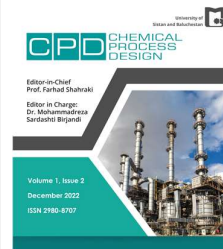




University of Sistan
and Baluchestan

Chemical Process Design

Available online at <http://cpd.usb.ac.ir/>



Modelling of Fluid Flow and Heat Transfer around a Transversely Oscillating Circular Cylinder

Hamid Reza Shahbazi¹, Ataallah Soltani Goharrizi¹, Bahador Abolpour^{2,*}

¹Department of Chemical Engineering, Shahid Bahonar University of Kerman, Kerman, Iran

²Department of Chemical Engineering, Sirjan University of Technology, Sirjan, Iran

ARTICLE INFO

Article history:

Received: 2022-11-23

Received in revised form: 2022-12-28

Accepted: 2023-01-10

Published online: 2023-01-11

Keywords:

Heat transfer; Oscillating cylinder;
Nusselt number; Vortex shedding

DOI: 10.22111/cpd.2023.44062.1013

ABSTRACT

One of the favorite topics in the industrial and educational applications is external flows and the fluid and heat flows around a perpendicular cylinder, specially. This problem is greatly applicable in designing heat exchangers, fuel cooling, fuel elements and similar engineering equipment. In this study, the heat transfer in a laminar incompressible fluid flow around a cylinder that oscillate perpendicular to the flow direction, have been investigated. For this purpose, the OpenFOAM software has been used to solve the governing equations and obtaining the Nusselt number around this cylinder. Different Reynolds numbers, from 10 to 1000, and oscillation frequency ratios, from 0.8 to 1.2, have been investigated. The Nusselt number has been obtained in two effective Reynolds numbers and the changes in the Nusselt number and the pressure coefficient around the cylinder have been also calculated. The results show that increasing Reynolds number increases the heat transfer rate and the oscillation frequency ratio equal to 1 has the highest heat transfer rate.

1. Introduction

One of the favorite topics in the industrial and educational applications is external flows and the fluid and heat flows around a perpendicular cylinder, specially. This problem is greatly applicable in designing heat exchangers, fuel cooling, fuel elements and similar engineering equipment. Kramers [1] investigated the heat transfer around a fixed cylinder perpendicular to a fluid flow with the Reynolds numbers between 3 and 1000, experimentally. He presented a relation between the Nusselt, Reynolds and Prandtl numbers. Fand [2] studied the forced convective heat transfer in a fluid flow around a cylinder with the Reynolds number between 0.1 and 105, experimentally. He also presented an empirical relation for calculating the Nusselt number, which was depended on the Prandtl and Reynolds numbers. Karniadakis [3] simulated the forced convective heat transfer in a cross-flow around a cylinder with the Reynolds numbers less than 200 and a Prandtl number equal to 0.7 by solving the Navier-Stokes and energy equations. His

Corresponding author. Tel.: +98 937 806 14 40;

E-mail address: bahadorabolpor1363@sirjantech.ac.ir (B. Abolpour)

numerical predictions for the size of vortexes behind the cylinder, the time structures, the distance between the Von Karman vortex stresses, the coefficient of drag and lift forces versus time, and the unstable local heat transfer coefficient were validated using the experimental data.

Baranyi [4] studied a two-dimensional, unsteady state and incompressible laminar heat and fluid flows around a rotating cylinder with a constant temperature in the Reynolds numbers among 50 to 180, by solving the Navier-Stokes, continuity, Poisson and energy equations. The predicted values for the Strouhal number, the mean time of the drag coefficient, the pressure coefficient and the Nusselt number were in good agreement with the experimental data.

Travnicek et al. [5] studied the laminar vortexes shedding behind a cold cylinder, experimentally. They observed that this cold cylinder made unstable wakes in the fluid behind the cylinder and decreasing the cylinder temperature increased the frequency of vortex shedding. Golani and Decimal [6] simulated a two-dimensional unsteady state fluid and heat flows around a cylinder with the Reynold numbers among 50 to 180 and the Prandtl number equal to 0.7. They investigated the effects of Reynolds number on the drag and lift coefficients, the Strouhal number, and the characters of heat transfer.

Saxena and Laird [7] studied the heat transfer from a cylinder oscillating in a cross-flow with the Reynolds Number equal to 3500 with a range of amplitude to cylinder diameter ratio from 0.89 to 1.99 and an oscillation frequency range from 0.4 to 1.2, experimentally. They concluded that these amplitude and frequency increases the heat transfer coefficient, with a same extent, up to 60%. Karanth et al. [8] simulated the forced convective heat transfer from an oscillating cylinder using the finite difference method. They investigated the effects of this oscillation on the mean and local Nusselt numbers at the Reynolds number equal to 200. They concluded that the average Nusselt number for an oscillating cylinder with a natural-frequency is almost twice a fixed cylinder and increasing this oscillation increases the heat transfer rate.

Cheng et al. [9] studied the convective heat transfer around a cylinder, experimentally. They used a modified method to observe the flow patterns and calculate the heat transfer coefficient in a range of Reynolds numbers less than 4000, the frequency domain ratio less than 0.628 and the non-dimensional oscillation frequency less than 0.65. Their resulted that, as turbulence and wake can increase the heat transfer, the cylinder oscillation has this ability as well. They observed this increase up to 35%. They also presented an approximate relation for calculating the effect of the cylinder oscillation on heat transfer. Cheng et al. [10] predicted the effects of wake on the convection heat transfer from an oscillating cylinder, numerically. They used the Synchronized Over Lap-Add method to solve the velocity field and the finite volume method to solve the energy equation. They obtained the time variations of the Nusselt number and the drag and lift coefficients in different conditions of the cylinder oscillation. They considered the Reynolds number less than 300, dimensionless frequency less than 0.3, dimensionless oscillation amplitude less than 0.7 and the Prandtl number from 0.71 to 7. They concluded that the oscillation of the cylinder affects the amount of heat transfer in the wake region of the cylinder and the cylinder oscillation has no effect on the heat transfer outside the wake region. They provided a relation for calculating the Nusselt number.

Gau et al. [11] analyzed the improvement of heat transfer and the structure of flow vortexes for an oscillating cylinder in a flow path, experimentally. They used a smoke wire to observe the flow and measure the local heat transfer around the cylinder. They selected the ratio of the cylinder oscillation frequency less than 3 (frequencies that make harmonic, subharmonic, super harmonic, and nonharmonic vorticities). They concluded that the vortex harmony does not only occur at the frequency ratio of 1, but also occurs at the frequency ratio of 3, which has a great effect on increasing the

heat transfer. They mentioned that the simultaneous heat transfers at the stagnation point (upstream) and the lower region, or the wake region, is the factor of the instability of the tensile layer behind the cylinder. They changed the Reynolds number from 1600 to 4800, the amplitude from 0.016 to 0.064 times the diameter of the cylinder during their tests.

