International Journal of Engineering

Numerical Study on Hydrodynamics and Heat Transfer Characteristics Around a Cylinder with Inclined Splitter Plates

S. E. Razavi, A. Hosseinpour Shafaghi*, N. Piroozfam

Faculty of Mechanical Engineering, University of Tabriz, Tabriz, Iran

PAPER INFO

ABSTRACT

In the current paper, the effect of length and angle of a splitter plate on hydro-thermal field in a range of Reynolds number from 40 to 1000 are numerically studied by solving the two-dimensional Navier-Stokes equations. For discretization of governing equations, PISO algorithm was imposed to segregate the pressure-velocity coupled equations, and second-order upwind discretization scheme was applied for momentum and energy values. A convergence criterion was set to 10^{-6}. The influence of splitter plate attachment on the fluctuating drag forces, vortex shedding and heat transfer behavior was investigated. It was found that the drag force decreases as the splitter plate elongates and the vortices vanish. The average Nusselt number rises with increasing the angle of splitter plate. A reduction in drag force was observed at about 25º. The overall heat transfer increased due to surface enlargement resulting from the splitter plate. In addition, it was seen that by increasing the plate angle up to 25º the outflow temperature grows.

doi: 10.5829/idosi.ije.2016.29.04a.14

NOMENCLATURE

A	Surface area (m^2)	**Greek Symbols**	
Q	Total power (W)	μ	Fluid dynamic viscosity (Pa.s)
Re	Reynolds number	ρ	Fluid density (kg/m^3)
U	Flow velocity (m/s)	θ	Angle of splitter plate (Degree)
K	Thermal conductivity (W/m.K)	**Subscripts**	
T	Temperature (K)	∞	Free stream
C_d	Drag coefficient		
h	Heat transfer coefficient (W/m^2.K)		
Nu	Nusselt number		

1. INTRODUCTION

Unsteady flow around the cylindrical structure is encountered in a variety of engineering applications. Flow around the circular cylinder is an important issue that has been considered by many researchers [1-3]. Nowadays, due to the great developments in different industries, demand for oil and gas has increased enormously. When a pipe is exposed to flows such as sea currents, the flow regime around it will change, particularly behind the pipe. This will appear as the phenomenon of vortex generation due to the flow separation from the pipe at some special Reynolds number (Re > 40) [4]. Experiments and numerical simulations on thermo-flow characteristics around the cylinder have been reported by a number of researchers. Nakamura [5] showed that the presence of a splitter plate along the center-line of a circular cylinder, could greatly affect the upstream flow. To examine the

Corresponding Author's Email: ali.hpour.sh@gmail.com (A. Hosseinpour Shafaghi)

