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External forced convection from circular cylinders with surface protrusions

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ABSTRACT

The application of surface structures to heat exchanging devices can help to enhance their heat transfer performance. In this study, surface protrusions were added as a modification to the circular cylinder in crossflow. The modified cylinder maintained a constant temperature and heated the cool air that flowed over it. We first investigated the influence on the heat transfer performance of the number of protrusions, the non-dimensional protrusion height, and two alignment modes of the modified cylinders. For the modified cylinders with no more than six protrusions, we observed increase in the temporally and spatially averaged Nusselt number. Then, we inspected the local Nusselt number along the modified cylinder surface as well as the temperature and flow fields, and found that the notches between the protrusions caused major deterioration to local heat transfer. Based on the observation, two alternative configurations to the initial protrusion design were proposed to further enhance the heat transfer performance. The first alternative was to apply a pair of protrusions symmetrically on the cylinder surface, in which case we studied the effects of the protrusion height, protrusion width, and two series of protrusion placements. The second alternative was to gradually fill the notches between the protrusions, in which case we studied the effects of the protrusion height, degree of filling, and two modes of alignment. Compared to the circular cylinder, the dual protrusion design and the notch-filling design achieved as much as 7% and 2% increase in the temporally and spatially averaged Nusselt number, while being accompanied by 8% and 16% drag penalty, respectively.

1. Introduction

Since most of the channels which transport heat-transferring fluids possess round cross-section, circular cylinders and tubes are a very important type of configuration applied in thermal engineering equipment design [1–8]. For decades, researchers have been investigating new methods and modifications to enhance external convection, mostly from circular cylinders, which has long been a popular heat exchanger configuration. Presently, the most widely used enhancement technique for external forced convection from cylinders are the application of surface attachments such as fins and pins, which augment the heat transfer capability of the devices mainly through the added heat-exchanging area [1]. However, the surface attachments are not compact enough for certain scenarios such as small-scale heat exchangers. Other more compact heat transfer augmentation treatments are under active investigation, one of which is applying surface structures, including dimples (also referred to as concaves, cavities or depressions) [9–18], protrusions [9,10,13], and grooves [11,19–24].

To the authors' knowledge, only limited investigations focused on structures applied to the surface of cylinders in the crossflow, whereas the majority of the literature focused on surface structures applied to the interior of rectangular channels. The results show that the surface structures are a viable option to enhancing forced convection. Won et al. [12] studied experimentally the dimple depth's effect on the flow characteristics and heat transfer performance of a rectangular channel with one dimpled wall. The optimal depth and the corresponding characteristics were identified. Elyyan et al. [14] conducted numerical simulation on a fin bank with a dimple-protrusion combination for Reynolds number ranging from laminar flow to fully turbulent flow using two dimple pitches. Xiao et al. [15] studied systematically the Nusselt number distribution as well as the friction factor of a channel with an array of dimples subjected to laminar flow. Turnow et al. [16] studied numerically the vortex structures and heat transfer enhancement mechanisms of turbulent flow in a narrow channel with a staggered array of dimples. They gave the optimal channel height to

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Nomenclature

A	reference area, m^2
C_D	drag coefficient
c_p	air specific heat at constant pressure, J/(kg·K)
D	outer diameter of the cylinder with protrusions, m
D_{base}	diameter of the base cylinder, m
D_{fill}	diameter of the filling circle, m
$\tilde{F}$	non-dimensional measure of filling
F_D	drag force, N
$\tilde{H}$	non-dimensional protrusion height
h	convective heat transfer coefficient averaged over time and surface, $W/(m^2{\cdot}K)$
k	thermal conductivity, W/(m·K)
P	pressure, N/m^2
Pr	Prandtl number
$\tilde{N}$	number of protrusions
Nu	Nusselt number
Re	Reynolds number
T	temperature, K
T_∞	far-field temperature, K
T_H	surface temperature of the cylinder, K
U	fluid velocity, m/s
u	stream-wise fluid velocity, m/s
U_∞	far-field flow velocity, m/s
v	span-wise fluid velocity, m/s
$\tilde{W}$	non-dimensional protrusion width
x	stream-wise direction of the coordinate, m
y	span-wise direction of the coordinate, m

