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The Control of Natural Convective Heat Transfer from a Horizontal Circular Cylinder

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ABSTRACT

This work is analyzing the control of natural convective heat transfer from a horizontal circular cylinder using low conductivity radial baffles. The influence of the systems parameters on the average Nusselt number is presented.
***Keywords**: heat transfer, circular cylinder, fins, baffles*

1. Introduction

The management of heat transfer from a pipe ([9], [14], [15]) or, generally, from a cylinder ([1], [8], [16], [18], [19], [22]) is a subject of intense study due to its application in various fields such as: environment protection, oil industry, heat exchangers, refrigerators, etc.

The way of treating the subject varies according to the simplification that the researchers can do to the real problem: the cylinder can have a horizontal or vertical orientation, it can be surrounded by a fluid or it can be embedded in a porous media; it can have a solid or a permeable wall; sometimes, it is desired to enhance the heat transfer from the cylinder while sometimes, on the contrary, it is desired to decrease that heat transfer.

One way to manage the heat transfer from a cylinder implies the internal ([10], [12], [21]), or external fins, permeable, ([4], [7]) or low conductivity baffles ([2], [3], [5], [6], [13]) in natural, forced or mixed convection situations. It was proved numerically that the low conductivity baffles decrease the loss of heat from a cylinder, while the high conductivity permeable fins increase the heat transfer from a cylinder.

This paper is analyzing the management of heat transfer from a horizontal circular cylinder with a constant heat flux at its surface, with low conductivity baffles, for the case of natural convection. The problem has not only a theoretical interest ([11], [19], [20]) but also a practical one.

2. Mathematical model

The mathematical model has as point of start the work of Abu-Hijleh regarding the natural convection from a horizontal cylinder (Fig. 1a) with exterior low conductivity baffles uniformly spaced on the periphery af a constant temperature cylinder and without thickness [2]. No baffles were considered at $\varphi=0$ and $\varphi=\pi$ locations. The fluid considered was air. Due to symmetry, only half of the domain will be analyzed (Fig. 1a).

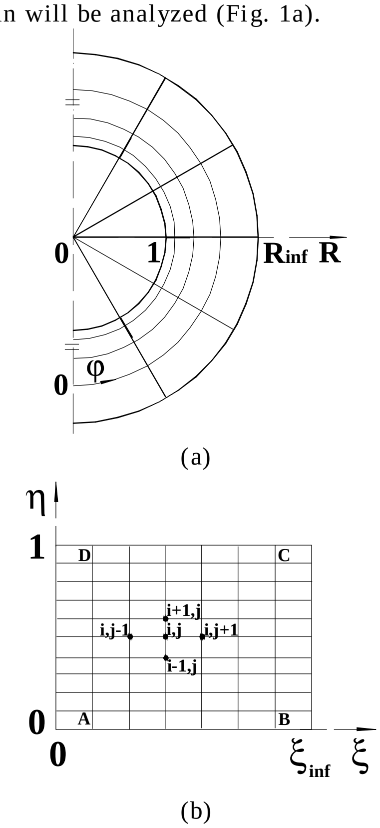

Fig. 1. *Dimensionless (a) and computation domain (b) for a horizontal cylinder with external baffles.*

The governing equations for the fluid (1÷3), in the cylindrical coordinate system defined by Fig. 1a, in dimensionless form, in the vorticity – potential function formulation, are [8]:

$$\omega = -\Delta\psi\,; \tag{1}$$

$$\frac{\partial^2\omega}{\partial R^2} + \frac{1}{R}\cdot\frac{\partial\omega}{\partial R} + \frac{1}{R^2}\cdot\frac{\partial^2\omega}{\partial\varphi^2} = \frac{1}{Pr}\left[U\frac{\partial\omega}{\partial R} + V\frac{\partial\omega}{\partial\varphi}\right] - Ra\left[\sin\varphi\frac{\partial\theta}{\partial R} + \frac{\cos\varphi}{R}\frac{\partial\theta}{\partial\varphi}\right]; \tag{2}$$

$$U\frac{\partial\theta}{\partial R} + \frac{V}{R}\frac{\partial\theta}{\partial\varphi} = \Delta\theta\,, \tag{3}$$

where the potential function, ψ, is defined through the following two definitions: U=1/R ·∂ψ/∂φ and V=-∂ψ/∂R, while the vorticity, ω, is defined as ω=-(1/R)∂U/∂φ+(1/R)∂(RV)/ ∂R. The boundary conditions used are:

- at the cylinder surface: no slip and no penetration conditions imply $y = \partial y / \partial R = 0$, while the constant heat flux condition requires $\partial q / \partial R = -1$;
- at infinity: if V<0 (the inflow region), then θ=0 else (the outflow region) ∂θ/∂R=0; the velocity condition, $\partial V / \partial R = 0$, imposes $\partial^2 y / \partial R^2 = 0$;
- on the symmetry plane: the symmetry of velocity and temperature fields demands $y = w = \partial q / \partial j = 0$;
- on the baffle surface: ψ=0 while the temperature is the average of the radial neighbor points temperature.

