

On The Effect of Flow Direction on Mixed Convection Around Heated Circular Cylinder

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Abstract

A numerical investigation of laminar mixed convection around horizontal isothermal cylinder is presented. The free stream direction varies between the vertically upward (assisting flow) and vertically downward (opposing flow). The governing equation in terms of the stream function, vorticity and temperature are expressed in a body-fitted coordinate system and solved numerically by explicit method. Results are presented for Reynolds number from 20 to 300 with Grashof numbers from 0 to 120000. The Prandtl number was kept constant at 0.7. Correlation for the average Nusselt number around the cylinder in the forced and mixed convection regime is suggested. Comparison with previous theoretical and experimental results shows good agreement. It was established that the maximum heat transfer from cylinder occurs in case of assisting flow.

Keywords: Stream function-vorticity, time marching, mixed convection

تأثير اتجاه الجريان على الحمل المختلط حول اسطوانة مسخنة

الخلاصة

أجريت دراسة عددية للحمل المختلط الطبقي حول اسطوانة أفقية ثابتة درجة الحرارة. اتجاه الجريان الحر يتغير من الأعلى (الجريان المساعد) إلى الأسفل (الجريان المعاكس). استخدمت معادلات الدوامية-دالة الانسياب-درجة الحرارة بدلالة نظام مطابقة إحداثيات الجسم وقد حلت عددياً بطريقة التعاقب المفرط. تم استعراض النتائج لعدد رينولد من 20-300 وعدد كراشوف من 0-120000. ثبت عدد برانتل عند 0.7. تم اقتراح علاقات لمعدل عدد نسلت حول الاسطوانة لنظام الحمل القسري و المختلط. أظهرت المقارنات مع النتائج النظرية والعملية تطابق جيد. وقد تبين بوضوح إن اعلى انتقال حرارة من الاسطوانة هو لحالة الجريان المساعد.

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Nomenclature

D	cylinder diameter	α	thermal diffusivity
g	gravity acceleration	$\alpha', \beta', \lambda'$	transforming coefficient
Gr	Grashof number $((g.\beta.(T-T_w).D^3/\nu^2)$	γ	thermal expansion coefficient
n	outer normal vector	β	density of fluid
Nu	local Nusselt number $(h.D/k)$	ρ	viscosity of fluid
\bar{Nu}	average Nusselt number $(\bar{h}.D/k)$	μ	kinematic viscosity of fluid
\bar{h}, h	local and average heat transfer coefficient	ν	dimensionless time
IT	iteration	τ	free stream direction
J	Jacobain of transformation	λ	angular position
K	thermal conductivity	γ	stream function
P	pressure	ψ	dimensionless stream function
Pr	Prandtl number (ν/α)	Ψ	vorticity
Pe	Peclete number $(Re.Pr)$	Ω	dimensionless vorticity
Re	Reynolds number $(u_\infty.D/\nu)$	ω	dimensionless temperature
t	time	θ	$((T - T_\infty)/(T_w - T_\infty))$
T	fluid temperature	Subscripts	
T_w	cylinder surface temperature		grid points in direction of (ζ, η)
T_∞	inlet temperature	i, j	
u,v	velocity components	w	at the cylinder surface
U, V	dimensionless velocity components	o	at inlet
u_∞	velocity average	f	forced convection
x, y	physical coordinates	max	maximum value
X,Y	dimensionless x, y coordinates $(X=x/D, Y=y/D)$	∞	free stream
ζ, η	general coordinates	n, n+1	time step

Introduction

Due to the prominent importance of heat transfer in energy technology, several practical applications involving mixed convection from heated cylinder with various orientations continue to command substantial attention. These applications include heat exchangers. The first comprehensive experimental work on the effect of various parameters on the rate of heat transfer from a circular cylinder was carried out by Hatton [1]. In their work, heat transfer measurements were performed for Reynolds numbers up to 45 and Rayleigh numbers up to 10. Combined free and forced convection from the horizontal cylinders, at different angles of air flow direction, was experimentally investigated by Oosthuizen and Madan [2]. Other experimental studies are found in References [3-5]. On the other hand, the influence of free stream direction on Mixed

convection heat transfer from a circular cylinder was numerically investigated by Badr [6].The cylinder, which has an isothermal surface, is placed with its axis horizontal and normal to the oncoming flow. The free stream direction varies between the vertically upward (assisting flow) and the vertically downward (opposing flow) directions. The study was based on the solution of the full conservation equations of mass, momentum and energy. The study was limited to Reynolds numbers up to $(Re = 40)$ and Grashof numbers of $(Gr = Re^2)$. Other theoretical studies are found in References [6-19].The main objective of this work is to conduct a theoretical investigation of the effect of flow direction on the heat transfer process for Reynolds number up to 300 and Grashof number up to 120000. The study is based on the solution of full Navier-Stokes and energyequatio

