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Effect of Opposing Buoyancy on Two-Dimensional Laminar Flow and Heat Transfer Across a Confined Circular Cylinder

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Nomenclature

B - volume expansion coefficient,1/K; C_D - drag coefficient; *d* - cylinder size, m; *F* - drag force, N; *g* - gravitational acceleration, m/s^2; *Gr* - Grashof number; *H* - Channel width, m; *h* - Local convective heat transfer coefficient, W/(m^{2}K); *k* - fluid thermal conductivity, W/(m^{2}K); L_d - downstream distance, m; L_u - upstream distance, m; n_s - direction normal to the cylinder surface; *Nu* - average total Nusselt number; *p* - pressure, Pa; *P* - dimensionless pressure; *Pr* - Prandtl number; *Re* - Reynolds number; *Ri*- Richardson number; *T* - temperature, K; *U* - dimensionless stream-wise velocity; *u*-stream-wise velocity, m/s; *V* - dimensionless cross-stream velocity; *v* - velocity cross-stream velocity, m/s; *X* - dimensionless stream-wise coordinate; *Y* - dimensionless cross-stream coordinate; *y* - cross-stream coordinate, m.

greek letters-

η - dynamic viscosity, Pa s; ρ - fluid density kg/m^3; β - blockage ratio; θ - dimensionless temperature;

subscript-

in - inlet; *out* - outlet; *w* - wall; *max* - maximum; ave - average.

1. Introduction

The flow field and the vortex structure formation around bluff bodies (such as circular and/or square cylinder) at low Reynolds number (*Re*) has got principal theoretical importance and huge practical engineering applications. Such transport processes are mainly encountered in electronic cooling, refrigeration systems, heat exchangers, and nuclear stations etc. the results reported that the vortex structure depends on large number of parameters such as type of fluid flow (compressible or incompressible) [1-2], confined or unconfined [3- 4], geometrical shape such as symmetrically or asymmetrically [5-6].

The flow even becomes more interacted when the wake even influenced by heat transfer. It is worth to understand that at low Reynolds number, the buoyancy strength can significantly muddle the flow field around the confined obstacle. Thereby, the heat transfer is also influenced by this factor. Recently, many research works are available in the literature that devoted for fluid flow and heat transfer around circular cylinder. The majority of these works emphasize on thermo hydrodynamic characteristics of fluid subjected to aiding thermal buoyancy for flow around confined cylinder [7-10]. However there are limited resources for the coupled fluid flow and heat transfer over a confined circular cylinder under opposing thermal buoyancy in a horizontal channel. Therefore, an attempt has been provided in this paper to fill this gap.

In the context of flow field under aiding thermal buoyancy, H. Laidoudi et al. [7] have numerically investigated the effect of superimposed thermal buoyancy as well as asymmetrically confined circular cylinder submerged in incompressible Poseuille liquid, this work is done only at fixed value of blockage ratio β = 20%, the governing equations of continuity, momentum and energy have been solve by the ANSYS-CFX Software. In order to interpret the behavior of buoyancy strength, the results are depicted in terms of streamlines and isotherms contours. Moreover, the total drag coefficient and Nusselt number are computed in this range of conditions: *Ri* = 0-4, *Re* = 10-40, at *Pr* = 1. The obtained results showed that the total drag coefficient increases and Nusselt number decreases with increasing Richardson number. Also, the thermal buoyancy generates a vortex over and below the cylinder. Furthermore, the eccentricity factor has the tendency to increase the heat transfer rate. Dipankar Chatterjee et al. [8] numerically predicted the effect of aiding thermal buoyancy over a square cylinder at low Reynolds number; the governing equations are solved in unsteady state, the range of Reynolds number is chosen between 5 and 40, the reported results presented that fluid flow becomes unstable when thermal buoyancy is increased, at some critical parameter of Richardson number, periodic vortex shedding is observed. The Strouhal, Nusselt numbers are also calculated in this work. Neha Sharma et al. [9] reported numerically the mixed convection flow and heat transfer a long cylinder of square cross-section under the influence of aiding thermal buoyancy in vertical unconfined configuration, the obtained results have been calculated and discussed in this range of conditions: *Re* = 1-40, *Ri* = 0-1, at fixed value of *Pr* = 0.7. The semi-explicit finite volume method has been employed to solve the governing equations. The flow is found to be steady for range of these conditions. Moreover, the friction, pressure, and the total drag force are found to increase with Richardson number, it is also found that the heat transfer increases with increase in Reynolds number and/or Richardson number. Finally, simple expressions of wake length, average Nusselt number are delivered for the range of condition covered in this work. Dipankar Chatterjee et al. [10] also carried out numerically to understand the effects of thermal buoyancy and Prandtl number on flow characteristics and mixed convection heat transfer over two equal isothermal square cylinders placed in tandem arrangement within a channel at low Reynolds number. The numerical results are presented for the range of conditions as: $1 \leq Re \leq 30$, $0.7 \leq Pr \leq 100$, and $0 \leq Ri \leq 1$. The governing equations are solved in unsteady state with a finite volume method; it is found that the flow is completely steady for this range of condition.