Fu and Tong [12] investigated the heat transfer around a heated cylinder, numerically. They categorized the variation of the flow and heat fields in the moving boundary of the problem and considered the moving intersection between the fluid and the cylinder. They adopted an arbitrary description of the Lagrangian-Eulerian kinematic method to describe the fluid and temperature fields. They used finite element method to solve governing equations. They provided details on the vortex shedding and the characteristics of heat transfer around the heated cylinder, and investigated the effects of Reynolds number, oscillation amplitude and oscillation velocity on the flow structure and heat transfer characteristics. They also pointed out in their studies that the interaction between the cylinder oscillation and the vortex shedding from the cylinder, dominated the wake states formed behind the cylinder.

Pham et al. [13] presented a numerical study of a 2D laminar flow ($Re=185$) passing an oscillating circular cylinder, in a range of cylinder oscillation frequency between 0.8 and 1.2 of the natural vortex shedding frequency, and the oscillation amplitude extended up to 50% of the cylinder diameter, using the finite volume method. They observed that the primary vortex shedding frequency was equal to the exciting cylinder frequency and when the exciting frequency exceeds the natural vortex shedding frequency, the secondary vortex shedding frequency appeared with the value less than the natural shedding frequency. Guilmineau and Queutey [14] investigated the vortex shedding from an oscillating circular cylinder, numerically, by solving 2D unsteady Navier–Stokes equations. Two phenomena were investigated. 1st was the flow induced by the harmonic in-line oscillation of cylinder in water at rest at Reynolds number equal to 100 and Keulegan–Carpenter number equal to 5. 2nd was a transversely oscillating cylinder in a uniform flow at Reynolds number equal to 185 and the cylinder oscillation frequency ranges from 0.8 to 1.2 of the natural vortex-shedding frequency, and the oscillation amplitude equal to 20% of the cylinder diameter.

Nobari and Naderian [15] presented a 2D fluid flow simulation around an oscillating circular cylinder (with different values of oscillation frequency and amplitude) using a finite element method to solve Arbitrary Lagrangian–Eulerian formulation in 2 cases (*i.e.* cross flow and inline oscillation). Their numerical results had a suitable agreement with the experimental data. Krishnamoorthy et al. [16] investigated cross-flow passing a circular cylinder with forced harmonic oscillations in the transverse plane in a water tunnel, experimentally, at Reynolds numbers ranging from 1250 to 1500. They observed that after a subsequent transition, the phase of vortex shedding relative to cylinder displacement switched by about π . Between these transitions, the vortex formation length was at minimum value.

Luo et al. [17] presented a numerical simulation for a fluid flow ($Re = 197, 248, 296$) and its heat transfer process passing an oscillating cylinder with different amplitude, frequency, and oscillating angle, using the Finite Volume Method based on the SIMPLE algorithm. They resulted that the variation in amplitude had a significant effect on changing of the flow field and also with the increase in amplitude and frequency, the heat transfer enhanced remarkably. In addition, it was observed that for different oscillating angles, the flow field displays different flow regimes and the optimized angle was located at 0° or 90° . Zhang et al. [18] investigated the flow ($Re=100$) interference between an upstream stationary cylinder and an inline oscillating cylinder, with a pitch ratio equal to 4, the amplitude among 0.25 to 1, and frequency ratio in a range from 0.5 to 2, using the lattice Boltzmann method. They concluded

that the response states of upstream and downstream wakes were similar under the conditions of small amplitude or low frequency.

In recent years, Derouich et al. [19] investigated the heat transfer in a mixed convective flow passing an oscillating square cylinder, at Prandtl number equal to 0.7, low Reynolds number ranging from 40 to 220 and tilt angles from 0 (inline oscillation) to $\pi/2$ (transverse oscillation). They solved the governing equations using a finite-volume technique and validated their simulations using the available data from other literature. They resulted that the heat transfer is increases when the angle of oscillation tends to $\pi/2$. Sarout et al. [20] investigated the vibrated flow around heated cylinders with different normalized corner radii at different Reynolds numbers. They solved the incompressible Navier-Stokes and energy equations and found that the heat transfer and wake structure parameters are dependent on the investigated parameters.

Kumar et al. [21] investigated an unsteady, 2D flow and heat transfer around a rotationally oscillating circular cylinder in a linear shear flow. They utilized a higher order compact finite difference method to solve the Navier–Stokes and energy equations using a nonuniform calculation mesh in cylindrical coordinate system and validated their model using existed literature studies. They observed partial and full vortex suppression in certain values of shear stress and concluded that at certain values of oscillation parameter, the heat transfer rate were increased. Amini et al. [22] simulated the heat transfer from circular cylinders with four flexible fins in turbulent cross flows in turbulent flows, using finite element method and the $k-\omega$ SST model. They found that attached fins in and the flexural rigidity affect Nusselt number and very flexible fins can increase the Nusselt number by 26%.

The novelty of the presented model in this study is the investigation of variations of the Strouhal number in the effective Reynolds number. In this study, the frequency of vortex shedding and Strouhal number is calculated using the fast Fourier transform method. The Nusselt number has been obtained in two effective Reynolds numbers and the changes in the Nusselt number and the pressure coefficient around the cylinder have been also calculated. Then, in the oscillating cylinder case, the values of the Nusselt number ratio have been calculated in different frequency ratios. The developed OpenFOAM code in this study has been used for designing an experimental setup for investigating high performance heat exchangers. In this novel idea, an optimization mechanism has been considered using a combination of measured empirical parameters and the predicted values by the model.

2. Methodology

A schematic diagram from the investigated problem has been presented in Fig. 1 (A two-dimensional channel). All dimensions have been based on the diameter of the cylinder ($D=5$ mm). The distance from the entrance to the center of the cylinder and also the distance from the center of the cylinder to the top and bottom walls are more than $8D$, and the distance from the center of the cylinder to the output is $20D$. The input fluid velocity (U) is constant. The non-slip condition for the cylinder surface and the slip condition for the upper and lower levels have been considered. The output pressure is the same as the atmospheric pressure. The input fluid temperature and the wall temperature have been fixed as T_∞ and T_w , respectively.

