International Journal of Heat and Mass Transfer 126 (2018) 618–638

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Reynolds number effect on the fluid flow and heat transfer around a harbor seal vibrissa shaped cylinder

Hyo Ju Kim, Hyun Sik Yoon *

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

ARTICLE INFO

Article history:
Received 15 January 2018
Received in revised form 11 May 2018
Accepted 16 May 2018

Keywords:
Harbor seal vibrissa
Biomimetic
Reynolds number effect
Heat transfer
Flow control

ABSTRACT

This study numerically investigates the effect of the Reynolds number (*Re*) on the characteristics of the fluid flow and heat transfer from a biomimetic elliptical cylinder inspired by a harbor-seal vibrissa (HSV). We considered the Re range of 50–500 and Prandtl number (*Pr*) of 0.7. Circular and elliptical cylinders with the same hydraulic diameter were compared. The results confirm the effectiveness of the unique geometry of the HSV in the low Reynolds number regime for reduction drag and the suppression of lift fluctuation. The root-mean-square (RMS) value of the lift fluctuation is almost negligible for the unsteady regime of the HSV in this range of *Re*. The time histories of the force coefficients and flow structures revealed the onset of the unsteady flow for the HSV within the present range of *Re*. The spanwise dependency of the local surface-averaged Nusselt number becomes stronger as *Re* increases. In the unsteady flow regime, a periodic thermal plume appears at the nodes of the HSV, which was induced by the non-reverse flow region that expanded the isotherms downstream.

1. Introduction

The forced convection and fluid flow around bluff bodies have been popular topics because of their importance in academics and various applications. Examples include heat exchangers, offshore structures (including pipelines and risers), nuclear reactors, overhead cables, power generators, thermal apparatuses, boiler design, hotwire anemometry, and the rating of electrical conductors [1–15]. The heat transfer from a structure needs to be improved or suppressed in different applications. Thus, control of the forced convection is required. Forced convection is dominated by the fluid flow, and as a result, the control of the forced convection can fall into the flow control.

Among these flow controls, the bio-inspired technology is widely used in various research and applications. The main purposes of flow control are drag reduction, the reduction of lift fluctuation, the enhancement of lift force, the suppression of vortex-shedding, the reduction of flow-induced noise and vibration, and the improvement or suppression of mixing or heat transfer in systems exposed to the fluid flow. Therefore, numerous studies have been carried out [16–24].

A harbor seal vibrissa (HSV) has been considered as a subject of flow controls in several studies [25–31] owing to its ability to significantly suppress lift fluctuation due to its unique geometry. Kim and Yoon summarized the research on HSV-shaped cylinders [31]. That study has been the only one to investigate the characteristics of forced convection from an HSV. The HSV's three-dimensional geometry resulted in sinusoidal profiles of the local spanwise Nusselt number (Nu), which was identified using the flow structures. However, only one Reynolds number (*Re*) of 500 was considered to evaluate the effect of the HSV geometry on the forced convection.

The operation range of the HSV is about $10^2 < Re < 10^3$ [29]. Few studies have looked at the effect of the Reynolds number. Thus, the present study considers low Reynolds numbers of $50 \leq Re \leq 500$ to determine the effect on the fluid flow and the heat transfer from the HSV. The fluid flow around a circular cylinder according to *Re* also has been examined extensively by a number of researchers [32–34]. Beaudan and Moin [32] summarize the flow characteristics around a circular cylinder in laminar and transition flows. At approximately $Re = 40$, the flow transitions from a laminar and steady state to a periodic vortex-shedding regime [35–37]. It remains laminar up to $Re = 150$, and then a transition to three-dimensionality occurs in the near-wake region around $Re = 180$ [38–39]. At Reynolds numbers between 300 and 2×10^5 (the sub-critical range), the flow around the entire periphery of the cylinder is laminar, and a transition to turbulence occurs in the separated free shear layers [40].

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

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

https://doi.org/10.1016/j.ijheatmasstransfer.2018.05.083
0017-9310/

Nomenclature

a, b	radii of the vibrissal cross-section in the laterally narrow location
k, l	radii of the vibrissal cross-section in the laterally wide location
C_D	drag coefficient
C_L	lift coefficient
c_p	specific heat
D_h	hydraulic diameter (=$4A/U$)
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 (=$U_\infty D_h/\nu$)
t	time
T	temperature
U_∞	free-stream velocity
u, v, w	velocity components in x, y and z directions
x, y, z	cartesian coordinates

Greek symbols

α_{offset}	offset angle of maximum ellipses
β_{offset}	offset angle of minimum ellipses
θ	angle in the circumferential direction of the cylinder
λ_p	period length in the spanwise direction of the HSV
μ	dynamic viscosity
ν	kinematic viscosity
ρ	density

Sub/Superscripts

RMS	root mean square
z	spanwise local value
∞	free-stream
$\overline{\ }$	time-averaged quantity
$\langle\rangle$	spanwise local surface averaged quantity
$\langle\langle\rangle\rangle$	total surface averaged quantity

heat transfer from a circular cylinder [1]. Based on the experimental data, an empirical correlation suggested for the Reynolds number and overall Nusselt number over a wide range of Reynolds numbers of 2–2.3 $\times$ 10^5. Eckert and Soehngen [2] and Krall and Eckert [6] measured the local heat transfer around a circular cylinder for Re = 23–597 and Re = 10–4610, respectively. They suggested that the variation of the Nusselt number distribution was caused by the change in the flow regime, such as the change from steady to unsteady flow with the occurrence of vortex shedding.

