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Forced convection heat transfer from the helically twisted elliptic cylinder inspired by a daffodil stem

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ABSTRACT

The present study is an original research for the forced convection heat transfer around a helically twisted elliptic (*HTE*) cylinder inspired by a daffodil stem. Also, this study is an initial investigation to find the effect of the Reynolds number (*Re*) in the laminar flow regime. We carried out numerical simulations to investigate the flow and heat transfer around the *HTE* cylinder in $60 \leqslant Re \leqslant 150$ and Prandtl number (*Pr*) of 0.7. The circular cylinder is considered for the purpose of the comparison. The drag and lift fluctuation for the HTE cylinder are much smaller than those of the smooth cylinder. The decreasing rate of Strouhal number (*St*) for the *HTE* cylinder to that for the smooth cylinder is about 4–7% in the present Reynolds number range. The smaller *St* of the *HTE* cylinder than the smooth cylinder associate a longer vortex formation length of the *HTE* cylinder. The three-dimensional (3D) geometry of the HTE cylinder formed the spanwise variation of the Nusselt number (*Nu*), resulting in the sinusoidal profiles. This spanwise variation of the Nusselt number is identified by the flow structures and the isotherms distribution. The time- and total surface-averaged Nusselt number of the *HTE* cylinder decreases from about 1.2% to 2.8% in the present *HTE* configuration and *Re* range, compared to the smooth cylinder.

1. Introduction

The forced convection and fluid flow around bluff bodies has been extensively investigated by the numerous researchers. The fundamental importance of this topic is associated with not only academics but also diverse applications such as heat exchangers, offshore structures including pipelines and risers, nuclear reactors, overhead cables, power generators, thermal apparatus [1–15]. Hence, it is essential that needs of the improvement or the suppression of the heat transfer from the structure are faced to the applications. In order to achieve these purposes, the control of the forced convection is required. The forced convection is dominated by the fluid flow, resulting in that the control of the forced convection can be fallen into the flow control.

Recently, the bio-inspired technology among the flow control methods is broadly adopted into the various fields of the research and also application. The main purposes of flow control are the drag reduction, the reduction of the lift fluctuation, the enhancement of lift force, the suppression of the vortex-shedding, reduction of flow-induced noise and vibration, and improvement or suppression of mixing or heat transfer in systems exposed on the fluid flow. Thus, many researches have been performed and successively led to comprehensive reviews [16–24].

Among the biomimetic technologies for the flow control, recently, a stem of the daffodil has been focused by several researches [25–29] which reported that its' unique geometry considerably suppress the lift fluctuation and modify the periodical Karman vortices in the wake. The stem of a daffodil has an elliptic cross section with pointed ends on the major axis rotating along the stem axis. Thus, this geometry in nature is associated with the three-dimensional geometry disturbance.

Kim et al. [26] investigated the effects of the amplitude and wavelength of helically twisted ellipse on the flow around a *HTE* cylinder at $Re = 100$ and showed a preliminary result that the strength of vortex shedding and mean drag was significantly reduced.

Jung and Yoon [27] suggested a *HTE* cylinder as new passive control method associated with type of overall shape changes. The *HTE* cylinder achieved a reduction of about 13% and 96% in the mean drag and root mean square value of the lift fluctuation compared with those of a smooth cylinder at Reynolds number of 3000. They observed that the shear layer of the *HTE* cylinder covering the recirculation region is more elongated than those of the smooth cylinder, leading to the suppression of the vortex shedding from the *HTE* cylinder. In addition, the effect of the Reynolds

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Nomenclature

A	major diameter of the *HTE* cylinder
AR	aspect ratio of the *HTE* cylinder
B	minor diameter of the *HTE* cylinder
C_D	drag coefficient
C_L	lift coefficient
c_p	specific heat
D	diameter of the smooth cylinder and mean diameter of the major and minor diameters
h	convective heat transfer coefficient
k	thermal conductivity
L	spanwise length
Nu	Nusselt number
$\overline{Nu}$	time-averaged local Nusselt number
$\langle Nu \rangle$	spanwise local surface-averaged Nusselt number
$\langle \overline{Nu} \rangle$	time- and spanwise local surface-averaged Nusselt number
$\langle\langle Nu \rangle\rangle$	total surface-averaged Nusselt number
$\langle\langle \overline{Nu} \rangle\rangle$	time- and total surface-averaged Nusselt number
P	pressure
Pr	Prandtl number (=$c_p\mu/k$)
Re	Reynolds number (=$U_\infty D/\nu$)
t	time
T	temperature
U_∞	free-stream velocity
u, v, w	velocity components in x, y and $z$directions
x, y, z	Cartesian coordinates
Φ	pitch angle of the HTE cylinder
λ	wavelength in the spanwise direction of the HTE cylinder
μ	dynamic viscosity
ν	kinematic viscosity
ρ	density

