*Conference on Modelling Fluid Flow (CMFF'12)*
*The 15th International Conference on Fluid Flow Technologies*
*Budapest, Hungary, September 4-7, 2012*

# HEAT AND ENERGY TRANSFER FROM A CYLINDER PLACED IN AN OSCILLATORY LOW-REYNOLDS NUMBER FLOW

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## ABSTRACT

Heat transfer characteristics of a circular cylinder exposed to an oscillating flow are investigated numerically using the commercial software package Ansys Fluent based on the finite volume method (FVM). For in-line oscillation the influence of oscillation amplitude and temperature are analyzed at Reynolds number 120 and for frequency ratio 0.8 in the lock-in domain. For transverse motion the influence of temperature on force coefficients and heat transfer is investigated for *Re*=100, 120, 140, 160 and 180 and at four oscillation amplitude values at frequency ratio 0.8. Force coefficients, mechanical energy transfer and heat transfer are investigated for these cases.

**Keywords: heat transfer, heated cylinder, in-line oscillation, low Reynolds number, Nusselt number, transverse oscillation**

## NOMENCLATURE

| | | |
|---|---|---|
| $a_0$ | [-] | cylinder acceleration, nondimensionalised by $\tilde{U}_m{}^2/d$ |
| $A$ | [-] | amplitude of oscillation, nondimensionalised by $d$ |
| $C_D$ | [-] | drag coefficient |
| $C_L$ | [-] | lift coefficient |
| $d$ | [$m$] | cylinder diameter |
| $E$ | [-] | mechanical energy transfer |
| $f$ | [-] | oscillation frequency, nondimensionalised by $\tilde{U}_m / d$ |
| $f_v$ | [$1/s$] | vortex shedding frequency |
| $g$ | [$m/s^2$] | acceleration due to gravity |
| $h$ | [$W/(m^2K)$] | local convective heat transfer coefficient |
| $\underline{i}, \underline{j}$ | [-] | unit vectors in $x$ and $y$ directions |
| $k$ | [$W/(mK)$] | thermal conductivity of the fluid |
| $Nu$ | [-] | Nusselt number, $Nu=h\,d/k$ |
| $P$ | [-] | a period of a vortex shedding, $1/f$ |
| $\dot{q}$ | [$W/m^2$] | heat flux |
| $r$ | [-] | radius, nondimensionalised by $d$ |
| $Ri$ | [-] | Richardson number, $Ri = g\,\beta\,d\left(\tilde{T}_w - \tilde{T}_\infty\right)/\tilde{U}_m^2$ |
| $Re$ | [-] | Reynolds number, $Re=\tilde{U}_m\, d/\upsilon$ |
| $St$ | [-] | nondimensional vortex shedding frequency, $St=f_v\, d/\tilde{U}_m$ |
| $t$ | [-] | time, nondimensionalised by $d/\tilde{U}_m$ |
| $\tilde{T}$ | [$K$] | absolute temperature |
| $T$ | [-] | nondimensional temperature, $\left(\tilde{T} - \tilde{T}_\infty\right)/\left(\tilde{T}_w - \tilde{T}_\infty\right)$ |
| $T^*$ | [-] | temperature ratio, $T_w / T_\infty$ |
| $\tilde{U}_m$ | [$m/s$] | time-mean free stream velocity |
| $\underline{v}$ | [-] | free stream velocity vector, nondimensionalised by $\tilde{U}_m$ |
| $\beta$ | [$1/K$] | thermal expansion coefficient |
| $\upsilon$ | [$m^2/s$] | kinematic viscosity |

**Subscripts and Superscripts**

| | |
|---|---|
| *eff* | effective |
| *f* | film |
| *fb* | fixed body |
| *m* | time-mean for free stream velocity |
| *rms* | root-mean-square value |
| *x*, *y* | components in *x* and *y* directions |
| *w* | wall |
| 0 | for cylinder motion |
| $\infty$ | far from the cylinder |

## 1. INTRODUCTION

Flow around cylinders, always a topic of interest, becomes more complicated when oscillation is present, and when heating effects are involved. Such situations occur, for instance, with tube bundles of heat exchangers or hot wire anemometers.

Oscillation commonly occurs in elastically supported structures in wind or under water, especially oscillation transverse to the main stream. The flow past a circular cylinder oscillating transversely has been studied extensively, even at low Reynolds numbers. Williamson and Roshko [1] experimentally investigated the wake patterns behind an oscillating cylinder at low Reynolds numbers. Lu and Dalton [2] numerically simulated the flow over an oscillating cylinder at *Re*=185 to reproduce the experimental results of Gu et al. [3].

In-line oscillation has been studied experimentally and numerically. Low Reynolds number studies include [4], investigating a broad frequency ratio range numerically at *Re*=200, finding vortex switches. A low-Reynolds number numerical study identified vortex switches for in-line oscillation against oscillation amplitude Baranyi [5] and against frequency ratio ranging from 0.76 to 0.94 [6]. At some critical parameter values, flow pattern switched into a mirror image. An experimental study using in-line oscillatory low Reynolds flow reports on particle image velocimetry measurements obtained in the forced wake of a circular cylinder in a free stream flow with periodic velocity oscillations superimposed upon it [7]. This case is kinematically equivalent to that of a cylinder forced to oscillate in-line with a steady uniform flow.