Mathematical Formulation

Governing Equations

The problem considered in this study is a viscous incompressible, and laminar flow passing across heated cylinder as shown in Figure (1). The governing equations consist of full Navier-Stokes and energy equations formulated in terms of velocity, pressure, and temperature. Under the Boussinesq approximation [20], these equations are

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad \dots(1)$$

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = u \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) - \frac{1}{r} \frac{\partial p}{\partial x} + gb(T - T_\infty) \cos l \quad \dots(2)$$

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} = u \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) - \frac{1}{r} \frac{\partial p}{\partial y} + gb(T - T_\infty) \sin l \quad \dots(3)$$

$$\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = a \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) \quad \dots(4)$$

To eliminate pressure from the above equation, the vorticity-stream function method will be based on in the solution to obtain two equations are vorticity transport and stream function equations as follows:

$$\frac{\partial^2 \Psi}{\partial X^2} + \frac{\partial^2 \Psi}{\partial Y^2} = -w \quad (5)$$

$$\frac{\partial w}{\partial t} + \frac{\partial \Psi}{\partial Y} \frac{\partial w}{\partial X} - \frac{\partial \Psi}{\partial X} \frac{\partial w}{\partial Y} = \frac{1}{Re} \left(\frac{\partial^2 w}{\partial X^2} + \frac{\partial^2 w}{\partial Y^2} \right) + \frac{Gr}{Re^2} \left(\frac{\partial q}{\partial X} \sin l - \frac{\partial q}{\partial Y} \cos l \right) \quad (6)$$

$$\frac{\partial q}{\partial t} + \frac{\partial \Psi}{\partial Y} \frac{\partial q}{\partial X} - \frac{\partial \Psi}{\partial X} \frac{\partial q}{\partial Y} = \frac{1}{Pe} \left(\frac{\partial^2 q}{\partial X^2} + \frac{\partial^2 q}{\partial Y^2} \right) \quad \dots (7)$$

The initial conditions are $\Psi = \omega = \theta = 0$ in the region for $t = 0$ (8)

The boundary conditions used for computations are given as follows: uniform inflow with $\omega = \theta = 0$ and stream function will be a function to the length of inlet. At The cylinder surface, $\Psi = 0$ and $\theta = 1$ while the vorticity on the cylinder surface will not be treated easily, since its value depends on the average of the velocity components on the cylinder, which is unknown until the end of calculations. At upper and lower boundaries, $\omega = 0$ and $\theta_y = 0$. Also, stream function at upper

boundary and lower boundary are ($\Psi = 1$ and $\Psi = -1$) respectively. At outlet flow, $\Psi_x = \omega_x = \theta_x = 0$.

Coordinate Transformation

Due to curvilinear geometry of the boundary, a system of general coordinate has been adopted here in order to obtain a computationally convenient representation of the physical domain. If x and y are set as physical domain and ζ and η as computational domain, then the computational domain can be specified by the following rectangle region

$$0 \leq \zeta \leq 1, \quad 0 \leq \eta \leq 1.$$

The relationships of x , y and ζ , η for the present study are as follows

$$\zeta = \zeta(x, y) \quad \dots(9)$$

$$\eta = \eta(x, y) \quad \dots(10)$$

With the above, the governing equations in computational domain are expressed as

$$\left(I' \frac{\partial \Psi}{\partial \zeta} + S' \frac{\partial \Psi}{\partial \eta} + A' \frac{\partial^2 \Psi}{\partial \zeta^2} - 2B' \frac{\partial^2 \Psi}{\partial \zeta \partial \eta} + G' \frac{\partial^2 \Psi}{\partial \eta^2} \right) / J^2 = -w \quad \dots(11)$$

$$\frac{\partial w}{\partial t} + \frac{1}{J} \left(\frac{\partial \Psi}{\partial \zeta} \frac{\partial w}{\partial \eta} + \frac{\partial \Psi}{\partial \eta} \frac{\partial w}{\partial \zeta} \right) = \frac{1}{J^2 Re} \left(I' \frac{\partial \Psi}{\partial \zeta} + S' \frac{\partial \Psi}{\partial \eta} + A' \frac{\partial^2 \Psi}{\partial \zeta^2} - 2B' \frac{\partial^2 \Psi}{\partial \zeta \partial \eta} + G' \frac{\partial^2 \Psi}{\partial \eta^2} \right) + \left(\frac{Gr}{Re^2} \right) \left(\frac{\partial q}{\partial \zeta} \frac{\partial Y}{\partial \eta} + \frac{\partial q}{\partial \eta} \frac{\partial Y}{\partial \zeta} \right) \sin l - \left(\frac{\partial q}{\partial \eta} \frac{\partial X}{\partial \zeta} - \frac{\partial q}{\partial \zeta} \frac{\partial X}{\partial \eta} \right) \cos l \quad \dots(12)$$

