes the essence of our experimental contribution to the network.

The convective heat transfer in a heated or cooled vertical channel has been extensively studied since nearly fifty years. Two main flow regimes in a vertical channel were observed in experiments by E l e n b a a s [2], whose appearance has been noticed to be Rayleigh number dependent ($\Re a^*$ is partly based on the channel width and the aspect ratio between this width and the heated channel length). These main flow regimes were, respectively, a mode where the flow is fully developed in the channel (for low Rayleigh numbers (< 100)) and a mode where the flow is of boundary-layer type along the heated walls (for high Rayleigh numbers ($> 1,000$)). In the case of an asymmetrical heating (only one wall heated) and for sufficiently

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high Rayleigh numbers ($\Re a^* > 1,000$), the boundary-layer type flow regime is always present on the heated wall, and a reverse flow is also observed close to the unheated wall (A u n g *et al.*. [6]. [1]: W e b b and H i l l. [5]). However, although a great number of experimental studies concerning the vertical plane channel were carried out (Elenbaas, (*op. cit.*); W i r t z and S t u t z m a n, S p a r r o w *et al.*. [4]; Webb and Hill. (*op. cit.*)), most of them were limited to thermal measurements (for both Uniform Heat Flux and Uniform Wall Temperature problems). Very few studies were interested in the flow behaviour (Sparrow *et al.*, (*op. cit.*), O l s s o n, [3]). Thus, the objective of our work is to reproduce flow conditions similar to those of the experiments by Webb and Hill (*op. cit.*) established from a thermal viewpoint, in order to extend the analysis to the flow dynamics. Only convective effects related to natural ventilation are studied in the present paper. It is the reason why the study is carried out in water, in order to neglect the radiative effects.

2. Experimental Device

2.1. Geometry of the Channel

The experimental channel consists of a wall which is heated on its central part ($A = 180$ mm) and two adiabatic extensions (height, $A/2$), respectively, located at both the entry and the exit of the channel. The opposite wall is entirely adiabatic and its height is $2A$. The distance, b, between the two walls is adjustable by using end plates of variable size (Fig. 1).

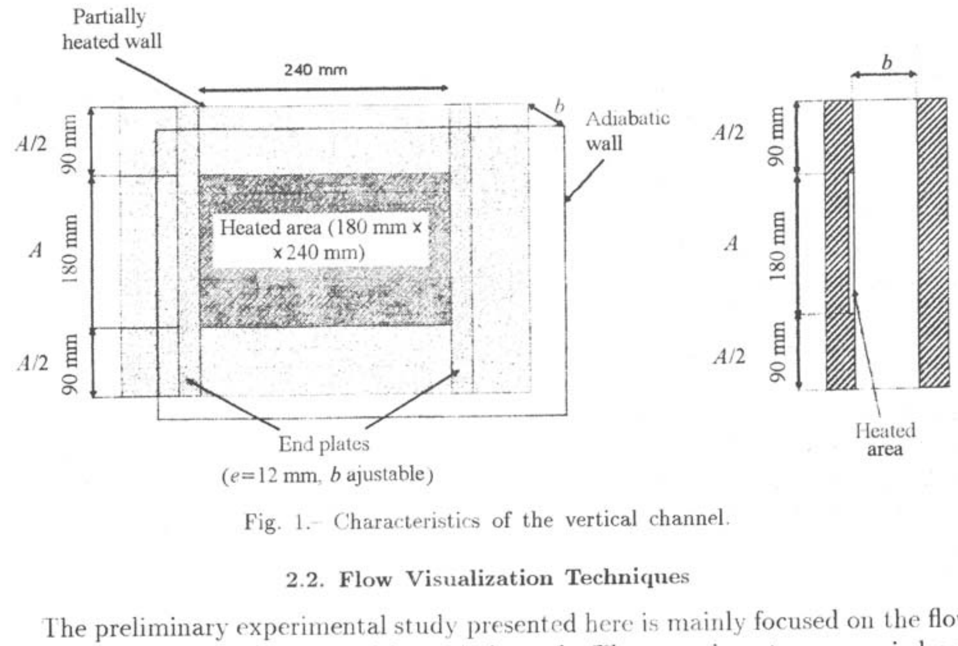


Fig. 1.– Characteristics of the vertical channel.