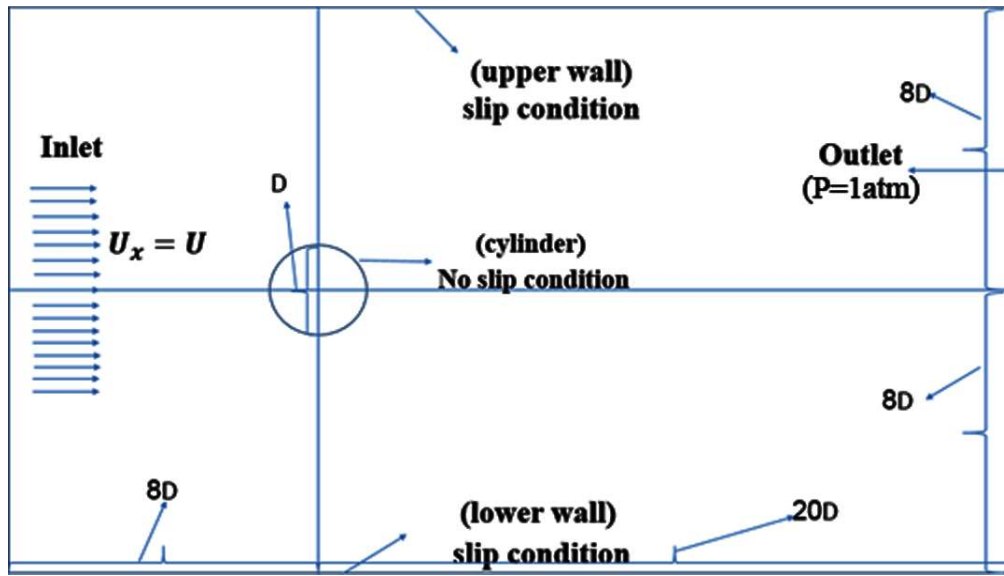


Fig. 1. A schematic diagram from the cylinder in a two-dimensional channel

The cylinder has been located in the center of the channel and its oscillation is perpendicular to the flow direction. Some non-dimensional numbers are used as $Re_{eff} = \frac{uD}{\nu_{eff}}$, $Pr = \frac{\nu}{\alpha}$, $Ri = \frac{Gr}{Re^2}$, $Co = \frac{u\Delta t}{\Delta x}$, $St = \frac{f_v D}{U}$, $Gr = \frac{\beta g (T_w - T_\infty) D^3}{\nu^2}$, $Nu = \frac{hD}{k} = \frac{QD}{k(T - T_\infty)}$, $f_r = \frac{f_e}{f_0}$, $A_r = \frac{A_e}{D}$, $\frac{\overline{Nu}}{Nu_0}$ and $\frac{S_c}{S_{c0}}$ [23]. Where ν_{eff} is the effective kinematic viscosity at the effective temperature ($T_{eff} = \frac{T_w + T_\infty}{2}$), α is thermal diffusion of the fluid, f_v is the vortex formation frequency, f_r is the vortex shedding frequency, f_e is the exciting frequency, f_0 is the natural shedding frequency of the fixed cylinder, A_r is the vortex shedding domain, A_e is the domain of exiting, g is the gravitational acceleration, β is the thermal expansion coefficient, Q is the transferred heat, h is the convective heat transfer coefficient, k is the conduction heat transfer coefficient, \overline{Nu} is the time (t) averaged overall Nu, \overline{Nu}_0 is the time averaged overall Nu for stationary cylinder, S_c is the dimensionless frequency of oscillation of cylinder ($S_c = \frac{f_e D}{U}$) and S_{c0} is the dimensionless natural shedding oscillation [23]. The governing equations for passing this Newtonian fluid over a perpendicular cylinder ignoring the dissipation of energy have been presented bellows [24]:

$$\nabla \cdot \vec{u} = 0 \quad (1)$$

$$\frac{D\vec{u}}{Dt} = -\frac{1}{\rho} \nabla P + \nu \nabla^2 \vec{u} \quad (2)$$

$$\frac{DT}{Dt} = \alpha \nabla^2 T \quad (3)$$

where P is the pressure, T is the temperature and ρ is the fluid density. In the present work, the finite volume method in the OpenFOAM open source software was used to plot geometry, gridding and solving these equations in the computational space. Fig. 2 shows the defined two-dimensional mesh in this study.

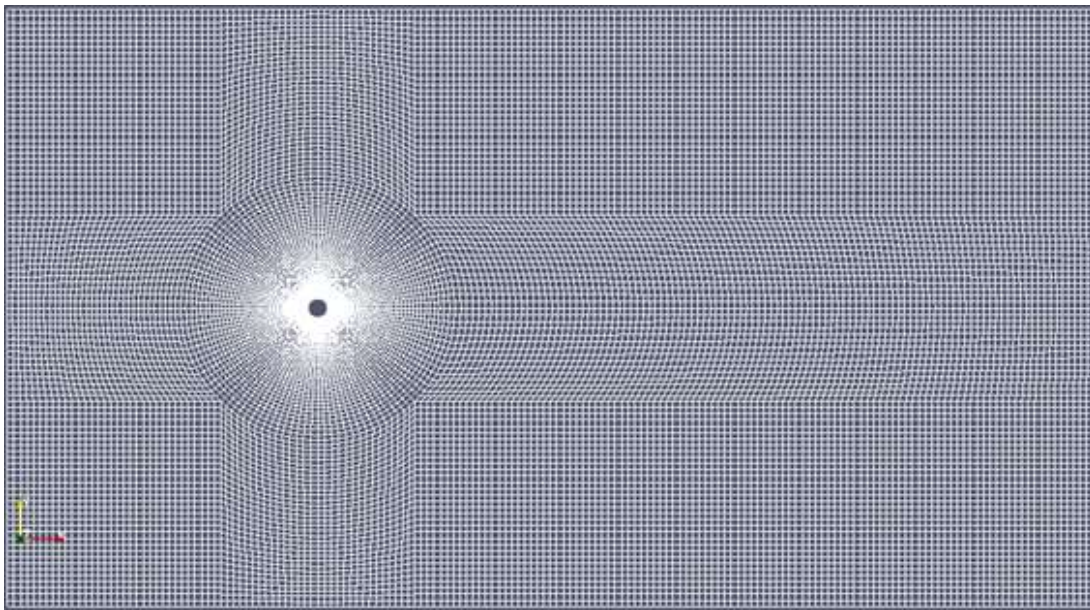


Fig. 2. Defined mesh

3. Results and discussion

For investigating the mesh independency of this simulation, the defined geometry with different numbers of grids was modeled. The suitable mesh was chosen according to the error obtained using the Strouhal number, which was the geometry with 22428 grids. For validating the predictions of this model for air flow (with $\beta=1.995 \times 10^{-3} \text{ K}^{-1}$, $\nu=1.995 \times 10^{-3} \text{ m}^2 \cdot \text{s}^{-1}$, $g=10 \text{ m} \cdot \text{s}^{-2}$, $\text{Pr}=0.71$ and $T_\infty=293.15 \text{ K}$) around the fixed cylinder (with $T_w=293.15$ or 471.97 K and the calculated $\text{Ri} = 6.958 \times 10^{-7} \ll 1$, therefore, the free convective heat transfer was ignorable), the Strouhal number were calculated in four different Reynolds numbers and were compared with the experimental values [5] in Table 1.

