# The Investigation of the Mixed Convection from a Confined Rotating Circular Cylinder

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## Abstract

*In this paper, a numerical study on the two-dimensional laminar mixed convective flow and heat transfer from an rotating circular horizontal and isothermal cylinder confined in a horizontal channel. The blockage ratio and the Prandtl number are fixed at 0.05 and 0.7 respectively. The continuity, momentum and energy equations are solved via the finite-volume method. Our results are in very good agreement with those resulting from preceding studies to Ri=0 and a=0, which makes it possible to validate on important extension of present work. The mixed convective flow and heat transfer is simulated by the Reynolds number is studied in the range 1 <Re <40, the Richardson number (Ri) demonstrating the influence of thermal buoyancy ranges from 0 to 1 and for rotational rate from α=0 to α=4. Major emphasis is given to the effect of rotating a circular cylinder on the mixed convection and also on the measurements of the local and average Nusselt numbers are also obtained. Furthermore, the representative streamlines and isotherm patterns are presented and discussed.*

## Keywords

*computational study, drag coefficients, rotating circular cylinder, mixed convective flows, Richardson number*

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## 1 Introduction

The combined forced and free convection heat transfer from cylinder has numerous industrial processes. The applications may include cylindrical cooling devices in plastics industries, oil and gas pipelines, phenomenon occurs in many engineering systems such as cooling of electronic components, tubular and compact heat exchangers, nuclear reactors, aircraft, automobiles, buildings. The analysis of mixed convection is more complicated than that of the forced or free convection alone. Besides this, the economically and performance is important to the knowledge of this type of flow for improving heat exchange (maximizing the heat exchange within a minimum volume of an industrial system). the flow around a rotating cylinder involves complex transport phenomenon because of many factors such as the effect of cylinder rotation on the production of lift force and drag, evolution of temperature field. This work is concerned with the mixed convection heat transfer from a rotating circular cylinder for varying values of Richardson numbers in the steady regime.

Numerical analysis of these kinds can be found in many literatures. Under isothermal conditions, the flow around a horizontal cylinder is relatively well-known, Zdravkovich [1, 2]. For small temperature difference, the convective flow is known as the forced convection regime. Although buoyant forces are negligible, temperature still modifies the thermo-physical properties of the fluid in the close vicinity of the cylinder. For $Re < 200$ and $Ri < 1$, Patnaik et al. [3] shed light on the laminarisation effect downstream from a heated cylinder. For the heat transfer from a stationary circular cylinder, the effects of Prandtl number are available regarding by [4-5]. The effect of Prandtl number on the heat transfer from a cylinder in the cross-flow configuration has been investigated by Dennis et al. [6] for Reynolds number up to 40. Bharti et al. [7] investigated the effects of Reynolds number, Prandtl number in uniform heat flux and constant wall temperature around the cylinder for the range $10 < Re < 45$ and $0.7 < Pr < 400$ in the steady regime.

Most of the mixed convection studies are available in the literature, these studies are concerned with the confined flow past stationary circular cylinder Farouk and Güceri [8] calculating

the mixed and natural convection through an isothermal circular cylinder which passes through a vertical two-dimensional channel with solid borders adiabatic. Singh et al. [9] numerically modelling mixed convection to a circular cylinder (heated / cooled) through a vertical channel. They found the destruction of Karman vortex from the Richardson number exceeding 0.15.

Badr et al. [10] presented the results for the steady flow at $Re$=5 and 20 ($\alpha$=0.1 – 1.0), and Badr and Dennis [11] investigated the problem of laminar heat transfer over an isothermal cylinder for the range $Re$=5-100 and $Pr$=0.7. The rate of heat transfer found to decrease with the increase of $\alpha$ for $\alpha \leq 4$. Recently, the flow and heat transfer around a rotating circular cylinder is studied by Paramane and Sharma [12] for the values of speed of rotation α varies from $0 \leq \propto \leq 6$ for Reynolds number range 20 - 160 and $Pr$=0.7. The values of drag coefficient as well as average Nusselt number are found to decrease with increasing the rotation rate.

Cheng et al. [13] studied numerically the unsteady flow past a rotationally oscillating circular cylinder over a much wider range of forcing frequency and amplitude. A hybrid vortex method, which was previously presented and applied to the situation of flow past a rotating circular cylinder (Chew et al. [14]; Cheng et al. [15]), is used to simulate this type of flow at the same Reynolds number, $Re$=1000.

Cheng et al. [16] developed a hybrid vortex method to simulate two-dimensional viscous incompressible flows over a bluff body. It was based on a combination of the diffusion-vortex method and the vortex-in-cell method whereby the flow field is divided into two regions. In the region near the body surface the diffusion-vortex method is used to solve the Navier-Stokes equations while the vortex-in-cell method is used in the exterior domain. They compared the results obtained with those from the finite difference method and experiments. This showed that the method is well adapted to calculate two-dimensional external flows at high Reynolds number.

Recently [17] have investigated the effects of Prandtl number on the heat transfer characteristics of an unconfined rotating circular cylinder for varying rotation rate (0≤ α ≤5) in the Reynolds number range of 1-35 and Prandtl numbers range of 0.7- 100 in the steady flow regime.

This paper present numerical investigation, the effects of rotation rate $\alpha$ on the characteristics of laminar fluid flow and heat transfer in mixed convection from an confined a rotating circular horizontal and isothermal cylinder in a rectangular channel are studied in detail, for the fixed value of the Prandtl number ($Pr$=0.71) as the operating fluid computations are performed at a representative Reynolds numbers in the range of 1<$Re$<40. The rotational rates from $\alpha$=0 to $\alpha$=4. Effect of buoyancy is brought about by considering the Richardson number ($Ri$) range 0.25<$Ri$<1. Flow visualization result is presented in the form of streamlines, and isotherms for various ratation rate

and Richardson numbers at $Re$=20 and $Re$=40. Characterization of flow and heat transfer pattern for the current ranges of $Ri$. Furthermore, velocity field on the rectangular channel, are computed with various $Ri$ and α. Finally the heat transfer characterizations are done by local and average Nusselt number for different values of $Ri$ and α.