2.2. Flow Visualization Techniques

The preliminary experimental study presented here is mainly focused on the flow dynamic features of the vertical heated channel. The experiments are carried out in a vertical tank ($50\times50\times100$ cm^3) filled with water, within which the channel is immersed. To simulate a solar flux on a wall or on a roof, a heating foil delivering a uniform heat flux density ($180 \leq \varphi_w \leq 3,600$ W.m^{-2}) has been used. To characterize the convective flow features, flow tomography has been used combined with two different techniques. The first consists of the use of discrete solid tracers which are fine suspended quasi-spherical Rilsan particles (1.06 g/cm^3). Deduced visualizations are used to provide the flow velocity field during the exposure time of the camera (MINOLTA Dimage 7i) from which one can deduce the streamline patterns (Fig. 2). The second technique employs two fluorescent tracers under laser excitation, namely fluorescein for the boundary layer type flow visualization and sulforhodamine for the reverse flow visualization (Fig. 3). Indeed, it is possible to clearly distinguish these two flows and to observe them simultaneously. These two visualization techniques are

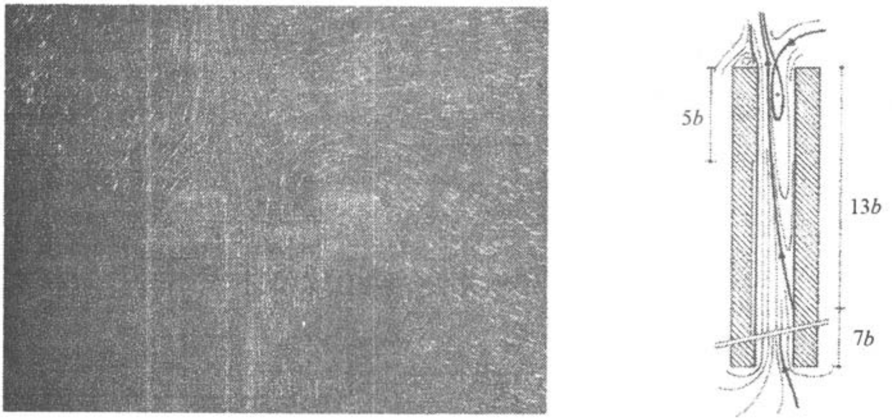


Fig. 2.- Flow visualization by solid particles at the exit of the channel (left) and corresponding streamline pattern in the whole channel (right) for $A/b = 10$.

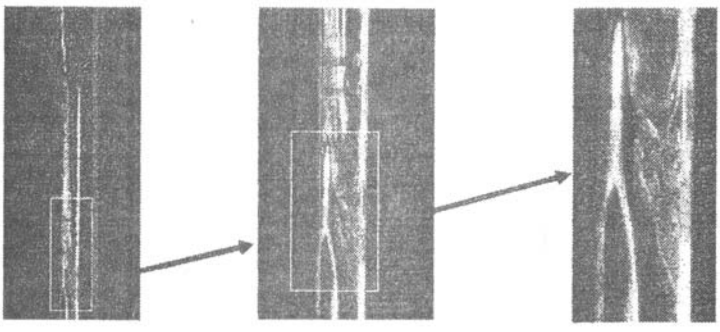


Fig. 3.- Details of the reverse flow with induced dynamic instabilities close to the adiabatic wall visualized by fluorescent tracers for $A/b = 10$.

used to obtain essential data concerning the convection flow features (such as the length of the recirculation zone and the flow pattern near the entry and exit of the test channel) to facilitate comprehension of ventilation mechanisms in double-skin envelopes for validation of numerical modellings.