Fig. 3 shows the velocity contours of the fluid flow around the cylinder (with $T_w=293.15 \text{ K}$) for different Reynolds numbers. It is clear that there is no vortex behind the cylinder in low Reynolds numbers. Fig. 4 shows the lift and drag coefficient variations for different Reynolds numbers. It is observed that increasing the Reynolds number decreases the required time for stability of the fluid flow. The average value of drag coefficient and the maximum value of lift coefficient in different Reynolds numbers have been compared with the obtained values in other references [25-28] in Table 2.

Table 1. Comparing the calculated Strouhal number for the fixed cylinder with the experimental data [5]

| Re_{eff} | This work | Travnicek et al [5] | Error (%) |
|--------------------------|-----------|---------------------|-----------|
| 195.9 | 0.1852 | 0.191 | 3 |
| 200 | 0.1932 | 0.1933 | 0.05 |
| 216.8 | 0.1938 | 0.1961 | 1.17 |
| 259.8 | 0.1935 | 0.199 | 2.7 |

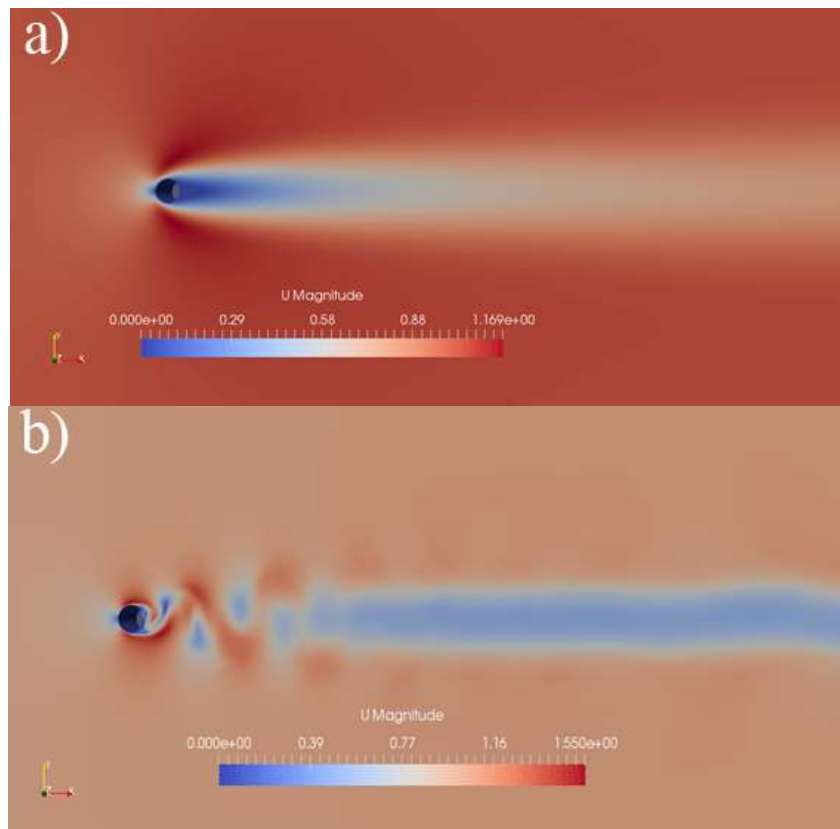


Fig. 3. Velocity contours of the fluid flow around the cylinder (with $T_w=293.15$ K) for (a) $Re=20$ and (b) $Re=1000$

Table 2. Comparing the calculated average values of drag coefficient and the maximum values of lift coefficient for the fixed cylinder with the obtained values in references [25-28]

| | Re=100 | | Re=200 | | Re=1000 | |
|--------------------------------------|-------------|------------|-------------|------------|-------------|------------|
| | \bar{C}_d | C_{lmax} | \bar{C}_d | C_{lmax} | \bar{C}_d | C_{lmax} |
| This work | 1.251 | 0.225 | 1.199 | 0.648 | 1.351 | 1.291 |
| Berthelsen and Faltinsen [25] | 1.38 | 0.34 | 1.37 | 0.7 | - | - |
| Franke et al. [26] | - | - | 1.31 | 0.65 | 1.47 | 1.36 |
| Mittal and Raghuvanshi [27] | 1.402 | 0.355 | - | - | - | - |
| Behr et al. [28] | 1.37 | 0.371 | - | - | - | - |

Fig. 5 shows the variations of these values with the Reynolds number. Table 3 presents a comparison among the calculated values for the Strouhal number in this study with the measured values by Williamson and Brown [29] for $T_w=293.15$ K and also Travnicek et al. [5] for $T_w=471.97$ K.

This dimensionless number indicates the extent of the vortex formation behind the cylinder and also convective heat transfer affects the extent of these vortices. It is observed that, increasing the Re increases this extent. The variation of the local Nusselt number and the coefficient of pressure ($C_p = \frac{P-P_\infty}{0.5\rho U^2}$) have been shown in Fig. 6 and Fig. 7, respectively. It is observed that the minimum and maximum values of the local Nu were located at $\theta=45^\circ$ and 180° , respectively. It is also clear that the separation point of the boundary velocity layer (the point with the minimum pressure) was located at $\theta=100^\circ$. The calculated values of the average Nusselt number around this cylinder in different Reynolds numbers have been compared with the obtained values with Kramers [1] and Fand [2] in Table 4. It is clear

that increasing the Reynolds number increases the average of Nusselt number. Fig. 8 shows the variations of the Courant number, and approves the stability of the solution.

