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Hydrodynamics and heat transfer of pulsating flow around a cylinder

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ABSTRACT

Vortex shedding and heat transfer around a cylinder in pulsating cross-flow have been studied experimentally. Analysis of flow visualization results enabled to classify flow patterns around the cylinder into four groups. New dimensionless number has been submitted, which is a ratio of the inertial force due to the oncoming flow acceleration in its global unsteady motion to the centrifugal inertial force due to curved streamlines around the cylinder. A map of flow patterns around the cylinder has been plotted in terms of the newly submitted dimensionless number and the relative amplitude of oncoming flow pulsations. Distributions of the local heat transfer coefficient over the cylinder surface depending on the flow pattern and the amplitude of forced flow pulsations have been obtained. It has been shown that forced pulsations of oncoming flow can enhance average heat transfer from the cylinder in the cross-flow.

1. Introduction

A circular cylinder in a cross-flow is not only a classical problem to consider when studying hydrodynamics and heat transfer in separated flows but also a flow configuration typically observed in engineering applications such as heat exchangers and power plants, nuclear reactors and measurement equipment.

Momentum and heat transfer in a cross-flow past a circular cylinder have been thoroughly studied [1–5], etc. Evolution of boundary layer separation on the cylinder surface in a wide range of Reynolds numbers has been described in detail by Chang [3]; the effects of free-stream turbulence intensity and blockage ratio on pressure distribution, heat transfer distribution along the cylinder surface, cylinder drag and average heat transfer have been examined in [4–8], etc. Characteristic patterns of vortex street and near-wake field downstream of the cylinder under such conditions have been established ([3,8–10], etc.). A whole range of empirical correlations are available, in which the average Nusselt number for the case of a cylinder in a cross-flow is expressed as a function of governing dimensionless numbers: Reynolds number (*Re*), Prandtl number (*Pr*), Grashof number (*Gr*) (accounting for natural convection), Schmidt number (*Sc*) (in case of mass transfer) ([11–16], etc.). Exponents of dimensionless numbers in these correlations depend on their variation range. Some authors state that these variations are associated with different flow patterns of the cylinder wake. Thus, Nakamura and Igarashi [16] showed that the exponent of Reynolds number varies depending on the cylinder flow pattern: laminar shedding, wake transition, or shear-layer transition. This exponent is lower for wake transition regime. Nakamura et al. explained this effect by nonmonotonic variation of the length of vortex shedding region past the cylinder in the considered Reynolds number range ($Re_d = 70 - 20{,}000$). Sanitjai and Goldstein [15] established that different exponents of the Reynolds number and Prandtl number correspond to three different regions of cylinder flow: laminar boundary layer, reattachment of the shear layer and periodic vortex flow region. They obtained data for the Reynolds number range $Re_d = 2 \times 10^3 \ldots 9 \times 10^4$ and Prandtl numbers from 0.7 to 176.

Hydrodynamics and heat transfer for the case of unsteady cross-flow around the cylinder have been studied far less. Some specific patterns of vortex shedding from the cylinder surface moving with acceleration or deceleration have been obtained using flow visualization [3,10,17,18]. Additionally, Ichikawa et al. [18] have established the correlation between the acceleration and drag of the cylinder.

However, the most complicated type of unsteadiness is pulsating oncoming flow with the velocity that complies with near harmonic law. In this case, when analyzing the flow-body interaction, at least two more dimensionless numbers should be considered: dimensionless frequency (Strouhal number) and relative amplitude, β.

Large number of papers on a cylinder in pulsating cross-flow deals with the lock-on effect (i.e. synchronization of vortex

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Nomenclature

A_t	amplitude of cylinder surface temperature oscillations
A_U	amplitude of flow velocity pulsations (m/s), $A_U = (u_{max} - u_{min})/2$
Bi	Biot number, $Bi = \alpha\delta/\lambda_w$
c	specific heat of the cylinder wall (J/kg K)
c_p	heat capacity of the fluid at constant pressure (J/kg K)
d	cylinder diameter (m)
f	frequency of forced flow pulsations (Hz)
f_{ac}	fundamental frequency of natural acoustic oscillations in the test section (Hz)
f_s	vortex shedding frequency in the forced flow
f_{s0}	vortex shedding frequency in the steady flow (Strouhal frequency)
Fr	Fressling number, $Fr = Nu/Re_d^{0.5}$
Fr_{st}	Fressling number in the steady oncoming flow
H	height of the channel (m)
Nu	Nusselt number, $Nu = \alpha\, d/\lambda$
Pr	Prandtl number, $Pr = \mu\, c_p/\lambda$
Re^+	pulsatory Reynolds number, $Re^+ = A_U\, d/\nu$
Re_d	Reynolds number, $Re_d = \langle U\rangle\, d/\nu$
S	area of the heat-release surface of the cylinder (m^2)
St	Strouhal number, $St = f\, d/\langle U\rangle$
t	temperature (°C)
t_0	the initial temperature of the cylinder wall that corresponds to the beginning of linear section of $\ln\theta(\tau)$ curve
t_f	temperature of the flow (°C)
u	instantaneous flow velocity (m/s)
$\langle U\rangle$	mean flow velocity (m/s)
u_{max}, u_{min}	peak flow velocity and minimum flow velocity averaged over multiple pulsation periods, respectively (m/s)
W	volume of the cylinder wall (m^3)