For opposing thermal buoyancy, there have been some limited works, for example Sandip Sarkar et al. [11] presented the mixed convection heat transfer from two identical cylinders in uniform upward flow at $Re = 100$, the effects of aiding and opposing buoyancy is brought about by varying Richardson number. The boundary conditions used in this work are: Ri = from -1 to 1, $Pr = 0.7$, this research emphasize on effect of thermal buoyancy on flow field and heat transfer rate as well as interaction between two cylinders. Atul Sharma et al. [12] studied the effect of channel-confinement of various degrees (blockage ratio 10%, 30%, and 50%) on upward flow and heat transfer characteristics around a heated/cooled square cylinder by considering the effect of aiding/opposing buoyancy at $-1 \leq Ri \leq 1$, for $Re = 100$ and $Pr = 0.7$. Principally, this paper investigates the influence of buoyancy and channel confinement on recirculation length, drag coefficient, Strouhal number, and heat transfer rate. Shiang-WuuPerng et al. [13] investigated the effect of aiding/opposing buoyancy on the turbulent flow field and heat transfer across a square cylinder in vertical channel, the level of wall confinement is similar to [12] with a constant Reynolds number (5000), under various Richardson number from -1 to 1. The results showed that, with increasing blockage ratio, the buoyancy effect is becoming weaker on the Nusselt number. Moreover, the turbulent heat transfer rate can be enhanced by increasing the blockage ratio.

From the critical evaluation of the mentioned literature in this field, it is obvious that although there are some available results for mixed convection heat transfer analysis around a confined cylinder by opposing buoyancy, there is no reported work on effect of opposing buoyancy of the fluid flow and heat transfer around a circular cylinder confined within a horizontal channel at low Reynolds number. For that purpose, our objective is to investigate correctly the role of opposing thermal buoyancy on the momentum and heat transfer characteristics of circular cylinder situated between parallel walls. The obtained are presented and discussed for this range of conditions: $10 \leq Re \leq 40$, $Pr = 1$, $0 \leq Ri \leq -4$, at fixed blockage ratio $B = 20\%$.

2. Problem statement and boundary conditions

The dimensionless equations for continuity, momentum, and energy equations with the Bousinesq approximation and negligible viscous dissipation can be expressed in following form:

- Continuity:

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}=0\,; \tag{1}$$

- Momentum:

$$U\frac{\partial U}{\partial X}+V\frac{\partial U}{\partial Y}=-\frac{\partial P}{\partial X}+\frac{1}{Re}\left(\frac{\partial^2 U}{\partial X^2}+\frac{\partial^2 V}{\partial Y^2}\right); \tag{2}$$

$$U\frac{\partial V}{\partial X}+V\frac{\partial V}{\partial Y}=-\frac{\partial P}{\partial Y}+\frac{1}{Re}\left(\frac{\partial^2 U}{\partial X^2}+\frac{\partial^2 V}{\partial Y^2}\right)+Ri\theta\,; \tag{3}$$

- Thermal energy:

$$U\frac{\partial \theta}{\partial X}+V\frac{\partial \theta}{\partial Y}=+\frac{1}{RePr}\left(\frac{\partial^2 \theta}{\partial X^2}+\frac{\partial^2 \theta}{\partial Y^2}\right). \tag{4}$$