$$\frac{\partial q}{\partial t} + \left(\frac{\partial \Psi}{\partial \zeta} \frac{\partial q}{\partial \eta} + \frac{\partial \Psi}{\partial \eta} \frac{\partial q}{\partial \zeta} \right) / J = \left(I' \frac{\partial q}{\partial \zeta} + S' \frac{\partial q}{\partial \eta} + A' \frac{\partial^2 q}{\partial \zeta^2} - 2B' \frac{\partial^2 q}{\partial \zeta \partial \eta} + G' \frac{\partial^2 q}{\partial \eta^2} \right) / (J^2 Pe) \quad \dots(13)$$

Where,

$$a' = x_h^2 + y_h^2$$

$$b' = x_z x_h + y_z y_h$$

$$g' = x_z^2 + y_z^2$$

$$I' = (x_h D_y - y_h D_x) / J$$

$$S' = (x_z D_x - y_z D_y) / J$$

$$D_x = a' x_{zz} - 2b' x_{zh} + g' x_{hh}$$

$$D_y = a' y_{zz} - 2b' y_{zh} + g' y_{hh}$$

Method Of Solution

The two equations of vorticity transport and energy will be solved by explicit method finite difference based on the time marching technique. The time marching technique used for solving the unsteady governing equations to obtain the steady velocity and temperature distributions is based on studying the time development of the velocity and thermal fields

until reaching steady conditions. These equations are

$$w_{(i,j)}^{n+1} = w_{(i,j)}^n + \Delta t \left[\left(\frac{\Psi_{(i+1,j)} - \Psi_{(i-1,j)}}{2\Delta x} \cdot \frac{w_{(i,j+1)}^n - w_{(i,j-1)}^n}{2\Delta h} - \frac{\Psi_{(i,j+1)} - \Psi_{(i,j-1)}}{2\Delta h} \cdot \frac{w_{(i+1,j)}^n - w_{(i-1,j)}^n}{2\Delta x} \right) / J_{(i,j)} + \left(I'_{(i,j)} \cdot \frac{w_{(i+1,j)}^n - w_{(i-1,j)}^n}{2\Delta x} + S'_{(i,j)} \cdot \frac{w_{(i,j+1)}^n - w_{(i,j-1)}^n}{2\Delta h} \right) + a'_{(i,j)} \cdot \frac{w_{(i+1,j)}^n - 2w_{(i,j)}^n + w_{(i-1,j)}^n}{\Delta x^2} - 2b'_{(i,j)} \cdot \frac{w_{(i+1,j+1)}^n - w_{(i+1,j-1)}^n - w_{(i-1,j+1)}^n + w_{(i-1,j-1)}^n}{4\Delta x \Delta h} - \frac{q_{(i,j+1)}^n - q_{(i,j-1)}^n}{2\Delta h} \cdot \frac{Y_{(i+1,j)} - Y_{(i-1,j)}}{2\Delta x} \right) \sin l \left(\frac{q_{(i,j+1)}^n - q_{(i,j-1)}^n}{2\Delta h} \cdot \frac{X_{(i+1,j)} - X_{(i-1,j)}}{2\Delta x} - \frac{q_{(i+1,j)}^n - q_{(i-1,j)}^n}{2\Delta x} \cdot \frac{X_{(i,j+1)} - X_{(i,j-1)}}{2\Delta h} \right) \cdot \frac{\cos l}{J_{(i,j)}} \right] \dots (14)$$

$$q_{(i,j)}^{n+1} = q_{(i,j)}^n + \Delta t \left[\left(\frac{\Psi_{(i+1,j)} - \Psi_{(i-1,j)}}{2\Delta x} \cdot \frac{q_{(i,j+1)}^n - q_{(i,j-1)}^n}{2\Delta h} - \frac{\Psi_{(i,j+1)} - \Psi_{(i,j-1)}}{2\Delta h} \cdot \frac{q_{(i+1,j)}^n - q_{(i-1,j)}^n}{2\Delta x} \right) / J_{(i,j)} + \left(I'_{(i,j)} \cdot \frac{q_{(i+1,j)}^n - q_{(i-1,j)}^n}{2\Delta x} + S'_{(i,j)} \cdot \frac{q_{(i,j+1)}^n - q_{(i,j-1)}^n}{2\Delta h} \right) + a'_{(i,j)} \cdot \frac{q_{(i+1,j)}^n - 2q_{(i,j)}^n + q_{(i-1,j)}^n}{\Delta x^2} - 2b'_{(i,j)} \cdot \frac{q_{(i+1,j+1)}^n - q_{(i+1,j-1)}^n - q_{(i-1,j+1)}^n + q_{(i-1,j-1)}^n}{4\Delta x \Delta h} + g'_{(i,j)} \cdot \frac{w_{(i,j+1)}^n - 2w_{(i,j)}^n + w_{(i,j-1)}^n}{\Delta h^2} \right) / Pe J^2_{(i,j)} \dots (15)$$

