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Flow past a square prism with an upstream control rod at incidence to uniform stream

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ABSTRACT

In the numerical study, it was mainly intended to test the capability of a control rod to reduce the drag and to suppress the fluctuating forces acting on the rod-square (total) system for various angles of incidence (α) and center-to-center spacing ratios (L/D). The Reynolds numbers (Re) based upon the diameter of control rod and the side length of the square prism are 50 and 200, respectively, for the control rod and the square prism. Seven distinct flow patterns were observed and it was demonstrated that the cavity flow pattern is the most effective in terms of simultaneous reduction of the time-averaged and RMS values of fluctuating force coefficients for both control rod and square prism. As the control rod located $2D$ or $3D$ upstream of the square prism at zero angle of incidence, the time-averaged drag coefficient of the total system i.e. the sum of the time-averaged drag coefficients of the control rod and the square prism is about 74% that of the square prism alone. Furthermore, the maximum reductions in RMS values of the fluctuating lift acting on the total system are 53% and 60%, respectively, for $2D$ and $3D$. On the other hand, the effectiveness of control rod in reducing the time-averaged drag coefficient of the total system was generally diminished with increasing α. Instantaneous and time-averaged flow fields were also presented in order to identify the flow patterns around the rod-square system.

1. Introduction

It is an effective way to utilize simplified and small-scale models in order to determine the flow characteristics around complex and large-scale structures or equipments (buildings, towers, bridges, offshore structures etc). In addition to this, to associate the flow control methods with the above-mentioned models helps to minimize, as much as possible, the negative or undesired effects of these characteristics on the models. Roughly two flow control methods (active and passive) were known with respect to energy expenditure (Gad-el-Hak, 2000). In active methods, an external energy input to the system is required. Surface heating, blowing and/or suction, injection of micro-bubbles or particles, periodic rotation or oscillation of the body, wall motion, and electromagnetic forces could be given as examples. Passive methods are concerned with the geometrical modification of the flow system without any additional energy input. Splitter plate, axial slit, trip wire, rounded edges, surface roughness, and control rod could be given as examples. More information related to the flow control methods and their major effects on the flow characteristics of the system could be found in the literature.

As a passive control method, control rod has a great significance due to its capabilities such as, reducing the drag and suppressing the fluctuating forces acting on a system, enhancing the heat transfer performance of a system and so on. In order to reveal the effects of an upstream control rod on both reducing the drag and enhancing the heat transfer performance of a square prism, Tsutsui et al. (2001) conducted experimental study for the Reynolds numbers range from 5300 to 32,000. It was found that, the maximum total drag reduction is about 80%. Under these conditions, the overall heat transfer enhancement is 30% compared to those of the square prism without a rod. Likewise, the optimum enhancement in the overall heat transfer is 34% and the total drag reduction is 70%, compared to those of the square prism without a rod. Three flow patterns were observed by flow visualization by means of smoke-wire and oil-flow methods. Lee et al. (2004) investigated the effects of installing a small control rod upstream of a circular cylinder experimentally with a focus on the drag characteristics and the wake structure behind the cylinder. In the study, Reynolds number based on the diameter of the main cylinder was about 20,000. It was reported that the total drag coefficient of entire system, including the main cylinder and the control rod, was reduced by about 25% when compared to the

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Nomenclature

A	area, (m^2)
C	coefficient
d	diameter of the control rod, (m)
D	side length of the square prism, (m)
f	vortex shedding frequency, (Hz)
F	force, (N)
h	vertical distance between the centers of the rod and square prism, (m)
H	height or width, (m)
l	horizontal distance between the centers of the rod and square prism, (m)
L	distance between the centers of the rod and square prism, (m)
L/D	center-to-center spacing ratio, spacing ratio
ΔP	difference between the surface and freestream static pressures, (Pa)
P	local pressure, (Pa)
Re	Reynolds number
St	Strouhal number
T	vortex shedding period, (s)
u, v	streamwise and cross-stream components of the velocity, (m/s)
U	velocity, (m/s)
x, y	streamwise and cross-stream coordinate directions, (m)
Δt	time step size, (s)