Another numerical study for in-line cylinder motion at *Re*=200 and frequency ratio 1 is Mureithi et al. [8]. A low order discrete model was developed based on symmetry-equivariance theory. The resulting simple model was found to capture the observed wake dynamics, predicting the sequence of bifurcations found in numerical computations.

For flows over a heated cylinder the fluid properties vary with temperature. This has a significant effect on flow characteristics, especially for the in-line and transverse cylinder motion. Karanth et al. [9] numerically investigated the effects of in-line and of transverse oscillation of the cylinder for *Re*=200 and concluded that the heat transfer rate from the oscillating cylinder increased with increasing of velocity amplitude for both motions. Cheng et al. [10] adopted the same numerical method to study the effect of transverse oscillation on flow patterns and on heat transfer from a cylinder. Their results indicated that the heat transfer increased remarkably as the flow approached the lock-in regime.

The main purpose of the present study is to investigate the effect of cylinder temperature and oscillation amplitude on the heat transfer and mechanical energy transfer *E* between the fluid and the cylinder at the frequency ratio of 0.8 in the lock-in domain. To the best knowledge of the authors the mechanical energy transfer has been investigated for unheated cylinders only [11]. In this study the mechanical energy transfer is also investigated for a heated cylinder for in-line and transverse motions.

For in-line flow oscillation the influence of oscillation amplitude on heat transfer is analysed for a single Reynolds number. Karanth et al. [9] also investigated heat transfer (Nusselt number), but at only the three oscillation amplitude values of 0, 0.25 and 0.5 for in-line motion, while we investigated over 80 oscillation amplitude values at two temperature ratios. For transverse oscillation the force coefficients, *E* and Nusselt number *Nu* versus Reynolds number are investigated at four oscillation amplitudes and five *Re* values.

## 2. NUMERICAL METHOD

The main set of simulations was carried out using Ansys Fluent commercial software based on the finite volume method (FVM). The two-dimensional (2D), unsteady, laminar, segregated solver is used to solve the incompressible oscillatory flow for the collocated grid arrangement. The second order upwind scheme was used to discretise the convective terms in the momentum equations. The semi-implicit method for the pressure linked equations (SIMPLE) scheme is applied for solving the pressure-velocity coupling.

The physical domain is illustrated in Figure 1. The inner circle represents the cylinder surface with diameter *d*, the outer circle the far field with diameter $d_\infty$. The origin of the Cartesian coordinates *x*, *y* is located in the centre of the cylinder and the positive *x*-axis is directed downstream. The accuracy of the computed results depends on the computational mesh, the time step, the size and shape of the computational domain. For uniform flow past an unheated stationary circular cylinder the effect of domain size, mesh, and time step was investigated to determine a combination at which the solution is roughly parameter independent [12]. In [13] computational results are compared with those of several studies, finding very good agreement.

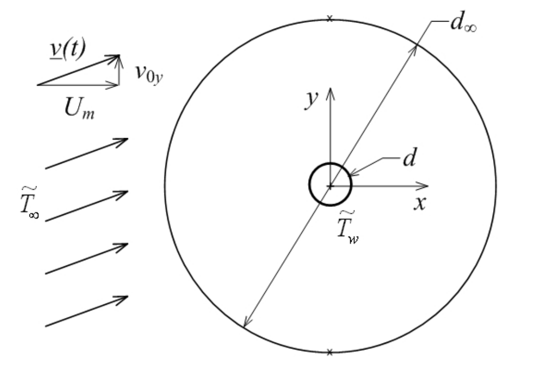


**Figure 1. Computational domain**

In this study the computational domain is characterised by $d_\infty/d$=180 with mesh points of 361x298 (peripheral x radial), respectively. In the physical domain logarithmically spaced radial cells are used, providing a fine grid scale near the cylinder wall and a coarse grid in the far field. A dimensionless time step of $\Delta t$=0.001 is used.

Flow past a cylinder oscillating in-line with a uniform free stream is modelled by a stationary cylinder combined with an unsteady free stream obtained by the superposition of a uniform flow and an oscillatory flow in in-line direction:

$$\underline{v}(t) = U_m \underline{i} - u_{0x} \underline{i} = U_m \underline{i} + 2\pi f A_x \sin(2\pi f t) \underline{i}. \qquad (1)$$

To model the transverse motion, the time-dependent free stream velocity vector can be written as

$$\underline{v}(t) = U_m \underline{i} + v_{0y} \underline{j} = U_m \underline{i} - 2\pi f A_y \cos(2\pi f t) \underline{j}. \qquad (2)$$

In Eqs. (1) and (2) everything is nondimensional; $t$ and $f$ are the time and oscillation frequency, $U_m$ is unity, $u_{0x}$ and $v_{0y}$ are the time dependent fluctuating velocities in in-line and transverse directions, respectively. $A_x$ and $A_y$ are the oscillation amplitudes for in-line and transverse motion, and $\underline{i}$, $\underline{j}$ are the unit vectors in $x$,$y$ directions, respectively. In Fig. 1 velocity vectors are shown for the transverse oscillatory flow.