Sub/Superscripts

rms	root mean square
∞	free-stream
$-$	time-averaged quantity
$\langle\ \rangle$	spanwise local surface averaged quantity
$\langle\langle\ \rangle\rangle$	total surface averaged quantity

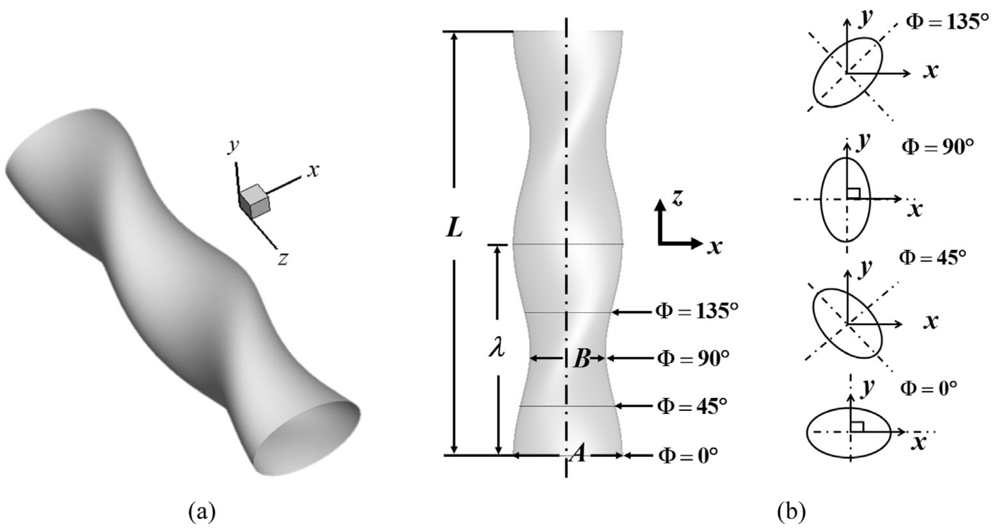

Fig. 1. (a) Geometry and (b) definition of the *HTE* cylinder.

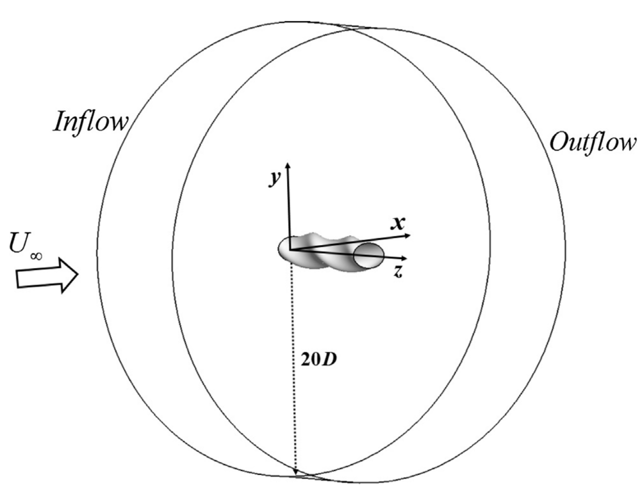

Fig. 2. Schematic of the computational domain and boundary conditions.

Table 1
Grid dependence test for a *HTE* cylinder at *Re* = 100.

Type	$N_r \times N_\theta \times N_z$	$\overline{C_D}$	$C_{L,rms}$	St	$\langle\langle \overline{Nu} \rangle\rangle$
Wei et al. [29]	128 × 128 × 64	1.28	0.072	0.156	–
Coarse	128 × 96 × 32	1.287	0.071	0.157	5.087
Medium	128 × 128 × 64	1.278	0.07	0.156	5.033
Fine	256 × 128 × 64	1.278	0.068	0.156	5.036

number on the force characteristics was investigated in the range of $3000 \le Re \le 10{,}000$.

Kim et al. [28] investigated flow over a *HTE* cylinder at Reynolds numbers of 100 and 3900, based on the free-stream velocity and square mean root the product of the lengths of its major and minor axes. Kim et al. [28] conducted parametric studies of the aspect ratio of the elliptic cross section and the helical spanwise wavelength (λ). Depending on the values of the aspect ratio (AR) and wavelength, the flow in the wake contains the characteristic