But, the stream function equation will be solved by relaxation method SOR as follows

$$I'_{(i,j)} \cdot \frac{\Psi_{(i+1,j)} - \Psi_{(i-1,j)}}{2\Delta x} + S'_{(i,j)} \cdot \frac{\Psi_{(i,j+1)} - \Psi_{(i,j-1)}}{2\Delta h} + a'_{(i,j)} \cdot \frac{\Psi_{(i+1,j)} - 2\Psi_{(i,j)} + \Psi_{(i-1,j)}}{\Delta x^2} + g'_{(i,j)} \cdot \frac{\Psi_{(i,j+1)} - 2\Psi_{(i,j)} + \Psi_{(i,j-1)}}{\Delta h^2} - 2b'_{(i,j)} \cdot \frac{1}{2\Delta x} \left(\frac{\Psi_{(i+1,j+1)} - \Psi_{(i+1,j-1)}}{2\Delta x} - \frac{\Psi_{(i-1,j+1)} - \Psi_{(i-1,j-1)}}{2\Delta h} \right) + J^2_{(i,j)} \cdot w_{(i,j)} = Error \approx 0 \dots (16)$$

The final form of stream function equation is

$$\Psi_{(IT+1)} = \Psi_{(IT)} + RF \cdot \Delta \Psi_{(i,j)} \dots (17)$$

Calculation of Nusselt number

When the solution convergence criterion is reached, the local and mean Nusselt numbers on the cylinder walls are calculated. From the balance of heat flux at the surface, the Nusselt number can be obtained as

$$Nu = - \frac{\partial q}{\partial n} \dots (18)$$

Now, Equation (18) is transformed into general coordinate(ζ,η) as follows[21]:

$$Nu = \frac{1}{J \sqrt{g'}} [g' \cdot q_h - b' \cdot q_x] \dots (19)$$

Since the temperature along the wall cylinder (w) is constant, $\frac{\partial q}{\partial x} = 0$, Equation (19) becomes:

$$Nu = \frac{g'}{J \sqrt{g'}} q_h \dots (20)$$

The Nusselt number in Equation (20) is the local Nusselt number. To find the average Nusselt, the local Nusselt number should be integrated by using numerical integration [22].

Results and Discussion

The numerical solution of the steady flow over the cylinder is obtained for different flow free stream direction at Reynolds numbers of 20, 40, 100, 200, 300 and for parametric values of Grashof number in each case. It is found from the results that the velocity and temperature field is highly influenced by the free stream direction. Figure (2) shows the streamline contours for mixed convection around cylinder at Reynolds number (40) and (Gr =8000) with different free stream directions. In general, it can be seen from figure that the size and orientation of wake region are completely dependent on the free stream direction (λ) and (Gr/Re²). No reverse flow takes place in the wake and the vortices completely disappear for (λ = 0°, 45° and 90°) and the flow separation at (γ = 180°, 200° and 210°) respectively. For opposing flow, the wake boundaries completely surround the cylinder forming a cylindrical dome. The circulation fluid inside the dome is driven by the buoyant forces and never gets entrained to the main stream. The separation occurs at stagnation point (γ = 180°). Also, it is found that the temperature gradient decreases as (λ) increases [see Figure (3)]. This is due to the fact that, when (λ = 0°), the buoyancy forces accelerate the flow, and the temperature gradient will increase. This effect will decrease as (λ) increase until reaching (λ = 180°). On the other hand, at (λ = 180°) the temperature gradient decreases. This is because, the circulating fluid in the wake is completely isolated from the main flow and heat is transferred from this region to the main flow by conduction across the wake