The nondimensional frequency of oscillation $f$ was set at 0.8 $St_0$, where $St_0$ is the nondimensional vortex shedding frequency, or Strouhal number, for a stationary cylinder at that Reynolds number. This frequency ratio value ensures that lock-in condition (vortex shedding frequency equal to that of the cylinder oscillation $f$) is reached at moderate amplitude values. In this study only locked-in cases were considered. Only one frequency ratio is investigated, due to the computational time needed.

The fluid is air, assumed to be incompressible. Both the absolute ambient temperature $\widetilde{T}_\infty$ and cylinder wall absolute temperature $\widetilde{T}_w$ are assumed to be constant. The temperature ratio $T^*$, which can also be interpreted as a nondimensional wall temperature, is defined as

$$T^* = \widetilde{T}_w / \widetilde{T}_\infty . \qquad (3)$$

Four temperature ratios of 0.9, 1.0, 1.1 and 1.5 are investigated. For flows over a heated cylinder the fluid properties such as viscosity, density and thermal conductivity vary with temperature. The dependence of the viscosity on temperature is given by Sutherland's formula [14] and further fluid properties are obtained from [15]. Since the maximal Richardson number $Ri$ was 0.35 for the investigated cases, free convection was neglected, as is standard for $Ri < 0.5$ [16].

For the unheated cases ($T^*$=1.0) the FVM results are compared with the data of the second author, who used his 2D in-house code based on the finite difference method (FDM). For FDM a non-inertial system fixed to the cylinder is used to compute the 2D low-Reynolds number unsteady flow around a circular cylinder placed in a uniform stream and forced to oscillate in in-line or transverse directions. The governing equations are the nondimensional Navier-Stokes equations for incompressible constant-property Newtonian fluid, the equation of continuity and the Poisson equation for pressure. On the cylinder surface, no-slip boundary condition is used for the velocity and a Neumann type boundary condition is used for the pressure. Potential flow is assumed in the far field. The code is thoroughly tested against experimental and computational results in Baranyi [17].

The FDM code is for a mechanically-oscillated cylinder placed in a uniform stream, while the present FVM simulation is for oscillatory flow around a stationary cylinder. When viewed from a system fixed to the cylinder, these two cases are kinematically identical and can thus be compared.

The shape of the computational domain for the FDM simulation is the same as for the FVM, but the domain size is different: for FDM the domain for in-line motion is $d_\infty/d$=360, while for transverse motion it is $d_\infty/d$=160.

Flow and heat transfer features are of interest in this study. Time-mean (TM) and root-mean-square (rms) values of lift $C_L$, drag $C_D$ coefficients were evaluated and plotted against the oscillation amplitude or Reynolds number. The lift and drag coefficients shown in this study do not contain inertial forces originating from the system fixed to the accelerating cylinder. Coefficients without inertial forces are often termed 'fixed body' coefficients [2]. The relationship between the two sets of coefficients can be written as

$$C_L = C_{Lfb} + \frac{\pi}{2} a_{0y}, \; C_D = C_{Dfb} + \frac{\pi}{2} a_{0x}, \qquad (4)$$

where subscript $fb$ refers to the fixed body (understood in an inertial system fixed to the stationary cylinder) Baranyi [18]. Here $a_{0x}$ and $a_{0y}$ are the dimensionless $x$ and $y$ components of cylinder acceleration. Since these accelerations are periodic their time-mean values vanish, resulting in identical TM values for the two setups. Equation (4) shows that for in-line motion the two lift coefficients are identical, and the drag coefficients are different from each other. For transverse cylinder motion it is exactly the other way round.

The mechanical energy transfer between the fluid and the cylinder for transverse motions was defined in [11] and was extended for two-degree-of-freedom cylinder motion by [17]. The total energy transfer $E$ can be divided into two parts,

$$E = E_1 + E_2 , \qquad (5)$$

where $E_1$ and $E_2$ are the energy transfer coefficients originating from transverse and in-line motion;

$$E_1 = \int_0^P C_L(t)\,\dot{y}_0(t)\,dt,\; E_2 = \int_0^P C_D(t)\,\dot{x}_0(t)\,dt, \qquad (6)$$

where $P$ is the motion period and $x_0$ and $y_0$ are the dimensionless cylinder displacement in $x$ and $y$ directions, respectively, and the over dot means differentiation by time. As can be seen in Eq. (6), for in-line cylinder motion $E_1$ is zero, so $E=E_2$; for transverse motion $E_2$ is zero, so $E=E_1$.

The heat transfer between the cylinder and the surrounding fluid is determined using the dimensionless, or local Nusselt number, obtained from (see e.g., [19])

$$Nu = \frac{h\,d}{k} = -\left(\frac{\partial T}{\partial r}\right)_{wall}, \qquad (7)$$

where $k$ is the thermal conductivity of the fluid, $r$ is the dimensionless radius. Here $T$ is the dimensionless temperature defined by $\left(\widetilde{T}-\widetilde{T}_\infty\right)/\left(\widetilde{T}_w-\widetilde{T}_\infty\right)$, where $\widetilde{T}$ is the temperature of the fluid in an arbitrary point measured in K, and $h$ is the local convective heat transfer coefficient

$$h = \frac{\dot{q}}{\widetilde{T}_w - \widetilde{T}_\infty}, \qquad (8)$$

where $\dot{q}$ is the heat flux from the cylinder wall to the fluid.