Greek symbols

α	heat transfer coefficient of the cylinder surface, α = W/m^2 K
β	relative amplitude of velocity pulsations, $\beta = A_U/\langle U\rangle$
δ	thickness of the cylinder wall (mm)
$\varepsilon = A_u/(2\pi f d)$	non-dimensional amplitude of forced velocity pulsations
θ	$\frac{t-t_f}{t_0-t_f}$
λ	thermal conductivity of the fluid (W/m K)
λ_w	thermal conductivity of the cylinder wall (W/m K)
μ	dynamic viscosity of the fluid (Pa s)
ν	kinematic viscosity (m^2/s)
π	mathematical constant, $\pi = 3.14$
ρ	density of the cylinder wall (kg/m^3)
σ_U	r.m.s. flow velocity fluctuations (m/s)
τ	time (s)
φ	angular coordinate counted from the stagnation point of the cylinder (°)

Subscripts

0	initial time
f	environment
w	cylinder wall

shedding frequency with the forced pulsations frequency). The first results have been probably obtained by Ferguson and Parkinson [19] for the case of self-induced oscillations of lightly damped cylinders. Jones et al. [20] and Barbi et al. [21,22] studied the lock-on phenomenon comparing visualization with measurements of velocity in the cylinder wake, measurements of skin friction and pressure distribution on the cylinder surface in pulsating oncoming flow. Air and water flows were studied, and results were mainly obtained for the Reynolds number based on the average flow velocity and the cylinder diameter Re_d = 35,000 and 40,000 (air) and Re_d = 3000 (water). Three vortex patterns in the cylinder wake were revealed depending on the frequency of forced pulsations. The first pattern was a regular Karman street (steady oncoming flow), which was observed when forced pulsation frequencies, f, were significantly less than Strouhal frequency, f_{s0}. The second pattern was typical of $f/f_{s0} = 1$ and was characterized by shedding of symmetric vortex pairs (twin vortices). The third pattern could be described as follows: one vortex was formed downstream of the cylinder, then it merged with another (counter rotating) vortex, which would form in steady conditions; then the newly formed powerful vortex was shed to the oncoming flow. According to Barbi et al. [22], the third pattern corresponds to the lock-on phenomenon, when vortex shedding is synchronized with the frequency of forced pulsations. It starts from $f/f_{s0} > 1$, which corresponds to $f_s/f = 0.5$. The shedding frequency is then equal to the subharmonic of the forced pulsations frequency and grows with the latter. Authors [22] observed the lock-on phenomenon up to $f/f_s \approx 1.8$ but believe it could occur up to $f/f_s = 4$. However, recent results [23] showed that vortex formation process of "secondary" lock-on ($f/f_s = 4$) differs from the one within fundamental lock-on range ($f/f_s \approx 1.8$). When "secondary" lock-on occurs, there are two possible vortex shedding patterns during one period of free-stream pulsations: a pair of symmetric vortices merging further downstream and forming two asymmetric vortices or two asymmetric vortices retaining their integrity and forming alternating vortex pairs downstream. For $f/f_{s0} < 1$, i.e. when the frequency of forced pulsations is lower than the frequency of lock-on onset, the frequency f_s falls with increasing f, i.e. the driving frequency "attracts" the shedding frequency.

The given classification of vortex patterns downstream of the cylinder in pulsating flow was derived for simultaneous variation of the frequency and relative amplitude of forced velocity pulsations since the parameter $\varepsilon = A_U/2\pi f d$ was kept constant throughout the experiments [22]. The parameter ε was chosen for convenient comparison of results with the previously obtained data on the forced motion of the cylinder. For example, the first pattern of flow past the cylinder occured at the relative amplitude of pulsations $\beta = 12.5\%$, second – at $\beta = 21.6\%$, and third – at $\beta = 35.2\%$. Hence individual effects of frequency and amplitude of pulsations on the cylinder flow patterns were not considered.

Similar data on vortex shedding synchronizing with the frequency of forced pulsations in pulsating cross-flow were experimentally obtained by Sung et al. [24].

It should be noted that the above mentioned and some other papers on pulsating flows around cylinders were initially intended to complement the series of studies of the lock-on phenomenon, more specifically, studies of synchronization of vortex shedding with the frequency of cylinder oscillations in steady oncoming flow [25,26]. Later [23,27,28], beside the lock-on phenomenon, evolution of vortices in the wake of an oscillating cylinder in steady flow or downstream of a fixed cylinder in pulsating oncoming flow was studied.

Griffin and Hall [29] reviewed numerical and experimental studies of steady cross-flows around oscillating bodies and pulsating flows around fixed bodies published until 1990s. The effect of frequency and amplitude on near-wake flow pattern was consid-