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THE VERTICAL THERMOSYPHON WITH LARGE RAYLEIGH NUMBERS, PRINCIPLES AND EXPERIMENTAL CHARACTERIZATION.

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ABSTRACT

In this paper we remind the two categories of thermosyphon and energy balances that govern their operation. Especially for thermosyphons of second order (where the condition of mechanical equilibrium is not verified), it is established the important influence of the pressure losses in the air flow system according to the operation of the chimney with temperature or flux density imposed. Velocity and temperature measurements were performed for different levels of obstruction of the chimney with large Rayleigh numbers. The results obtained allow us to validate the assumptions made on circulating flows and the possible occurrence of return flows in the output sections.

KEYWORDS: Thermosyphon, Pressure losses, Rayleigh numbers, Circulating flows, Return flows.

INTRODUCTION

The thermosyphon is an air circuit transport in convective heat which establishes a natural flow under the effect of buoyancy forces due to changes in fluid density. These forces generate movements which are, in general, localized in part of the air circuit which can be closed or opened. The latter is considered here in a simple example: the open channel level. Whether vertical or inclined operation is still poorly known in its principles and should be remembered here, with its applications (including building and renewable energy), giving it a renewed interest. We take advantage of the implementation of the differentially heated cavity of large dimension (4m high), to produce two identical and independent chimneys.

In this section, we recall, at first, the two categories of thermosyphon and energy balances that govern their operation. Especially for thermosyphons of 2nd order (for which the condition of mechanical equilibrium is not verified), it highlights the important influence of losses in the air system according to the operating temperature or flux density imposed. Then, the experimental device will be presented in a second time, and finally the results obtained in the framework of this study will be discussed in the third part..

MATERIALS AND METHODS

Thermosyphon principle

Buoyancy comes from the breakdown of hydrostatic equilibrium between pressure forces and the weight of a volume of fluid. This breakage is caused by the change in density of a volume of fluid. At equilibrium, we can write :

$$\rho_0 \vec{g}=\vec{\nabla} p_0 \qquad (1)$$

Heterogeneity of density causes the onset of up thrust force $\vec{B}$ such that:

$$\rho \vec{g}-\vec{\nabla} p_0=(\rho-\rho_0)\,\vec{g} \qquad (2)$$

The magnitude of this force depends directly on density variations that can, among others, be generated by variations of temperature in an expandable fluid. For negligeable temperature differences and variations in density due to the considerable pressure to those due to the temperature, the approximation can be made Boussinesq [1,2], namely

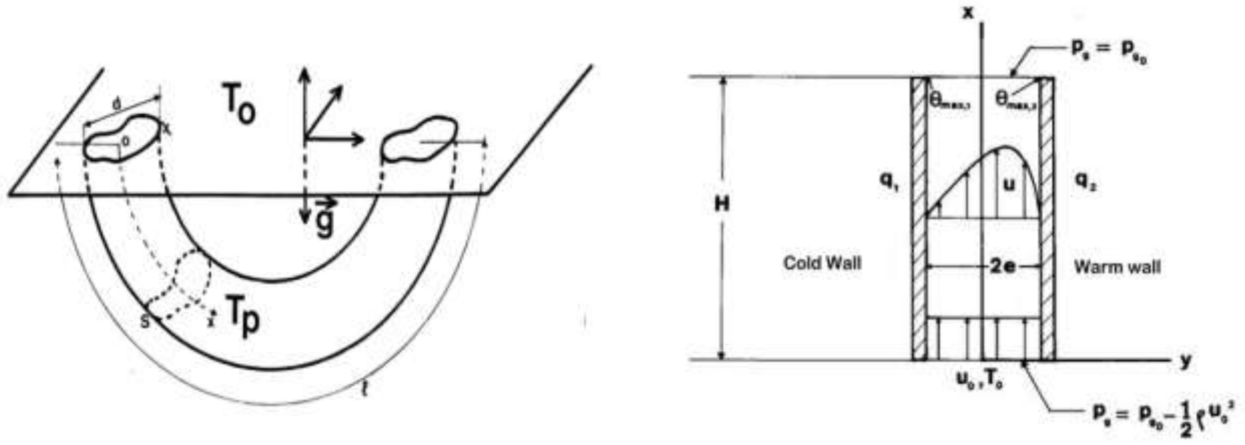
$$\rho-\rho_0=\rho_0 \beta(T-T_0) \qquad (3)$$