boundaries. Figure (4) shows the local Nusselt number distribution on the cylinder surface for case of $Re = 100$ and $Gr = 50000$ at different flow direction. In general, the local Nusselt number decreases over most of the cylinder surfaces as (λ) increases. This is expected to occur as a natural result of the slow down of the flow velocity near the cylinder surface. In assisting flow, the maximum Nusselt number occurs at stagnation point ($\gamma = 0^\circ$). It is found that for $(\lambda \leq 135^\circ)$, there is an increase in Nusselt number at $(\gamma = 230^\circ, 265^\circ$ and $325^\circ)$. This is due to the fact that at this location, the buoyancy forces aid the flow. It can be seen that for opposing flow, the maximum Nusselt number occurs at rare stagnation points ($\gamma = 0^\circ$ and 360°) and the minimum Nusselt number occurs near stagnation point. This is mainly because the buoyant forces aid the circulating flow close to the cylinder surface near $(\gamma = 0^\circ$ and $360^\circ)$. This effect causes Nusselt number to increase with the increase of Grashof number in the same region, while a decrease in the region surrounding the forward stagnation point ($\gamma = 0^\circ$). It is found that the average Nusselt number decreases as (λ) increases. This is because the buoyancy forces aid the flow around most of cylinder surfaces, and this effect decreases as (λ) increases (see Figure (5)). A comparison with previous theoretical and experimental results as shown in figures (6 and 7).

Correlation Equations

