THERMAL EXCHANGE BETWEEN A ROTATING HEATED SOLID AND A PERIODICAL FLOW

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ABSTRACT

This work concerns the thermal exchange study between a heated solid and a fluid flow which is evolving periodically in a cylindrical cavity. The influence of the two periodical combined motions; rotation of the solid and axial flow, on the thermal transfer mechanism is studied. The numerical resolution has been achieved with the finite elements method with the help of the software FIDAP. The founded results show the influence of the amplitude variation of the debit mechanism, as well as the one of the angular velocity of the solid, on the thermal transfer mechanism. The existence a difference of phase between motions of the solid and the flow has been studied for the case $\varphi = -\pi/2$. The boundary thermal conditions that are considered are relative to a constant wall temperature. The founded results are in good agreement with other numerical and experimental works.

NOMENCLATURE

A	Reference length	(m)
C_p	Calorific capacity	(J/Kg °K))
D	Orifice diameter	(m)
k	Thermal conductivity	(w/m °K)
K	Ratio of thermals conductivities	
L	Cavity Length	(m)
n	Normal at boundary	
P	Dimensioneless pression perturbation	
Pe	Peclet Number RePr	
Pr	Prandlt Number ,µCpf/kf	
Re	Reynolds Number ,$\rho_f w_e a/\mu$	
r	Dimensioneless radial coordinate	
R	Cavity Ray	
t	Dimensioneless time	(m)
Ta	Ambient temperature	(°K)
u, v, w	Dimensioneless component of vector velocity	
U	Dimensioneless vector velocity	
z	Dimensioneless axial coordinate	
Symbols		
a	Solid thermal diffusivity $k_s/\rho_s C_{ps}$	
m	Dynamic viscous flow	
r	Volumic mass	(kg / m^3)
q	Half angle cone	(rd)
e	Relative perturbation of magnitude	
w	Pulsation	
t	Dimensionneless time Period	
f	Angle of phase	(rd)
Exponents and indices		
e	Relative to the entry of the cavity	
f	Relative to fluid	
i	Relative to z	
j	Relative to r	
l	Relative to the outlet of the cavity	
n	Relative to t	
p	Relative to solid side	
s	Relative to Solid	

1. INTRODUCTION

The study of harmonic perturbation on the thermal transfer was the subject of several studies [1],[2],[3] and continuous to attract the attention of researchers, as testify some recent works [4]. Some works consider only the transverse conduction. The axial conduction is disregarded, as to the only mean velocity is considered. Other authors take into consideration the fluid-wall interaction by through the thermal condition at the solid-fluid interface. The exchange coefficients are function of both, the axial and transverse conduction. B. BOUROUGAT and B. FOURCHER [5] studied the behavior of different storage geometry in period regime. The results show that the performances of the storage are independent of its geometry and of the fluid coolant. A periodic thermal regime of the coupled conduction – convection, between a fluid in flow laminar and a wall has been made by M.T.ACKER and B.FOURCHER [6]. In this work, the equation of energy in the two regions are solved simultaneously, the solution is confronted that of a constant and uniform exchange coefficient. A theoretical study made by C. J. APELT and M. A. LEDWICH [7] concerns the heat transfer of a flow in transient regime around a heated sphere for Reynolds numbers of 1 to 40. Three cases of transient regime are studied, a pulsated evolution to 50 % of the amplitude velocity of permanent regime, a sinusoidal variation with an amplitude of a mean velocity. Results also included the wall transient transfer to a variable temperature of a cylinder. In the case of a sinusoidal variation of the velocity, the Reynolds number varies around the middle value corresponding at Re = 10 in the interval of 9 to 11,the period has been chosen equal is about the thermal characteristic time. The temperature is maintained constant everywhere. Results show that the quasi stationary answer, of the different dynamic and thermal coefficients, although periodic, are not sinusoidal. The heat transfer coefficient has an amplitude lower to the one that corresponds to the quasi stationary regime; we a 41°for the difference of phase between the heat transfer and the flow rate. The experimental results concerning the transfer phenomena between the wall of circular cylindrical pipe of large diameter and a turbulent flow of pulsed air are presented in a study by P. ANDRE and R.CREFF [2]. Results show that the Nusselt number in the pulsed flow decreases when the frequency increases, giving to the same exchange regime as that of the mean stationary flow case. Also the results show some specific frequency to enrich the heat transfer in the pulsed flow. Among the recent works one mentions those of Ashok Gopinath and al [9]. concerning an experimental study on the convective heat transfer behavior from a cylinder in an intense acoustic field in oscillatory flows [4], and that of FARIAS NETO and al [10] relative to the numerical simulation of the global mass transfer in a potential flow. The study of M. LACHI [11] relative to the insteady forced convection on a plate submitted to a periodical flux perturbation. He studied the influence of a harmonic type perturbation on the heat transfer between the heated solid and the fluid. In our work the transient regime was studied for the Reynolds number equal to 50. We determine the frequency corresponding to this case. The periodicity of the flow is assured by a periodic entry velocity or a periodic entry velocity superimposed to a rotation of the solid.