In the case of an ideal gas:

$$\beta=\frac{-1}{\rho}\left(\frac{\partial\rho}{\partial T}\right)_w=\frac{1}{T} \quad \text{(T is in Kelvin)} \qquad (4)$$

This approximation allows to explicitly introduce the temperature in the expression of the upthrust and $\vec{B}=\rho\vec{g}-\vec{\nabla}p_0=(\rho-\rho_0)\vec{g}$. The range of validity of this assumption is discussed by Gray and Giorgini among others [1976]. The operating principle is based on thermosyphon buoyancy. There are 2 types of thermosyphon. This classification is based upon the existence or not of a possible mechanical balance within the thermosyphon. It can be shown that a necessary condition (but not sufficient!) of mechanical equilibrium is that the fluid density is constant in the horizontal planes (normal plane to $\vec{g}$). Both are thermosyphon shown in Figure 1.10pt Times New Roman, Justified

Figure 1 :



1st order (with mechanical equilibrium) 2nd order (without mechanical equilibrium)

The two types of thermosyphon.9pt Times New Roman, Bold, Italic

In a thermosyphon of first other, although the temperature gradients are destabilizing, there are, as in the Rayleigh-Bénard problem, a critical Rayleigh number below which there is no movement. In a second order thermosyphon, the Archimede upthrust is balanced by the inertial and viscosity forces, thus causing a movement whenever there is a temperature difference. The operation of a thermosyphon always results from the balance between the loss of pressure p1 due to the viscosity and increasing pressure P2 due to temperature differences (within the Boussinesq approximation):

$$p_1(H)=\left(\frac{1}{2}+\alpha(0)+\alpha(H)+K\right)\rho_0 V_Q^2 \qquad (5)$$

$$p_2(H)=-\rho_0\int_0^H g_x\,\beta\,(T_m-T_0)\,dx \text{ ou } p_2(H)=-\frac{\rho_0}{S}\int_0^H\int_S g_x\,\beta\,(T_m-T_0)\,dS\,dx \qquad (6)$$

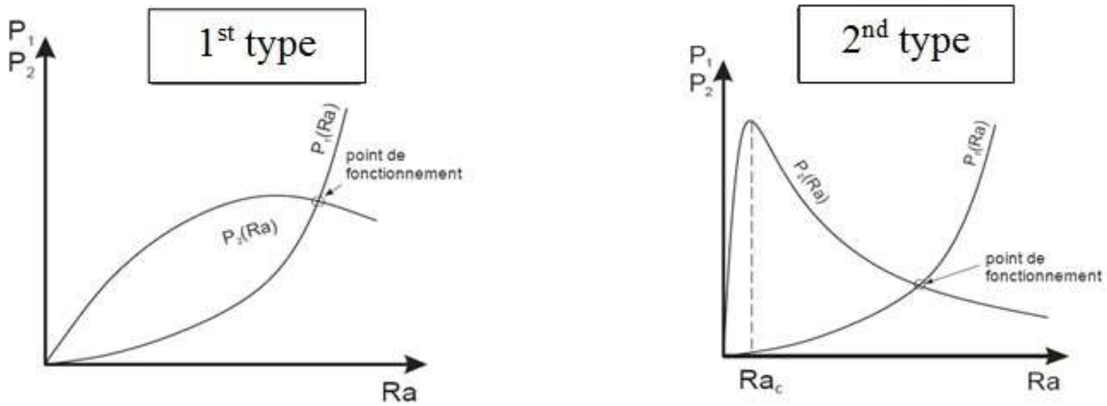
A graphical representation of these two curves provides the operating point (Figure 2) and therefore the flow rate through the thermosyphon. Indeed, the solution of the problem shows the distribution of temperature and velocity is : $P_1 = P_2$

