International Journal of Heat and Mass Transfer 127 (2018) 683–700

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Large eddy simulation of forced convection heat transfer from wavy cylinders with different wavelengths

Min Il Kim, Hyun Sik Yoon *

Department of Naval Architecture and Ocean Engineering, Pusan National University, 2, Busandaehak-ro 63beon-gil, Gumjeong-Gu, Busan 46241, Republic of Korea

ARTICLE INFO

Article history:
Received 2 July 2018
Received in revised form 18 August 2018
Accepted 20 August 2018

Keywords:
Wavy cylinder
Large eddy simulation
Forced convection heat transfer
Flow control

ABSTRACT

Large eddy simulation was carried out to investigate the forced convection around a wavy cylinder at a Reynolds number of 3000 in the subcritical regime and a Prandtl number of 0.7. This is initial research to find the effect of the wavelength (λ/D_m) on the forced convection at a subcritical Reynolds number. A wide wavelength range of $1.136 \leqslant \lambda/D_m \leqslant 6.06$ is considered, and the results are compared with those of a smooth cylinder. The local peaks of the time- and total surface-averaged Nusselt numbers for different wavelengths occur at the optimum wavelengths where the minimum and maximum drag occurs. Therefore, the variation of the time- and total surface-averaged Nusselt numbers along the wavelength correlates with the force coefficients on the wavy cylinder. The bifurcation of the location of the maximum Nusselt number from the node to the saddle occurs at the critical wavelength, which is the short optimal wavelength where the maximum drag reduction and suppression of the lift fluctuation appear. The position of the minimum Nusselt number moves from the middle toward the node with increasing wavelength and eventually saturates at the node. These variations of the local Nusselt number are supported by the isotherm distribution, which is strongly governed by wake structures based on shear layer separation.

1. Introduction

The forced convection and fluid flow around bluff bodies have been investigated extensively by numerous researchers. This topic is associated with diverse applications, such as heat exchangers, offshore structures (including pipelines and risers), nuclear reactors, overhead cables, power generators, and thermal apparatuses [1-18]. Hence, it is essential to understand the improvement or suppression of heat transfer from a structure. To achieve this, control of the forced convection is required, which is dominated by the fluid flow.

One approach in direct wake control methods is introducing some form of three-dimensional (3-D) geometric disturbances to the base form of a nominally two-dimensional (2-D) bluff body. One example is waviness on a cylinder with a sinusoidal variation in the cross sectional area along the spanwise direction, which has been investigated for its effect on flow characteristics such as wake vortices and body forces. The main purposes of flow control are drag reduction, reduction of the lift fluctuation, enhancement of the lift force, suppression of the vortex-shedding, reduction of flow-induced noise and vibration, and improvement or suppression of mixing or heat transfer in systems exposed to the fluid flow. Thus, many studies have been performed [19-30].

Lam and Lin [19,20] provided the optimal spanwise wavelength for turbulent flow to achieve drag reduction. In the laminar flow regime ($Re = 100 - 150$), Lam and Lin [21] revealed two optima of $\lambda/D_m = 2$ and 6.0 in the range of $1 \leqslant \lambda/D_m \leqslant 10$, where D_m is the mean value of the maximum and minimum diameters. At a subcritical $Re = 3 \times 10^3$, Lin et al. [27] identified an optimum at $\lambda/D_m = 6.06$ for relatively large wavelengths ($\lambda/D_m > 3.5$). Square cylinders with a wavy front face and wavy front and rear faces revealed similar optimal wavelengths to a wavy cylinder ($\lambda/D_m = 5.6$) [25,26].

However, two optimal wavelengths of $\lambda/D_m \approx 2.0$ [20] and 6.0 [27] correspond to distinct near wakes modifications and underlying force-reduction mechanisms. Flow separation around a wavy cylinder with $\lambda/D_m \approx 2.0$ occurs earlier at the saddle than the node [20]. This is connected to the near-surface flow heading toward the node from the saddle [20]. In contrast, the flow separation around a wavy cylinder with $\lambda/D_m \approx 6.0$ exhibits an invariant feature along the spanwise direction, which is similar to the behavior of a

* Corresponding author.
E-mail address: lesmodel@pusan.ac.kr (H.S. Yoon).

https://doi.org/10.1016/j.ijheatmasstransfer.2018.08.092
0017-9310/

Nomenclature

A	projected area of the cylinder facing the flow direction
C_D	total drag coefficient
C_L	total lift coefficient
c_p	specific heat
D_z	local diameter of the cylinder
$D_{\min}$	minimum local diameter of the cylinder
$D_{\max}$	maximum local diameter of the cylinder
D_m	mean diameter of the cylinder $D_m = (D_{\max} + D_{\min})/2$
F_D	total drag force
F_L	total lift force
f_s	frequency of the vortex shedding
h	convective heat transfer coefficient
k	thermal conductivity
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 (=$U_\infty D_m/\nu$)
S_t	Strouhal number
t	time
T	temperature
T_s	cylinder surface temperature
U_∞	free-stream velocity
u, v, w	velocity components in x, y and z directions
x, y, z	Cartesian coordinates
Greek symbols	
θ	angle in the circumferential direction of the cylinder
λ	spanwise wavelength of cylinder
μ	dynamic viscosity
ν	kinematic viscosity
ρ	density
Sub/superscripts	
rms	root mean square
z	spanwise local value
∞	free-stream
$\bar{}$	time-averaged quantity
$\langle\ \rangle$	spanwise local surface averaged quantity
$\langle\langle\ \rangle\rangle$	total surface averaged quantity