Only a non-uniform grid (Fig. 1a) could capture the thermal phenomena that are taking place especially in the vicinity of the cylinder and baffles surfaces but such a grid would complicate the programming and the computation procedures. Abu-Hijleh [2] suggested a coordinate transformation: $R=e^{\pi\xi}$; φ=πξ that generates a uniform grid in the computation domain (Fig. 1b) and the new form of the governing equations:

$$\omega = -\frac{1}{\pi e^{\pi\xi}}\left[\frac{\partial^2\psi}{\partial\xi^2} + \frac{\partial^2\psi}{\partial\eta^2}\right]; \tag{4}$$

$$\frac{\partial^2\omega}{\partial\xi^2} + \frac{\partial^2\omega}{\partial\eta^2} = \frac{1}{Pr}\left[\frac{\partial\psi}{\partial\eta}\frac{\partial\omega}{\partial\xi} - \frac{\partial\psi}{\partial\xi}\frac{\partial\omega}{\partial\eta}\right] - \pi e^{\pi\xi} Ra\left[\sin(\pi\eta)\frac{\partial\theta}{\partial\xi} + \cos(\pi\eta)\frac{\partial\theta}{\partial\eta}\right]; \tag{5}$$

$$\frac{\partial^2\theta}{\partial\xi^2} + \frac{\partial^2\theta}{\partial\eta^2} = \left[\frac{\partial\psi}{\partial\eta}\frac{\partial\theta}{\partial\xi} - \frac{\partial\psi}{\partial\xi}\frac{\partial\theta}{\partial\eta}\right]. \tag{6}$$

The new boundary conditions are:

- at the cylinder surface: ψ=∂ψ/∂ξ=0, $\partial q / \partial x = -p$;
- at infinity: if V<0 then θ=0, else ∂θ/∂ξ=0; $\partial^2 y / \partial x^2 = 0$;
- on the symmetry plane: $y = w = \partial q / \partial j = 0$;
- on the baffle surface: ψ=0 while the temperature is the average of the radial neighbor points temperature.

In order to solve the governing equations (4÷6), find the temperature, velocity and stream function fields (and consequently, the velocity field) and establish the heat transfer magnitude through the Nusselt number, a numerical code was built. The numerical method used for solving the governing equations was the finite differences method. The grid had 241×300 points in the η and ξ direction, respectively (Fig. 1b).

An iterative process solved the system of equations where the false transient term was discretized using a time step $\Delta t = 10^{-5}$ while the “Alternating Direction Implicit” method was used in the hybrid scheme. The iterative process stopped when the maximum relative error for temperature and the potential function fields was smaller than 10^{-2}.

3. Results and discussions

Figure 2a presents the isotherms and the Fig. 2b presents the streamlines for the case of three equally spaced baffles of height $H = 1.0$ for a Rayleigh number of 10^5. For the same conditions, Fig. 2c presents the surface temperature variation for two cases: with baffles and without baffles.

The three baffles obstruct the convection currents as Fig. 2b presents. We can notice, between baffles, “air pockets” that are blocking the heat transfer from the cylinder to the surrounding. Further, analyzing Fig. 2c, higher temperature values are noticed in the baffle vicinity and on the cylinder surface in the case of the three exterior baffles.

Consequently, we can deduce that, for a Rayleigh number of 10^5, the presence of the three baffles will determine smaller values of the average Nusselt number. This anticipated result will be presented and discussed later in this section (Fig. 4 and Fig. 5).