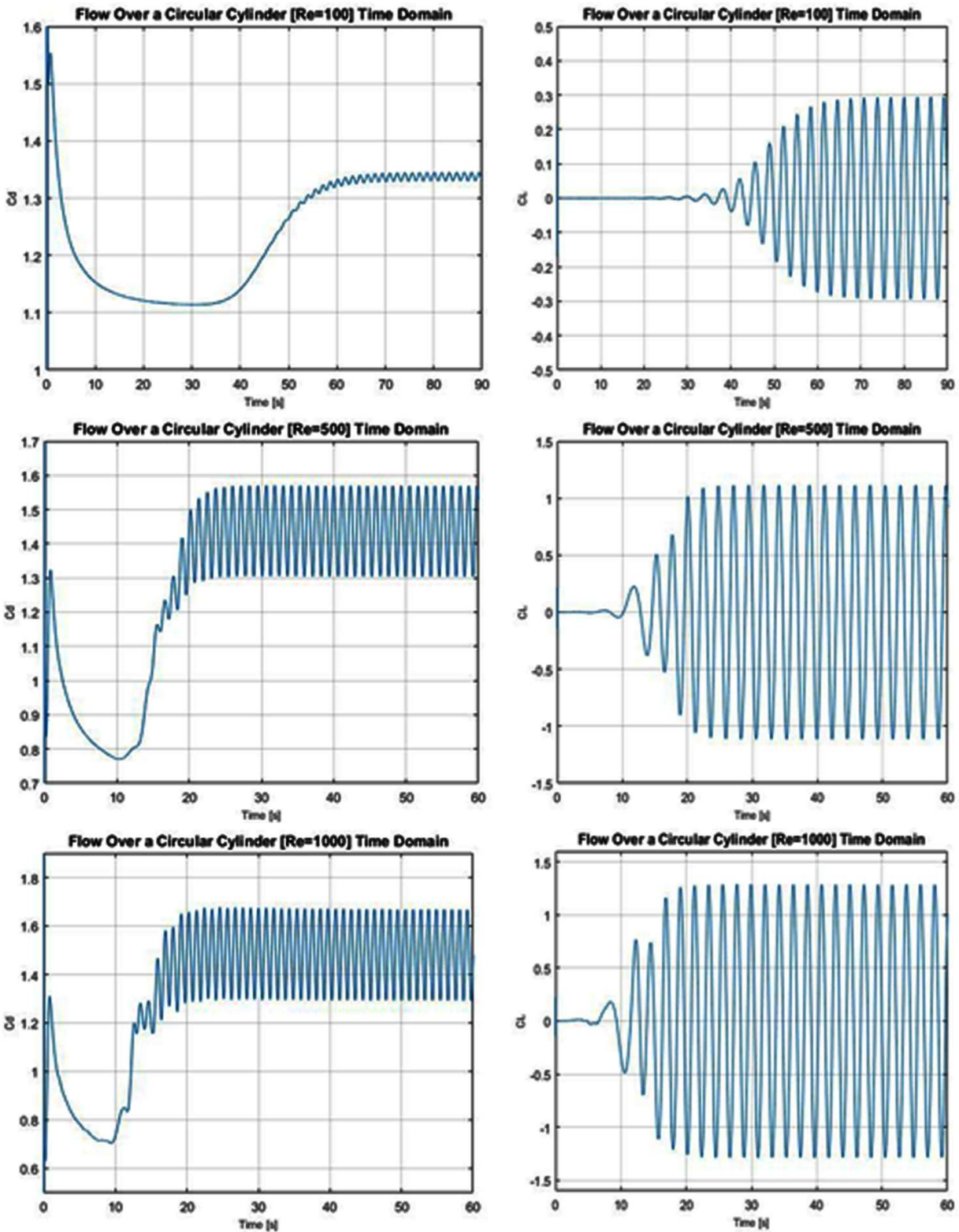


Fig. 4. The lift and drag coefficients variations

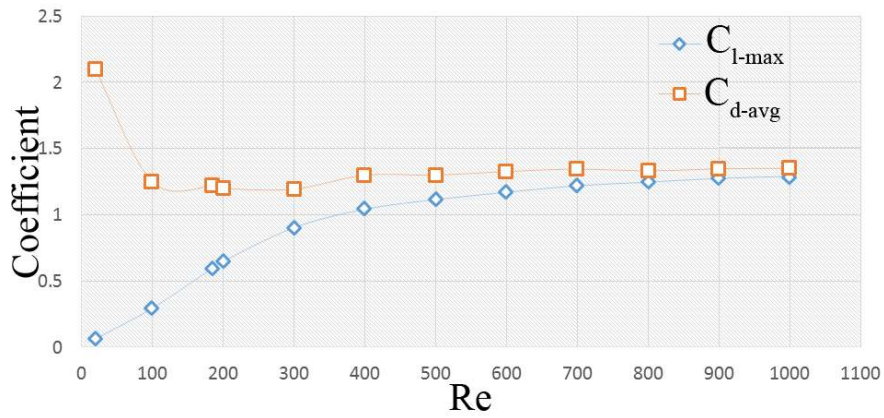


Fig. 5. Variations of the average drag coefficient and the maximum lift coefficient

Table 3. Comparing the calculated values of the Strouhal number for the fixed cylinder with the measured values by Williamson and Brown [29] and Travnicek et al. [5]

| Re_{eff} | f_v | St ($T_w=293.15K$) | | | St ($T_w=471.97 K$) | | |
|------------|-------|----------------------|---------------------------|-----------|-----------------------|----------------------|-----------|
| | | This work | Williamson and Brown [29] | Error (%) | This work | Travnicek et al. [5] | Error (%) |
| 100 | 0.323 | 0.164 | 0.167 | 1.5 | - | - | - |
| 185 | 0.374 | 0.187 | 0.194 | 3.55 | - | - | - |
| 195.9 | - | - | - | - | 0.185 | 0.191 | 3 |
| 200 | 0.378 | 0.189 | 0.197 | 4.1 | 0.193 | 0.193 | 0.05 |
| 216.8 | - | - | - | - | 0.194 | 0.196 | 1.17 |
| 259.8 | - | - | - | - | 0.194 | 0.199 | 2.7 |
| 300 | 0.397 | 0.198 | 0.21 | 5.68 | - | - | - |
| 400 | 0.412 | 0.206 | 0.219 | 5.74 | - | - | - |
| 500 | 0.427 | 0.214 | 0.224 | 4.72 | - | - | - |
| 600 | 0.442 | 0.221 | 0.228 | 7.6 | - | - | - |
| 700 | 0.442 | 0.221 | 0.232 | 4.45 | - | - | - |
| 800 | 0.457 | 0.228 | 0.234 | 2.56 | - | - | - |
| 900 | 0.457 | 0.229 | 0.236 | 3.35 | - | - | - |
| 1000 | 0.458 | 0.229 | 0.238 | 3.95 | - | - | - |

