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Computer simulation of momentum and heat transfer across an expanded trapezoidal bluff body

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ABSTRACT

Steady and unsteady forced convection flow and heat transfer past a long expanded trapezoidal bluff body are investigated for the air as working fluid for Re = 1–150. The wake length increases as the Reynolds number increases in the steady flow regime ($1 \leqslant Re \leqslant 47$). The transition from steady regime to unsteady regime occurs between Re = 47 and 48. The total drag coefficient decreases with the increasing value of the Reynolds number up to Re = 90 and thereafter it increases with Reynolds number. However, heat transfer as well as Strouhal number increase with the increasing value of the Reynolds number. The maximum augmentation in heat transfer for the expanded trapezoidal cylinder with respect to the tapered trapezoidal cylinder is found to be approximately 146%. On the other hand, pressure drop shows an enhancement of approximately 97% for the expanded trapezoidal cylinder when compared with the tapered one. Simple correlations of wake length, drag, average Nusselt number and Strouhal number with Reynolds number have also been established.

1. Introduction

The trapezoidal bluff body is a typical configuration of vortex shedding bodies mounted on vortex flow meters and is widely used in various other engineering applications, such as electronic cooling, heat exchange systems, designing of various offshore structures like oil buoys and floating structures, probes and sensors such as convex array ultrasound probe, piezoelectric sensors and so on. The design, construction and operation of vortex flow meters are totally dependent on the trapezoidal bluff bodies. The speed brakes to control the flow through a canal are usually trapezoidal in shape. The flow around such obstacles is more complicated than regular geometries and very limited information is available in the literature. The present work is concerned with the forced convection flow and heat transfer around an unconfined long expanded trapezoidal cylinder in both steady and unsteady regimes. However, it is useful to briefly review the previous works on the momentum and heat transfer around a cylinder of trapezoidal cross-section and the effects of physical parameters on flow and heat transfer characteristics.

Steggel and Rockliff [1] demonstrated the effect of after body geometry on the vortex shedding characteristics of bluff bodies by investigating the viscous flow around rectangles. They stated that the after body geometry has a significant effect on the shedding characteristics due to interaction of the rear edge of the body with the separated shear layer which is formed on the body and which oscillates as a result of the shearing at the rear edge. With longer bodies and with the ones with greater relative vertical dimension at the rear end, the presence of the body surface limits the oscillation and hence the possible lift force is generated. Similarly, Singha and Balachandra [2] investigated the coherent structure statistics in the wake of a sharp-edged bluff body placed vertically in a shallow channel and concluded that the wakes formed behind bluff bodies are found to contain a considerable number of coherent structures of both senses of rotation. The maximum size of the structures can be as big as twice the width of the bluff body.

The vortex shedding from a bluff body of trapezoidal cross-section is experimentally investigated by Goujon-Durand et al. [3]. They obtained the scaling laws for the evolution of the global mode describing the envelope of the peak to peak amplitude velocity oscillation in the wake flow downstream of the body. The early stages of the symmetrical wake flow developments around a tapered trapezoidal cylinder are numerically studied by Lee [4] for Re = 25, 50, 150, 250, 500 and 1000. The flow starts with no separation and the symmetrical standing zone of recirculation develops aft of the trapezoidal cylinder with time. However, no information is provided on the onset of transition to unsteady. Pankanin [5] made a detailed analysis of the various methods of investigating phenomena of the vortex flow meter and observed that the bluff body most suitable

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Nomenclature

a	front side of an expanded trapezoidal cylinder, m
b	rear side of an expanded trapezoidal cylinder, m
c_p	specific heat of the fluid, J kg^{-1} K^{-1}
C_D	total drag coefficient ($= 2F_D/\rho U_\infty^2 b$)
C_{DF}	friction drag coefficient ($= 2F_{DF}/\rho U_\infty^2 b$)
C_{DP}	pressure drag coefficient ($= 2F_{DP}/\rho U_\infty^2 b$)
C_{Drms}	RMS value of the drag coefficient
C_L	total lift coefficient ($= 2F_L/\rho U_\infty^2 b$)
C_{Lrms}	RMS value of the lift coefficient
dP	pressure drop
f	vortex shedding frequency, s^{-1}
F_D	drag force per unit length of the cylinder, N m^{-1}
F_{DF}	friction drag force per unit length of the cylinder, N m^{-1}
F_{DP}	pressure drag force per unit length of the cylinder, N m^{-1}
F_L	lift force per unit length of the cylinder, N m^{-1}
h	local heat transfer coefficient, W m^{-2} K^{-1}
$\bar{h}$	average heat transfer coefficient, W m^{-2} K^{-1}
H	height of the computational domain, m
k	thermal conductivity of the fluid, W m^{-1} K^{-1}
L	length of the computational domain, m
L_r	wake or recirculation length, m
Nu	local Nusselt number (=hb/k)
$\bar{Nu}$	average Nusselt number ($= \bar{h}b/k$)
Nu_{rms}	RMS value of the average Nusselt number
p	pressure, Pa
Pr	Prandtl number (=$\mu c_p/k$)
Re	Reynolds number (=$\rho U_\infty b/\mu$)
St	Strouhal number (=fb/U_∞)
T	temperature, K
T_∞	temperature of the fluid at the inlet, K
T_w	constant wall temperature at the surface of the cylinder, K
t	time, s
U_∞	uniform velocity at the inlet, m s^{-1}
V_x	component of the velocity in the x-direction, m s^{-1}
V_y	component of the velocity in the y-direction, m s^{-1}
x	stream-wise coordinate, m
X_d	downstream distance, m
X_u	upstream distance, m
y	transverse coordinate, m