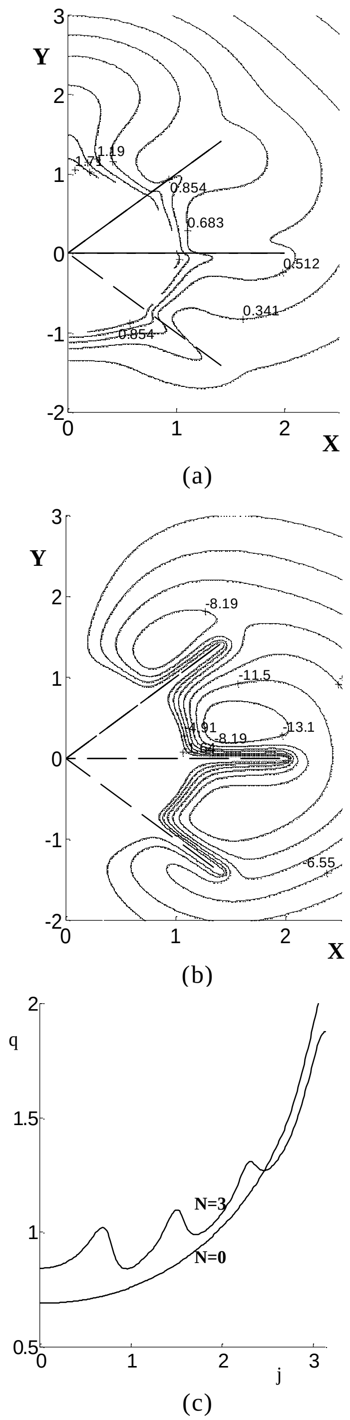

Fig. 2. *Isotherms (a), streamlines (b) and surface temperature variation (c) for $Ra_D=10^5$, N=3 and H=1.*

Figure 3 presents the isotherms (Fig. 3a), the streamlines (Fig. 3b) and the cylinder surface temperature (Fig. 3c) for the natural convection around a circular cylinder with three exterior, uniformly distributed, low conductivity baffles of height H=1.0 and for a Rayleigh number of 10^3.

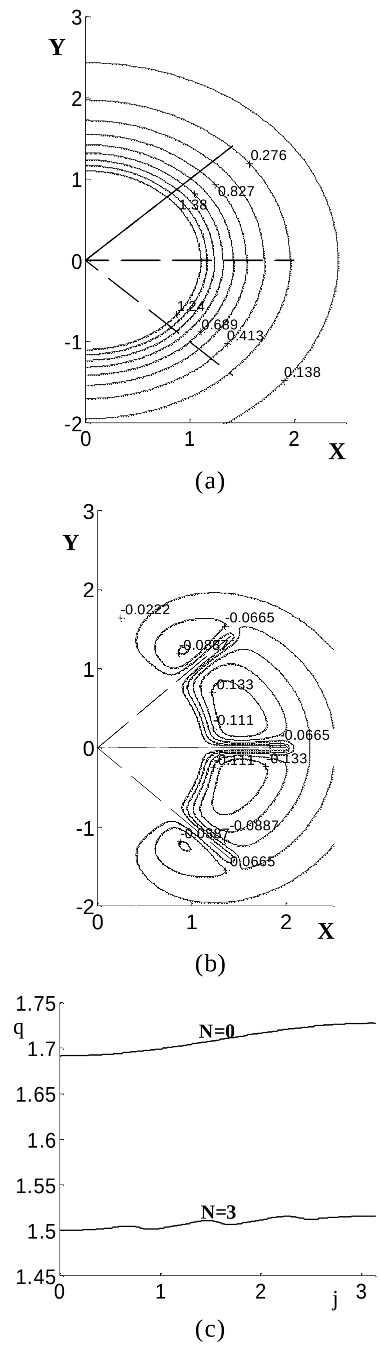

Fig. 3. *Isotherms (a), streamlines (b) and surface temperature variation (c) for $Ra_D=10^3$, N=3 and H=1.*

For $Ra_D=10^3$ case, the boundary layer is thicker and it is "energized" [2] by the exterior baffles that enhance the heat transfer from the cylinder to the fluid. Consequently, smaller values of cylinder surface temperature (Fig. 3c) and higher Nusselt numbers (Fig. 4 and Fig. 5) are registered.

Figure 4 presents the average Nusselt number variation as a function of baffle height for two values of Rayleigh number: 10^3 and 10^5. As we can notice, increasing the baffle height, the supression of convection currents increases.

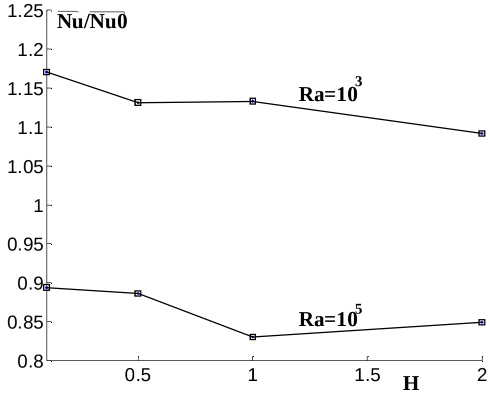

Fig. 4. *The ratio of the average Nusselt number with/without baffles variation as a function of baffles height for three exterior equally spaced baffles.*

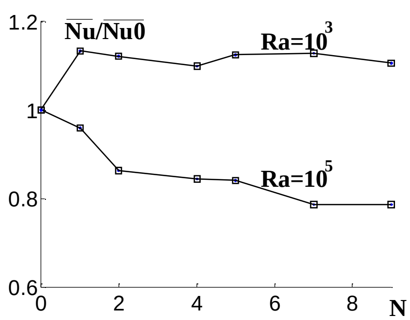

Fig. 5. *The ratio of the average Nusselt number with/without baffles variation as a function baffles number. The baffles height H=1.0.*

Figure 4 presents the average Nusselt number variation as a function of the number of baffles of height, $H = 1.0$, for the same two values of Rayleigh number. If a clear tendency to decrease when the number of baffles increases was noticed for $Ra_D = 10^5$ case, this tendency is not well defined for $Ra_D = 10^3$ case.