From the above critical evaluation of the pertinent available literature in the subject area, it is obvious that there are some results for the forced and mixed convection heat transfer analysis around a circular cylinder. Additionally, to the authors' best knowledge, a detail investigation on the combined effect of $Ri$ and α on flow topology and mixed convective heat transfer from an confined a rotating circular horizontal and isothermal cylinder has not been carried out yet.

## 2 Analysis
### 2.1 Description of the problem
The problem here consists of a two dimensional flow around a horizontal circular cylinder of diameter $D$ and rotating with a constant angular velocity of w. It is exposed to a parabolic velocity field and at a uniform temperature $T_\infty$ at the inlet (Fig. 1(a)). The obstacle is located in the middle at a distance of 10$D$ from the inlet and at 20$D$ from the outlet. The height of the computational domain in the lateral direction is 20$D$, whith defines the blockage ratio of 0.05.

### 2.2 Governing Equations
The system is considered to be two dimensional laminar, incompressible and steady state. Physical properties except for the body force term in the momentum equation (Boussinesq approximation), are given their conservative forms. Based on the dimensionless variables above the governing can be written as:
Continuity equation:

$$\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = 0 \tag{1}$$

$x$-Momentum equation:

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

$y$-Momentum equation:

$$U\frac{\partial V}{\partial x} + V\frac{\partial V}{\partial y} = -\frac{\partial P}{\partial y} + \frac{1}{Re}\left(\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2}\right) + RiT \tag{3}$$

Energy equation:

$$U\frac{\partial T}{\partial x} + V\frac{\partial T}{\partial y} = \frac{1}{RePr}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) \tag{4}$$

The non-dimensional parameters that appear in the formulation are the Reynolds number ($Re = D . U_{max} / v$), the Richardson number ($Ri = Gr / Re^2$) and Prandtl number ($Pr = v/a$).
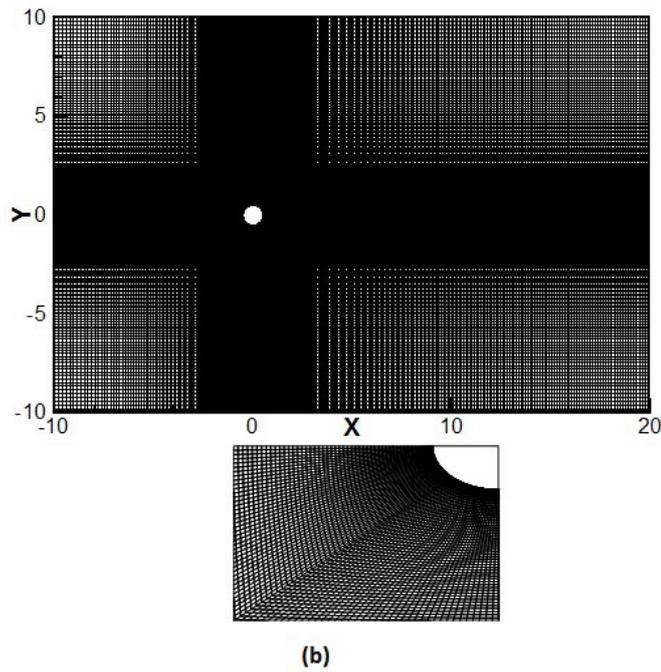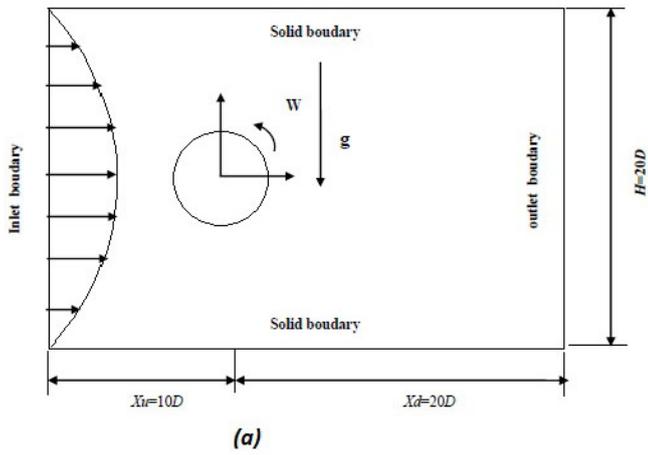
**Fig. 1** (a) Schematic of the confined flow and heat transfer around a rotating circular cylinder (b) refining the mesh near the wall circular cylinder

## 2.3 Boundary Conditions

The dimensionless boundary conditions for the flow across a rotating circular cylinder can be written as follows (Fig. 1 (a)):
At the inlet boundary: $U = 4\beta y(1 - \beta y)$;

$$V = 0; \quad T = 0 \tag{5}$$

At the outlet boundary: $\partial \Phi / \partial x = 0$, where $\Phi$ is a dependent variable, $u$ or $v$;

$$T = 0 \tag{6}$$

On the surface of the circular cylinder:

$$U = -\propto \sin(\varnothing); \quad V = -\propto \cos(\varnothing); \quad T = 1 \tag{7}$$

On the Lower and upper boundary:

$$U = 0; \quad V = 0; \quad \partial T / \partial y = 0 \tag{8}$$

## 2.4 Choices of numerical parameters and validation

In the present study, three non-uniform grids of 103425, 81200 and 40149 cells with 50, 80 and 100 grid points on the surface of the cylinder respectively. This study allows us to choose an optimal mesh 81200 cells.

Extensive benchmarking of the present heat transfer results with literature values is carried out here for $Re$=20 and 40 for a stationary cylinder for Prandtl numbers of 0.7 (Table 1) in the steady flow regime. The present results of the drag coefficient, recirculation zone are in excellent agreement with the literature values for example Dennis and Chang (1970) [18].

This validates the present numerical solution procedure investigating the extension of results used for a steady flow around a cylinder mixed convection.