2.3. Experimental Conditions

The experiments were undertaken for various values of the modified Rayleigh number ($\Re a^*$). This number, depending on both the channel width (b) and the aspect ratio of the heated part (A/b), is defined by the relation [1]

$$\Re a^* = \frac{g\beta\varphi_p b^4}{k\nu^2} \cdot \frac{b}{A}\mathcal{P}r, \tag{1}$$

where: g is the acceleration of gravity, β, k, ν and $\mathcal{P}r$ are, respectively, the volume expansion coefficient, the thermal conductivity, the kinematic viscosity and the Prandtl number of the fluid. φ_p is defined as the wall heat flux density. Five values of $\Re a^*$ were retained (10^6, 2×10^6, 5×10^6, 10^7 et 2×10^7), and were obtained by adjusting the thermal power delivered by the heating foil.

3. Results

3.1. Study of the Transient Regime

Initially we are interested in the establishing the convection channel flow after the start of the wall heating. The evolution of the dynamics of the flow during this transitional stage may be observed *via* flow visualizations by particles carried out in the middle plane of the channel.

Fig. 4 presents the flow structure in the whole channel for five different times from the origin ($t = 0$ s) which corresponds to the heating start. For this experiment, a modified Rayleigh number, $\Re a^* = 10^7$, and an aspect ratio, $A/b = 5$, were selected. At the very first moments ($t = 60$ s), one can observe a flow which goes up in the whole channel. Increasing the time, the ascending flow occupies all the width of the channel only in its lower part ($t = 100$ s). In the upper part, the ascending jet seems to be confined on the side of the partially heated wall. During the same time, the channel is fed with cold fluid from its upper part on the side of the adiabatic wall. This reverse flow is clearly evidenced from $t = 115$ s. The cold fluid goes down along the adiabatic wall for more channel height and then is swept along with the hot jet along the heated wall up to the channel exit. This phenomenon is accompanied by a separation of the ascending boundary layer type flow close to the adiabatic wall. At the following moments ($t = 170$ s and $t = 300$ s), one observes a flow behaviour which is seemingly stabilized. But, although the flows have similar overall structures at these two moments, strongly unsteady phenomena may be observed as well on the separation line between the hot jet and the reverse flow as within the reverse flow. This unsteady character had already been highlighted on the flow visualizations by fluorescent tracers (Fig. 3) carried out with a doubled aspect ratio ($A/b = 10$). One can note, in particular, the presence of instabilities of both gravitational and Kelvin-Helmholtz types.

