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Complementary temperature-sensitive paint measurements and CFD analysis of wall heat transfer of cubes-in-tandem in a turbulent channel flow

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ABSTRACT

The influence of cubes-in-tandem on wall heat transfer in turbulent channel flow is investigated using complementary methods of temperature-sensitive paint (TSP) measurements and computational fluid dynamics (CFD). Three systems—a single cube and cubes-in-tandem at spacing-to-span-wise widths (S/d) of 3 and 4—were comparatively studied. For the single cube, a high level of turbulence in opposite-circulation vortices occurred for significant augmentation of convective heat transfer. For the tandem system at $3d$, circulation was periodically advected downstream from two symmetric vortices, in alternating fashion; this mechanism was found to promote a high heat transfer rate across the leading face of the downstream cube. When the spacing was increased sufficiently, i.e., $4d$, a new horseshoe vortex system occurred for substantial enhancement along the front face of the downstream cube. As such, the system at $4d$ promoted a distinct flow field in the wake region of the downstream cube, which was responsible for larger augmentation of the heat transfer area. The results showed that the heat transfer was enhanced in the inter-body space of the system at $4d$ as compared with the single cube. Behind the downstream cubes, the enhancement of heat transfer was pertinent to the unsteadiness of circulation vortices; meanwhile, the heat transfer monotonically decreased by the stream-wise distance for the single cube.

1. Introduction

Intensification of wall heat transfer by placing a bluff body in turbulent flow is important in many engineering applications. Previous studies [1–6] have reported the complex structure of the three-dimensional flow field around a single cube and the resultant vortices, dominated by the horseshoe vortex, corner vortex, and wake of opposite circulation vortices. The vortices entrain high-momentum fluid close to the wall and promote mixing, thus increasing the heat exchange between the wall and fluid. Such bluff body-like structures can also be found as tandems or groups in many practical situations, i.e., heat exchangers, cooling of gas turbine blades, cooling of electronic devices, cooling systems for nuclear power plants, offshore structures, chimneys, struts, and in both air and water flow [7]. Bluff bodies-in-tandem is a complex problem of great practical importance because of the high aerodynamic loads that result from neighboring structures [8]. In such circumstances, the second body is situated in the wake of the first, inducing complex interactions between the shear layers, vortices, and vortex shedding, which vary substantially with the inter-body spacing. However, such a complex flow field promotes complex heat transfer mechanisms, which is of fundamental importance in a wide variety of heat transfer applications. Therefore, the influence of bluff bodies-in-tandem on wall heat transfer is fundamentally important from a practical perspective.

A survey of the literature shows that a considerable amount of heat transfer research has focused primarily on a single bluff body in internal flows. Goldstein et al. [9] applied the naphthalene sublimation technique to investigate the influence of appendage shape in the wake of a circular cylinder. Yoo et al. [3] investigated the effect of vortices for a square bluff body with various angles of attack on the local mass transfer distributions. Chyu and Natarajan [1] performed comparative mass transfer measurements using the naphthalene sublimation technique for a cylinder, a cube, and a diamond to examine the geometrical effect of three-dimensional single bodies on the wall mass transfer. With liquid crystal and particle image velocimetry experiments, Praisner and Smith [10] studied the dynamics of the horseshoe vortex and associated heat transfer at the cylindrical leading edge of an airfoil. Morie et al. [11] examined the influence of Reynolds number on wall heat transfer near an upstream cylindrical-wall junction. Ghorbani-Tari et al. [2] applied liquid crystals to measure the wall heat transfer of a single

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Nomenclature

A	heat transfer area
D_h	hydraulic diameter of the channel
d	span-wise width of cube
Gr	Grashof number
h	heat transfer coefficient
H	height of channel
H_b	height of cube
I_{ref}	luminescence intensity of TSP at reference temperature
I	luminescence intensity of TSP
L	heated surface length
p	gauge pressure
q_{conv}	heat flux on the wall
Q_c	heat loss by conduction
Q_{el}	input power to the heater
Re_H	Reynolds number
S	inter-body space
$T_{air,x}$	bulk temperature of air at x-position
T_w	wall temperature
t	time
u	local velocity
u_O	mean velocity in the channel
W	width of channel
x	stream-wise direction
y	wall-normal direction
z	span-wise direction