influence of splitter plate length on drag and vortex shedding, Apelt and West [6, 7] performed experimental investigations. They found that the short splitter plates ($L < 2D$) significantly changed the behavior of downstream flow. However, longer splitter plates reduced the drag coefficient. Sudhakar [8] studied the vortex characteristics and drag forces on a cylinder by an oscillating splitter plate. He showed that the vortex shedding could be completely suppressed by using a short splitter plate (L=D) if it is given a simple harmonic oscillation at very low oscillating frequencies. Therefore, in applications with space constraints limit, a shorter splitter plate with enforced oscillations can be used to suppress the vortex shedding instead of larger ones (L=5D). The flow behavior around a cam-shaped tube in a cross flow has been investigated experimentally by Nouri-Borujerdi and Lavasani [9]. Their results show that the pressure drag coefficient of the cam-shaped tube is lower than that of a circular tube with the same surface area. Razavi et al. [10] investigated the effect of a splitter plate length on the thermal behavior of flow around a circular cylinder at low Reynolds numbers by the finite volume method. A significant reduction in the drag force as well as the average Nusselt number was observed in the presence of a splitter plate. Furthermore, stabilization of the wake region and accordingly reduction of the vortex shedding was seen. Their results showed that by increasing Reynolds number, the heat transfers from the plain cylinder rises. Kahrom et al. [11] conducted a numerical research to find how a square rod and splitter downstream at the rear side of SR may affect local and average heat transfer from a flat plate. The results showed that a square rod significantly changes the structure of turbulent boundary layer and provokes local heat transfer on the neighboring flat plate. Drag reduction of a circular cylinder using dual detached splitter plates was studied numerically by Hwang et al. [12]. Two splitter plates with the same length as the cylinder diameter was placed along the horizontal centerline; one located upstream on the cylinder and the other in the near-wake region. The upstream splitter plate reduced the stagnation pressure by friction, while the downstream one increased the base pressure by suppressing the vortex shedding. These combined effects cause a significant drag reduction on the cylinder. Gu et al. [13] conducted an experimental investigation in a wind tunnel on the flow around a circular cylinder attached with ten splitter plates freely rotatable around the cylinder axis with different ratios of cylinder length to diameter (L/D). It was found that, the rotation angle of splitter plate is related to the plate length. This indicates that, plates with extended lengths produce a smaller number of angles [14]. Direct numerical simulation of turbulent flow behind a cylinder, wake flow, using the random vortex method for an incompressible fluid in two dimensions is studied by Heidarinejad et al. [15]. They showed that the variation of geometrical and physical parameters of the flow strongly depend on the Reynolds number. Emamgholizadeh [16] studied experimentally the effectiveness of a flat plate placed along the stagnation line of a square cylinder. It was reported that the optimum width of the plate for suppressing fluid forces was approximately 0.1 of the cylinder diameter. Emamgholizadeh et al. [17] carried out an experimental study to investigate the under-scoring of vibrating cylinder due to vortex-induced vibration (VIV) under steady current and clear water conditions with and without splitter plate. It was noticed that for the cylinder with splitter plate for any value of the reduced velocity, when its angle to the horizon is less or equal to 30 degrees, the dimensions of the equilibrium scour profile are reduced significantly compared to the cylinder without a splitter plate. Malekzadeh and Sohankar [18] studied the heat transfer around a square cylinder in a laminar flow regime by passive control and found that the Nusselt number on the front side of the cube has the minimum value. The overall heat transfer coefficient increased compared to a circular cylinder [19]. Tiwari et al. [20] carried out numerical simulations of thermo-flow around a circular cylinder with a splitter plate inside the channel. They found that splitter plate caused a reduction in the size of a wake zone in comparison with that of a plain circular cylinder, where the narrowing of a wake zone reduced convective heat transfer; however, splitter plate increased the area for conductive heat transfer.

Shukla et al. [21] executed an experimental investigation on a water tunnel to study the impact of a hinged-splitter plate in the wake of a circular cylinder. The connection between shear layers was not completely destroyed by hinged splitter plate, and pressure differences across the splitter plate caused stable vibrations of the plate. Razavi et al. [22] studied a Splitter Plate Pin-Fin Heat Sink (SPPFHS) as a new kind of heat sink to enhance hydro-thermal performance of heat sinks. According to their results, placing the splitter behind the pin-fin, reduced the thermal resistance and pressure drop on the heat sink.

In this work, the effect of plate angle of the cylinder is investigated. The main purpose of this study is to demonstrate the influences on fluctuating drag and lift forces, and vortex shedding behavior of an attached splitter plate having different angles, and also the heat transfer characteristics around the circular cylinder.

2. GOVERNING EQUATIONS

Momentum and energy conservation equations along with continuity should be solved as governing equations. To reach the following governing equations, it is assumed that the flow is incompressible and viscous

dissipations are also negligible. Incompressible Navier-Stokes equations and energy equations are as follows:

Continuity:

$$\frac{\partial u_i}{\partial t} + \frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

Momentum:

$$\rho(\frac{\partial u_i}{\partial t} + u_j\frac{\partial u_i}{\partial x_j}) = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\upsilon\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] \tag{2}$$