The system of equations is completed by the energy equation gives stationary :

$$\rho c_p\int_{outer} v(T-T_0)\,dS_{outer}=Q_{wall} \qquad (7)$$

When the flow of wall is imposed, the energy injected must be evacuated. If the speed is small then the temperature difference is great. Whereas when the wall temperature is imposed, the problem is different because we can have T = Tw and v = 0 at every points.

Figure 2 :

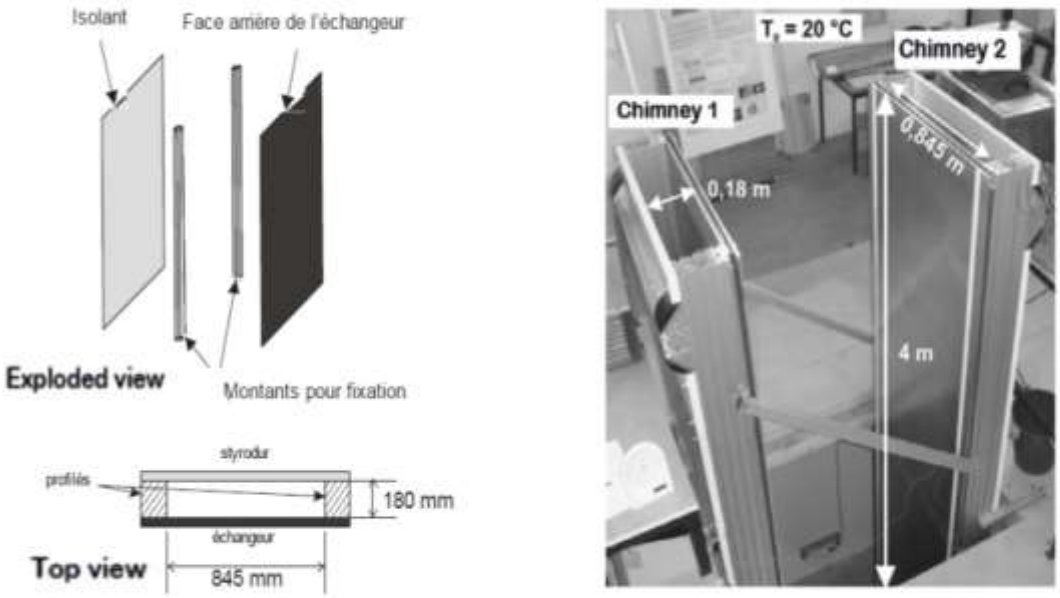


Determination of the operating point.

Experimental setup Sub-subheading

For this experimental set up with a 4 m height chimney, we used the hot and cold walls provided for the construction of a large cavity differentially heated. A photograph of the two chimneys is shown in Figure 3.

Figure 3 :



Photograph of two chimneys.