Operators

$<..>$	the average over time of the enclosed quantity

Greek symbols

α	angle of incidence, (°)
ρ	density of the fluid, (kg/m^3)
υ	kinematic viscosity of the fluid, (m^2/s)

Subscripts

Cr	critical
D	drag
L	lift
0	single, isolated body
P	pressure
R	control rod
RMS	root mean square value of a quantity
S	square prism
T	total (rod-square) system
∞	freestream

Superscripts

′	frontal
*	planform

main cylinder without rod. The flow was visualized by smoke-wire method and two different flow patterns were observed between the control rod and the main cylinder when pitch ratio was varied. Igarashi (1997) performed experimental study on drag reduction of a square prism by an upstream control rod at a Reynolds number of 32,000. Main result of study was that the system drag coefficient was reduced about 70% when compared to the single square prism. It was expressed that two flow patterns with and without vortex shedding from the rod occurred according to the longitudinal spacing (L/D) and the rod diameter (d/D). As a numerical study at low Reynolds number (Re=200), Zhang et al. (2006) investigated the mechanism of the formation and the convection of vortices shedding from the cylinder with an upstream rod. The main parameters in this study are normalized control rod diameter (d/D) and center-to-center spacing ratio (L/D). It was obtained that, in optimum conditions, the drag coefficient of entire system is reduced about 35% and root-mean-square (RMS) value of fluctuating lift coefficient of the bare cylinder is reduced by up to 73%. It was expressed that two flow modes appeared with the variation of the spacing ratio.

The cross-section of the control body can be different from a circle. Prasad and Williamson (1997) utilized a small flat plate placed upstream of and parallel to the cylinder as a drag reduction device. The Reynolds number based on the cylinder diameter was approximately 50,000 in the experimental study. It was found that the optimal geometrical configuration consisting of a plate height one-third the cylinder diameter placed 1.5 diameters upstream of the cylinder reduced the system drag by 62% compared to the drag of the bare cylinder. As the gap width increased, the existence of two distinct flow modes of the flow was suggested by aid of smoke-wire flow visualization. Zhou et al. (2005) placed a control plate upstream in order to control the flow around square cylinder in a two-dimensional (2-D) channel at Re=250 based on the square width and the maximum incoming flow velocity. In numerical study, lattice Boltzmann method (LBM) was applied to simulate isothermal channel flow. The main parameters were plate height (h/D) and perpendicular distance between the control plate and the square cylinder (s/D). It was stated that, negative drag on square cylinder was achieved, total drag coefficient, i.e. the sum of the drag coefficient of the square cylinder and the control plate, was decreased markedly and the amplitude of the fluctuating lift acting on the square cylinder was well suppressed. Rosales et al. (2000) performed numerical simulations to investigate the flow and the heat transfer characteristics of single and tandem pair of the square prisms in a channel with a fully developed inlet velocity profile at Re=500 based on side length of the square prism. The side length of the eddy-promoting upstream square cylinder is one-half of the downstream heated one. It was reported that the existence of the upstream eddy-promoting cylinder slightly increased the overall heat transfer and reduced the drag of the downstream heated cylinder.

It is clear from the literature that upstream control body has significant effects on aerodynamic and heat transfer characteristics of the total system in tandem arrangement. But, the total system subjected to cross-flow is not axisymmetric such like a single circular cylinder. Therefore, it is also important to know that how will these characteristics be affected by staggered arrangement which is also encountered in practical applications. Zhang et al. (2005) investigated the effects of upstream rod in staggered arrangement on drag reduction of fixed square cylinder at a Reynolds number of 82,000. It was reported that, for tandem arrangement, the drag coefficient of square cylinder can be reduced up to 10% that of the single square cylinder. It was stated that mean drag coefficient of the downstream square cylinder kept a low value for $\alpha < 3°–5°$, increased steadily up to $\alpha = 20°$ and remained unchanged for $\alpha > 20°$. Besides that, six different flow modes were identified and showed via flow visualization by using hydrogen bubble technique. Wang et al. (2006) studied on drag