Energy:

$$\rho(\frac{\partial T}{\partial t} + u_j\frac{\partial T}{\partial x_j}) = \frac{\partial}{\partial x_j}\left[\frac{K}{\rho c_p}\left(\frac{\partial T}{\partial x_j} + \frac{\partial T}{\partial x_i}\right)\right] \tag{3}$$

where, u expresses the velocity. The Reynolds number is calculated using the following equation:

$$Re = \frac{\rho u D}{\mu} \tag{4}$$

where, D is the cylinder diameter. The average heat transfer coefficient over the entire cylinder is defined as:

$$h = \frac{q/A}{T - T_\infty} \tag{5}$$

where A and q represent the surface area and total power transferred through the surface area, T is the cylinder surface temperature, and T_∞ is the freestream temperature. The average Nusselt number is then:

$$Nu = \frac{h.D}{K} \tag{6}$$

The geometry and the grid generation were performed using GAMBIT software as shown in Figure 1. There is a cylinder with an attached splitter plate $\left(0.5 \leq \frac{L}{D} \leq 2\right)$, where L is the plate length in a two dimensional domain of (2.4× 3.3 m). In addition, different inclination angles ($0 \leq \theta \leq 65$) of a splitter plate were considered.

Equations (1)-(3), should be solved considering accurate boundary conditions. A fully developed velocity profile with known inlet temperature and pressure boundary conditions were applied to inflow and outflow, respectively. Also, to cover the energy equation, and velocity field, adiabatic walls and no-slip boundary condition were imposed on the walls. Triangular type of meshes was constructed in the fluid zone (Figure 1). Also to ensure the numerical accuracy, mesh independency was performed using drag coefficient of cylinder and finally 21040 meshes were chosen for the case of L=D and $\theta = 0$. This procedure was repeated for other simulations, and proper mesh numbers was also obtained for different lengths and angels.

It is assumed that the cylinder and splitter plate is made of aluminum with conductivity of 202.4 W/m.K,

and the fluid is water. The mesh file was successfully conducted into Fluent (version 6.3.26). The problem was investigated for the range of $40 \leq Re \leq 1000$. The PISO algorithm was imposed to segregate the pressure-velocity coupled equations, and second-order upwind discretization scheme is applied for momentum and energy values. A convergence criterion was set to 10^{-6}.

3. RESULTS AND DISCUSSION

3. 1. Effects of Splitter Plate Length   The drag coefficient and the average Nusselt number data of the circular cylinder show a good agreement with other investigators results, which is shown in Figure 2 and Figure 3, respectively. From Figure 2, it can be observed that the drag coefficient decreases with the growth of Reynolds number. Figure 3 depicts the effect of Reynolds number on the Nusselt number. It can be concluded that the Nusselt number elevates with increasing Reynolds number.

Comparison of the results confirms the validity of our simulation. At Reynolds number of 40, adding a splitter plate with a length less than D (its diameter), caused a slight increase in symmetric vortices length. However, when the Reynolds number rose to 100 and more, significantly smoother vortices created, which can be eliminated by increasing the length of the plate (Figure 4).
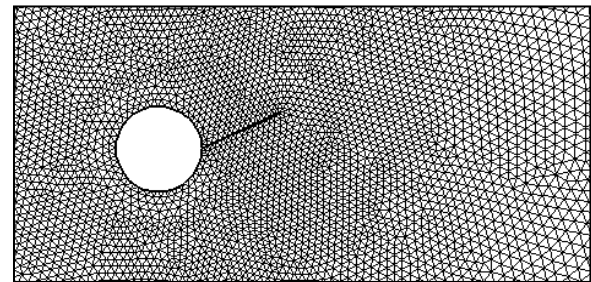

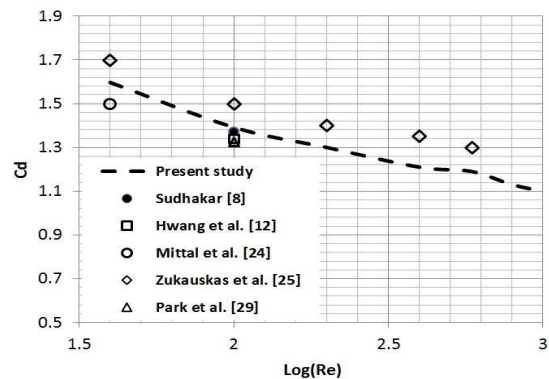**Figure 1.** Computational domain and grid configuration at $\theta=25°$ and L=D