**Table 1** Comparison of Cd, θd and L/R the present results at (α = 0) with literature values

| Re | Name / Year | Ref. | L/R | θd | Cd |
|----|-------------|------|-----|-----|-----|
| 20 | Dennis and Chang (1970) | [18] | 1.880 | 43.70 | 2.045 |
| | Nieuwstadt and Keller (1973) | [19] | 1.786 | 43.37 | 2.053 |
| | Coutanceau and Bouar (1977) | [20] | 1.860 | 44.80 | - |
| | Fornberg (1980) | [21] | 1.820 | - | 2.00 |
| | He and Doolen (1997) | [22] | 1.842 | 42.96 | 2.152 |
| | **Present work** | | **1.856** | | **2.046** |
| 40 | Dennis and Chang (1970) | [18] | 4.690 | 53.80 | 1.522 |
| | Nieuwstadt and Keller (1973) | [19] | 4.357 | 53.34 | 1.550 |
| | Coutanceau and Bouar (1977) | [20] | 4.260 | 53.50 | - |
| | Fornberg (1980) | [21] | 4.480 | - | 1.498 |
| | He and Doolen (1997) | [22] | 4.490 | 52.84 | 1.499 |
| | **Present work** | | **4.381** | | **1.515** |

## 2.5 Numerical simulation

Since detailed description of the problem and of the choice of numerical parameters and validation. only the salient features are recapitulated here. The governing equations (Eqs. (1)–(4)) with the corresponding boundary conditions (Eqs. (5)–(8)) are solved using a finite volume method based solver FLUENT [23]. The system of the algebraic equations is solved in a iterative manner. The Semi Implicit Method for the Pressure Linked Equations (SIMPLE) algorithm is used to avoid pressure–velocity decoupling. The main importance of choosing SIMPLE algorithm is its stable convergence behavior for steady problems. The above procedure is linked with an algebraic multigrid method and the set of equations is solved by a point or block Gauss-Seidel technique. A second order upwind scheme has been used to discretize the convective terms in the momentum and energy equations. The absolute convergence criterion of $10^{-9}$ is used for the residuals of continuity, x-momentum, y-momentum equations and the energy equation.

Fig. 2 shows the streamlines for flow past a circular cylinder at *Re*=20 and *Re*=40. One can verify a good agreement of the flow topology when compared with the works the (S.Taneda) and outher. Moreover, it can be concluded that the vortices obtained in the present work are in a similar position and have approximately the same size as those presented by the other authors. The flow is symmetric relative to the central axis of the stream and also between the upstream and the downstream of the circular cylinder for *Re*=1. There is a separation on two side of the cylinder. The release point moves in the upstream direction of the cylinder when the Reynolds number increases. The flow is stable and remaining stationary and symmetrical about the longitudinal axis. Downstream of detachment, form two almost symmetrical lobes attached to the cylinder contra recirculation (*Re*=20 and *Re*= 40). The point of attachment, which is defined as the placed where the longitudinal speed is zero on the centreline of the track, away from the cylinder when the Reynolds number1increases.
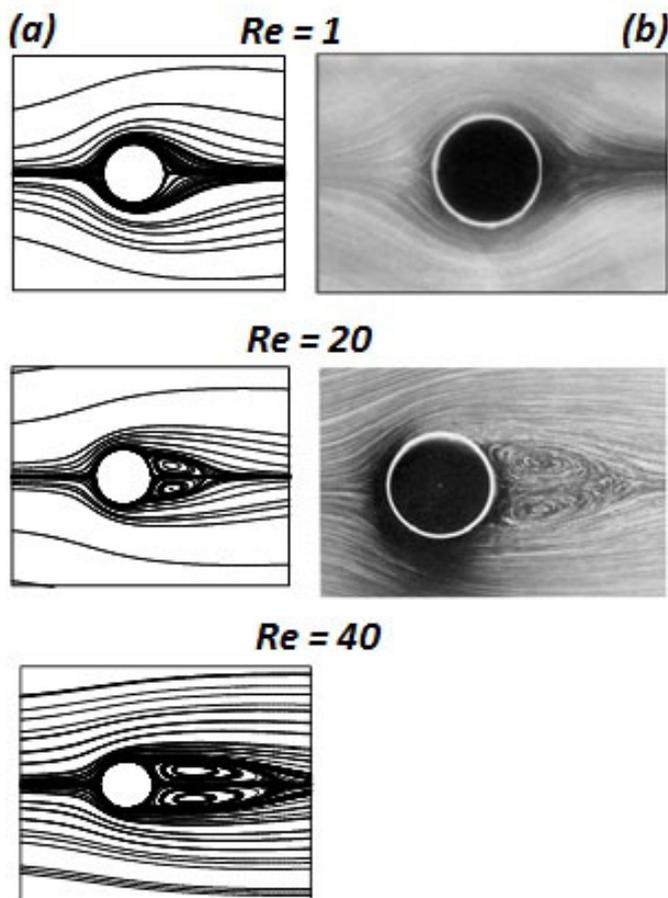


**Fig. 2** Qualitative comparisons of Present work (a) with actual visualization (S. Taneda (b)) extract of Van Dyke [24]

# 3 Results and Discussion
## 3.1 Qualitative comparisons

Streamlines indicate the flow pattern close to the circular cylinder for *Re*=20 and 40 for *pr*=0.7at different values of the Richardson number and rotation rate. The latter shows that The influence of buoyancy and rotation rate on the fluid flow in the wake region is shown in Fig. 3 and 4. In contrast the symmetric (about the mid-plane) streamline profiles for Ri=0 (Fig. 2), in the presence of buoyancy this symmetry is lost as seen in Figs. 3 and 4. The degree of asymmetry increases as the value of the Richardson number gradually increases from Ri=0 to 1. This effect becomes more accentuated with the increasing rotation rate.

Figs. 5 and 6 present the typical isotherm profiles around the rotating cylinder for various values of rotation rates for the Reynolds numbers of 20 and 40 for Richardson number of 0.25, 0.5 and 1 at Prandtl numbers of 0.7, first of all it is noticed that a stationary cylinder a high temperature gradient in the front surface of the cylinder due to the maximum density of isotherms. This indicates the higher values of local Nusselt number near the front stagnation point on the front surface as compared to the other surface of the cylinder. This effect can be explained as on increasing the Reynolds number. To besides, the temperature field not only becomes asymmetric with the introduction of buoyancy, but this increases with the increasing Richardson number. As well on increasing the value of the rotation rate, the maximum density of isotherms shifts from front surface towards the bottom surface of the rotating cylinder for the fixed Richardson number and Reynolds numbers. That the wake is deflected upwardly around the cylinder. Then, there is a decrease in the slope under the effect of gravity. The rear of the cylinder is an important feature on both observed effect that increased turnover rate and the effect of growth in the number of Richardson on the geometry of the thermal boundary layer and also on the distribution of local Nusselt number.