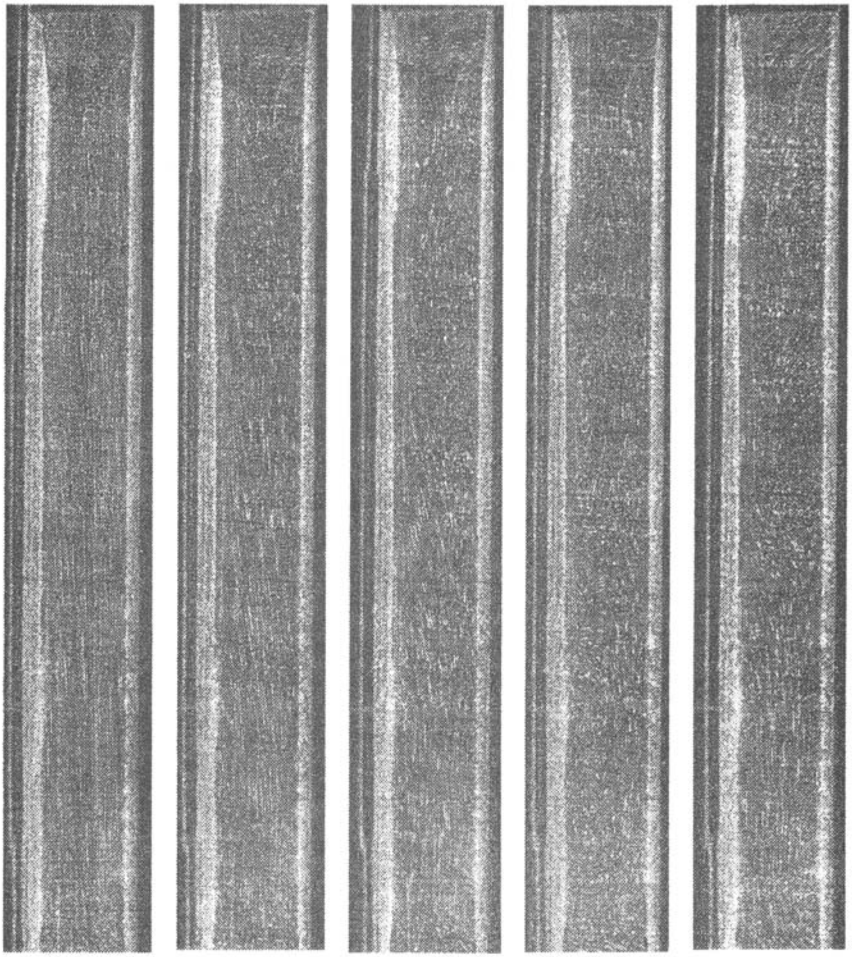
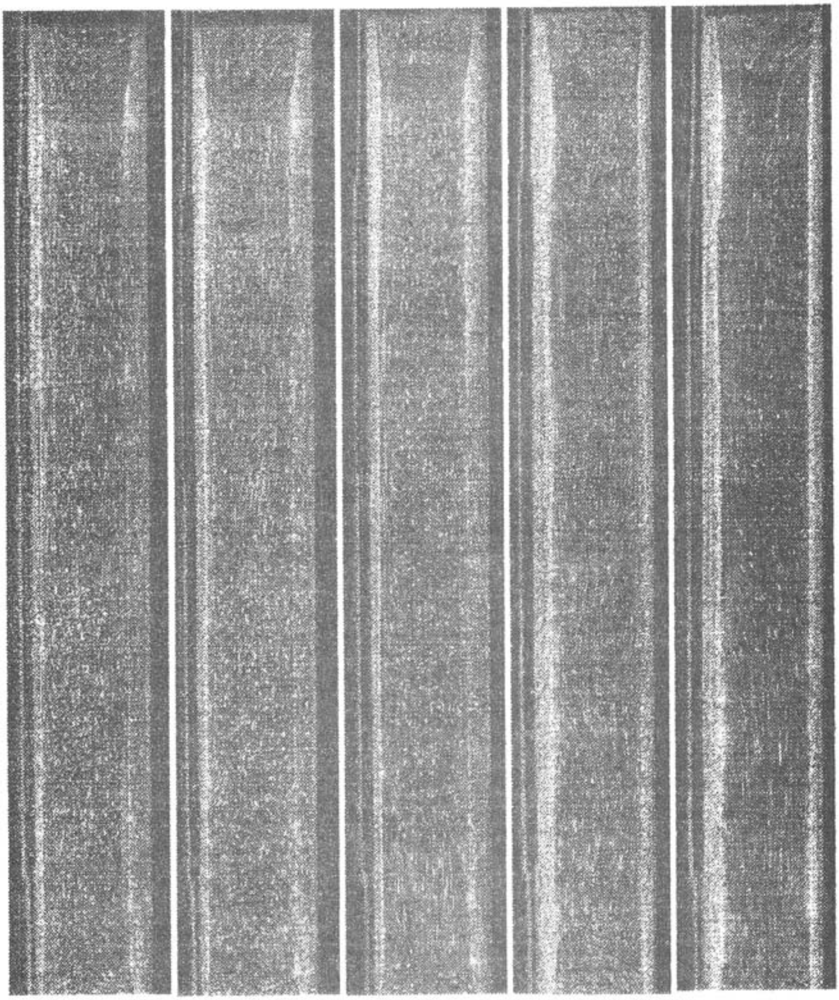


Fig. 4.– Flow visualizations by solid tracers in the whole channel at five consecutive times in the transient regime; $\Re a^* = 2 \times 10^7$ and $A/b = 5$.