Greek symbols

μ	viscosity of the fluid, kg m^{-1} s^{-1}
ρ	density of the fluid, kg m^{-3}

for the design of this type of device is a sharp edged trapezoidal cylinder. Chung and Kang [6] studied the variation of Strouhal number from tapered trapezoidal cylinders for the values of Reynolds numbers of 100, 150 and 200 at different height ratios. The Strouhal number has minimum values at height ratios of 0.7 and 0.85 for Reynolds numbers of 100 and 150, respectively. The movement of the flow separation point from the rear to front corners and the change of secondary vortex strength are important factors in determining the shedding structures for Reynolds numbers of 100 and 150. However, no information is available on drag and lift coefficients. Kahawita and Wang [7] carried out the numerical computations of the Benard von Karman hydrodynamic instability behind tapered trapezoidal bluff bodies using the spline method of fractional steps. The influence of the trapezoidal height is dominant on the value of Strouhal number, when compared with the effect of the smaller trapezoidal base width. They also stated that a trapezoidal shape is more desirable than a cylinder, since well-defined vortex emission due to clean separation at its sharp edges is assured. In recent times, Venugopal et al. [8] carried out experimental investigations on the vortex flow meter with the differential wall pressure measurement method. They also demonstrated that the vortex flow meter comprising of a trapezoidal cross-section is one of the major contributors in the field of flow metering. The accuracy, reliability and rangeability are factors which place vortex flow meters ahead of other differential pressure devices. More recently, Dhiman and Hasan [9] demonstrated the flow and heat transfer over a tapered trapezoidal cylinder in both steady and unsteady regimes (Re = 1–150 and Pr = 0.7). The onset of flow separation is observed to exist between Re = 5 and 6. The critical value of the Reynolds number (i.e., transition to unsteady) exists between Re = 46 and 47. The drag coefficient is found to decrease with the increasing Reynolds number in the steady regime; however, the drag is observed to increase with Reynolds number in the unsteady regime. The Strouhal number and the average Nusselt number increase with the increasing value of the Reynolds number.

On the flow around an expanded trapezoidal cylinder, Lee [10] performed the two-dimensional (2-D) numerical study of early stages of an impulsively started unsteady laminar flow past expanded trapezoidal cylinders in another work which concluded that the characteristics of the developing flow recirculation, flow separation and regimes caused by interacting of flows are strongly dependent on the approaching Reynolds number ($25 \leqslant \text{Re} \leqslant 1000$). Chen et al. [11] analyzed the 2-D flow around a porous expanded trapezoidal cylinder using a finite volume method, based on the body-fitted, non-orthogonal grids and multi-block technique. At large Darcy number, the Reynolds number has to be higher before the vortex shedding phenomena occurs and the fluctuation-amplitude of drag coefficient decreases. The effects of the stress jump parameters (related to viscous and inertial effects) are provided for Reynolds numbers of 20, 40, 100 and 200.

Thus, based on the above discussion, it can be stated that very limited work is currently available on the flow and heat transfer around an unconfined expanded trapezoidal bluff body. For instance, only Lee [10] and Chen et al. [11] investigated the flow around an expanded trapezoidal cylinder. However, no information is available on the onset of transition to unsteady and on engineering parameters such as drag and pressure drop. Also, no one dealt with the heat transfer around the expanded cylinder. This

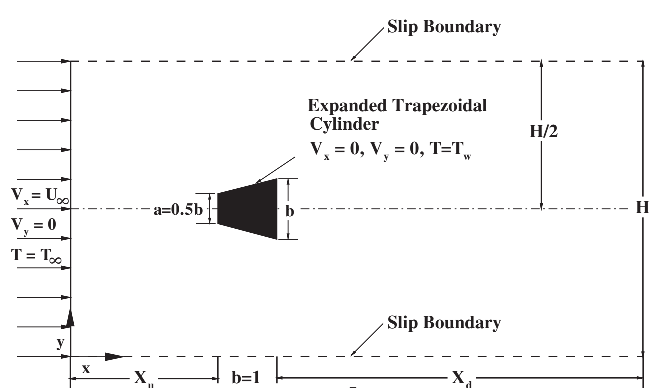

Fig. 1. Schematics of the flow and heat transfer around an expanded trapezoidal cylinder in the unconfined domain.