### 3.1.1 Velocity field

Fig. 7 shows the velocity profiles close to the rotating circular cylinder for various values of rotation rates for the Reynolds numbers of 40 for Richardson number of 0, 0.5 and 1 at Prandtl numbers of 0.7. In contrast the symmetric velocity profiles about the mid-plane for $\propto$ =0, $Ri = 0$, the wake formed is symmetry in the rear of the circular cylinder. Furthermore in the presence of buoyancy ($Ri > 0$) and increasing the value of the rotation rate, this symmetry is lost. The degree of asymmetry increases as the value of the ($Ri$ and $\propto$) gradually increase. This effect becomes due to the higher mass flow rate passing beneath the circular cylinder than that above. The latter also clearly observed in the deviation of the wake up under the effect of buoyancy forces.
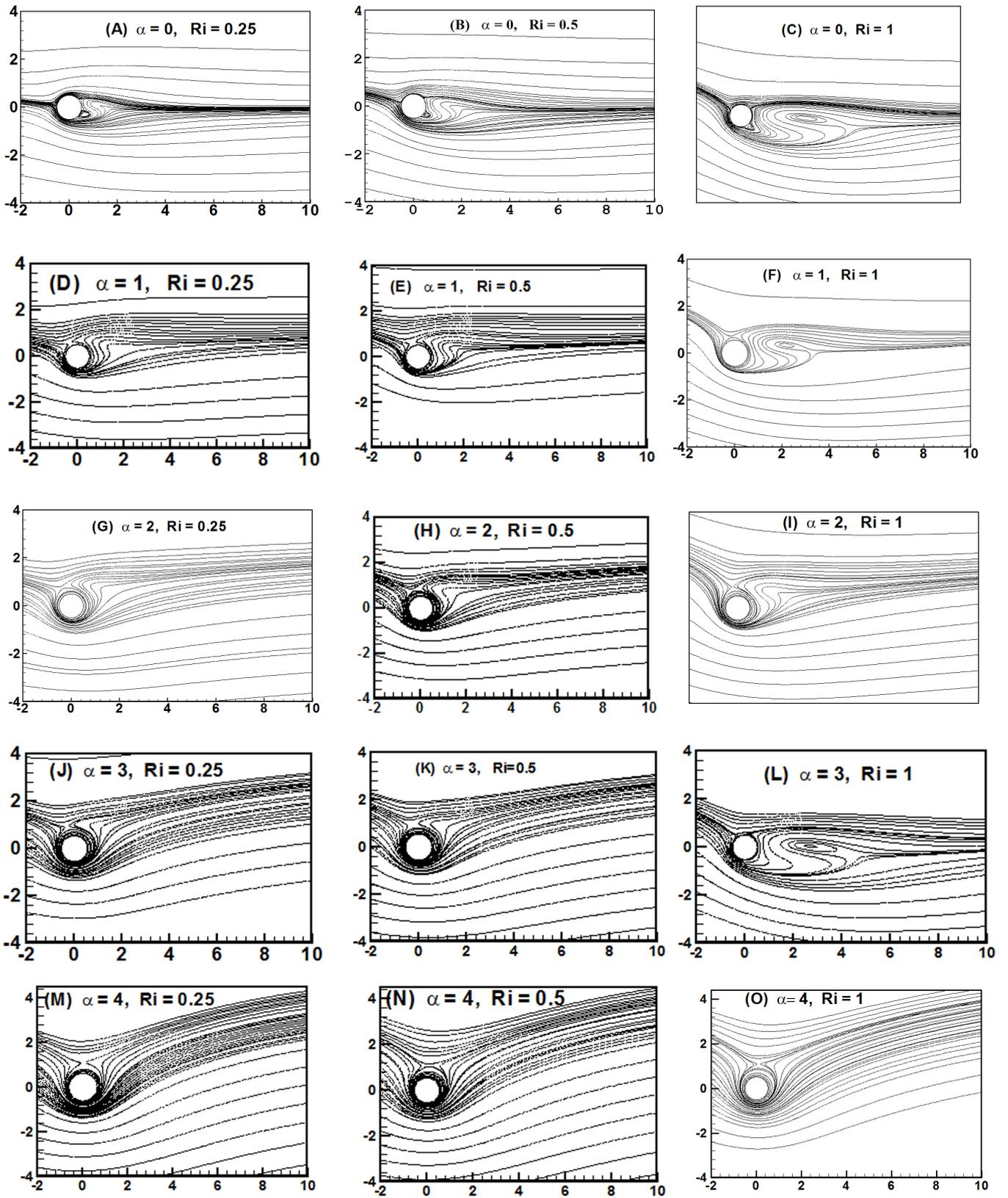
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**Fig. 3** The streamline profiles at *Re* = 20 for varying values of Richardson number and rotation rate
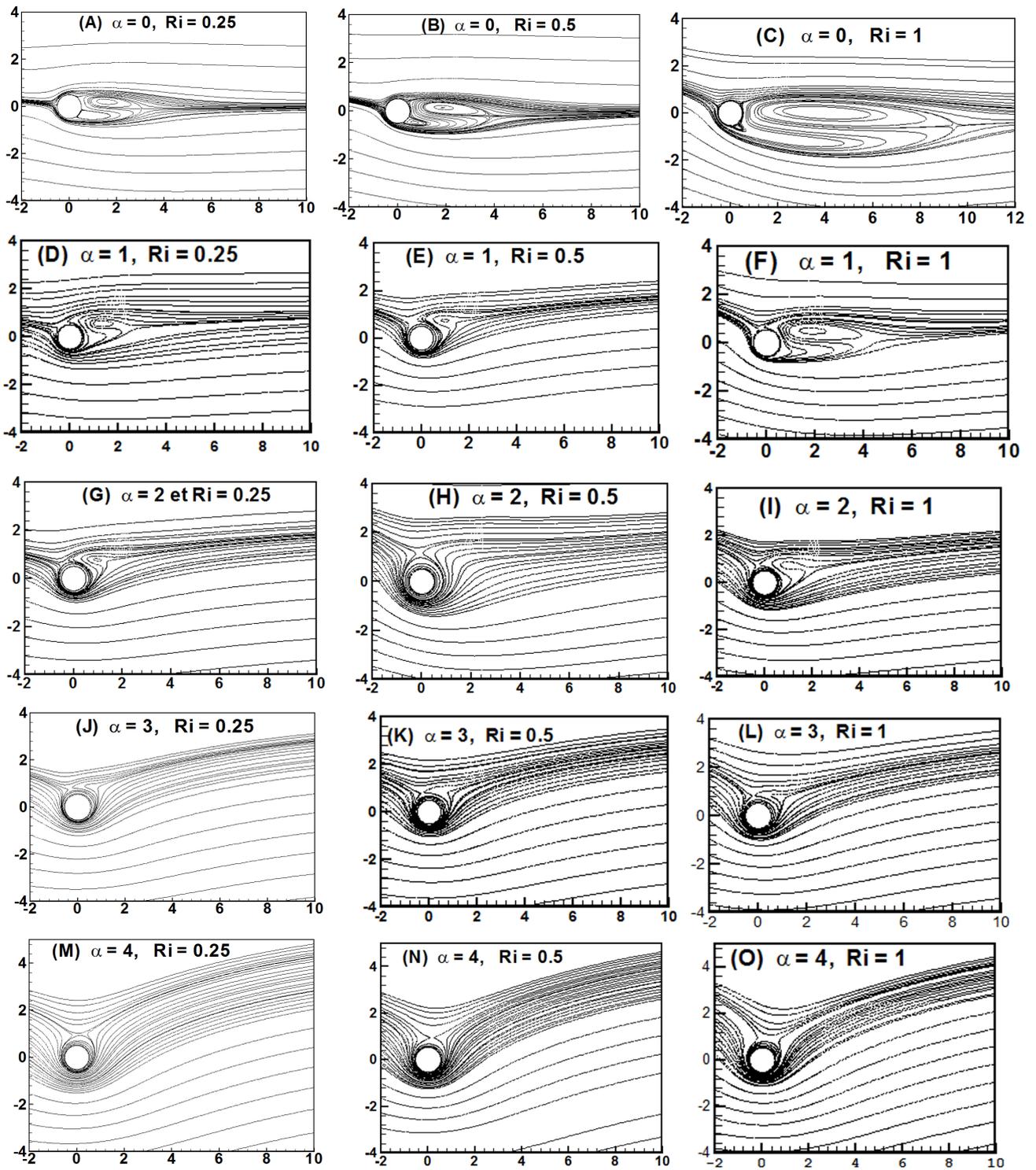
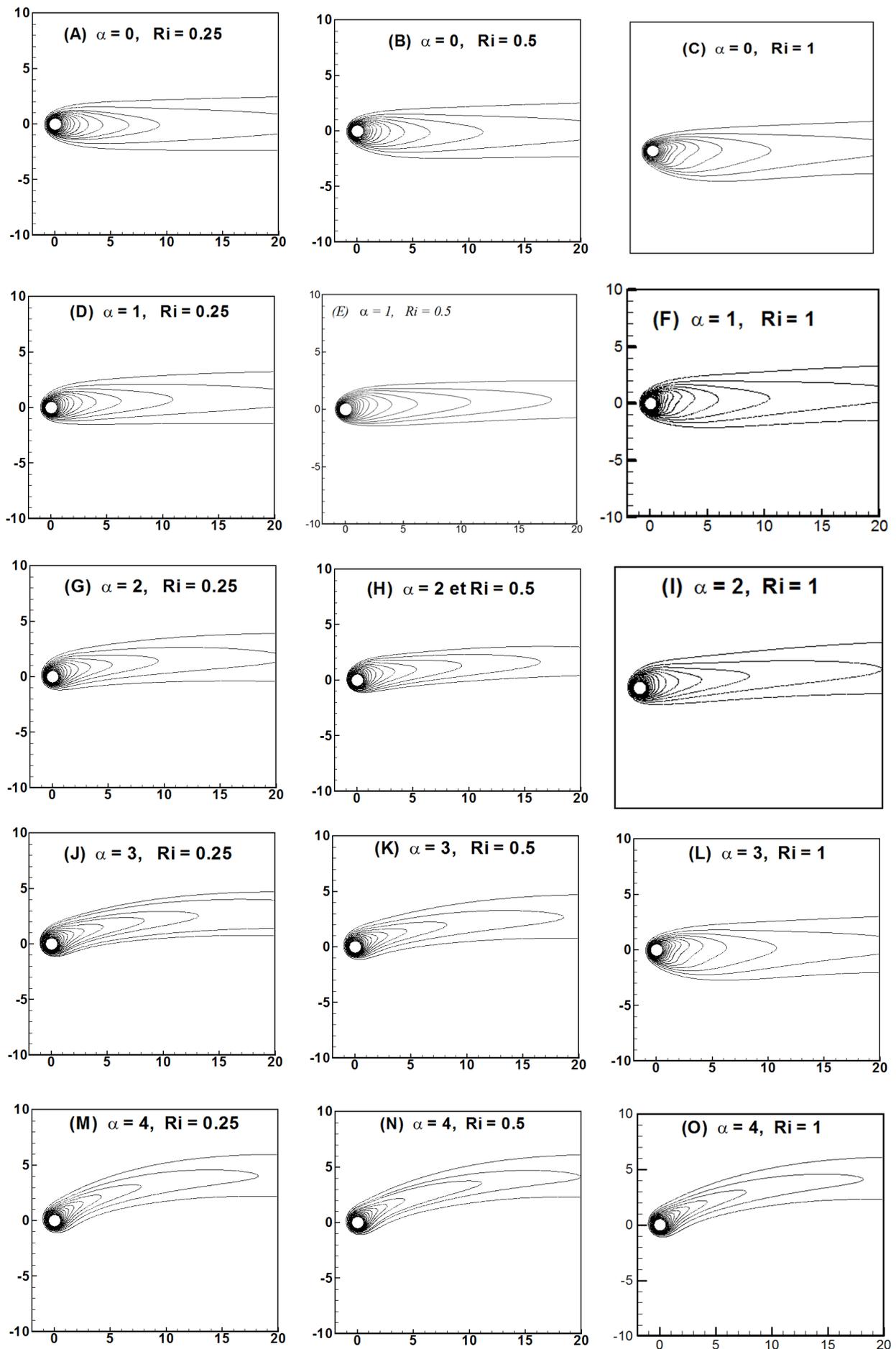**Fig. 4** The streamline profiles at *Re*=40 for varying values of Richardson number and rotation rate