Greek symbols

$\tilde{\Theta}$	non-dimensional excess temperature
μ	dynamic viscosity, kg/(m·s)
ρ	density, kg/m^3

Superscripts

$\sim$	non-dimensional variables
—	variables averaged over time
=	variables averaged over time and the cylinder surface
*	normalized variables

Subscripts

cyl	variables pertaining to the unmodified circular cylinder

dimple diameter ratio in terms of heat transfer and thermo-hydraulic performance. Through numerical simulation and design of experiments of a channel with staggered spherical dimple array, Lee and Lee [17] gave the correlation between the dimple depth, channel height, dimple span-wise pitch, dimple stream-wise pitch and the critical Reynolds number, average Nusselt number, as well as the friction factor.

Among the small number of investigations that focused on cylinders with surface structures, Kimura and Tsutahara [19], along with Yamagishi and Oki [20–22] investigated the drag reduction resulting from the use of cylinders with grooves. More recently, the cactus-inspired grooved cylinder also started gaining much interest [23,24]. Kovalenko and Khalatov [11] presented fluid flow and heat transfer characteristics of fluid over three dimpled cylinders arranged in the span-wise direction, considering several dimple configurations and Reynolds number from 8000 to 115,000.

Some of the previous research results indicate that the application of protrusions yields better heat transfer performance than that of dimples. Ligrani et al. [9] gave experimental results on channels with one dimpled side opposite one smooth side as well as channels with one dimpled side opposite one protruded side. The results show that the dimple/protrusion combination provide better heat transfer enhancement than the dimple/smooth wall combination [10] due to more favorable secondary flow. However, the drag of the dimple/protrusion combination is also apparent. Hwang et al. [13] conducted experimental investigations on rectangular ducts with dimples or protrusions installed on one or two sides. They found that at Reynolds number 1000, the enhancement of the double protrusion wall is twice that of the double dimple wall, and both are higher than that of the single dimple/protrusion wall configuration. However, we have not found studies that applied to circular cylinders surface protrusions, which may offer better heat transfer enhancement than dimples or grooves. Surface protrusions have the potential to augment the heat transfer performance of forced convection from the circular cylinder while retaining the compactness, and should receive due attention.

In this study, surface protrusions were systematically added to modify the surface of the circular cylinder in the crossflow. First, the impact of the number and height of the protrusions on heat transfer and drag were investigated. Then, based on the observation we made that major heat transfer deterioration occurs at the notches between neighboring protrusions, we proposed two alternative configurations for heat transfer performance optimization. The first one was to add only two protrusions symmetrically on the cylinder. The second one was to gradually fill up the notches. Further parametric studies were carried out for the two alternatives. Compared to the normal circular cylinder, we achieved better heat transfer performance in some of the configurations. The optimal parameters in terms of heat transfer or drag for both configurations were found.

2. Numerical model

Consider the cylinder with surface protrusions in Fig. 1. We suppose that the cylinder has very large aspect ratio. And for each configuration, it has a consistent cross-sectional shape. The surface of the cylinder maintains constant temperature T_H and is placed in an infinite air field. The air has far-field temperature $T_\infty < T_H$, and is heated as it flows over the cylinder. The objective is to investigate the effects of the protrusions on the heat transfer and drag of the cylinder.

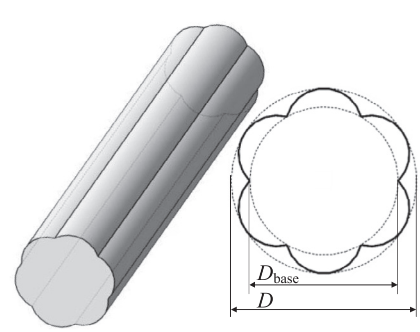

Fig. 1. Schematics of the cylinder with surface protrusions.