Figure 2. Comparison of drag coefficients for plain cylinder

Enhancement of splitter plate length results in the formation of shorter vortices on the splitter plate surface that gradually spread across the plate as shown in Figure 4 (b to d). The effect of splitter plate length on the drag coefficient is shown in Figure 5. It can be seen that by growing the length of a splitter plate at low Reynolds, the drag coefficient is declined. The flow around the cylinder becomes linear (streamlines are formed) using a splitter plate, thus, the wake area is stabilized and smooth vortices are created and consequently; the pressure coefficient is reduced. Hence, both the pressure and the friction coefficients are reduced and a significant reduction is observed in drag coefficient. Table 1 compares the available results with the present study.

Increasing the splitter's length weakens the vortex behind the cylinder that causes reduction in convective heat transfer as it can be seen in our data. This reduction is also related to the splitter role in flow stabilization. Figure 6 indicates that the average Nusselt number decreases in response to enlargement of splitter plate length. The overall heat transfer in the case of a circular cylinder with splitter plate was compared to a plain cylinder (Figure 7). The ratio of overall heat transfer of circular cylinder with a splitter plate to plain cylinder reveals a significant heat transfer enhancement (Figure 7). With extending the splitter plate length, increment in Nusselt number is observed due to elevated surface-induced heat transfer.

However, it appears that this phenomenon has occurred due to growing surface that caused more heat transfer. Similar findings have already been reported [20, 25] whose works support our heat transfer results despite their different undertaken geometrical configurations.
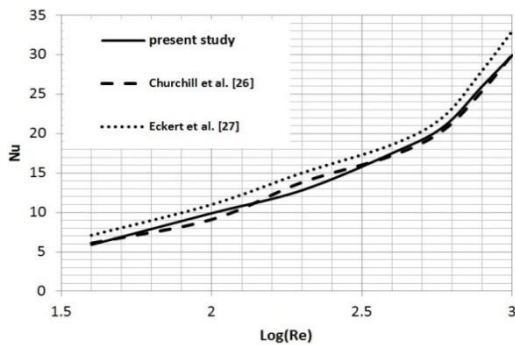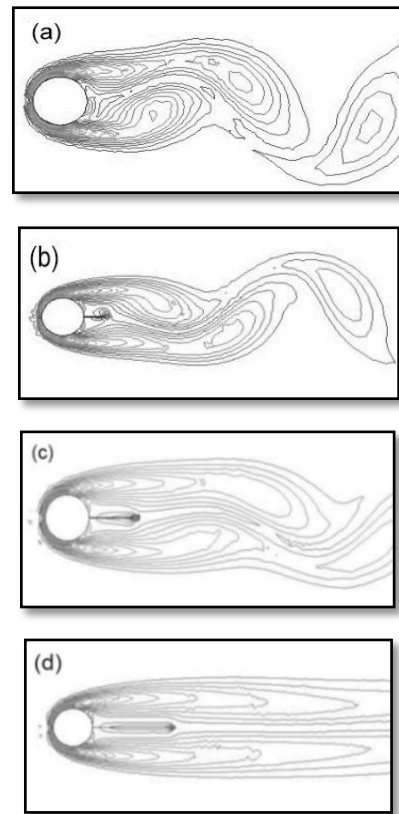

Figure 4. Vortex contours at Re = 100 for cylinder with splitter plate (a) L=0, (b) L=0. 5D, (c) L=D, (d) L=2D
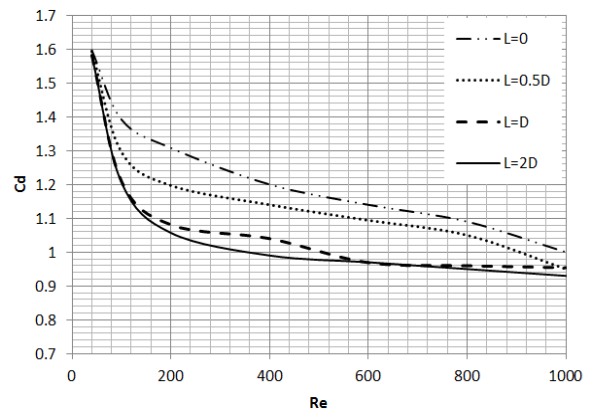
Figure 5. Effect of splitter plate length on the overall drag coefficient