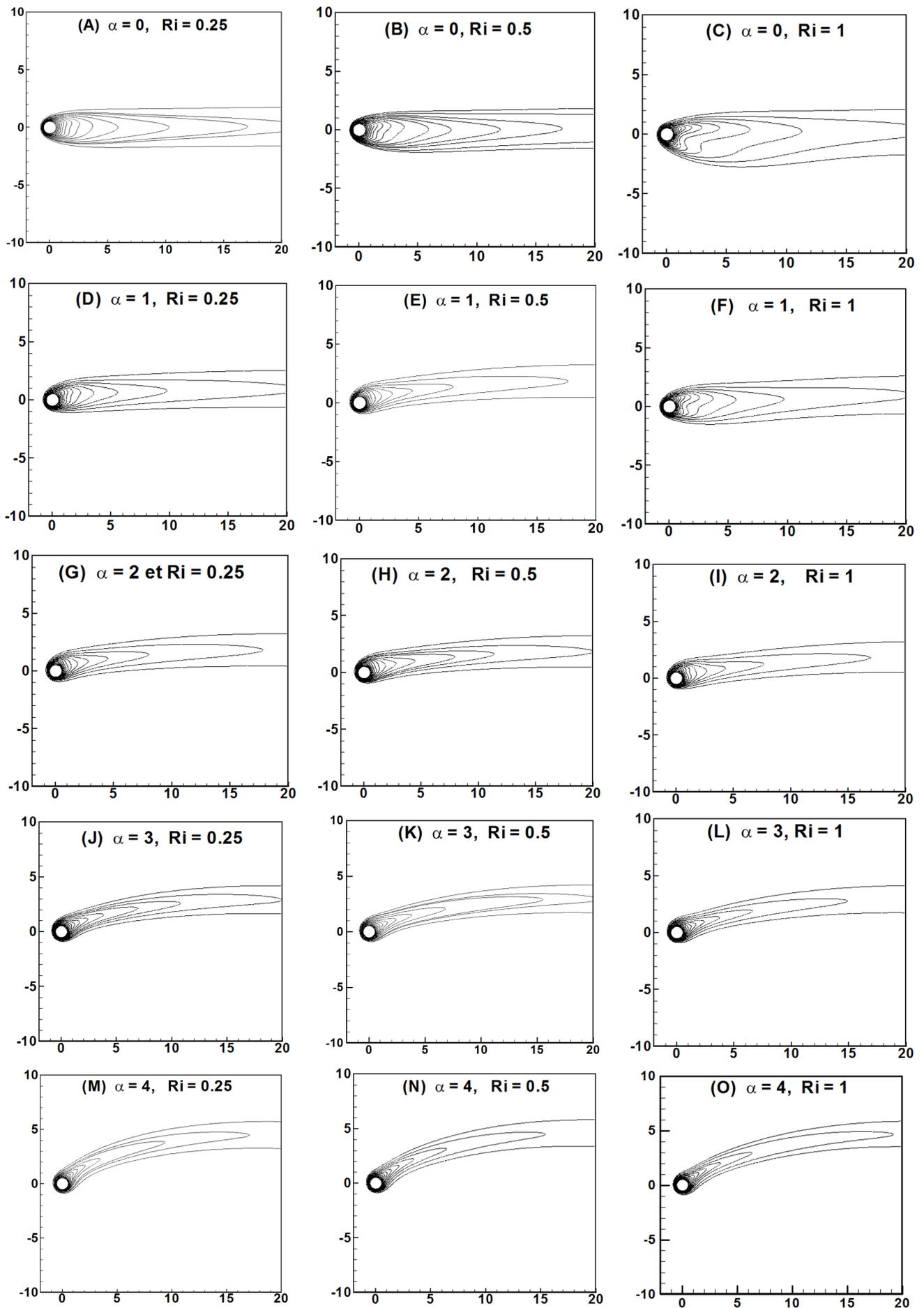**Fig. 5** Isotherm profiles at *Re* = 20 for varying values of Richardson number and rotation rate

**Fig. 6** Isotherm profiles at *Re* = 40 for varying values of Richardson number and rotation rate
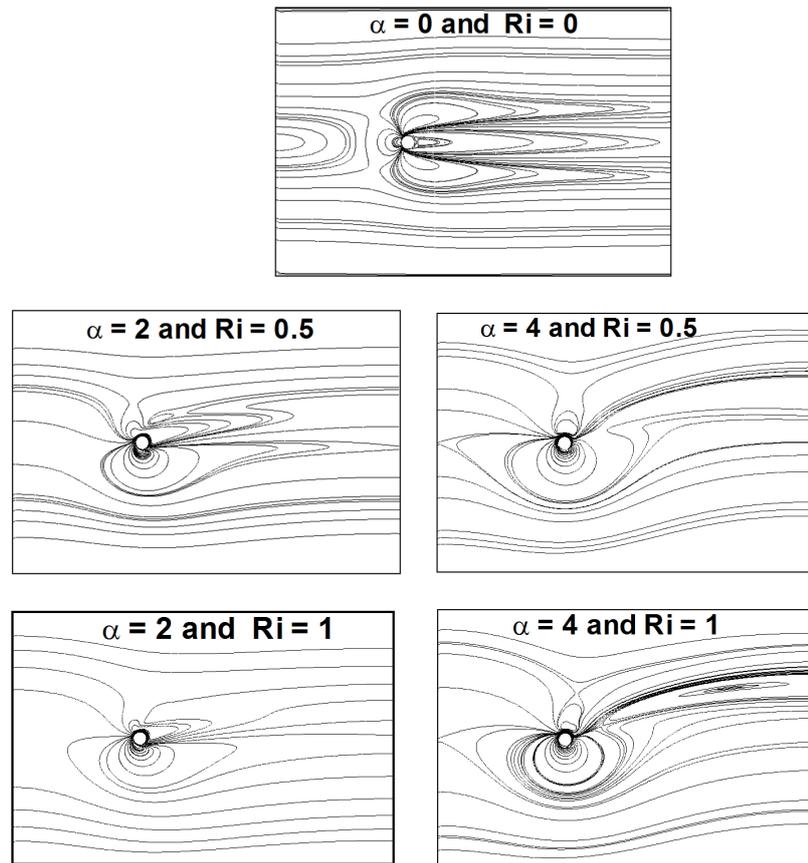
**Fig. 7** Velocity field at *Re* = 40 for varying values of *Ri* and rotation rate