2. FORMULATION OF THE PROBLEM

A heated cylinder - conical obstacle is inside a cylindrical conduct filled of fluid to the ambient temperature (Fig.1). The regime of the flow is assured by the injection of a fluid of a same nature that the fluid into the conduct, from the entry of the cylinder, in a periodical variations. The thermal exchange between the solid and the fluid is studied in presence and in absence of the rotation velocity of the solid and with a temperature of wall maintained equal constant to 400°. The flow is to axial symmetry, the physical properties of the fluid are supposed constants and the viscous dissipation's its negligible.

2.1. The governing equations of the problem

$$\frac{\partial u}{\partial r}+\frac{\partial w}{\partial z}+\frac{u}{r}=0 \qquad (1)$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial r}+w\frac{\partial u}{\partial z}-\frac{v^2}{r}=-\frac{\partial P}{\partial r}+\frac{1}{Re}\left[\frac{\partial^2 u}{\partial r^2}+\frac{1}{r}\frac{\partial u}{\partial r}+\frac{\partial^2 u}{\partial z^2}-\frac{u}{r^2}\right] \qquad (2)$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial r}+w\frac{\partial v}{\partial z}+\frac{uv}{r}=\frac{1}{Re}\left[\frac{\partial^2 v}{\partial r^2}+\frac{1}{r}\frac{\partial v}{\partial r}+\frac{\partial^2 v}{\partial z^2}+\frac{v}{r^2}\right] \qquad (3)$$

$$\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial r}+w\frac{\partial w}{\partial z}=-\frac{\partial P}{\partial z}+\frac{1}{Re}\left[\frac{\partial^2 w}{\partial r^2}+\frac{1}{r}\frac{\partial w}{\partial r}+\frac{\partial^2 w}{\partial z^2}\right] \quad (4)$$

$$\frac{\partial T_f}{\partial t}+u\frac{\partial T_f}{\partial r}+w\frac{\partial T_f}{\partial z}=\frac{1}{Pe}\left[\frac{\partial^2 T_f}{\partial r^2}+\frac{1}{r}\frac{\partial T_f}{\partial r}+\frac{\partial^2 T_f}{\partial z^2}\right] \quad (5)$$

The conduction of the heat to inside of the obstacle is represented by the adimensionnal Fourrier equation :

$$\frac{\partial T_s}{\partial t}=a\Delta T_s \quad (6)$$

The coupling of equations of the energy (5) and (6) makes himself by the condition of flux equality through the interface that expresses himself of the following way:

$$\frac{\partial T_f}{\partial n}=K\frac{\partial T_s}{\partial n} \quad (7)$$

The initial conditions and to limits associated to equations are the following:
At the instant t = 0 $u(r, z, 0) = v(r, z, 0) = w(r, z, 0) = T_f(r,z,0) = P(r, z, 0) = 0$ in the fluid sub-domain .
at the instant t > 0
to the entry, z = 0, $0 < r \le r_e$:

$$u(r, 0, t) = v(r, 0, t) = 0 \quad w(r,0,t)=w_0(1+e_w \sin wt) \quad T_f(r, 0, t) = 0$$