In the present work fluid properties are not constant for heated cylinders so the thermal conductivity of the fluid $k$ also depends on the temperature, which influences the Nusselt number value. The physical properties of the working fluids are evaluated at the free stream temperature $\widetilde{T}_\infty$ or the film temperature $\widetilde{T}_f$, which can be defined as the arithmetic mean of the cylinder wall temperature and the free-stream temperature [20]. Some studies have indicated that the vortex shedding in an air flow can be reduced or even completely suppressed by increasing the cylinder temperature [21, 22]. The temperature variation leads to changes in the kinematic viscosity of fluid, so the local Reynolds number varies in the near field of the heated cylinder. This phenomenon leads to the development of the effective temperature concept, which models the varying kinematic viscosity in the non-isothermal wake behind a heated circular cylinder by defining an effective temperature

$$\widetilde{T}_{eff} = \widetilde{T}_\infty + c\left(\widetilde{T}_w - \widetilde{T}_\infty\right), \qquad (9)$$

where $c$ is a constant. This concept was first introduced by Lecordier et al. [21] and later refined by Wang and Travnicek [16], who successfully correlated their experimental data for Nusselt number and suggested $c$=0.36. In the present work we use the Nusselt number $Nu_{eff}$=$Nu(\widetilde{T}_{eff})$ based on the effective temperature $\widetilde{T}_{eff}$, where $c$ = 0.36.

## 3. RESULTS

In the present study, computations were carried out for in-line and transverse oscillatory flows at a frequency ratio of $f/St_0$=0.8 in the lock-in domain. This frequency ratio value ensures that lock-in condition is reached at moderate amplitude values. This keeps amplitudes well within the range of reliability of the computational procedure. In addition, it appears that in practice the frequency ratio of oscillating bodies is in the vicinity of unity [11, 23]. For both motions the rms and TM of force coefficients, Nusselt number and the mechanical energy transfer between the fluid and the cylinder are analysed.

### 3.1 In-line Oscillation

For in-line motion the computations are performed at $Re$=120 and at two temperature ratios of $T^*$=1.0 and 1.5 with amplitude of oscillation as the independent variable.

Figure 2 shows the time-mean (TM) of lift (and the identical fixed body lift) against the oscillation amplitude for two temperature ratios. For the unheated case ($T^*$=1.0) the results obtained by FVM and FDM are in good agreement. The solution jumps between two states, as was found earlier by [5]. The state curves compare well for the two methods but the location and number of jumps are different. This is not surprising, since the system boundary separating the basins of the two attractors of this nonlinear system can be very complex, and a tiny change in the parameters can trigger a switch to the other attractor of the system [17]. As can also be seen in the figure, the two state curves are mirror images of each other, as was found earlier in [5]. State curves for the heated ($T^*$=1.5) and unheated ($T^*$=1.0) cases are nearly identical. It can also be seen that for increasing temperature ratio the lower boundary of the locked-in domain shifts towards smaller amplitude values. The lock-in domain begins at $A_y$=0.35 for the unheated case and at $A_y$=0.305 for $T^*$=1.5.

The rms of drag coefficient is shown in Figure 3 for $T^*$=1.0 and 1.5 at $Re$=120. The two methods compare well. It can be seen that the rms values increase with both amplitude and temperature ratio.

The mechanical energy transfer $E$ between the fluid and the body was also investigated for in-line flow oscillation. Figure 4 shows $E=E_2$ against oscillation amplitude $A_x$ at $Re$=120 for $T^*$=1.0 and 1.5. The values of $E$ were found to be negative in the entire lock-in domain investigated. This means that the fluid acts against the cylinder motion, with a dampening effect. The absolute value of $E$

increases with amplitude but decreases with temperature ratio. The agreement between FDM and FVM results is very good.