It is usual to express the main governing variables by the way of putting a set of the correlation equations. These equations are responsible for the description of the whole results obtained.

The following equation is concerned with mixed convection around circular

$$\frac{\overline{Nu}}{Nu_f} = 0.99 \left[1 + (0.148 - 0.234 \cos \lambda) \left(\frac{Gr}{Re^2} \right) + 0.005 \left(\frac{Gr}{Re^2} \right)^{1.304} \right] \dots(1)$$

The average Nusselt number for pure forced convection is correlated as

$$\overline{Nu}_f = 0.5145 Re^{0.5} + 0.0004 Re \dots(2)$$

Conclusions

A numerical, finite – difference approach has been utilized for solving the governing equations for laminar, mixed convection around isothermal circular cylinder in cross flow. Results for local and average Nusselt number are obtained for $Pr = 0.7$ and $(0^\circ \leq \lambda \leq 180^\circ)$. Ranges of Reynolds and Grashof numbers are $(20 - 300)$ and $(0-120000)$ respectively. From these results, the following conclusions can be drawn:

1. Free stream direction has a strong effect on the distributions of Nusselt number. The values of Nusselt number decrease over most of the cylinder surfaces as (λ) increases.
2. For low value of Grashof number, the average Nusselt number decreases as (λ) increases. As Grashof number increases, the average Nusselt number increases monotonically for $(\lambda \leq 135^\circ)$, while, the average Nusselt number decreases for $(\lambda > 135^\circ)$ as Grashof number increases.

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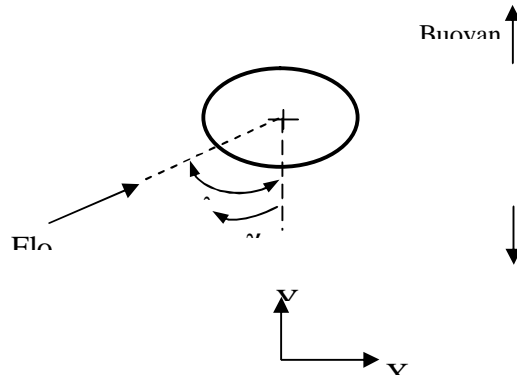
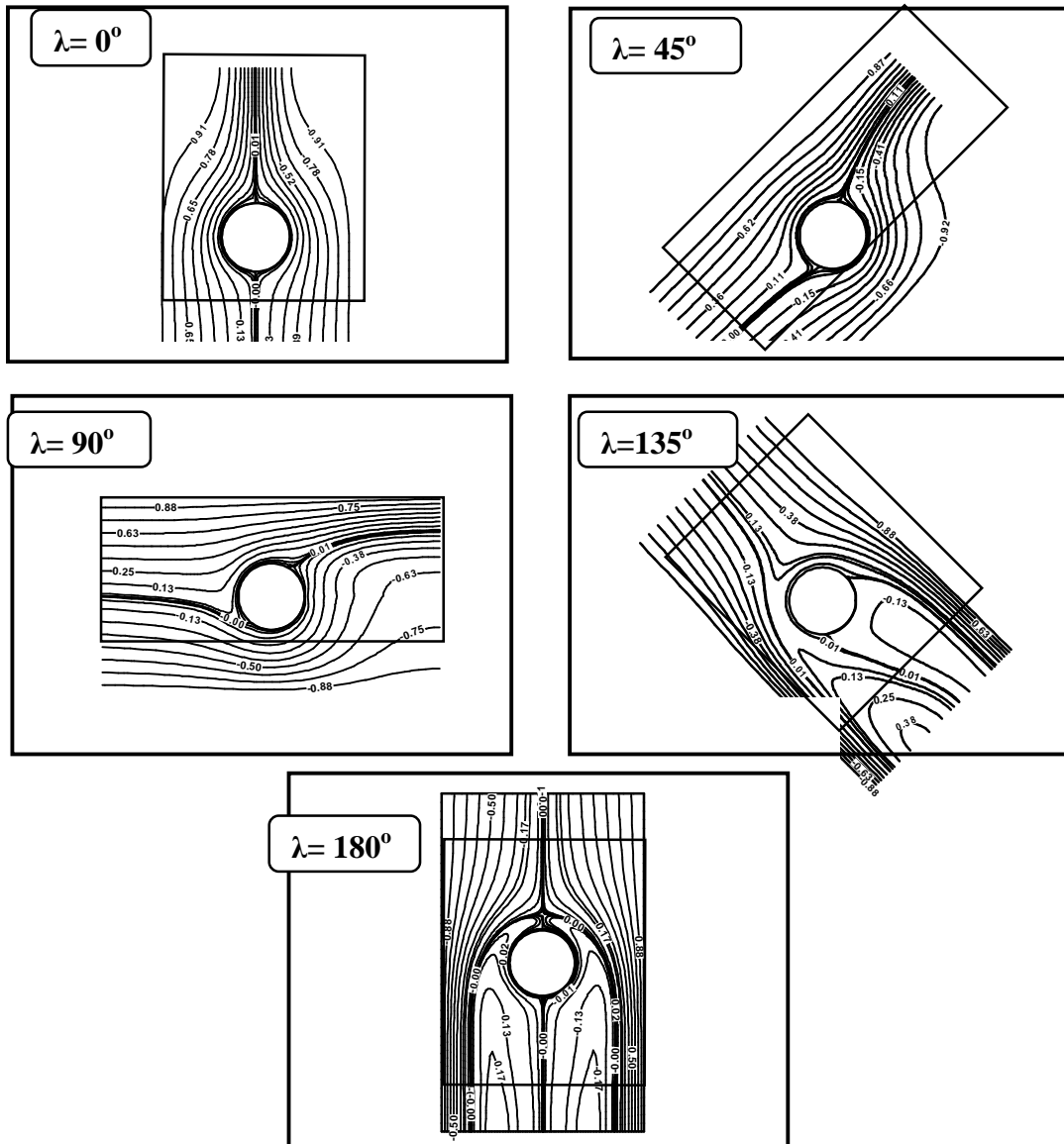