Figure 3. Comparison of average Nusselt numbers for plain cylinder

TABLE 1. Comparison of drag coefficients for flow over a circular cylinder with and without splitter plate

Test cases		Hwang et al. [12]	Park et al. [23]	Kwon and Choi [24]	Sudhakar [8]	Present
Without splitter plate Re = 100	C_D	1.34	1.33	-	1.37	1.39
With splitter plate Re = 100, $\frac{L}{D} = 1$	C_D	1.17	-	1.18	1.17	1.19

The impact of a splitter plate along the cylinder centerline on the total temperature at the outflow domain is shown in Figure 8. As can be seen, the total temperature drops as the Reynolds number grows, and the temperature reduction near the cylinder with splitter plate becomes more noticeable.

3. 2. Effect of Splitter Plate Angle

The effects of various plate angles on the cylinder were examined and the following results were obtained. As can be realized from Figure 9, in case of a 25 degrees angle, there is a reduction in drag coefficient compared to an angle of 0 degrees. Up to 25 degrees, there is no substantial change in the coefficients, but after that, a large elevation in the drag coefficient can be seen (Figure 9). From Figure 10, it can be understood that obvious changes in the Nusselt number were not found with increasing the angle of a splitter plate up to 25 degrees. However, with further increase in the value of splitter plate angles, a significant increase was observed.

According to the results, it is realized that drag coefficient is decreased by increasing the plate length.
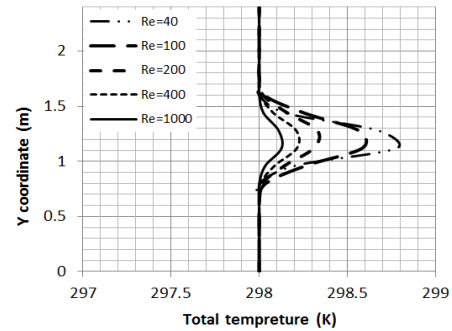

Figure 6. Effect of splitter plate length on the average Nusselt number
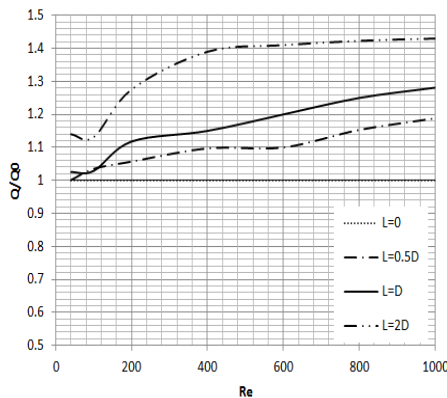
Figure 7. Overall heat transfer ratio of cylinder with splitter plate to plain cylinder

Figure 8. The impact of a splitter plate with L=D on total temperature (K), splitter with $\theta = 0$

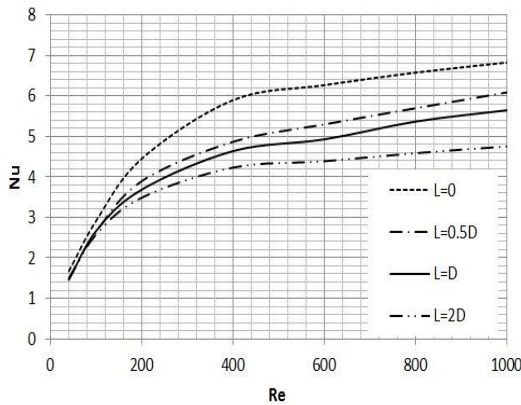**Figure 9.** Effect of plate angle on the drag coefficient, L=D

In cases with space limitations, instead of elongating the plate length, one can use a shorter plate with a 25° angle. In Figure 11, the structure of vortices at different plate angles is shown. When the plate is placed at a higher angle, the vortices begin to take shape and turbulent vortex structure behind the cylinder is increased. These vortices gradually decrease by reducing the angle and join the main vortices. Also, when the plate inclination enlarges, due to the interaction between the small and large scale vortices, the mixing process is amplified. As a result, an increase in the rate of heat transfer is generated.