In governing equations U, V, P, θ, Re, Ri and Pr are dimensionless fluid velocities, temperature, pressure, Reynolds number, Richardson number, and Prandtl number ($Pr = 1$), respectively. The dimensionless forms of the variables are:

$$U=\frac{u}{U_{max}},V=\frac{v}{U_{max}},X=\frac{x}{d},Y=\frac{y}{d}, \tag{5}$$

$$P=\frac{p}{\rho V_{max}^2},\theta=\frac{T-T_{in}}{T_w-T_{in}}, \tag{6}$$

$$Re=\frac{\rho d U_{max}}{m},Ri=\frac{Gr}{Re^2}, \tag{7}$$

where Gr is the Grashof number which can be written as:

$$Gr=\frac{gB(T_w-T_{in})d^3\rho^2}{\eta^2}, \tag{8}$$

where g, B is the gravitational acceleration, the volumetric expansion coefficient respectively. The drag coefficient is computed from:

$$C_D=\frac{2F}{\rho U_{\max}^2 d}, \tag{9}$$

where F is the total drag force exerted on cylinder surface.

The heat transfer between the cylinder and the surrounding fluid is calculated by the Nusselt number. The local Nusselt number based on the cylinder dimension is given by:

$$Nu=\frac{hd}{k}=-\frac{\partial\theta}{\partial n_s}, \tag{10}$$

where h is the local heat transfer coefficient, k is the thermal conductivity of the fluid and n_s is the direction normal to the cylinder surface. Surface average heat transfer at each face of the cylinder is obtained by integrating the local Nusselt number along the cylinder face.

Fig. 1 shows the computational domain used in this investigation. Here H is the height of the channel, L_u, L_d is the upstream and downstream distance respectively, which are taken as $10d$ and $20d$ respectively, d is the diameter of cylinder.

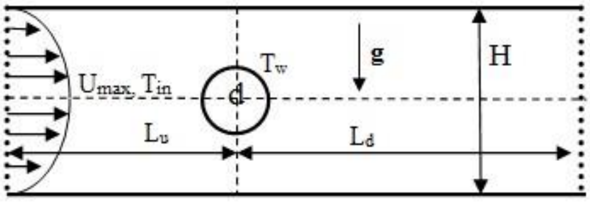

Fig. 1 Physical domain with boundary conditions

At the inlet a fully developed velocity profile for laminar flow fluids with a constant temperature, this is given by:

$$u = U_{max}(1-|2y\beta|)^{(2)}, v = 0, T = T_{in} . \quad (11)$$

On the surface of the obstacle cylinder: The standard no-slip condition is used and the cylinder is maintained and heated with a constant temperature T_w.

$$u = 0, v = 0, T = T_w . \quad (12)$$

At the channel walls, the usual no-slip condition for flow and adiabatic condition for energy are used.

$$u = 0, v = 0, Adiabatic . \quad (13)$$

At the outlet Neumann boundary condition for field variables is employed:

$$\frac{\partial U}{\partial X} = 0, \frac{\partial V}{\partial Y} = 0, \frac{\partial \theta}{\partial Y} = 0 . \quad (14)$$

3. Numerical details

The computational domain is divided into 120,350 trilateral elements. The mesh is finer near the walls of cylinder with 300 times 4 nodes to resolve the high gradients in the thermal and hydrodynamic boundary layer. The grid independence results for this work were discussed in our earlier investigation [7].

The governing equations subjected to the aforementioned boundary conditions are solved numerically using *ANSYS-CFX (16.0)*, this code is a general purpose fluid mechanics program that is capable of solving diverse complex configurations. Moreover, this package uses the fundamental equations of continuity, momentum and energy to describe the fluid flow behavior and heat transfer rate; it also combines some specific numbers of mathematical models such as (Boussinesq approximation) that can be used simultaneously with fundamental equations to describe other physical and chemical phenomena such as combustion, turbulence, etc. This present CFD package applies the finite volume method to covert the governing partial differential equations into a system of discrete algebraic equations by discretizing the computational domain into grid mesh.