3.2. Study of the Steady State

In the previous section we could observe that the flow structure, although strongly unsteady, was overall stabilized at about $t = 300$ s. Similar observation can be made for the four other experimental conditions for which only $\Re a^*$ is varying. On the other hand, this structure strongly depends on the value of the Rayleigh number. Fig. 5

allows a comparison of the dynamic characteristics at $t = 300$ s, always for $A/b = 5$. One observes different lengths of the recirculation zone for $\Re a^* = 10^6, 2 \times 10^6, 10^7$ and 2×10^7. The cold fluid penetration phenomenon from the upper part of the channel is highly evidenced. The case $\Re a^* = 5 \times 10^6$ is singular because one observe neither recirculation phenomena, nor penetration of cold fluid from the upper part of the channel. In addition, some of the dynamic structures observed for the various experimental conditions suggest a three-dimensional behaviour, as confirmed with the rotating cell shape which is present at the first lower third of the channel for $\Re a^* = 10^7$.



$\Re a^* = 10^6$ $\Re a^* = 2 \times 10^6$ $\Re a^* = 5 \times 10^6$ $\Re a^* = 10^7$ $\Re a^* = 2 \times 10^7$

Fig. 5.– Visualizations by discrete tracers of the flow in the whole channel in stabilized regime ($t = 300$ s) for $\Re a^* = 10^6, 2 \times 10^6, 5 \times 10^6, 10^7$ and for $A/b = 5$.

4. Conclusion

An experimental preliminary study of a heated vertical plane channel, representative of walls of double-skin type, was undertaken. This study was focused on the dynamics of the free convection flow resulting from the uniform heating of one of the walls on its central half. The visualization techniques used made it possible to show the strongly unsteady character of the convection flow as well in the establishing phase (beginning of the heating) of the flow, as in the steady state regime. These visualizations have confirmed the presence, in the range of studied Rayleigh numbers, of a reverse flow of variable length except for the singular case $\Re a^* = 5 \times 10^6$. Three-dimensional dynamic structures were also observed for the various modes of flow, represented by the presence of gravitational and Kelvin-Helmholtz type instabilities in the reverse flow. All these observations confirm the diversity and the complexity of the dynamic phenomena to take into account in order to obtain reliable modelling predictions of the behaviour of such a flow.

To complete the present work, the studies to come will be focused on the quantitative analysis of velocity profiles within the channel.

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SIMULĂRI EXPERIMENTALE PRIVIND
MODURILE DE VENTILARE IN FAŢADE DUBLE

(Rezumat)

Un studiu experimental a fost realizat intr-un canal plan, vertical şi incălzit cu aplicaţii practice în faţadele duble. Acest studiu analizează aspectul dinamic al unei curgeri in convecţie naturală rezultată în urma încălzirii uniforme a unuia dintre pereţi în partea lui centrală. Având aplicaţii

practice în ventilaţia naturală, doar aspectul convectiv a fost luat în consideraţie, efectuând experienţele în apă. Astfel, transferul de căldură prin radiaţie a fost neglijat. Pe de o parte, tehnica de vizualizare a pus în evidenţă caracterul puternic nestaţionar şi tridimensional al curgerii rezultante şi pe de altă parte a permis observarea prezenţei unor zone de recirculare de lungimi variabile pentru diferite numere ale lui Rayleigh modificat ($10^6 \leq \mathcal{R}a^* \leq 2 \times 10^7$).