Figure 12 illustrates that increase of splitter plate angle does not have a significant effect on the Nusselt number. Based on Figure 12, when the plate is located at angle 25° to the centerline, we have the optimal of Nusselt number. The Nusselt number rises sharply with further increase in plate angle.

Furthermore, with increasing Reynolds number or the flow velocity, Nusselt coefficient increases. At Reynolds number of 200, adding a splitter plate with

L=D at different angles affects the outflow temperature, as can be noted from Figure 13. Except for the angle of 25°, by raising the plate angle up to 65°, the total temperature grows. At angle of 25°, the temperature suddenly drops. This effect becomes more pronounced near the cylinder with splitter plate.
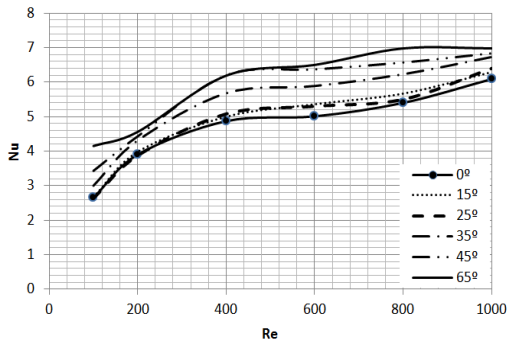
Figure 10. Variation of the average Nusselt number for cylinder with splitter plate at varying angular position, L=D.
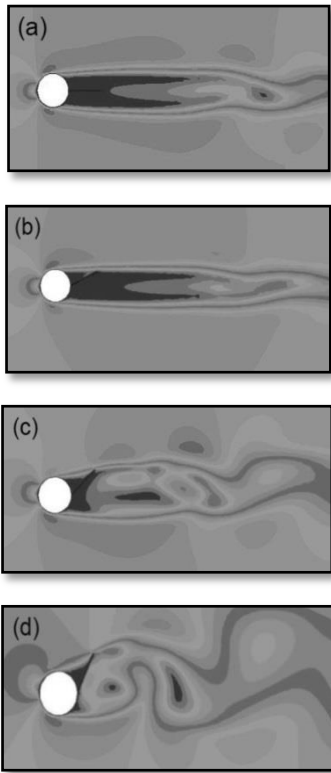

Figure 11. Vortex patterns at Re=1000 (a) $\theta = 0°$, (b) $\theta = 25°$, (c) $\theta = 45°$ and (d) $\theta = 65°$
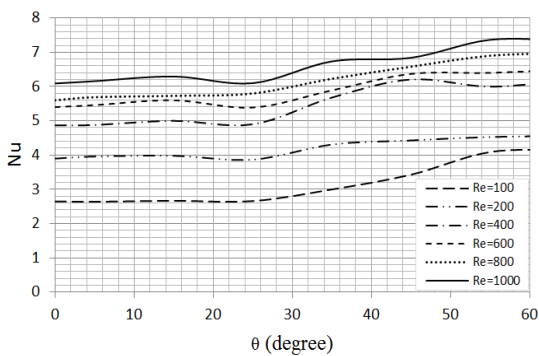

Figure 12. Impact of plate angle on Nusselt Number, L=D
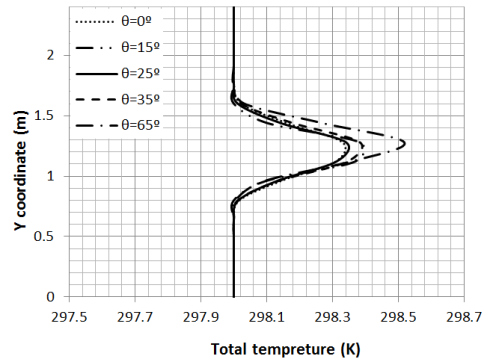

Figure 13. Effect of plate angle on the total outlet temperature at Re=200 and L=D