In order to justify the accuracy of our obtained results, it is obligated to test our numerical methodology, to do so; the numerical solution procedure used herein has been validated by comparing the present values with the previous results on forced and mixed convection heat transfer from symmetrically square cylinder. More information about this point is presented in detail in our earlier work [7].

4. Results and discussion

The effect of opposing thermal buoyancy on the flow field and heat transfer rate are presented, also some principal dimensionless global hydrodynamic and thermal parameters such as drag coefficient and average Nusselt number are provided for laminar incompressible Newtonian fluid over a confined circular cylinder placed in horizontal channel under opposing buoyancy for the controlling parameters like *Re*, and *Ri* ranging from 5 to 40 and -0.1 to -4 respectively at Pr = 1 and β = 0.2.

In order to present the streamlines contours for forced convection (Ri = 0) H. Laidoudi et al. [7] reported that the flow separation behind cylinder is found to be symmetric about the centre line for all *Re* number, and the wake region increases with increasing *Re* number along the stream-wise as well as transversal directions with Reynolds number.

For mixed convection Fig. 2 depicts the streamlines contours for Richardson number in the range of -0.1 to -1 at fixed *Re* number Re = 20. From Fig. 2 the flow pattern loses its symmetry when buoyancy is opposed. However, the degree of asymmetry is found to be increased with decrease in the value of Richardson. Moreover, the recirculation zone which contains two bubbles also becomes asymmetric and both bubbles interact and move towards the rear edge of the cylinder and accordingly the recirculation region gradually diminishes, it is also observed that at some critical value of *Ri* the flow does not separate at all behind the object. It is also shown that the interaction between the upper and down vortex increases by increasing the opposing effect of buoyancy. Furthermore, the down vortex suppresses earlier than the upper, this due to the fact that as *Ri* decreases, the velocity of particles behind the cylinder increases and moves toward the down wall of channel, the inertia force is added with viscous force, resulting in the down vortex delay first. Consequently, the incoming flow will be accelerated over the cylinder owing to the mass conservation principle, and this behavior led to increase the flow separation in the upper half of cylinder.

Fig. 3 presents streamlines contours for Richardson number range of -1.5 to -4, and for different Reynolds value. It is depicted that, a counter rotating region appears under the cylinder. The recirculation size increases with increase in Reynolds number and/or decreasing Richardson number in both directions. This behavior can be explained as follows: under the value -1 of *Ri* the free convection dominates over forced convection accordingly, most fluid flows over the cylinder. Hence, the mass flow rate becomes less beneath the cylinder than above it which reveals the flow under the cylinder. Moreover, a second region appeared under the upper channel wall behind the cylinder, this region is seen to be increased in both directions by increasing the value of *Re* and/or decreasing the value of *Ri*. It is due to the opposing thermal buoyancy effect which tows the flow towards the down channel wall. In the whole, from streamline contours of opposing buoyancy and research of [7] it can be concluded that the opposing buoyancy effect is symmetrically to aiding effect.