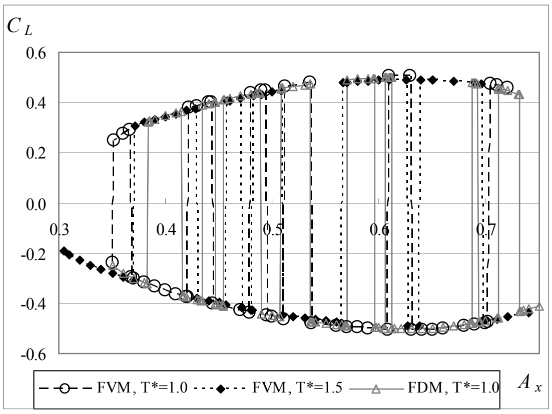


**Figure 2. Time-mean of lift versus in-line oscillation amplitude for two temperature ratios**

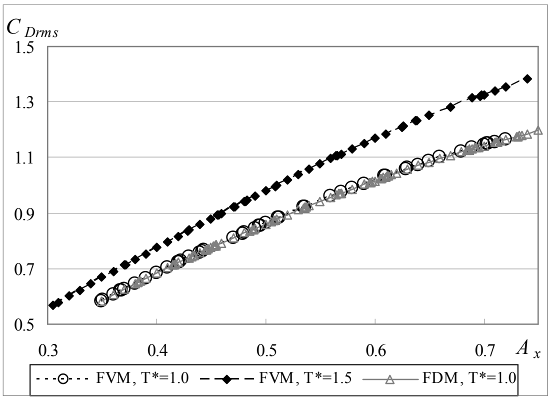


**Figure 3. The rms of lift versus in-line oscillation amplitude**

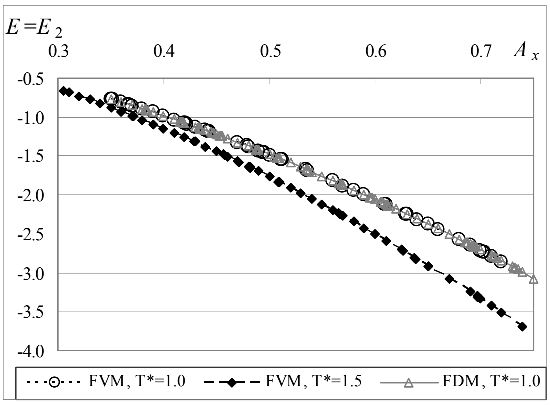


**Figure 4. Mechanical energy transfer versus in-line oscillation amplitude**

The heat transfer between the cylinder and the surrounding fluid is calculated using the effective Nusselt number $Nu_{eff}$ based on the effective temperature (see Eq. (9)). In a previous study [24] the uniform flow past a heated stationary cylinder ($A_x$=$A_y$=0) was investigated and $Nu_{eff}$ agreed well with the experimental data of [16, 22] for different Reynolds numbers.

Figure 5 shows $Nu_{eff}$ versus oscillation amplitude at $T$*=1.0 and 1.5 for in-line oscillation. It was earlier found that for a heated stationary cylinder $Nu_{eff}$ increases with $Re$ and decreases with $T$* [24]; here, for in-line motion, a similar tendency was found at given amplitude values for $Nu_{eff}$. As can be seen in Fig. 5, $Nu_{eff}$ first increases with increasing oscillation amplitude, reaches a maximum value at around $A_x$=0.55, and then decreases slightly, indicating that higher amplitude values may suppress the temperature effects. This seemingly contradicts the claim of Karanth et al. that $Nu_{eff}$ increases with increasing velocity amplitude [9]. However, in their study of the flow past and heat transfer from a cylinder oscillated in in-line direction at $Re$=200 they investigated only the three oscillation amplitude values of $A_x$=0, 0.25 and 0.5, which fall into the rising range.

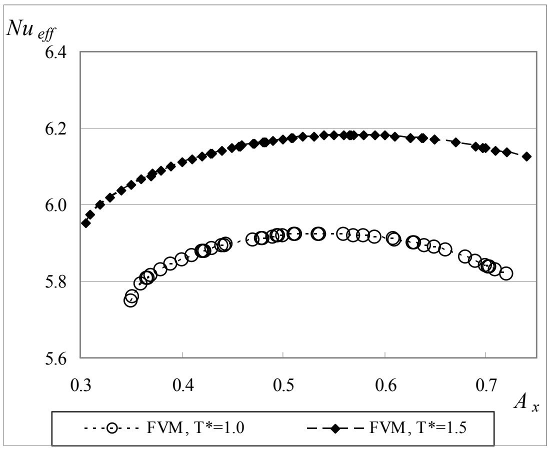


**Figure 5. $Nu_{eff}$ versus in-line oscillation amplitude at $T$*=1.0 and 1.5**

## 3.2 Transverse Oscillation

Here we compare results for an unheated ($T$*=1.0) cylinder, a cooled cylinder ($T$*=0.9), and a heated cylinder ($T$*=1.1 and 1.5). The Reynolds numbers of $Re$=100, 120, 140, 160 and 180 are investigated at four oscillation amplitude values.

### 3.2.1. Unheated case

Results at $T$*=1.0 are given in Figure 6 for the TM of drag obtained by FVM and FDM, while the rms of fixed body lift coefficient is shown in Figure 7. No jumps were found in any curves, similarly to earlier results for a stationary unheated cylinder [5].

The TM of drag (Fig. 6) decreases with increasing $Re$, but for a given $Re$, $C_D$ increases with increasing oscillation amplitude. The rms of lift (Fig. 7) increases with increasing oscillation amplitude for a given $Re$ and it increases as well with increasing *Re* for a given amplitude. The two CFD methods yield practically the same results.