Figure (1) Geometry and coordinate system for the present



Figure(2) Streamline contours for different free stream directions at $Re = 40$ and $Gr = 8000$.

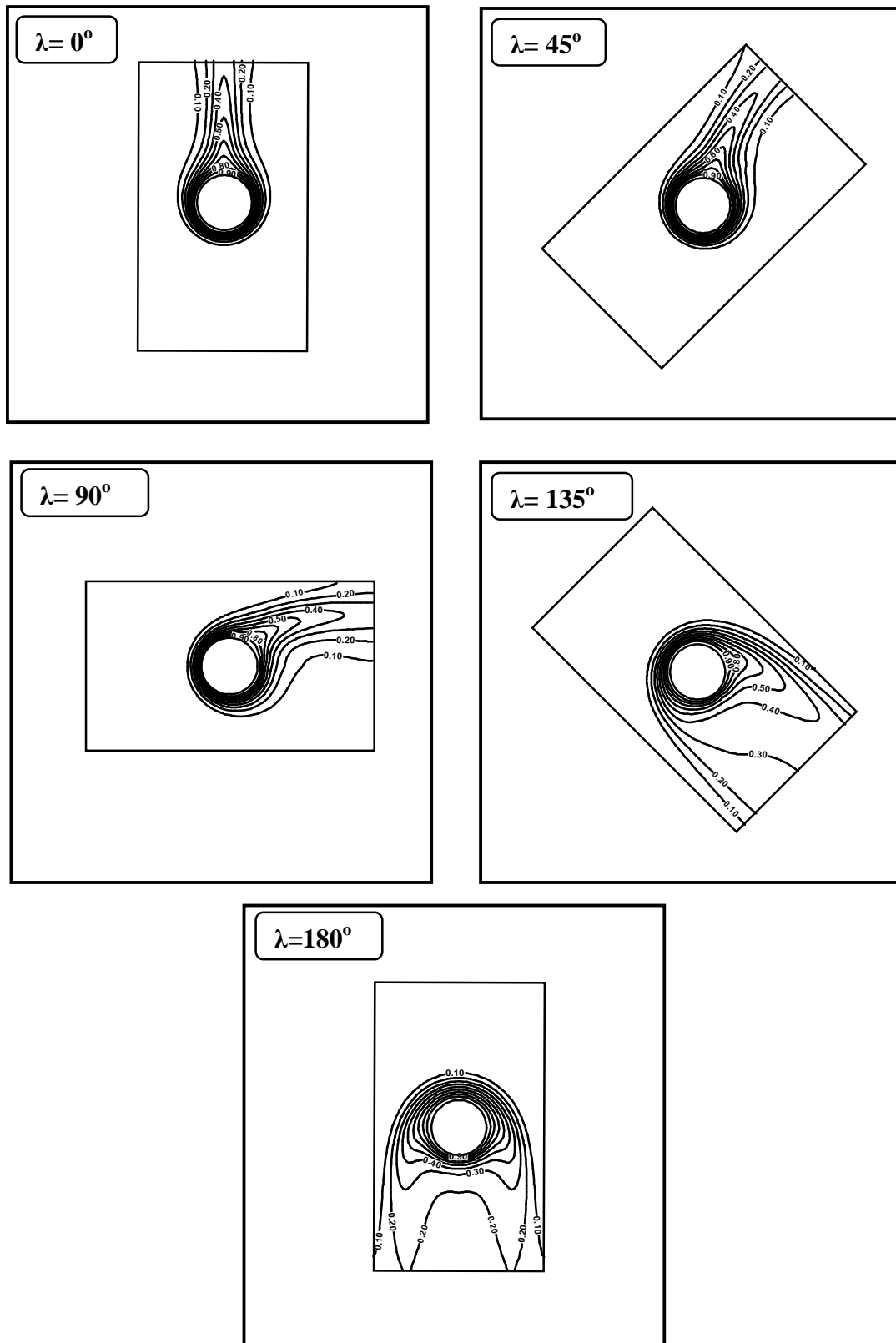


Figure (3) Isotherm line contours for different free stream directions at $Re = 40$ and $Gr = 8000$.

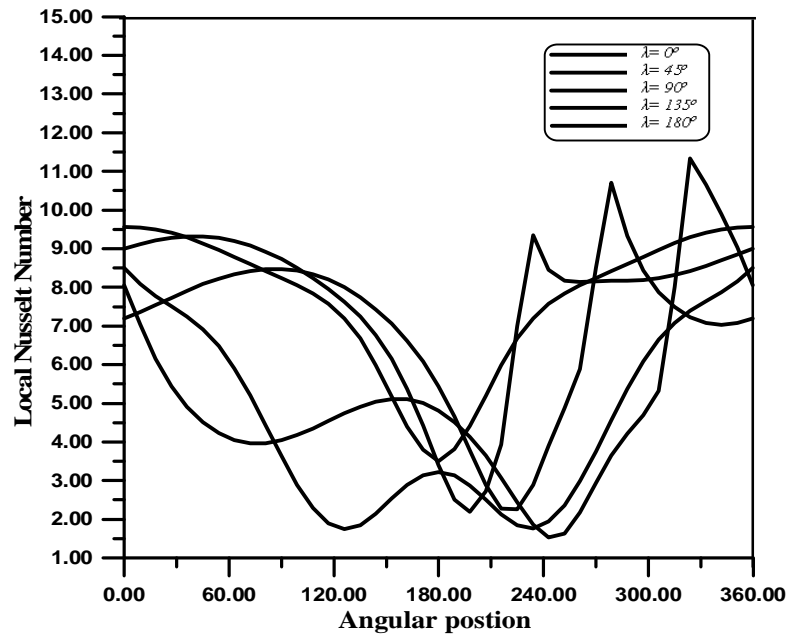


Figure (4) Local Nusselt number distribution on the cylinder surface for different free stream directions at $Re = 100$ and $Gr = 50000$.