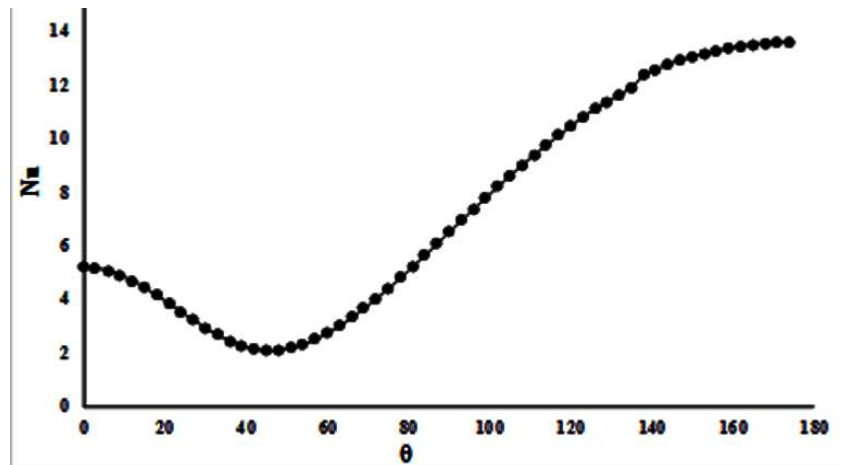


Fig. 6. Variations of the local Nusselt number

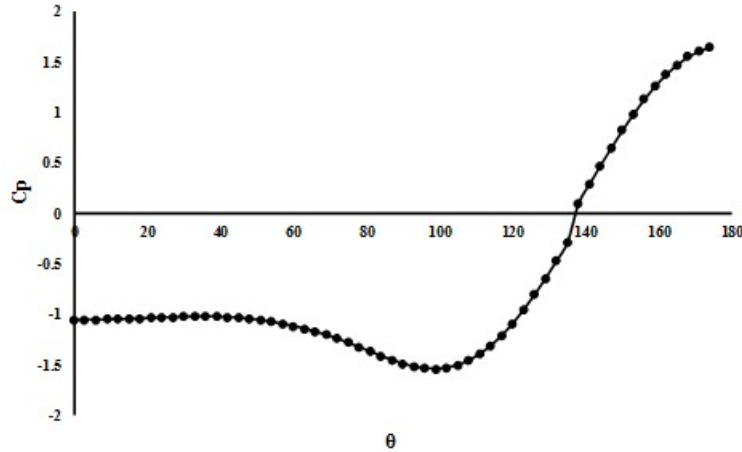


Fig. 7. Variation of the coefficient of pressure

Table 4. Comparing the calculated values of the average Nusselt number around the fixed cylinder with the obtained values with Kramers [1] and Fand [2]

| Re _{eff} | This work | Kramers [1] | | Fand [2] | |
|-------------------|-----------|-------------|-----------|----------|-----------|
| | | value | Error (%) | value | Error (%) |
| 195.9 | 7.394 | 7.591 | 2.59 | 7.524 | 1.73 |
| 200 | 7.443 | 7.666 | 2.9 | 7.601 | 2 |

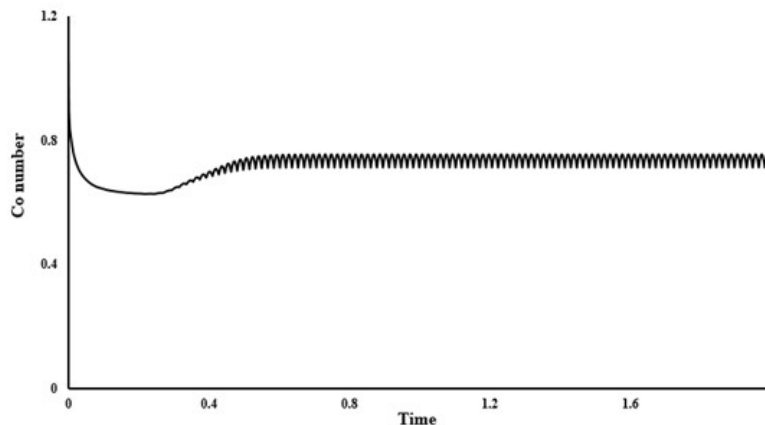


Fig. 8. Variations of the Courant number for the fixed cylinder

For study the effects of the oscillation of the cylinder on the fluid and heat flows, the defined cylinder has been considered to oscillate within the channel of fluid flow, perpendicularly. Table 5 compares the calculated average values of drag coefficient in this study with the obtained values with other researchers for $A_r=0.2$ and $Re=185$ [13, 14]. It is observed that the maximum value of this parameter is at $f_r=1$.

Fig. 9 and Fig. 10 show the variations of the values of $\overline{C_d}$ and C_l for this oscillating cylinder, respectively, with changing its oscillation parameters, i.e. A_r and f_r . Table 6 compares the predicted values of $\frac{\overline{Nu}}{Nu_0}$ with the present model for the oscillating cylinder (with $T_w=471.97$ K, $A_r=0.14$, $Re=200$ and the calculated $Ri = 9.045 \times 10^{-7} \ll 1$, therefore, the free convective heat transfer was ignorable) with the obtained values in other references [9, 10]. It is observed that the highest heat transfer occurs at the frequency ratio of 1.

Table 5. Comparing the calculated average values of drag coefficient for the oscillating cylinder with the obtained values with other researchers [13, 14]

| f_r | This work | Pham et al. [13] | | Guilmineau and Queutey [14] | |
|-------|-----------|------------------|-----------|-----------------------------|-----------|
| | | Value | Error (%) | Value | Error (%) |
| 0.8 | 1.28 | 1.26 | 1.6 | 1.25 | 2.4 |
| 0.9 | 1.35 | 1.36 | 0.73 | 1.34 | 0.74 |
| 0.95 | 1.4 | 1.44 | 2.7 | - | - |
| 1 | 1.45 | 1.52 | 4.6 | 1.5 | 3.3 |
| 1.1 | 1.37 | 1.39 | 1.4 | 1.4 | 2.1 |
| 1.2 | 1.365 | 1.375 | 0.73 | 1.39 | 1.8 |