$r_e < r < R$:

$$u(r, 0, t) = v(r, 0, t) = w(r, 0, t) = 0, \quad \frac{\partial T_f}{\partial z}(r,0,t)=0$$

to the wall of the cavity, r = R,

$$u(R, z, t) = w(R, z, t) = 0, \quad \frac{\partial T_r}{\partial z}(r,0,t)=0$$

to the wall of the obstacle, $r = r_p$, $z = z_p$,

$$u(r_p, z_p, t) = 0, \quad w(r_p, z_p, t) = 0 \text{ and } v(r_p, z_p, t) = v_0(1+\varepsilon_s in\ \omega t)$$

$$\frac{\partial T_f}{\partial z}(r_p,z_p,t)=K\frac{\partial T_s}{\partial z}(r_p,z_p,t)$$

to the exit, z = L et $0 < r < r_p$:

$$\frac{\partial T_s}{\partial z}(r,L,t)=0$$

$r_p < r < R$:

$$\frac{\partial u}{\partial z}(r,L,t)=\frac{\partial v}{\partial z}(r,L,t)=\frac{\partial w}{\partial z}(r,L,t)=\frac{\partial T_f}{\partial z}(r,L,t)=0$$

on the axis, r = 0, $0 \le z < z_p$:

$$u(0, z,t) = 0, \quad \frac{\partial v}{\partial r}(0,z,t)=\frac{\partial w}{\partial r}(0,z,t)=\frac{\partial T_f}{\partial r}(0,z,t)=0$$

$$z_p \le z \le L: \frac{\partial T_s}{\partial r}(0,z,t)=0$$

3. NUMERICAL RESOLUTION:

The previous equations associated to the initial conditions and limits have been solved by the finite elements method. The domain of calculation has been divided in nine regions delimiting parts fluid and solid, as well as all borders (fig.2). calculations have been done on a SUN station while using the FIDAP software. The step in time considered is 1/64. The period of the movement has been calculated from the transient regime correspondent to a Reynolds number not provoking any dynamic and thermal instabilities within the flow. In the case of a number of Reynolds R_e=50, the constant of the time, corresponding to the establishment of the transient regime is about of the value $\tau = 520\Delta t$. It is this value that is taken equal to the period of the movement (fig.3) for Reynolds numbers ≤ 100.