Figure 4 and Fig. 5 show that we can modify the heat transfer from a horizontal cylinder with low conductivity equally spaced exterior baffles in the situation when the exterior surface of the cylinder is subjected to a constant heat flux changing the baffles number and height.

Further studies should be done to examine the possibility to manage the heat transfer from a cylinder with a constant heat flux surface using high conductivity permeable exterior fins.

4. Conclusions

- A numerical model for the natural convection over a horizontal cylinder with a constant heat flux and equally spaced exterior low conductivity baffles was constructed using the finite differences method.
- The numerical code developed by the author was validated for the case of a horizontal cylinder with a constant temperature surface.
- The boundary condition was modified for the constant heat flux surface case. An analysis of the temperature and velocity fields was realized.
- The variation of the average Nusselt number as a function of baffles number and height was presented for two values of Rayleigh number: 10^3 and 10^5. These results indicate the possibility to influence the natural convective heat transfer from a horizontal circular cylinder with a constant heat flux at its surface and equally spaced exterior low conductivity baffles changing the baffles number and height.

NOMENCLATURE

D- cylinder diameter, *m*
Gr - Grashof number, $Gr = Ra_D / \Pr$
h - convective heat transfer coefficient, $W.m^{-2}.K^{-1}$
h_b – baffle height, *m*
H - dimensionless baffle height, $H = h_b / r_0$
k - fluid thermal conductivity, $W.m^{-1}.K^{-1}$
N – number of exterior equally spaced baffles
Nu - local Nusselt number with baffles,

$$Nu = hD / k$$

$\overline{Nu}$ - average Nusselt number with baffles,

$$\overline{Nu} = \frac{1}{p}\int_0^p Nu \, dj$$

Nu0 - local Nusselt number without baffles,

$$Nu0 = hD / k$$

$\overline{Nu0}$ - average Nusselt number without baffles,

$$\overline{Nu0} = \frac{1}{p}\int_0^p Nu0 \, dj$$

Pr - Prandtl number, $\Pr = \nu / \alpha$
q - constant surface heat flux, $W.m^{-2}$
r – radius, *m*
r_0 - exterior cylinder radius, *m*
r_{inf} - radius defining the boundary domain, *m*

R - dimensionless radius, $R = r / r_0$

R_{inf} - dimensionless radius defining the boundary domain, $R_{inf} = r_{inf} / r_0$

Ra - Rayleigh number based on cylinder radius, $Ra = g\beta r_0^3 qD / (k\alpha\nu)$

Ra_D - Rayleigh number based on cylinder diameter, $Ra = g\beta qD^4 (k\alpha\nu)$

T – fluid temperature, K

u - radial velocity, $m.s^{-1}$

U - dimensionless radial velocity, $U = u.r_0 / \alpha$

v - tangential velocity, $m.s^{-1}$

V - dimensionless tangential velocity, $V = v.r_0 / \alpha$

X – horizontal axis

Y – vertical axis

Greek symbols

α – fluid thermal diffusivity, $m^2.s^{-1}$

β - coefficient of thermal expansion

ξ_{inf} - dimensionless radius defining the boundary domain, $R_{inf} = e^{\pi\xi_{inf}}$

η- calculation coordinate, $\theta=\pi\eta$

θ - dimensionless temperature, $\theta = (T - T_\infty)/(qD/k)$

ν - kinematic viscosity, $m^2.s^{-1}$

ξ - calculation coordinate, $R = e^{px}$

φ - angle

ψ - dimensionless stream function

ω - the dimensionless vorticity

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Controlul transferului de căldura prin convecție naturală în jurul unui cilindru orizontal

Rezumat

Aceasta lucrare analizează controlul procesului de convecție naturală de la un cilindru orizontal utilizând nervuri radiale cu conductivitate termică redusă. Influenta parametrilor sistemului asupra numărului Nusselt mediu este prezentată.

Die Kontrolle der natürlichen convective Hitze-Übertragung von einer horizontalen kreisförmigen Zylinder

Zusammenfassung

Diese Arbeit analysiert die Kontrolle der natürlichen convective-Hitze-Übertragung von einem kreisförmigen horizontalen Zylinder mit niedriger Leitfähigkeit radiale Leitbleche. Der Einfluss der Systeme Parameter auf die durchschnittliche Anzahl Nusselt wird.