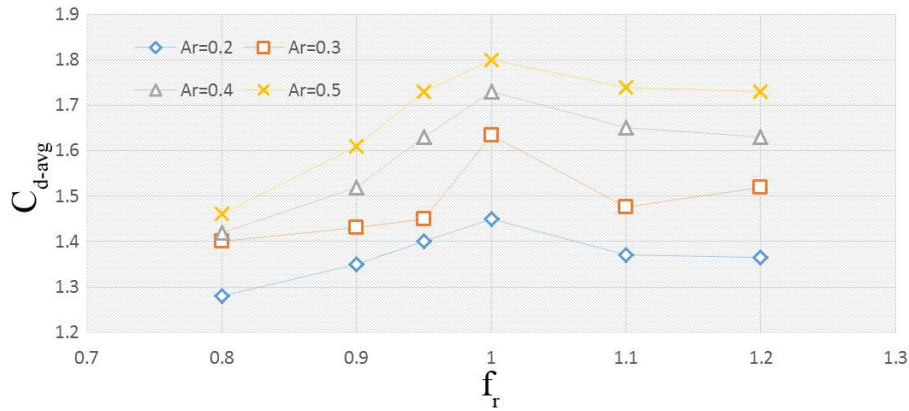


Fig. 9. Variations of $\overline{C_d}$ for the oscillating cylinder

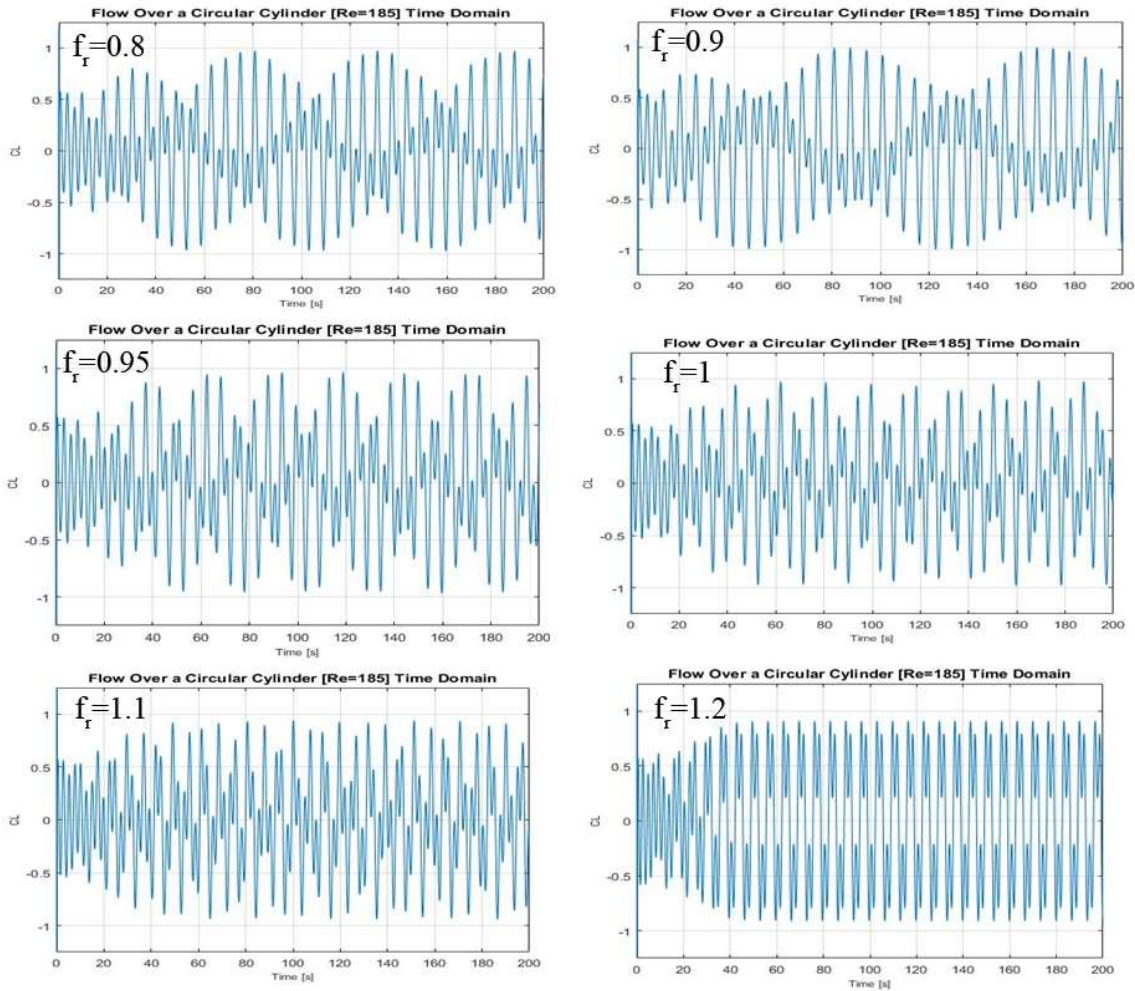


Fig. 10. Variations of C_l for the oscillating cylinder with $Ar=0.2$

Table 6. Comparing the calculated values of the Nusselt number ratio the oscillating cylinder with the obtained values in references [9, 10]

| $\frac{S_c}{S_{c0}}$ | This work | Cheng et al. [9] | | Cheng et al. [10] | |
|----------------------|-----------|------------------|-----------|-------------------|-----------|
| | | Value | Error (%) | Value | Error (%) |
| 0 | 1 | 1 | 0 | 1 | 0 |
| 0.5 | 1.04 | 1.004 | 3.58 | 1.0034 | 3.64 |
| 0.75 | 1.60 | 1.012 | 4.7 | 0.998 | 6.2 |
| 1 | 1.084 | 1.035 | 4.7 | 1.022 | 6 |
| 1.25 | 1.057 | 1.013 | 4.3 | 1 | 5.7 |
| 1.5 | 1.042 | 1.006 | 3.57 | 1.0052 | 3.6 |

4. Conclusion

In the presented study, the fluid and heat flows around an oscillating cylinder in a cross-flow were investigated, numerically. For this purpose, the continuity, momentum and energy equations were solved using the finite volume method. The dependency of the Strouhal number on the Reynolds number was studied. The frequency of vortex shedding and Strouhal number was calculated using the fast Fourier transform method. The Nusselt number was obtained in two effective Reynolds numbers and the changes in the Nusselt number and the pressure coefficient around the cylinder were also calculated. For the oscillating cylinder case, the values of the Nusselt number ratio were calculated in different frequency ratios. Comparing the predictions of the presented model with the obtained results in different previous studies approved the accuracy of these predictions. It is resulted that, increasing the effective Reynolds number increase the Strouhal number behind a heated fixed cylinder. This increment also increases the Nusselt number. The highest amount of heat transfer in the front of the cylinder occurs at the stagnation point, and the maximum amount of heat transfer in the behind of this cylinder is at $\theta=180^\circ$. The maximum value of the Nusselt number ratio is at the non-dimensional frequency equal to 1, because of the synchronization of the vortex shedding frequency with the oscillation frequency of the cylinder.

Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this article.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

References

- [1] Kramers, H., 1946. Heat transfer from spheres to flowing media, *Physica*, 12(2), 61-80. [https://doi.org/10.1016/S0031-8914\(46\)80024-7](https://doi.org/10.1016/S0031-8914(46)80024-7)
- [2] Fand, R. M., 1965. Heat transfer by forced convection from a cylinder to water in crossflow, *International Journal of Heat and Mass Transfer*, 8, 995-1010. [https://doi.org/10.1016/0017-9310\(65\)90084-0](https://doi.org/10.1016/0017-9310(65)90084-0)
- [3] Karniadakis, G. E., 1988. Numerical simulation of forced convection heat transfer from a cylinder in crossflow, *International Journal of Heat and Mass Transfer*, 31(1), 107-118. [https://doi.org/10.1016/0017-9310\(88\)90227-X](https://doi.org/10.1016/0017-9310(88)90227-X)
- [4] Baranyi, L., 2003. Computation of unsteady momentum and heat transfer from a fixed circular cylinder in laminar flow, *Journal of Computational and Applied Mechanics*, 4(1), 13-25.
- [5] Travnicsek, Z., Wang, A. B., Tu, W., 2014. Laminar vortex shedding behind a cooled circular cylinder, *Experimental Fluids*, 55, 1679. <https://doi.org/10.1007/s00348-014-1679-7>
- [6] Golani, R., Dhiman, A. K., 2014. Fluid flow and heat transfer across a circular cylinder in the unsteady flow regime, *The International Journal of Engineering and Science*, 3(3), 8-19.
- [7] Saxena, U. C., Laird, A. D. K., 1978. Heat transfer from a cylinder oscillating in a cross-flow, 100, 684-689. <https://doi.org/10.1115/1.3450877>