smooth cylinder [27]. Consequently, at $\lambda/D_m \approx 2.0$, there is a wide wake at the saddle and a narrow wake at the node [20], as well as enhanced and stabilized waviness of the near wake, which leads to the largest reductions in fluid forces. At $\lambda/D_m \approx 6.0$, the shear layers are greatly stabilized, and the formation of mature vortices is postponed, leading to elongated vortex formation and reduced fluid forces [27].

The heat transfer reflects the flow characteristics near the body surface, and the characteristics of heat transfer are likely to change in the same manner for each flow regime. Hilpert measured the heat transfer from a circular cylinder [17]. Based on experimental data, an empirical correlation was suggested for the Reynolds number and overall Nusselt number over a wide range of Reynolds numbers of 2–2.3 × 105. Eckert and Soehngen [31] and Krall and Eckert [32] measured the local heat transfer around a circular cylinder at $Re = 23 - 597$ and $Re = 10 - 4610$, respectively. They suggested that the variation of the Nusselt number distribution is caused by changes in the flow regime, such as from steady to unsteady flow with the occurrence of vortex shedding.

Nakamura and Igarashi [6] measured the heat transfer and vortex formation length in the separated flow behind a circular cylinder to identify the change in the heat transfer according to the flow regimes in the range of Re = 70–30000. Analytical calculations were carried out for the fluid flow around circular and elliptical cylinders and the heat transfer from them [9,10]. This was done using an integral boundary-layer analysis method under isothermal and iso-flux thermal boundary conditions. Recently, bio-inspired cylinder geometry was investigated for its effect on the forced convection.

Kim and Yoon [15] numerically investigated the forced-convection heat transfer around a biomimetic elliptic cylinder inspired by a harbor seal vibrissa (HSV) at a Reynolds number of 500 and Prandtl number of 0.7. The HSV provided stable heat transfer behavior by significantly suppressing the Nusselt number fluctuation. The HSV formed spanwise sinusoidal variation of the Nusselt number, resulting in sinusoidal profiles with a maximum and a minimum at the saddle and node, respectively. This spanwise variation of the Nusselt number was identified by the flow structures.

Yoon et al. [33] considered a helically twisted elliptical (HTE) cylinder inspired by a daffodil stem. They carried out numerical simulations to investigate the flow and heat transfer around the cylinder in the range of $60 \leqslant Re \leqslant 150$ with a Prandtl number of 0.7. The 3D geometry of the HTE cylinder resulted in spanwise variation of the Nusselt number (Nu) and sinusoidal profiles. This spanwise variation was identified by the flow structures and the isotherm distribution. The time- and total surface-averaged Nusselt number of the HTE cylinder decreases from about 1.2% to 2.8% compared to a smooth cylinder. Consequently, the heat transfer characteristics strongly correlate with the flow modification by the unique HSV and HTE geometries.

Previous studies mainly focused on the effect of the wavelength on the fluid flow regarding flow control for force reduction. However, few studies have dealt with heat transfer around a wavy cylinder and the effect of the wavelength on the heat transfer. Only Ahn et al. [12] dealt with the forced heat transfer around a wavy cylinder for three different wavelengths of $\lambda = \pi/2$, $\pi/3$, and $\pi/4$ with a fixed wavy amplitude of 0.1 at a Reynolds number of 300 and a Prandtl number of 0.71. They considered shorter wavelengths than the optimal wavelength of $\lambda/D_m \approx 2.0$ [20]. They showed that the variation of time- and local surface-averaged Nusselt numbers for a wavy cylinder along the spanwise direction have a strong dependence on the location in the spanwise direction with a larger value at the node than at the saddle of the wavy cylinder. The time- and total surface-averaged Nusselt numbers at $\lambda = \pi/2$ are higher than that of a smooth cylinder, whereas the values at $\lambda = \pi/4$ and $\pi/3$ are lower.

The way cylinder gives apparently the drag reduction and the suppression of the lift fluctuation, which has been well known by many researches as reviewed above. However, the characteristics of the heat transfer around the wavy cylinder and especially the effect of the wavelength on the heat transfer at the subcritical Reynolds number are very rare. Therefore, this study aims to provide the information of the heat transfer around the wavy cylinders with different wavelengths. As mentioned above, except the work of Ahn et al. [12], there is no systematical study to find the effect of the wavy geometry on the force convection. However, the wavelengths of Ahn et al. [12] are short and very limited to identify