## 3.2 Quantitative comparison
### 3.2.1 Distribution of Nusselt number
#### 3.2.1.1 Local Nusselt number

Fig. 8 shows the variation of the local Nusselt number on the surface of the circular cylinder for the conjugate effect of different rotation rates ($\propto \leq 4$) and mixed convection ($Ri \leq 1$) for a range Reynolds numbers from 1 to 40 for fixed Prandtl number of 0.7. for a stationary cylinder ($\alpha = 0$), figures (a, and b) the maximum value of the local Nusselt number occurs at the bottom surface of the circular cylinder, due to the effect of Richardson number for all Reynolds numbers. Concerning for increasing Richardson number (Fig. (c)), clearly changed in the rear surface, in other words, the local Nusselt number is changed.

For a rotating circular cylinder, the maximum in the value of the local Nusselt number shifts in the direction of the rotation, however. Increasing the value of the Richardson number (influence of buoyancy). It can also be observed for the local Nusselt number decreases with increasing rotation rate for the fixed value of the Reynolds number at $Ri = 0.25$ and 0.5. for a $Ri=1$, the value of the local Nusselt number almost change due to increasing of effect the buoyancy.

#### 3.2.1.2 Average Nusselt number

The average Nusselt number variation is presented in Figs. 9 for the Richardson number (0.25, 0.5 and 1) in the steady regime. At increasing the value of the rotation rate ($\alpha\leq3$), for all value of the Richardson number and for all Reynolds numbers studied here, the value of the average Nusselt number increasing. This value of the average Nusselt number decreases with the value of the rotation rate ($\alpha=4$). For a fixed rotation rate, the value of the average Nusselt number increases with increasing Reynolds number and Richardson number. In other words, the average Nusselt number shows qualitatively similar dependence on *Re, Ri* for the fixed value of $\alpha$. Furthermore for the decrease in the rotation rate for fixed *Ri and Re*, the size vortex increases, therefore conduction heat transfer decreases. This explain the average Nusselt number increases.

## 4 Conclusions

In the present study, mixed convection heat transfer for varying values of the Richardson number ($0 \leq Ri \leq 1$) has been studied across a long rotating circular cylinder. The cylinder is rotating at a rotation rate ($\propto \leq 4$) in the Reynolds number range 1 - 40 and fixed value of the Prandtl number in 0.7 in the 2-*D* steady flow regime. The influence of rotating a circular
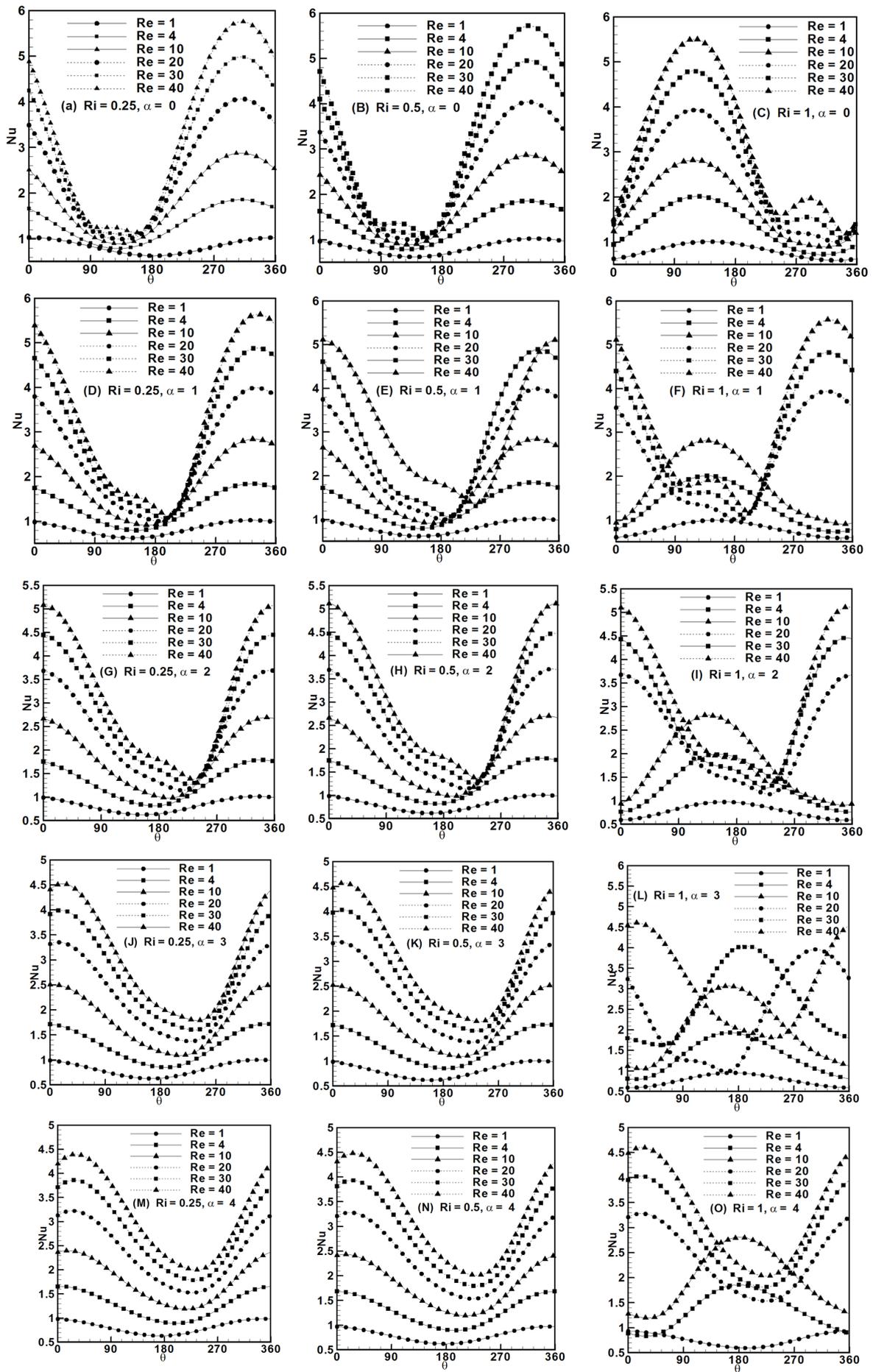
**Fig. 8** Local Nusselt number variation for *Ri* = 0.25, 0.5 and 1 for varying values of *Re* and rotation rate
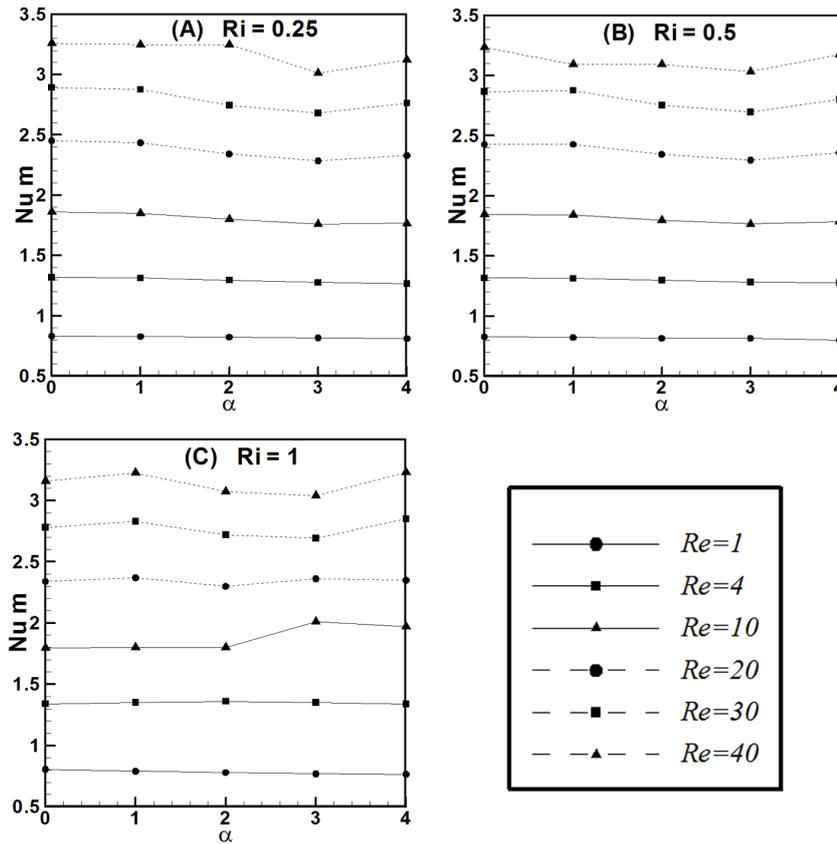
**Fig. 9** The average Nusselt number variation with increasing α for *Ri* = 0.25, 0.5and 1 for varying Re