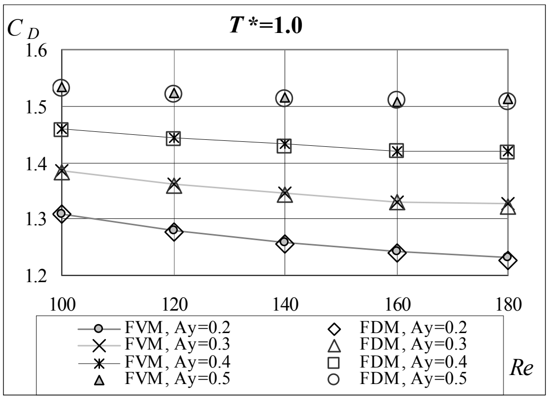


**Figure 6. Time-mean of drag versus *Re* at four transverse oscillation amplitudes, *T**=1.0**

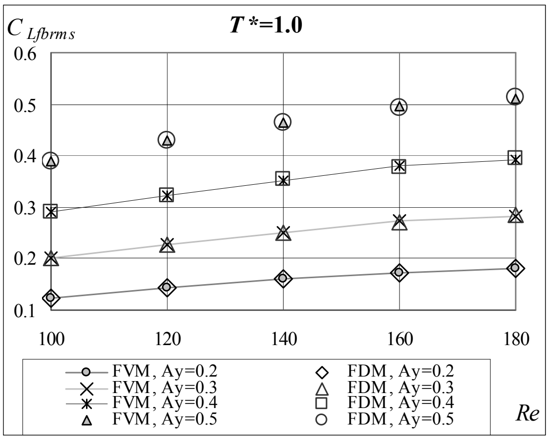


**Figure 7. $C_{Lfbrms}$ versus *Re* at four transverse oscillation amplitudes, *T**=1.0**

Figure 8 shows the mechanical energy transfer ($E$=$E_1$) versus *Re* at different amplitudes for both methods. When the oscillation amplitude is held constant, the value of *E* increases with *Re*. The two methods yield good agreement.

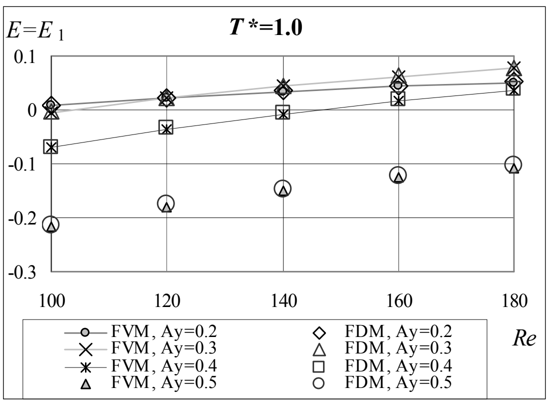


**Figure 8. Mechanical energy transfer versus *Re* at four transverse oscillation amplitudes, *T**=1.0**

We can see that the *E* for $A_y$=0.5 is always negative in the lock-in domain, for $A_y$=0.2 *E* is always positive, and the other two curves change from negative to positive *E* with increasing *Re*. Positive *E* values mean that energy is added to the cylinder from the fluid, and so flow-induced vibration is liable to occur in the free vibration case. Negative *E* values, on the other hand, tend to dampen vibration [17].

### 3.2.2. Heated or cooled cylinder

Although four oscillation amplitudes were investigated, here we present results for only one value, $A_y$=0.2. Similar trends to the results shown here were found for the other $A_y$ values.

Figure 9 shows the TM of drag against Reynolds number for different temperature ratios. As can be seen in the figure, the drag increases with increasing temperature ratio and decreases with increasing *Re*, similarly to the uniform flow around a stationary heated cylinder [24].

The rms of the fixed body lift coefficient $C_{Lfbrms}$ is shown in Figure 10. Rms increases fairly steadily with increasing *Re.* At a given Reynolds number, $C_{Lfbrms}$ decreases with increasing temperature ratio.

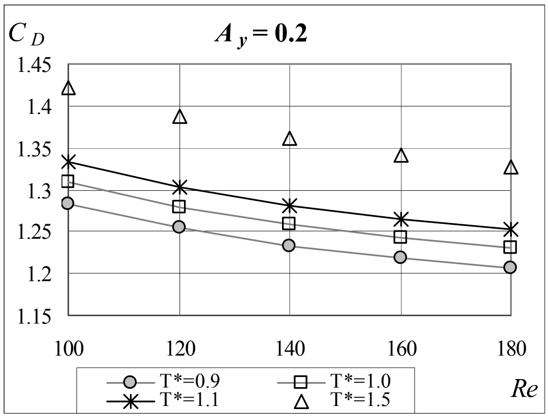


**Figure 9. Time-mean of drag versus *Re* at four temperature ratios, $A_y$=0.2**

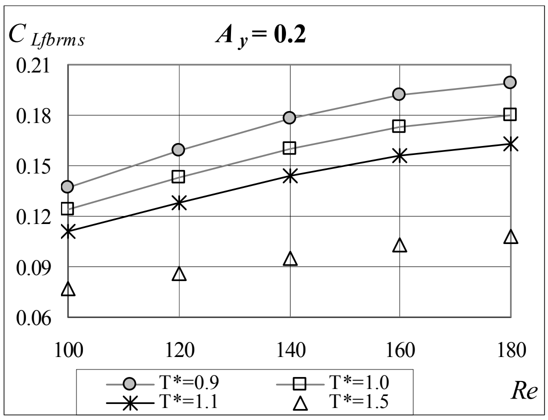


**Figure 10. The rms of lift versus *Re* at four temperature ratios, $A_y$=0.2**

Figure 11 shows the mechanical energy transfer ($E$=$E_1$) versus *Re* at different temperature ratios *T** for $A_y$=0.2. It can be seen in the figure that *E* decreases with increasing *T** for a given *Re*, and is primarily positive in the lock-in domain.