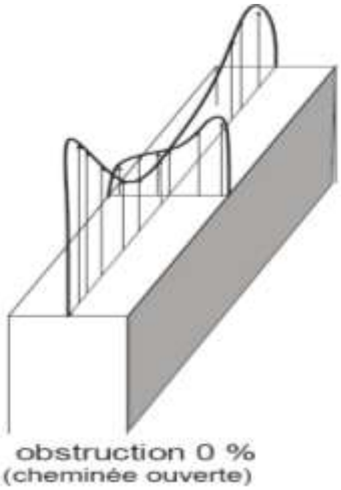
This large device (4 m high) thus comprises two independent, vertical and open at the top and the bottom chimney. The two stacks are identical and differ only in the temperature of the active wall. The side walls of these pipes are formed by an "active" wall, two aluminum profiles, and an adiabatic wall (extruded polystyrene, e = 3 cm, k = 0.035 $Wm^{-1}.K^{-1}$). The active wall (of each stack) is a heat exchanger formed with a low-emissivity material ($\varepsilon = 0.15$) and heat conductor (duralumin). A glycol water circulation, whose temperature is kept constant at a desired set point by an autonomous cryothermostat, controls the temperature of the wall and also ensures a uniform and constant temperature over the entire active walls (with accuracy of 0.1 ° C). All these four side walls is a vertical stack of 4 m high, 0.845 m long and 0.18 m wide (see Figure 3).

In order to vary the flow circulating in the thermosyphon, the inputs of these chimneys were partially obstructed, there by changing the pressure drop at the input (α (0) in equation (5)), and therefore the operating point. The boundary conditions of this study are as follows: three of the four sides are maintained at constant temperature Tw, the last face is insulated (adiabatic). Cold temperature (Tc <T0) and hot temperature (Th> T0) are imposed at each of these chimneys. It should be noted that their dynamic (driven by a constant surface temperature) differs substantially from the chimneys of constant flux density. Indeed, the presence of a pure conduction mode can lead to the arrest of a thermosyphon with constant temperature unlike to a chimney with flux density imposed, where this flow mode cannot appear. The speed measurements chimney outlet were performed by a hot wire DANTEC mark. This also permits to measure the air temperature. It should be noted that it was difficult to measure the speed of output given the large velocity fluctuations observed at the output. To overcome this, an integration time of 180s was chosen for calculating the average speed. In addition a thermocouple of 100 µm in diameter of type K was used to measure the temperature of the insulation on its inner face.Sub-subheading should be 10pt Times new roman, Italic, Justified.

RESULTS AND DISCUSSION

Within the stack, several types of flows were observed (unidirectional or a recirculational zone at the exit). Profiles output speeds in the mid-planes have been established and are presented below. The shape of the velocity profile is shown in Figure 4 in the case where the shaft is fully open. We observe the influence of three hot faces that accelerate the near-wall layers and this explains the observed speeding on the three sides heated.

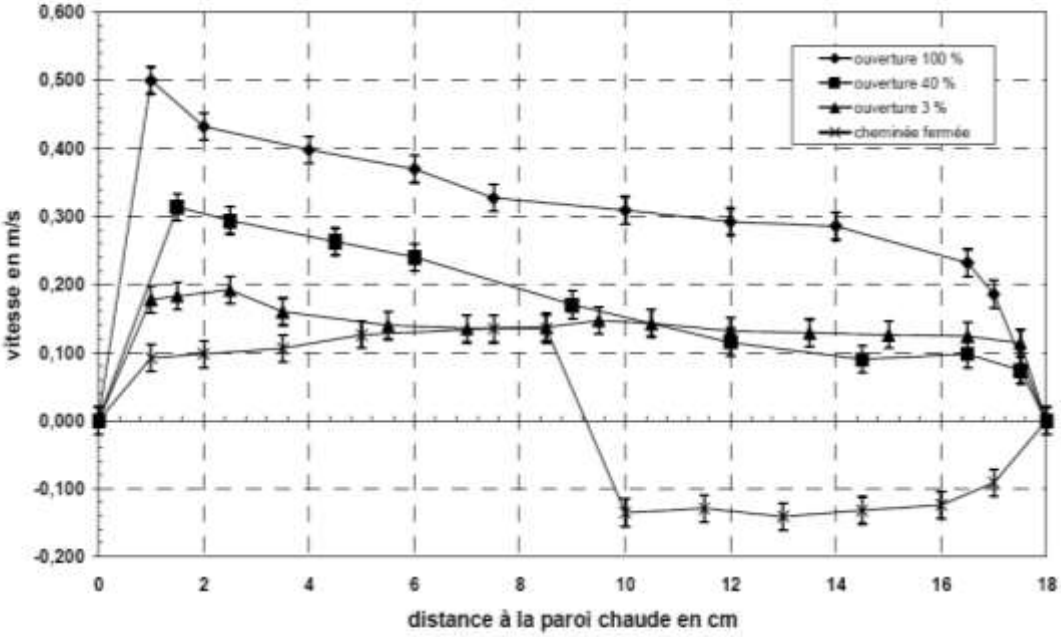
Figure 4 :