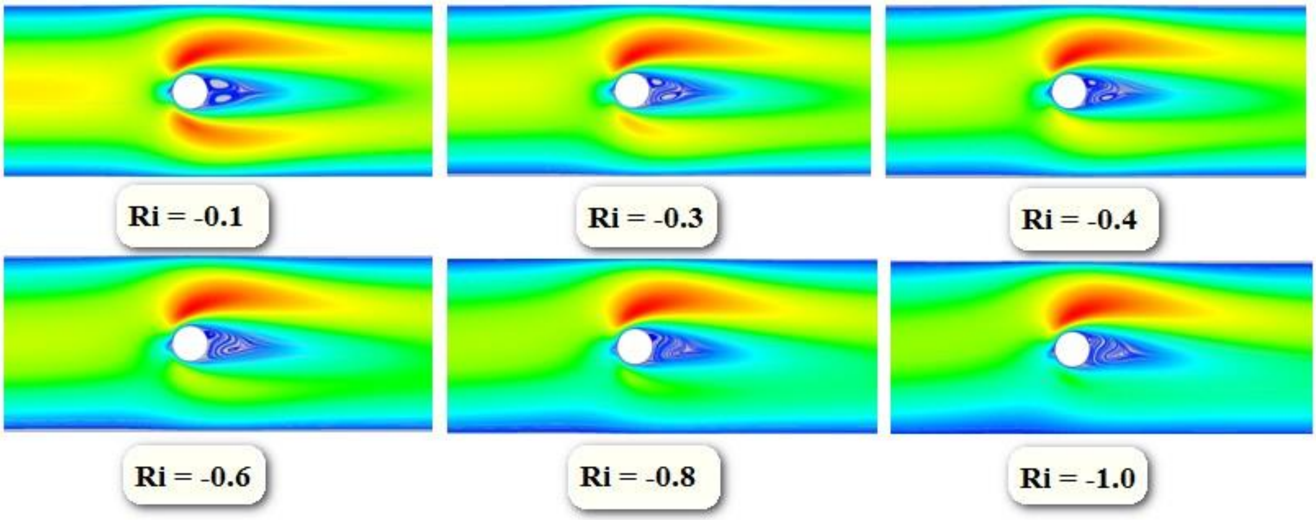

Fig. 2 Streamlines around the cylinder for *Ri* =-0.1 to -1, *Re* = 20, and *Pr* =1

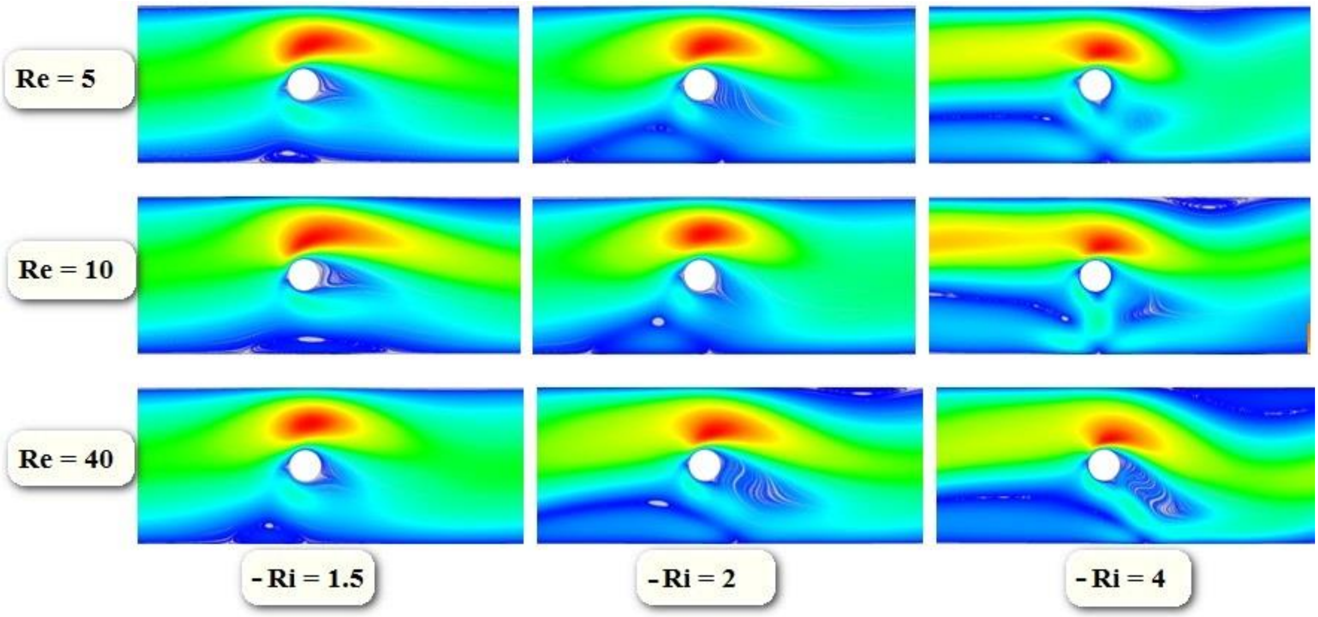

Fig. 3 Streamlines around the cylinder for *Ri* =-1.5 to -4, *Re* = 5 - 40, and *Pr* =1