Greek symbols

θ	momentum thickness
μ	dynamic viscosity of air
ν	kinematic viscosity of air

Abbreviations

CCD	charged-couple device
CFD	computational fluid dynamics
RANS	Reynolds average Navier–Stokes
TKE	turbulence kinetic energy
TSP	temperature-sensitive paint
SST	shear stress transport

rectangular body and observed the influence of a corner vortex pair near the upstream junction and downstream region. Recently, Ghorbani-Tari et al. [4] determined the influence of a single rectangular bluff body with different heights on the wall heat transfer using temperature-sensitive paint (TSP) measurements. The above heat transfer studies for a single bluff body with different geometries are summarized in Table 1. As to the case of two bluff bodies-in-tandem, although the literature regarding flow fields is abundant, few data related to wall heat transfer exist. Grannis and Sparrow [12,13] performed experimental and numerical simulations for two diamond-shaped fin geometries; they focused on fluid flow characteristics, and did not consider wall heat transfer. Rosales et al. [14] performed a numerical investigation to analyze the unsteady flow field and heat transfer characteristics for a tandem pair of square bluff bodies in a laminar channel flow; the end wall effect was not considered. Tatsutani et al. [15] reported pressure distributions over square bluff bodies-in-tandem with different height blockage ratios.

In continuation to previous study by Ghorbani-Tari et al. [4], the present study focused on complementary temperature-sensitive paint measurements and computational fluid dynamics (TSP-CFD) analysis of wall heat transfer in three different systems, i.e., a single cube system and two cubes-in-tandem systems with space-to-diameter ratios, S/d, of 3 and 4. Here, the system with a single cube served as the benchmark configuration; the cubes had a square cross section and fully blocked the height of the channel flow. TSP measurements and CFD simulation were then used to determine the wall heat transfer and the time-averaged flow pattern, respectively. Particular attention was paid to wake disturbances resulting from the downstream cube. The wall heat transfer was found to be closely related to the spatial variation of the unsteady two symmetric vortices, which depended on the location of the downstream cube.

2. Experimental apparatus and measurement techniques

2.1. Experimental apparatus

The experimental measurements were performed in an open-circuit, suction-type airflow channel reported by Ghorbani-Tari et al. [4]. The flow channel was built vertically with a total length of 2400 mm and a rectangular cross-section 320 mm in width (W) by 80 mm in height (H). The hydraulic diameter (D_h) of the channel was 128 mm. The channel was manufactured using 10-mm-thick transparent Plexiglas plates to provide optical access for the TSP experiments. The rectangular channel consisted of three sections: a 1165-mm-long inlet section, a 500-mm-long test section ($4D_h$ long), and a 735-mm-long outlet section. The heat transfer experiments were performed in the test section, which was a thin heated plate ($W = 320$ mm and $L = 500$ mm) with lateral and frontal unheated Plexiglas walls. The heated plate was made of a stainless-steel sheet (less than 0.5 mm thick) onto which a plane heating foil was glued to provide a controllable uniform heat flux. The heater was a thin heating foil of etched Inconel® foil (Calesco Norrells, Sweden) packaged into a plastic film. The thickness of the heater was around 0.1 mm. TSP was coated on the stainless-steel sheet on the side exposed to the airflow to measure the wall temperature. The outside of the test section was insulated with thermal insulation material (20 mm thick) to minimize conduction heat loss to the environment. Electric power was supplied by a DC source, and a voltmeter and an amperometer were used to measure voltage and current, respectively. The reference wall temperature was taken using four T-type thermocouples located along the stream-wise direction. A Fluke 2638A digital

Table 1
Summary of experimental wall heat transfer studies for a single bluff body.

Study	Year	Measurement technique (s)	Bluff body configuration
Goldstein et al. [9]	1985	Naphthalene sublimation	Single circular
Yoo et al. [3]	1992	Naphthalene sublimation	Single cube
Chyu and Natarajan [1]	1995	Naphthalene sublimation	Single circular, cube, diamond
Praisner and Smith [10]	2006	Liquid crystal & PIV	Single airfoil
Morie et al. [11]	2007	Naphthalene sublimation & PIV	Single airfoil
Ghorbani-Tari et al. [2]	2013	Liquid crystal	Single cube
Ghorbani-Tari et al. [4]	2017	TSP	Single cube
Present study	2017	TSP	Single cube, cubes-in-tandem