Photograph of two chimneys.

For different conditions of obstruction to the inlet of a thermosyphon, velocity profiles output of the chimney were made and are shown in Figure 5. The adiabatic temperature side was measured using a thermocouple. It has thus been found that this temperature is above ambient temperature. This can be explained by radiative exchange within the chimney which raises the temperature. Thus, regardless of the pressure drop at the inlet of the thermosyphon, the four faces of the stack are active and drive the air upwardly. This could partly explain why the recirculation zone at the top appears only when the thermosyphon is completely obstructed.

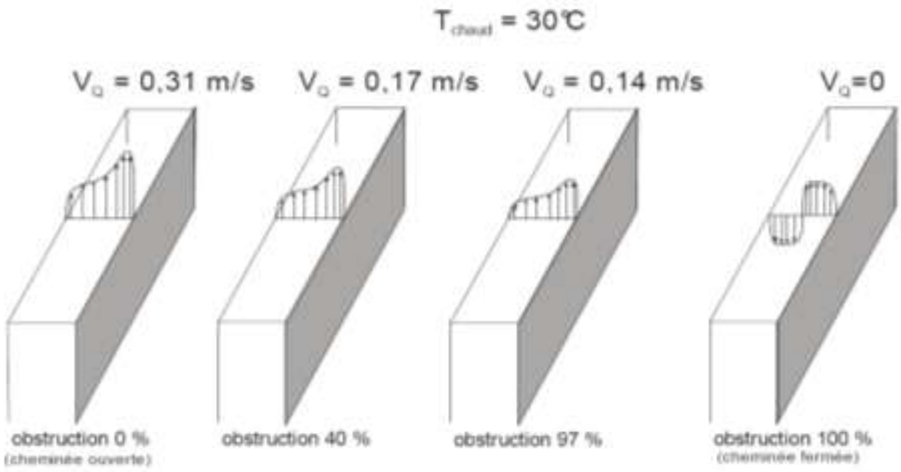
Figure 5 :



Velocity profiles in chimney outlet for various obstructions.

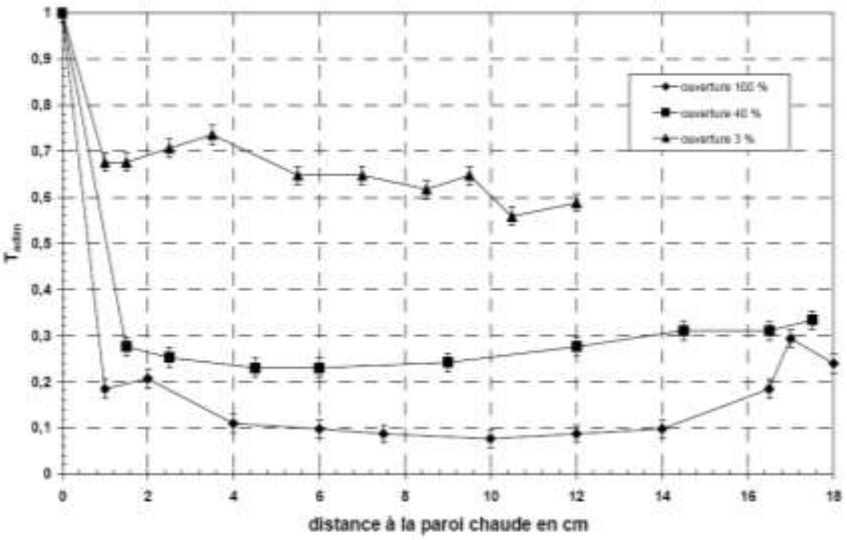
When the thermosyphon is completely blocked, we observe the appearance of a recirculation zone in the adiabatic face. Indeed, it is the case where an input of air at room temperature is carried out by adiabatic face creating a recirculation zone at the output: the air at ambient temperature enters the adiabatic side and goes out through the other side (heat side). Measurements and visualizations made are however not possible to have information on the penetration depth of the recirculation zone. Figure 6 shows the typical evolution (observed during the measurement campaign) of velocity profiles at the outlet of a thermosyphon for different conditions of obstruction for a hot wall temperature of 30 °C (T_0= 20 °C). The flow velocity is reported above each configuration.