4. CONCLUSION

By placing a splitter plate at the central line of a cylinder it is found that the flow around the cylinder is streamlined and consequently, reduces the lift coefficient and generally causes a significant reduction in the drag coefficient. Rate of heat transfer from the cylinder is reduced; however, the conductive heat transfer is increased due to the extra heat transfer area generated by the splitter plate. Additionally, the effects of plate length on the flow characteristics are evaluated. The drag coefficient is reduced by increasing the splitter plate length and vortices disappear. However, the heat transfer coefficient boosts up due to the increased heat transfer area. On the other hand, because of space constraints, this function cannot be used everywhere. Another factor is tested by placing a plate attached to a cylinder with various angles. It is observed that by increasing the angle to about 25°, drag coefficient decreases, but with further enhancement in splitter plate angle in addition to the elevation of these coefficients, new vertices are generated at the top of the plate. Additionally, it is observed that by increasing the plate angle up to 25° the outflow temperature grows, but at angle of 25° the temperature suddenly drops and then the temperature rises with further increase in the angle.

5. REFERENCES

1. Gerrard, J., "The mechanics of the formation region of vortices behind bluff bodies", *Journal of Fluid Mechanics*, Vol. 25, No. 02, (1966), 401-413.

2. Chen, H., Huang, P. G. and LeBeau, R. P., "A cell-centered pressure based method for two/three-dimensional unstructured incompressible navier-stokes solver", in 43rd AIAA Aerospace Sciences Meeting and Exhibit, (2005), 10-13.

3. Boisaubert, N. and Texier, A., "Effect of a splitter plate on the near-wake development of a semi-circular cylinder", *Experimental Thermal and Fluid Science*, Vol. 16, No. 1, (1998), 100-111.

4.   Molki, M. and Fotouhi, D., "Thermal field around a circular cylinder with periodic vortex shedding", *International Journal of Engineering*, Vol. 10, No. 1, (1997), 27-36.

5.   Nakamura, Y., "Vortex shedding from bluff bodies with splitter plates", *Journal of Fluids and Structures*, Vol. 10, No. 2, (1996), 147-158.

6.   Apelt, C. and West, G., "The effects of wake splitter plates on bluff-body flow in the range $10^4 <$ Re$< 5 \times 10^4$. Part 2", *Journal of Fluid Mechanics*, Vol. 71, No. 01, (1975), 145-160.

7.   Apelt, C., West, G. and Szewczyk, A. A., "The effects of wake splitter plates on the flow past a circular cylinder in the range $10^4 <$ Re$< 5 \times 10^{4}$", *Journal of Fluid Mechanics*, Vol. 61, No. 01, (1973), 187-198.

8.   Sudhakar, Y. and Vengadesan, S., "Vortex shedding characteristics of a circular cylinder with an oscillating wake splitter plate", *Computers & Fluids*, Vol. 53, (2012), 40-52.

9.   Nouri-Borujerdi, A. and Lavasani, A., "Flow visualization around a non-circular tube", *International Journal of Engineering Transactions B Applications*, Vol. 19, No. 1, (2006), 73-82.

10. Razavi, S. E., Farhangmehr, V. and Barar, F., "Impact of a splitter plate on flow and heat transfer around circular cylinder at low reynolds numbers", *Journal of Applied Science*, Vol. 8, No. 7, (2008), 1286-1292.

11. Kahrom, M., "The effect of square splittered and unsplittered rods in flat plate heat transfer enhancement", *International Journal of Engineering*, (2007).

12. Hwang, J.-Y. and Yang, K.-S., "Drag reduction on a circular cylinder using dual detached splitter plates", *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 95, No. 7, (2007), 551-564.

13. Gu, F., Wang, J., Qiao, X. and Huang, Z., "Pressure distribution, fluctuating forces and vortex shedding behavior of circular cylinder with rotatable splitter plates", *Journal of Fluids and Structures*, Vol. 28, (2012), 263-278.

14. Ozono, S., "Flow control of vortex shedding by a short splitter plate asymmetrically arranged downstream of a cylinder", *Physics of Fluids*, Vol. 11, (1999), 2928-2934.