The isotherms around cylinder for the range of *Ri*, and *Re,* at fixed *Pr* = 1 are depicted in Fig. 4. The isotherm contours are the reflection of physical phenomena seen from the analyzes of streamlines patterns, more crowding of temperature profiles is seen near to the curved surface of obstacle compared to the flat surface, which hints a higher value of heat transfer rate on the curved surface. The crowding temperature is found to be depended with Richardson number as well as Reynolds number; this means that the heat transfer rate is depending with increasing in the value of Reynolds number or decreasing in the value of Richardson number. Like the streamline patterns, the isotherm contours become also asymmetric when the thermal buoyancy is opposed, and this asymmetry is seen to be increased with increasing the opposing of buoyancy. In the range of Richardson number of -0.1 to -1, the opposing buoyancy influences the flow on the rear part of cylinder surface much more than that on the other part of cylinder. Meanwhile, this effect appears on down part of obstacle surface in the range of *Ri* = -1.5 to -3and this due to effect of opposing thermal buoyancy which be pronounced in this range. Furthermore, from the obtained isotherm contours and the previous work of H. Laidoudi et al. [7] it can be concluded that the effects of adding and opposing buoyancy on the isotherm contours of confined circular cylinder are symmetrically in the range of *Ri* = -4 to 4.

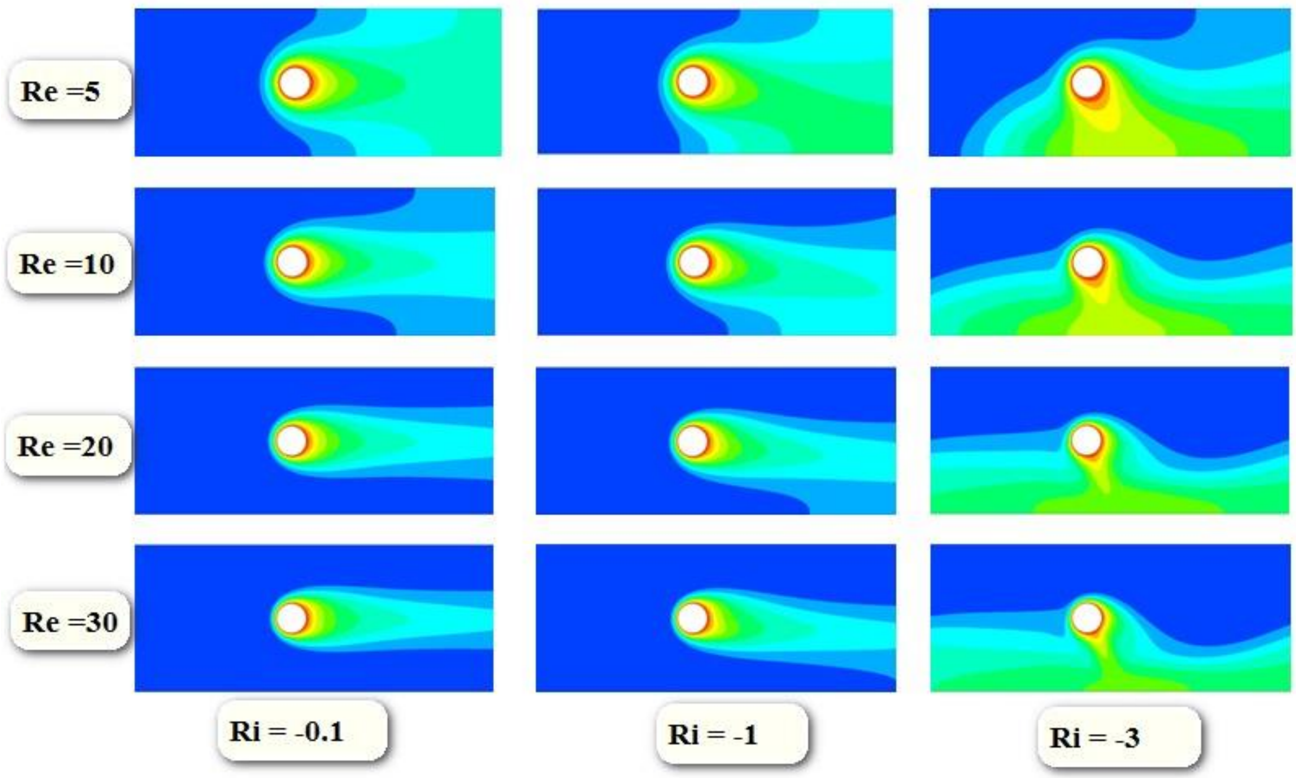

Fig. 4 Isotherm contours around the cylinder for =-0.1 to 3, *Re* = 5 - 30, and *Pr* =1