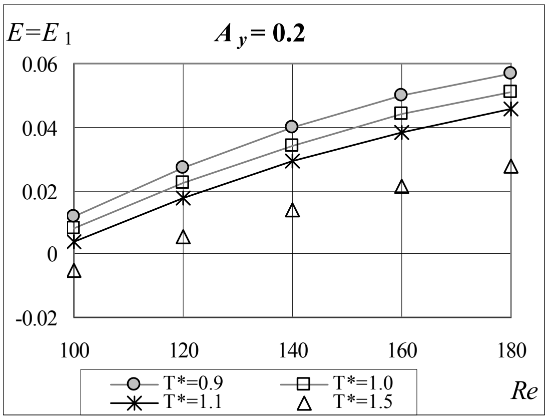


**Figure 11. Mechanical energy transfer versus *Re* at four temperature ratios, $A_y$=0.2**

For transverse motion the heat transfer is also investigated. Figure 12 shows the effective Nusselt number versus Reynolds number for different amplitudes for *T**=1.0. Although it was found for in-line motion that the curve of $Nu_{eff}$ is not linear (see Fig. 5), for transverse motion $Nu_{eff}$ increases linearly with oscillation amplitude, similarly to the results of [9]. When the oscillation amplitude is held constant, the value of $Nu_{eff}$ increases linearly with *Re*. As *Re* is increased, the distance between the $Nu_{eff}$ curves belonging to different oscillation amplitudes increases slightly.

The effect of temperature ratio on the effective Nusselt number is shown for different amplitude values and different Reynolds numbers in Figure 13. When the oscillation amplitude is held constant $Nu_{eff}$ values increase linearly with Reynolds number. Increasing the temperature lowers $Nu_{eff}$.

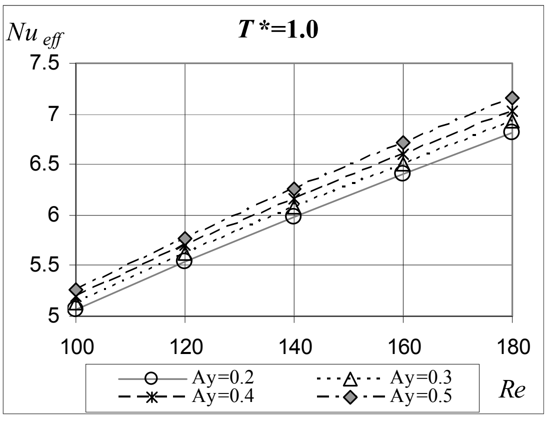


**Figure 12. $Nu_{eff}$ versus *Re* at four transverse oscillation amplitudes, *T**=1.0**

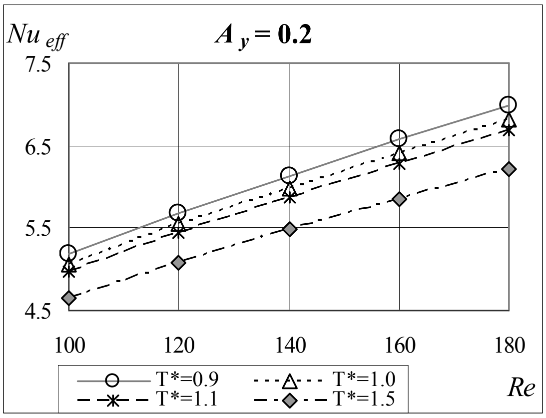


**Figure 13. $Nu_{eff}$ versus *Re* at different *T**, $A_y$=0.2**

## 4. SUMMARY

The present work numerically investigated the effect of temperature ratio (wall temperature over ambient temperature), amplitude of oscillation, and Reynolds number on heat transfer, mechanical energy transfer and force coefficients from a heated circular cylinder placed in oscillating flow in in-line or in transverse direction. For the unheated case the computational results obtained by the finite volume method (Ansys Fluent) are compared with those of a finite difference method, finding good agreement.

For in-line oscillation practically the same state curves are found for unheated and heated cases, but curves of larger temperature ratio shift the lock-in domain to smaller amplitude values.

For a given amplitude value the effective Nusselt number $Nu_{\mathrm{eff}}$ decreases with increasing temperature ratio for in-line and transverse oscillation, while with increasing oscillation amplitude for in-line motion $Nu_{\mathrm{eff}}$ first increases, reaches a maximum value and then decreases slightly, indicating that higher amplitude values may suppress the temperature effects. For transverse oscillation $Nu_{\mathrm{eff}}$ increases linearly with amplitude and with Reynolds number.

The mechanical energy transfer *E* for in-line motion results is always negative (flow acts against cylinder motion), while for transverse motion both positive (enhancing cylinder motion) and negative values occur. With increasing temperature the value of *E* decreases for in-line oscillation. For transverse motion the energy transfer increases with Reynolds number for a given amplitude.

A possible further step in the research is the further investigation of the combined effect of oscillation amplitude and surface temperature for a heated cylinder oscillating in-line.

## ACKNOWLEDGEMENTS


This study has been supported by the Hungarian National Fund for Science and Research under Project No. OTKA K 76085. The work was carried out as part of the TÁMOP-4.2.1.B-

10/2/KONV-2010-0001 project in the framework of the New Hungarian Development Plan. The realization of this project is supported by the European Union, co-financed by the European Social Fund.