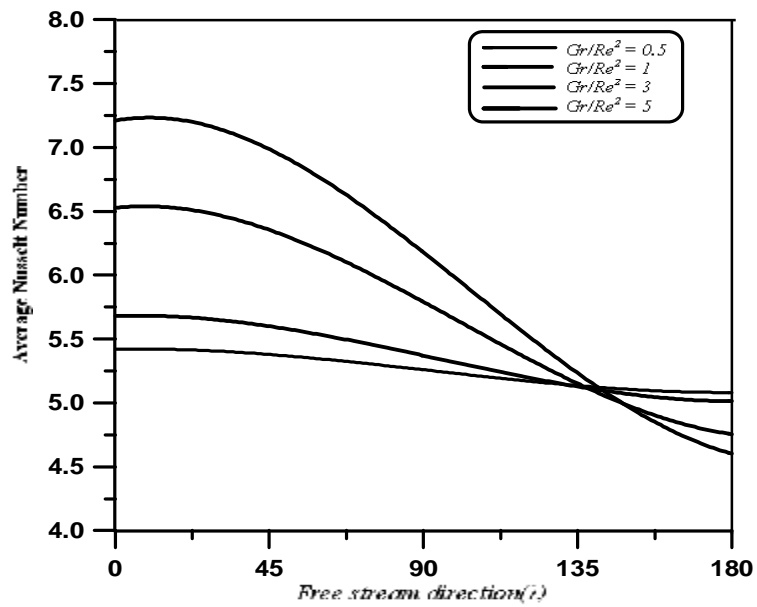
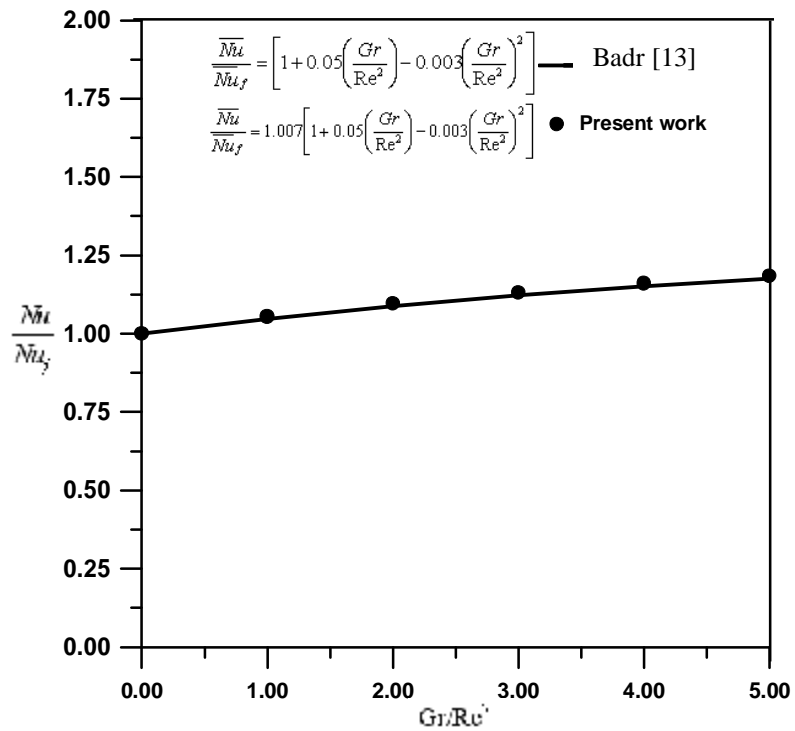


Figure (5) Variation of average Nusselt number with free stream direction at $Re = 40$.



Figure(6) Comparison between present work and theoretical result by Badr [13] at $Re = 100$ and $\lambda = 0^\circ$.

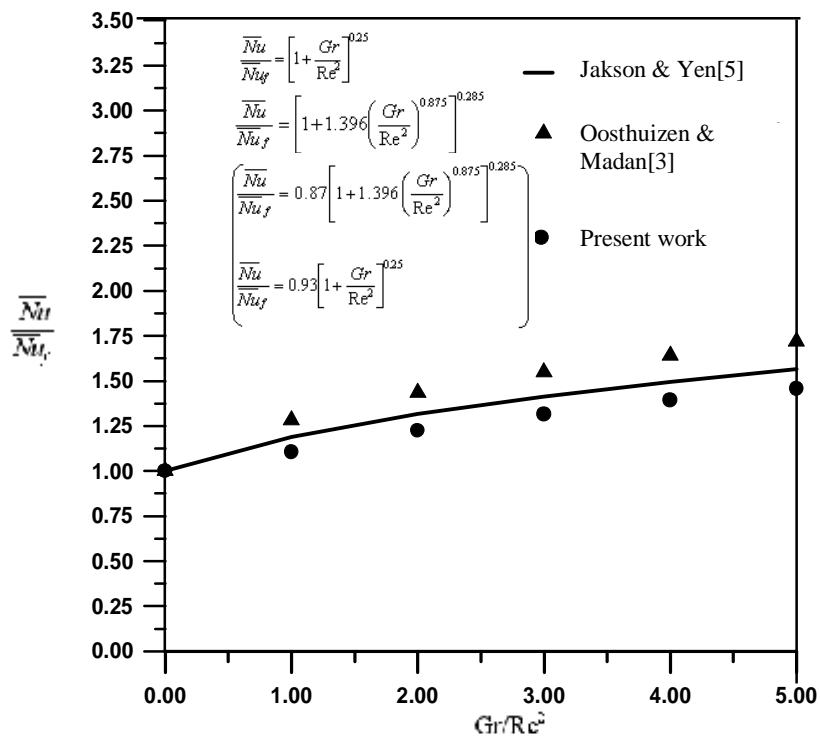


Figure (7) Comparison between present work and previous experimental results at $Re = 100$ and $\lambda = 0^\circ$.