Figs. 5 and 6 show the variation of drag coefficient various Richardson number for different value of Reynolds number. The Richardson number in Fig. 5 is limited between -0.1 to -1, meanwhile in Fig. 6 is ranged from -1 to -4. From Fig. 5 it is shown that increase in the value of Reynolds decreases the drag coefficient due to the lowering of viscous force. Moreover, decrease in the value of Richardson increases slightly the drag coefficient, and this effect decreases by increasing Reynolds number.

Fig. 6 depicts that decrease in the value of Richardson in the range of -1 to -4 increases significantly the total drag coefficient, and this behavior due to the fact that as *Ri* decreases gradually more and more fluid comes over the cylinder which results in a important reduction of pressure at the bottom and behind obstacle and accordingly the drag coefficient increases. This behavior becomes very pronounced when *Ri*>-1.

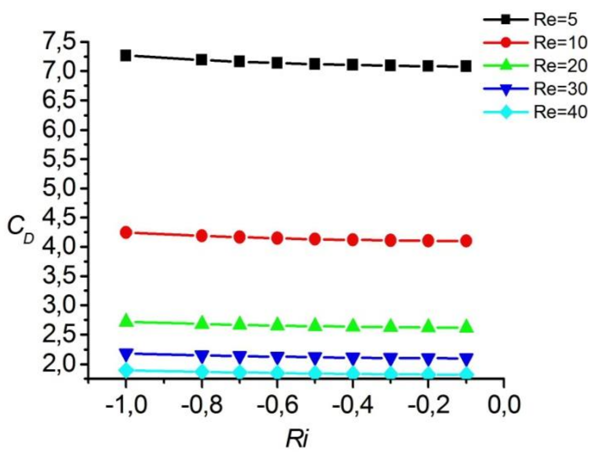

Fig. 5 The variation of drag coefficient for *Ri*= -0.1to -.

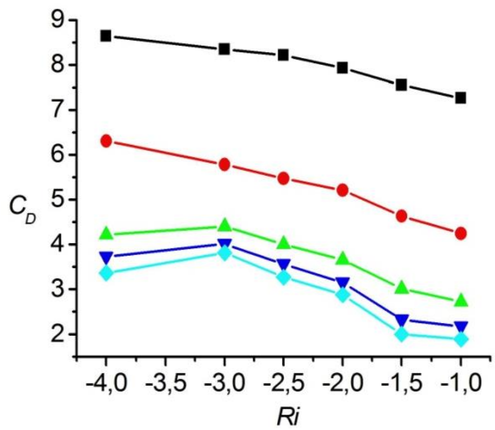

Fig. 6 The variation of drag coefficient for *Ri*= -1to -4

Figs. 7and 8 present the variations of average Nusselt number on the circular cylinder with Richardson number for different Reynolds number. Like the total drag coefficient the first figure is limited for *Ri* = -0.1 to -1 but in the second *Ri* = -1 to -4. The surface average heat transfer is obtained by surface averaging the integral local Nusselt number along the cylinder surface. Form the Figs. 7 and 8 the average Nusselt increases as usual with Reynolds number.

In Fig. 7 decrease in the value of *Ri* for -0.1 to -1 does not show a big variation in the value of heat transfer rate. Meanwhile in the range of -1 to -4 it is shown that depending upon the value of Richardson number, the average Nusselt number may increase or decrease thereby suggestion a non monotonic relationship between the average Nsselt number and the value of Richardson number, this behavior can be referred to wake regions that are appeared above and behind the cylinder.