Figure 6 :



Evolution of velocity profiles after obstruction.

Figure 7 :



Evolution of the temperature at the outlet chimney.

In the case of a stack at a constant temperature, it is found that it is essential to substantially completely close the chimney to observe at the recirculation outlet. In fact even with a ratio Sdown/Sup of 3 %, the discharging cross rates are low (VQ = 0,14 m/s ie VQ/VCN = 12,3 %) and no recirculation could be observed. To better interpret these results it is necessary to know the temperature of the mixture output. The evolution of the temperature at the outlet stack is shown in Figure 7 to the different case traités.et obstruction was rescaled as follows:

$$T_{dim}=\frac{T-T_0}{T_h-T_0} \qquad (8)$$

Table 1 summarizes the results of measuring hot and thermocouple wire and the ambient conditions. So we really have the duct is completely obstructed so that we get a situation like cavity or duct opened up.

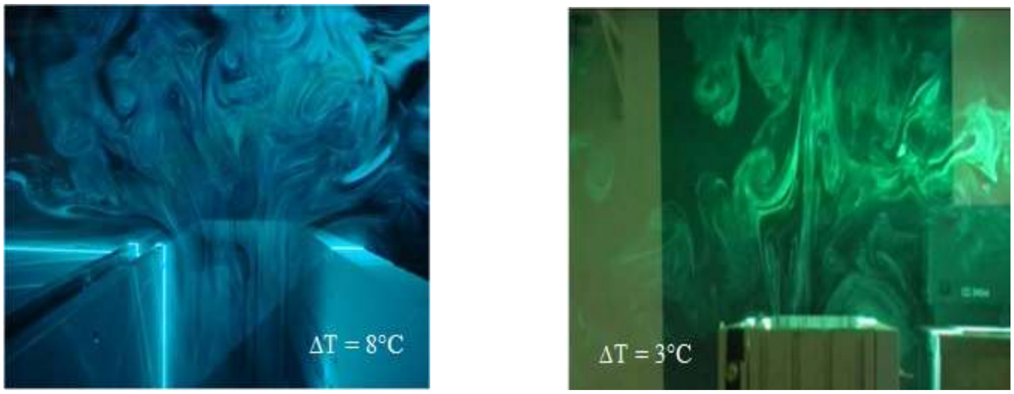
Table 1. Synthesis of the velocity measurements at the output side as a function of the input obstruction.

Obstruction [%]	T_0 [°C]	T_h [°C]	T_{dim}	V_Q [m/s]	V_{CN} [m/s]	V_Q/V_{CN}
100	20.8	30	0.1	0.314	1.10	0.286
40	21.3	30	0.3	0.170	1.07	0.159
3	20.6	30	0.65	0.137	1.11	0.123
0	20.6	30	----	-0.001	1.11	0.001

In all other cases, it is the balance sheet (5) - (7) which governs this thermosyphon. On one hand, when the input pressure loss increases, the air temperature at the outlet is further away from the ambient temperature, due to a longer residence time of the air in the thermosyphon (Table 1 Tdim output column). On the other hand, the increase of pressure loss causes increasingly slow flow (even if the increase in temperature results in greater buoyancy effects). In the same time, the singular pressure loss at the entrance becomes, more important (it is almost proportional to the inverse of the square of the section).