Nakamura and Igarashi [11] measured the heat transfer and the vortex formation length in the separated flow behind the circular cylinder to identify the change in the heat transfer according to the flow regimes in the range of Re = 70–30,000. Analytical calculations were carried out for the fluid flow around circular and elliptical cylinders and the heat transfer from them [13,14]. This was done using an integral boundary-layer analysis method under isothermal and iso-flux thermal boundary conditions.

As mentioned above, the main purpose of this present study is to investigate the effect of the Reynolds number on the flow and heat transfer, since there is no previous study to consider the Reynolds number effect on the forced convection around the HSV. The motivation of the present study is that one is the operation range of HSV is in $10^2 < Re < 10^3$ and another is the role of the Reynolds number to determine the flow regime and the heat transfer.

We can expect the observation of the 3D development of the flow and heat transfer according to the Reynolds number by the unique HSV geometry. We present the 3D flow structures and spanwise local Nusselt number for different Reynolds numbers. To provide a physical interpretation of the spanwise local heat-transfer characteristics, the mean temperature and streamwise velocity distribution in the x-z plane are considered according to Re. In addition, the flow transition in the limited Reynolds number conditions is discussed.

2. Numerical details

2.1. Governing equations and numerical methods

The Navier-Stokes, continuity, and energy equations are considered to simulate the unsteady three-dimensional incompressible laminar flow and thermal fields around the cylinders:

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial u_i}{\partial t} + \frac{\partial u_i u_j}{\partial x_j} = -\frac{\partial P}{\partial x_i} + \frac{1}{Re}\frac{\partial^2 u_i}{\partial x_j \partial x_j} \tag{2}$$

$$\frac{\partial T}{\partial t} + \frac{\partial u_j T}{\partial x_j} = \frac{1}{RePr}\frac{\partial^2 T}{\partial x_j^2} \tag{3}$$

where u_i and T are the corresponding velocity components and the temperature; t is time; and P is the pressure. All the variables are non-dimensionalized by the hydraulic diameter of the cylinders, D_h, the free-stream velocity, U_∞ and the difference temperature between cylinder surface and inlet boundary, $T_S - T_\infty$, respectively, that is, $u_i = u_i^*/U_\infty$, $T = T^*/(T_S - T_\infty)$ and $t = t^* D_h/U_\infty$ (where, superscript * means dimensioned variables).

Grid-filtered equations for large eddy evolution are used to solve the unsteady three-dimensional incompressible turbulent flow and thermal fields:

$$\frac{\partial \overline{u_i}}{\partial x_i} = 0 \tag{4}$$

$$\frac{\partial \overline{u_i}}{\partial t} + \frac{\partial \overline{u_i u_j}}{\partial x_j} = -\frac{\partial \overline{P}}{\partial x_i} + \frac{1}{Re}\frac{\partial^2 \overline{u_i}}{\partial x_j \partial x_j} - \frac{\partial \tau_{ij}}{\partial x_j} \tag{5}$$

$$\frac{\partial \overline{T}}{\partial t} + \frac{\partial \overline{u_j}\overline{T}}{\partial x_j} = \frac{1}{RePr}\frac{\partial^2 \overline{T}}{\partial x_j^2} - \frac{\partial q_j}{\partial x_j} \tag{6}$$

where τ_{ij} is the sub-grid scale stress tensor ($\tau_{ij} = \overline{u_i u_j} - \overline{u_i}\overline{u_j}$), resulting in an effect of the sub-grid scales on the resolved scales. In Eq. (6), q_j is the sub-grid flux ($q_j = \overline{Tu_j} - \overline{T}\overline{u_j}$). The dynamic Smagorinsky subgrid scale (SGS) model proposed by Germano et al. [41] is considered to represent the effects of unresolved small-scale fluid motions. Further details of the SGS model and mathematical formation for scalar transport can be found in other studies [42–44].

In Eqs. (3) and (6), Re is the Reynolds number ($Re = U_\infty D_h/\upsilon$), and Pr is the Prandtl number ($Pr = c_p\mu/k$). c_p is the specific heat, and μ and k are the dynamic viscosity and thermal conductivity, respectively. The Prandtl number is $Pr = 0.7$, which corresponds to air, and the Reynolds number is $Re = 50$—500.