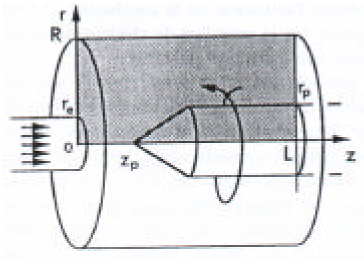


Fig. 1: General sketch of study

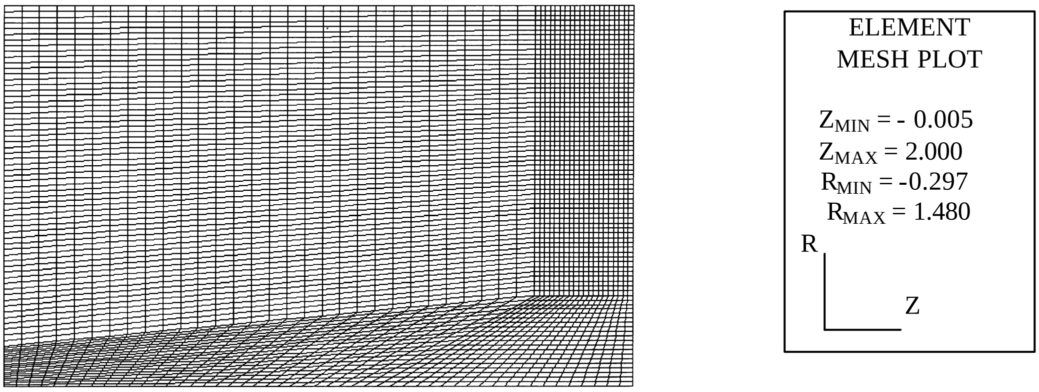


Fig. 2 Integration domain by finite elements

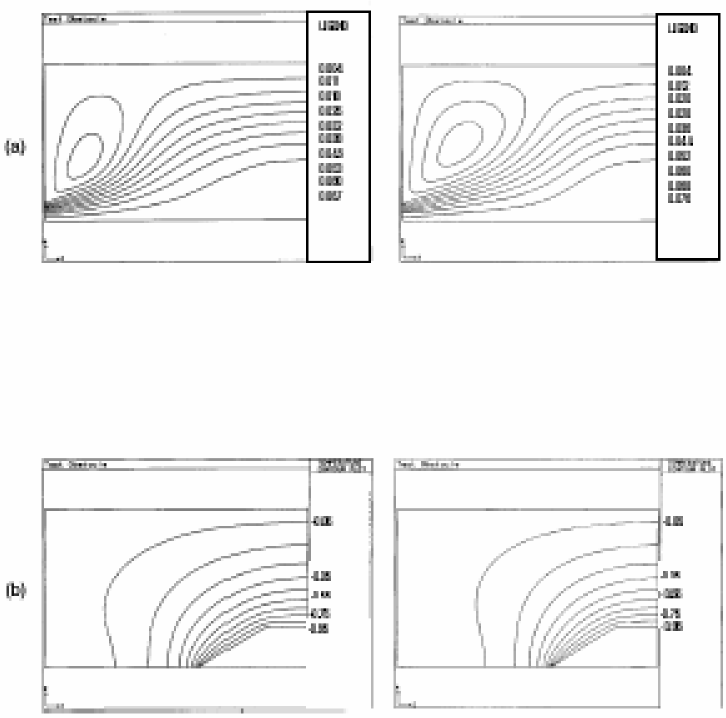


Fig. 3 : Transient regime ,stream lines (a) ,isoterme lines (b) ,for different times ,from left to rihgt ($t=t_1=2.03, t=t_2=5t_1$),case Re=50

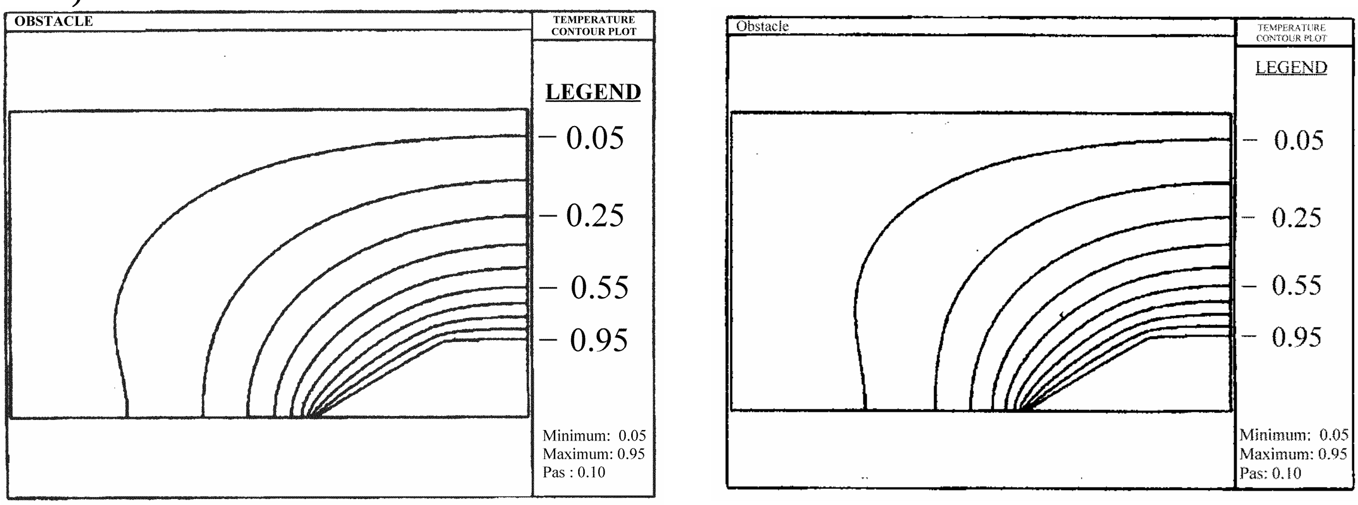
4. RESULTS AND DISCUSSIONS:

Results obtained show the dynamical and thermal field evolution of the flow in the course of a time interval equal to 5/4 of the period. In the absence of the speed of rotation of the obstacle, one notices that the increase of the amplitude has for effect on one hand to displace zones of recirculation of fluid in the direction of the flow and on the other hand to give rise to an increasing periodical behavior of the axial component of the speed as the amplitude grows .It Also appears an wavy form for large values of the amplitude.