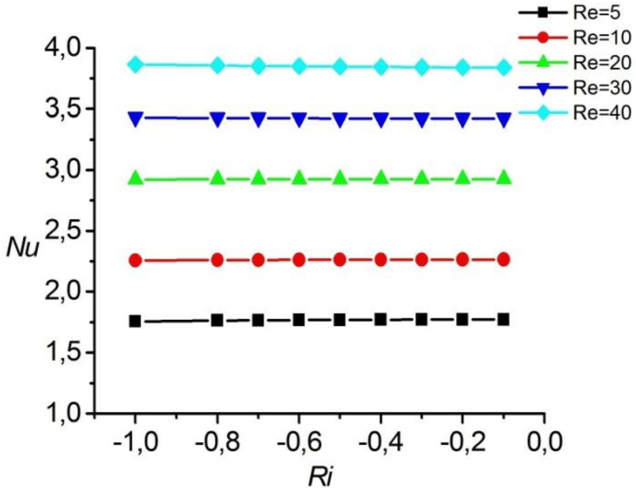

Fig. 7 The variation of Nusselt number for Ri= -0.1to -1

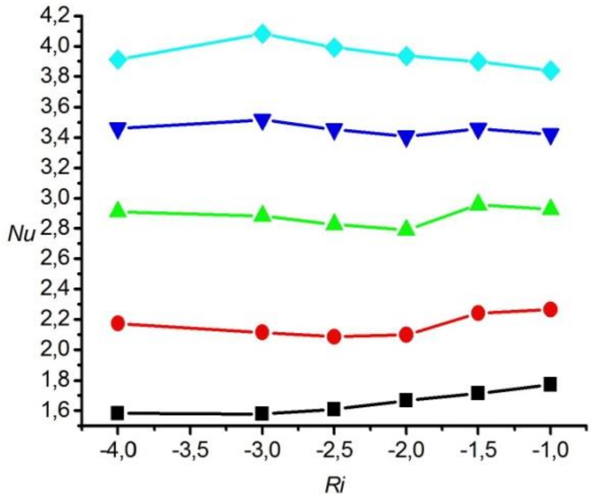

Fig. 8 The variation of Nusselt number for Ri= -1 to -4

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4. Conclusions

The numerical simulation of the effect of opposing thermal buoyancy Ri = -0.1 to -4 on the flow field and heat transfer rate around a circular cylinder confined in two-dimensional channel for laminar and steady flow regime Re = 5 to 40 has been presented in this paper, the main results are presented in term of streamline and isotherm contours to interpret the effect of opposing buoyancy on them. The principal results are summarized as follow:

- The effect of aiding and opposing thermal buoyancy on the fluid flow and temperature distribution for a horizontal circular cylinder are symmetrically in the range of -4 to 4.
- From Ri = -1 to -4 two Recirculation zone appear under the cylinder and down the above wall of channel, and they increase in both direction by increasing the Reynolds number or decreasing the Richardson number.
- From Ri = -0.1 to -4 the recirculation zone behind the cylinder decreases gradually and at critical value of Richardson is vanished at all behind the object.
- From Ri = -0.1 to -1 both of C_D and Nu increases slightly with decreasing in the value of Richardson number. Meanwhile a significant evolutions of C_D and Nu are seen in the range of Ri = -1 to -4.

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EFFECT OF OPPOSING BUOYANCY ON TWO-DIMENSIONAL LAMINAR FLOW AND HEAT TRANSFER ACROSS A CONFINED CIRCULAR CYLINDER

S u m m a r y

This research examines the effect of opposing thermal buoyancy on momentum and heat transfer characteristics of a confined cylinder submerged in Newtonian fluid. The detailed flow and temperature field are shown in term of streamlines and isotherm contours. The numerical investigation are done for the range of conditions as Re = 5 to 40, Richardson number Ri = -0.1 to -4, Pr = 1, and blockage ratio β = 0.2. When the buoyancy is opposed, it is depicted that the flow separation becomes asymmetrically and diminishes gradually and at some critical value of Richardson number it totally disappears resulting a creeping flow. Two rotating regions appear under the cylinder and behind the cylinder under the upper channel wall. Moreover, the total drag coefficient and the average Nusselt number are calculated.

Keywords: opposing buoyancy, Richardson number, drag coefficient, Nusselt number, steady regime, vortex.

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