15. Heidarinejad, G. and Delfani, S., "Direct numerical simulation

16. Emamgholizadeh, M., Gharabaghi, A. M., Abedi, K. and Sedaaghi, M., "Experimental investigation of the effect of splitter plate angle on the under-scouring of submarine pipeline due to steady current and clear water condition", *International Journal of Engineering-Transactions C: Aspects*, Vol. 28, No. 3, (2014), 368-377.

17. Alam, M. M., Sakamoto, H. and Zhou, Y., "Effect of a t-shaped plate on reduction in fluid forces on two tandem cylinders in a cross-flow", *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 94, No. 7, (2006), 525-551.

18. Malekzadeh, S. and Sohankar, A., "Reduction of fluid forces and heat transfer on a square cylinder in a laminar flow regime using a control plate", *International Journal of Heat and Fluid Flow*, Vol. 34, (2012), 15-27.

19. Kawai, H., "Discrete vortex simulation for flow around a circular cylinder with a splitter plate", *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 33, No. 1, (1990), 153-160.

20. Tiwari, S., Chakraborty, D., Biswas, G. and Panigrahi, P., "Numerical prediction of flow and heat transfer in a channel in the presence of a built-in circular tube with and without an integral wake splitter", *International Journal of Heat and Mass Transfer*, Vol. 48, No. 2, (2005), 439-453.

21. Shukla, S., Govardhan, R. and Arakeri, J., "Flow over a cylinder with a hinged-splitter plate", *Journal of Fluids and Structures*, Vol. 25, No. 04, (2009), 713-720.

22. Razavi, S., Osanloo, B. and Sajedi, R., "Application of splitter plate on the modification of hydro-thermal behavior of PPFHS", *Applied Thermal Engineering*, Vol. 80, (2015), 97-108.

23. Park, J., Kwon, K. and Choi, H., "Numerical solutions of flow past a circular cylinder at reynolds numbers up to 160", *KSME International Journal*, Vol. 12, No. 6, (1998), 1200-1205.

24. Kwon, K. and Choi, H., "Control of laminar vortex shedding behind a circular cylinder using splitter plates ,"*Physics of Fluids (1994-present)*, Vol. 8, No. 2, (1996), 479-486.

25. Eckert, E. R. G. and Drake Jr, R. M., "Analysis of heat and mass transfer", (1987).

of the wake flow behind a cylinder using random vortex method in medium to high reynolds numbers", *International Journal of Engineering*, Vol. 13, No. 3, (2000), 33-50.

Numerical Study on Hydrodynamics and Heat Transfer Characteristics Around a Cylinder with Inclined Splitter Plates

S. E. Razavi, A. Hosseinpour Shafaghi, N. Piroozfam

Faculty of Mechanical Engineering, University of Tabriz, Tabriz, Iran

چکیده

در مقاله حاضر، تاثیر طول و زاویه صفحه جداگر بر روی خصوصیات هیدرودینامیکی و حرارتی در محدوده اعداد رینولدز ٤٠ تا ۱۰۰۰ به صورت عددی با حل معادله دو بعدی ناویر – استوکس بررسی شده است. برای گسسته سازی معادلات، الگوریتم PISO برای معادلات به هم پیوسته فشار– سرعت و روش مرتبه دوم پیشرو برای مقادیر مومنتوم و انرژی به کار گرفته شده است. معیار همگرایی بر روی ۱۰⁻٦ تنظیم شده است. تاثیر صفحه جداگر بر روی نیروی درگ، ساختار گردابه ها و رفتار انتقال حرارت بررسی شده است. مشاهده شد که نیروی درگ با افزایش طول صفحه جداگر کاهش می یابد و گردابه ها به تدریج ناپدید می شوند. متوسط عدد ناسلت با افزایش زاویه صفحه جداگر افزایش می یابد. در زاویه حدود ۲۵ درجه، افت نیروی درگ مشاهده شد. انتقال حرارت کلی به دلیل افزایش سطح تماس ناشی از صفحه جداگر افزایش یافت. علاوه بر این، مشاهده شد که با افزایش زاویه صفحه جداگر تا ۲۵ درجه دمای خروجی زیاد شد.

doi: *10.5829/idosi.ije.2016.29.04a.14*