4. 1. Influence of periodicity on the thermal exchange:

The expression of the entry velocity is: $W = W_0(1+\varepsilon_W \, sin \, \omega t)$ where W_0 is the mean velocity, it's taken equal to the half of the reference velocity, ε_W is the amplitude ($0 \le \varepsilon_W \le 0{,}9$), w the frequency. T being the period of the movement (T = 8,12). The periodicity of the entry velocity appears dynamically especially on the axial component of the velocity. In fact (fig.4a) shows that this last varies a periodic manner during the time, where equal value curves to change positions in a cyclic manner during the time. In the annular part, the axial velocity component presents a parabolic shape where the maximum value of the curve varies a cyclic manner (fig.4b). This influences of the dynamic periodicity on the thermal exchange between the solid and the fluid in the region upstream of the solid, it is the region concerned by the convection movement.
The isotherm lines in this region change position in a cyclic manner during the time. On the other hand in the region close to the solid, where phenomena of pure conduction appear solidly, the thermal exchange between the solid and the fluid reaches its equilibrium. The radial profile of the temperature corresponding to the cylindrical part presents a shape that varies very little during the time.
The existence of velocity of a rotation of the solid enrich generally the radial velocity component of the flow. The periodic shape of this velocity influences on the dynamic and thermal behaviour of the flow. The dynamic field tends to present a shape of periodicity during the time more perceptible that for the thermal field. The studied cases concern the amplitude of axial velocity varying of $\varepsilon_W = 0{,}1$ to $\varepsilon_W = 0{,}9$ with amplitude of rotation velocity varying of $\varepsilon_V = 0{,}1$ to $\varepsilon_V = 0{,}4$. The velocity of the solid is governed by the equation:
$V = 0.5\ V_{max}\,(1+\varepsilon_v \sin \omega t)$. Where V_{max} is the maximal rotation velocity permitting the dynamic stability of the non periodic flow ($V_{max} = 1$).. This pulsation is taken equal to the one of the entry velocity in order to eliminate the modulation of the resulting amplitude of the two superposed periodic movements. The perturbation of amplitude ε is chosen in order to not to create instabilities within the flow. In this study the reached maximal value is equal to 0,4. [12] [13] [14]. The configuration of the radial profiles of components velocity shows that the amplitude of the two components, axial and radial, has a comparable values and present a certain periodicity during the time. It is to signal that this periodicity is more perceptible for the axial component that for the radial component. This phenomenon plays a role in the mechanism of the thermal exchange between the solid and the fluid.
When the velocity rotation believes $\varepsilon_V = 0.\ 4$, the radial velocity component increases while to enrich the thermal convection. The periodicity shape of the thermal exchange becomes more and more perceptible when the amplitude of the rotation velocity increases. We noted that the region close to the solid ,where the thermal exchange to be made by pure conduction ,is nearly insensible to the periodicity of the flow.

a)



b)