- [8] Karanth, D., Rankin, G.W., Sridhar, K., 1994. A finite difference calculation of forced convective heat transfer from an oscillating cylinder, *International Journal of Heat and Mass Transfer*, 37(11), 1619-1630, [https://doi.org/10.1016/0017-9310\(94\)90177-5](https://doi.org/10.1016/0017-9310(94)90177-5)
- [9] Cheng, C. H., Chen, H. N., Aung, W., 1997. Experimental study of the effect of transverse oscillation on convection heat transfer from a circular cylinder, *Journal of Heat Transfer*, 119, 474-482. <https://doi.org/10.1115/1.2824121>
- [10] Cheng, C. H., Hong, J. L., Aung, W., 1997. Numerical prediction of lock-on effect on convective heat transfer from a transversely oscillating circular cylinder, *International Journal of Heat and Mass Transfer*, 40(8), 1825-1834. [https://doi.org/10.1016/S0017-9310\(96\)00255-4](https://doi.org/10.1016/S0017-9310(96)00255-4)
- [11] Gau, C., Wu, J. M., Liang, C.Y., 1999. Heat transfer enhancement and vortex flow structure over a heated cylinder oscillating in the crossflow direction, 121, 789-795. <https://doi.org/10.1115/1.2826067>
- [12] Fu, W. S., Tong, B. H., 2002. Numerical investigation of heat transfer from a heated oscillating cylinder in a cross flow, *International Journal of Heat and Mass Transfer*, 45, 3033-3043. [https://doi.org/10.1016/S0017-9310\(02\)00016-9](https://doi.org/10.1016/S0017-9310(02)00016-9)
- [13] Pham, A. H., Lee, C. Y., Seo, J. H., Chun, H. H., Kim, H. J., Yoon, H. S., Kim, J. H., Park, D. W., Park, R., 2010. Laminar flow past an oscillating circular cylinder in cross flow, *Journal of Marine Science and Technology*, 18(3), 361-368. <https://doi.org/10.51400/2709-6998.1881>
- [14] Guilmineau, E., Queutey, P., 2002. A numerical simulation of vortex shedding from an oscillating circular cylinder, *Journal of Fluids and Structure*, 16, 773-794. <https://doi.org/10.1006/jfls.2002.0449>
- [15] Nobari, M.R.H., Naderan, H., 2006. A numerical study of flow past a cylinder with cross flow and inline oscillation, *Computers & Fluids*, 35(4), 393-415. <https://doi.org/10.1016/j.compfluid.2005.02.004>
- [16] Krishnamoorthy, S., Price, S. J., Paidoussis, M., 2001. Cross-flow past an oscillating circular cylinder: Synchronization phenomena in the near wake, *Journal of Fluids and Structures*, 15(7), 955-980. <https://doi.org/10.1006/jfls.2001.0382>
- [17] Luo, X., Zhang, W., Dong, H., Thakur, A. K., 2021. Numerical analysis of heat transfer enhancement of fluid past an oscillating circular cylinder in laminar flow regime, *Progress in Nuclear Energy* 139, 103853. <https://doi.org/10.1016/j.pnucene.2021.103853>
- [18] Zhang, Y., Zhu, K., 2016. Flow over an inline oscillating circular cylinder in the wake of a stationary circular cylinder, *Fluid Dynamic Research*, 49(1), 015504. <https://doi.org/10.1088/0169-5983/49/1/015504>
- [19] Derouich, Y., Nasri, Z., Abide, S., Laatar, A. H., 2018. Inclination effects on heat transfer by an oscillating square cylinder in channel flow, *International Journal of Heat and Mass Transfer*, 125, 1105-1120. <https://doi.org/10.1016/j.ijheatmasstransfer.2018.04.103>
- [20] Sarout, Y., Islam, M., Fatt, Y., Janajreh, I., 2022. Flow around an Oscillating Cylinder at Low Reynolds Number with Forced Convection: Effect of Corner Radius and Reynolds Number, *Energies*, 15, 9145-9168. <https://doi.org/10.3390/en15239145>
- [21] Kumar, A., Ray, R. K., Mittal, H.V.R., 2022. Heat Transfer Past a Rotationally Oscillating Circular Cylinder in Linear Shear Flow, *Journal of Heat Transfer*, 144(7), 071802. <https://doi.org/10.1115/1.4054350>
- [22] Amini, Y., Zahed, I., Izadpanah, E., 2022. Heat transfer enhancement of a cylinder by flexible fins in turbulent flow, *Scientia Iranica*. <https://doi.org/10.24200/SCI.2022.59271.6147>
- [23] Holman, J. P., 2010. *Heat Transfer*, 10th edition, McGraw-Hill Education, USA.
- [24] Abolpour, B., Hekmatkhah, R., Shamsoddini, R., 2021. Multi-objective optimum design for double baffle heat exchangers, *Thermal Science and Engineering Progress*, 26. <https://doi.org/10.1016/j.tsep.2021.101132>
- [25] Berthelsen, P. A., Faltinsen, O. M., 2008. A local directional ghost cell approach for incompressible viscous flow problems with irregular boundaries, *Journal of Computational Physics*, 227(9), 4354-4397. <https://doi.org/10.1016/j.jcp.2007.12.022>
- [26] Franke, R., Rodi, W., Schonung, B., 1990. Numerical calculation of laminar vortex-shedding flow past cylinders, *Journal of Wind Engineering and Industrial Aerodynamics*, 35, 237-257. [https://doi.org/10.1016/0167-6105\(90\)90219-3](https://doi.org/10.1016/0167-6105(90)90219-3)
- [27] Mittal, S., Raghuvanshi, A., 2001. Control of vortex shedding behind circular cylinder for flows at low Reynolds numbers, *International Journal for Numerical Methods in Fluids*, 35(4), 421-447. [https://doi.org/10.1002/1097-0363\(20010228\)35:4<421::AID-FLD100>3.0.CO;2-M](https://doi.org/10.1002/1097-0363(20010228)35:4<421::AID-FLD100>3.0.CO;2-M)
- [28] Behr, M., Hastreiter, D., Mittal, S., Tezduyar, T. E., 1995. Incompressible flow past a circular cylinder: dependence of the computed flow field on the location of the lateral boundaries, *Computer Methods in Applied Mechanics and Engineering*, 123 (1), 309-316. [https://doi.org/10.1016/0045-7825\(94\)00736-7](https://doi.org/10.1016/0045-7825(94)00736-7)
- [29] Williamson, C.H., Brown, G. L., 1998. A series in $1/\sqrt{Re}$ to represent the Strouhal– Reynolds number relationship of the cylinder wake, *Journal of Fluids and Structures*, 12(8), 1073-1085. <https://doi.org/10.1006/jfls.1998.0184>