cylinder for mixed convection are presented and analyzed for the above range of conditions. At a fixed point on the surface of the circular cylinder, the local Nusselt number increases with an increase in the values of the Reynolds number and/or of the Richardson number for the fixed value of the rotation rate. The average Nusselt number decreases with decreasing Reynolds number for the fixed value of the Richardson number for the particular value of α, while a cause the thermal buoyancy, the heat flux transferred from the upstream cylinder is higher than that of downstream cylinder. Increase in rotational rate causes reduction in thermal boundary layer thickness. The average Nusselt number decreases with increasing ∝ for fixed value of *Ri* and *Re*. The value of Nusselt number increases in comparison of the forced convection value.

## Nomenclature
### Values dimensional

$C_p$:    Specific heat of fluid at constant pressure (*J / kg. K*)

*D:*    diameter of the circular cylinder (*m*)

*g*:    acceleration due to gravity (*m/s²*)

*h*:    local heat transfer coefficient (*w/m² . k*)

$T_\infty$:    temperature of the fluid at the inlet (K)

$T_w$:    constant wall temperature at the surface of the cylinder, (K)

*u*:    stream-wise velocity (*m/s*)

*v*:    cross stream velocity (*m/s*)

$U_{max}$:    maximum velocity of the fluid at the inlet (*m/s*)

*H*:    length of the domaine (*m*)

θd:    Separation angle

L/R:    Wake length over the radius

*ω*:    constant angular velocity of cylinder rotation (rad/s)

### Values dimensionless

*x*:    stream wise coordinate, dimensionless [= *x'/ D*]

*y*:    Transverse coordinate, dimensionless [= *y'/ D*]

*T*:    non-dimensional temperature, [= (T' − $T_\infty$)( T'$_w$ − $T_\infty$)]

*U*:    component of velocity in x-direction, dimensionless [= *u / $U_{max}$*)]

*V*:    component of velocity in y-direction, dimensionless [= *v / $U_{max}$*]

### Numbers dimensionless

*Gr*:    Grashof number [= *gβ(T$_p$-$T_\infty$) D³ / v³*]

*Re*:    Reynolds number [= *D.$U_{max}$ / v*]

*Ri*:    Richardson number [= *Gr / Re²*]

*Pr*:    Prandtl number [= *v / α*]

*Nu*:    Nusselt number [= *h.D / λ*]

### Greek symbols

$β_v$:    thermal expansion coefficient (K⁻¹)

*β*:    Blockage ration, dimensionless [= D/H]

*a*:    thermal diffusivity [=λ/p.c$_p$]

μ: dynamic viscosity [$Pa.s$]

$\nu$: kinematic viscosity [$= \mu / p$] ($m^2/s$)

p: density of the flud ($Kg / m^3$)

$\lambda$: thermal conductivity [$w / m. \, k^{-1}$]

$\alpha$: non-dimensional rotation rate [$= D\omega/2U_\infty$]

ø: angle measured from the front stagnation point (deg)

## Superscript

'  dimensional variable

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