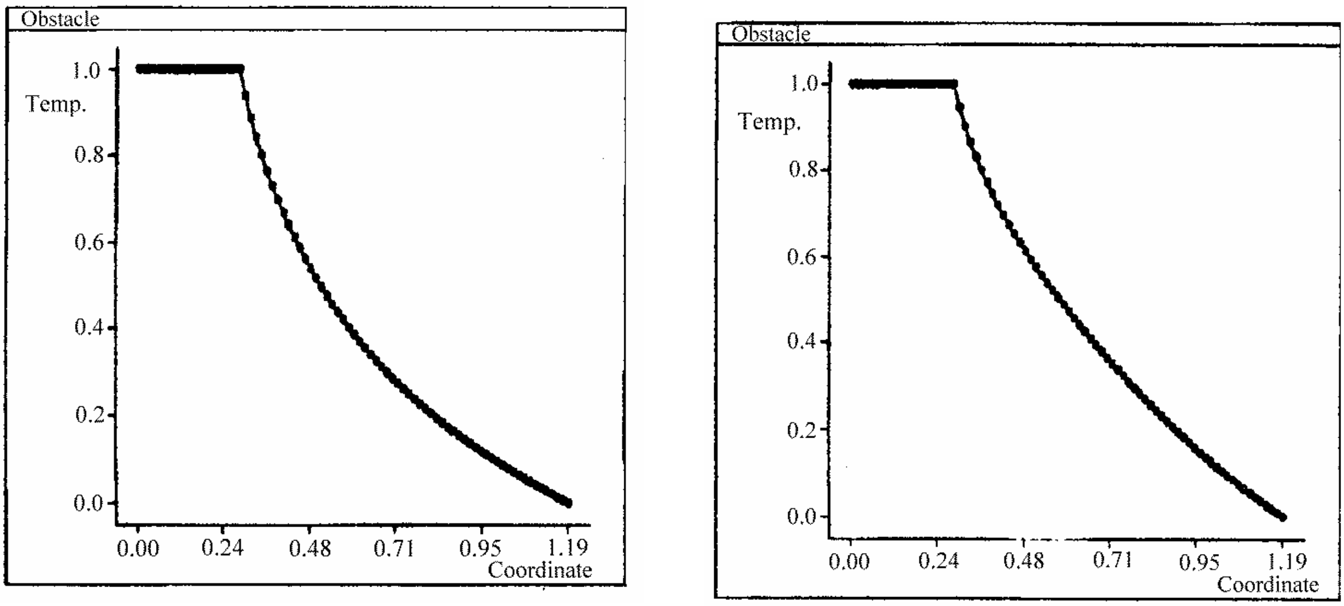


Fig.5 : Isotherm lines configuration. (a) Radial profiles of temperature on cross-section relative to cylindrical solid part (Z= 1.69). (b) For two different times (from left to right :t = t_1 = T/4 ; t = t_4 = T).

4. 2. Influence of difference of phase between the entry and the rotation velocity:

The variation of two periodic movements superimposed with a difference of phase between them influences on the mechanism of the thermal exchange between the heated solid and the fluid. One presents in this study a difference of phase: $\varphi = -\pi/2$, and one compares it to the case $(\varphi = 0)$. The isotherm lines shows the time evolution for the two cited cases. One notices the relative curves to isothermal lines present points of inflection in the two regions annular and conical near of the solid wall. In the cylindrical zone, the axial conduction begins to appear in presence of the existence of the difference of phase. The analysis of isotherm lines and the radial variation of the temperature shows that in the case of the difference of phase is equal to $-\pi/2$, the zones touched by the thermal convection in the cylindrical part are more extended that in the absence of the difference of phase. On the other hand it is the inverse phenomenon that occurs in the zones near the conical wall. One also notes that the radial gradient of the temperature presents an inversely proportional variation with the difference of phase in the annular region and proportional variations in the conical region.

5. CONCLUSION:

A numerical study relative to the influence of a type sinusoidal perturbation on the dynamic and thermal behaviour of a real fluid flow is achieved by the finite ele ments method. In the absence of the solid rotational motion, the flow is characterised by an axial aspect. A certain periodicity in the variation of the axial component of the velocity during the time appears. The thermal exchange between the heated solid and the fluid in the conical region, are to the upstream of the arrival flow and therefore more dependent of the variation of the axial velocity, what gives a certain periodicity in the convective movement. The other region, be in the annular part is characterised by a radial profile of the temperature that has tendency to keep the same shape during the time.
In the case of the superposition to the periodic movement of fluid entry velocity and the solid periodic rotation, the thermal field present a periodicity shape during the time. This shape is more and more perceptible as the amplitude of the rotation velocity increases. That notes that the augmentations of the radial velocity component increases the thermal exchange by convection between the fluid and the solid. Nevertheless the maximal value of the rotation velocity is conditioned by the maintenance of the dynamic and thermal stability of the flow, the ratio of amplitudes, axial and azimuth is equal to 0,3 in this study.

The case corresponding to a difference of phase equal to a $-\pi/2$ between the entry velocity and the rotation velocity has been studied and has been compared to the case of the with out of phase absence. The results show that the mechanism of the thermal exchange by conduction is dependent of the difference of phase existence. With regard to the thermal convection in the annular zone it is more important for the case with difference of phase existence. We noted that curves of temperature present points of inflection in presence of with out of phase, what can contribute to the thermal instability apparition.

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