## REFERENCES

[1] Williamson, C.H.K., and Roshko, A., 1988, "Vortex formation in the wake of an oscillating cylinder", *Journal of Fluids and Structures*, Vol. 2, pp. 355-381.

[2] Lu, X.Y., and Dalton, C., 1996, "Calculation of the timing of vortex formation from an oscillating cylinder", *Journal of Fluids and Structures*, Vol**.** 10, pp. 527-541.

[3] Gu, W., Chyu, C., and Rockwell, D., 1994, "Timing of vortex formation from an oscillating cylinder", *Physics of Fluids*, Vol. 6, pp. 3677-3682.

[4] Al-Mdallal, Q.M., Lawrence, K.P., and Kocabiyik, S., 2007, "Forced streamwise oscillations of a circular cylinder: Locked-on modes and resulting fluid forces", *Journal of Fluids and Structures,* Vol. 23, pp. 681-701.

[5] Baranyi, L., 2009, "Sudden and gradual alteration of amplitude during the computation for flow around a cylinder oscillating in transverse or in-line direction", *ASME 2009 Pressure Vessels and Piping Conference*, *Symposium on Flow-Induced Vibration*. Prague, Paper No. PVP2009-77463.

[6] Baranyi, L., 2008, "Effect of frequency ratio on the force coefficients of a cylinder oscillated in a uniform stream", Proc. *7th JSME-KSME Thermal and Fluids Engineering Conference*, Sapporo, Japan, Paper No. L132.

[7] Konstantinidis, E., Balabani, S., and Yianneskis, M., 2005, "The timing of vortex shedding in a cylinder wake imposed by periodic inflow perturbations", *Journal of Fluid Mechanics*, Vol. 543, pp. 45-55.

[8] Mureithi, N.W., Huynh, K., and Pham, A., 2009, "Low order model dynamics of the forced cylinder wake", *ASME 2009 Pressure Vessels and Piping Conference*, *Symposium on Flow-Induced Vibration*. Prague, Paper No. PVP2009-78093

[9] Karanth, D., Rankin, G.W., and Sridhar, K., 1994, "A finite difference calculation of forced convective heat transfer from an oscillating cylinder", *International Journal of Heat and Mass Transfer*, Vol. 37, pp. 1619-1630.

[10] Cheng, W.H., Hong, J.L., and 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*, Vol. 40, pp.1825-1834.

[11] Blackburn, H.M., and Henderson, R.D., 1999, "A study of two-dimensional flow past an oscillating cylinder", *Journal of Fluid Mechanics*, Vol. 385, pp. 255-286.

[12] Bolló, B., 2010, "Grid independence study for flow around a stationary circular cylinder", Proc. *microCAD 2010, International Computer Science Conference*, Miskolc, Hungary, Section F, pp. 1-6.

[13] Bolló, B., and Baranyi, L., 2010, "Computation of low-Reynolds number flow around a stationary circular cylinder", Proc. *7th International Conference on Mechanical Engineering*, Budapest, pp. 891-896.

[14] White, F.M., 1999, *Fluid Mechanics*. 4th ed., McGraw-Hill.

[15] *VDI-Wärmeatlas*, 2002, 9th ed., Springer Verlag.

[16] Wang, A.B., and Trávníček, Z., 2001, "On the linear heat transfer correlation of a heated circular cylinder in laminar crossflow using a new representative temperature concept", *International Journal of Heat and Mass Transfer*, Vol. 44, pp. 4635-4647.

[17] Baranyi, L., 2008, "Numerical simulation of flow around an orbiting cylinder at different ellipticity values", *Journal of Fluids and Structures*, Vol. 24, pp. 883-906.

[18] Baranyi, L., 2005, "Lift and drag evaluation in translating and rotating non-inertial systems", *Journal of Fluids and Structures*, Vol. 20, pp. 25-34.

[19] Baranyi, L., 2003, "Computation of unsteady momentum and heat transfer from a fixed circular cylinder in laminar flow", *Journal of Computational and Applied Mechanics*, Vol. 4, pp. 13-25.

[20] Özisik, M.N., 1985. *Heat Transfer.* McGraw-Hill.

[21] Lecordier, J.C, Hamma, L., and Paranthoën, P., 1991, "The control of vortex shedding behind heated circular cylinder at low Reynolds numbers", *Experiments in Fluids*, Vol. 10, pp. 224-229.

[22] Wang, A.B., Trávníček, Z., and Chia, K.C., 2000, "On the relationship of effective Reynolds number and Strouhal number for the laminar vortex shedding of a heated circular cylinder", *Physics of Fluids*, Vol. 12, pp. 1401-1410.

[23] Kaiktsis, L., Triantafyllou, G.S., and Özbas, M., 2007, "Excitation, inertia, and drag forces on a cylinder vibrating transversely to a steady flow", *Journal of Fluids and Structures*, Vol. 23, pp. 1-21.

[24] Bolló, B., 2010, "Low Reynolds number flow around and heat transfer from a heated circular cylinder", *International Review of Applied Sciences and Engineering*, Vol. 1, pp. 15-20.