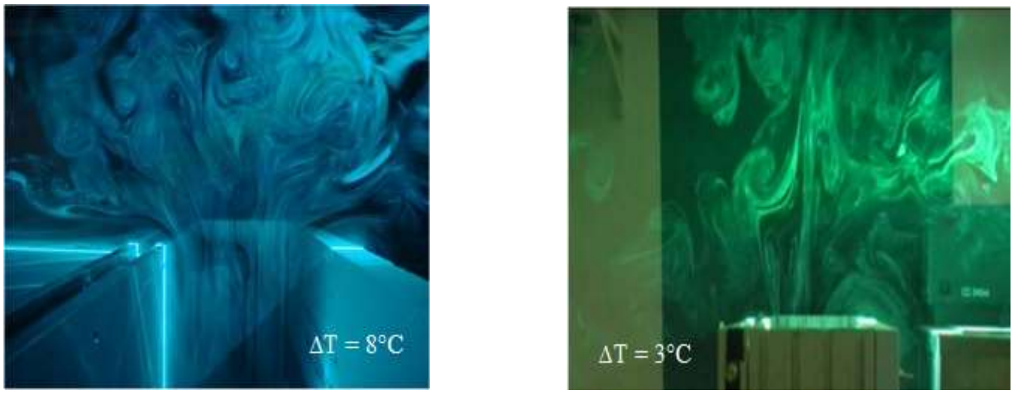
It is also found in Table 1 that in the case of a full opening, the flow velocity corresponds to approximately 30% of the rate of natural convection. This corresponds to about 9%, of temperature dimensionless mixing, neglecting the friction and singular losses. Finally it is observed that, in the case where the chimney is blocked (0% opening), this speed is generally zero (no flow), but a highly sheared flow is observed with reverse speeds along the walls. A recirculating flow estimation (mean positive vertical components, Figure 5) gives a value of 0.11 m/s, in the continuity of the values of speed discharging for partial obstruction. We then, notice that the character "self adaptive" of natural convection is observed. The system will branch off from a one-way flow solution to a two-way solution when the pressure losses become excessive. They remain, in any case, very similar in the two cases so that the balance (5) - (7) is verified. More visualization was also performed to determine the structures to the input (the cold chimney) and outlet (hot chimney) for various temperature differences and hence, different Rayleigh number. In Figure 8, we can see the structure at the entrance of the descending stack (cold) to a temperature difference of 3°C and 8°C. In Figure 9 and Figure 10, one can see the structure at the outlet of the rising chimney (hot) to a temperature difference of 10°C, in two perpendicular planes. Output, we see many rolls forms.

Figure 8 :



Views input chimney (cold) in the median plane for ΔT = 3 ° C and 8 ° C.

Figure 9 :



Velocity profiles in chimney outlet for various obstructions.

The results and discussion may be combined into a common section or obtainable separately. They may also be broken into subsets with short, revealing captions.

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Figure 10 :

Views output chimney (hot) in the median plane for ΔT=10 ° C

CONCLUSION

In this section, the principle of operation of the thermosyphon is given in the form of full balance sheet. Illustrations can confirm this operation. In particular, the analysis of velocity profiles and evaluation of circulating flow yield results which agree with the vision based on an integral formulation of the problem [7]. The obstruction of the input section leads to a linear decrease in flow relationship with the pressure drop. It may be noted, the "self-adaptive" character of natural convection. Indeed, the increase in pressure drop at the inlet causes the one-way flow passage of a shear flow (two-way) to which the inlet and the air outlet are on the same side.

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