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Influence of thermal buoyancy on boundary layer separation over a triangular surface

Dipankar Chatterjee [a,*], Sudipta Ray [b]

[a] Simulation & Modeling Laboratory, CSIR – Central Mechanical Engineering Research Institute, Durgapur 713209, India
[b] Robotics and Automation, CSIR – Central Mechanical Engineering Research Institute, Durgapur 713209, India

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ABSTRACT

We endeavour here to elucidate the role of the superimposed thermal buoyancy on the boundary layer separation over a two-dimensional triangular surface. Particular emphasis is given to analyze the response of different orientations of the triangular object with respect to the incoming flow under the action of aiding/opposing thermal buoyancy. The object is placed in a vertical unconfined domain with two different orientations, one when the apex of the object is facing the flow (C1) and the other when one of the bases of the object is exposed to the incoming fluid (C2). A similar study by Chatterjee and Mondal (2014) considering circular and square shaped objects reveals that the steady, laminar and separated flow over the objects at low Reynolds numbers can be degenerated to an attached flow under the action of aiding thermal buoyancy. However, unlike circular/square bodies, the triangular body shows significant deviations in the separation characteristics. The present effort aims at numerically obtaining the critical heating parameters for which the separated boundary layer on the triangular object can be suppressed and analyzing the influence of the object orientation on the thermally induced suppression phenomena. Furthermore, the opposing buoyancy is known to trigger the vortex shedding process at low Reynolds numbers which is already established for circular/square objects. This triggering of vortex shedding over different orientations of a triangular object under the action of opposing buoyancy is numerically demonstrated. The Reynolds number is kept in the range $5 \leqslant Re \leqslant 30$ keeping the Prandtl number fixed at $Pr = 50$ with varying Richardson number. The critical Richardson numbers for the onset of flow suppression as well as the complete suppression of flow separation and the critical Richardson number for the onset of vortex shedding are obtained for the two different orientations of the object. Important inferences are drawn on the fluid dynamic and thermal transport characteristics focussing the separation phenomena. It is observed that the configuration C1 needs more heating than C2 for flow suppression. Also, C1 needs more cooling than C2 for the initiation of the vortex shedding. Such quantification in regard to the critical heating parameters for flow suppression and triggering of vortex shedding over a triangular object is reported for the first time.

1. Introduction

The superimposed thermal buoyancy can inherently be a natural way to control the boundary layer separation over a solid body. When fluid flows over a heated/cooled object, the buoyancy force originates which strongly influences the separation mechanism depending on the direction of interaction of the buoyancy force with the free stream flow. Referring to Fig. 1, depicting flow around a triangular object, the buoyancy may aid or oppose the flow as well as can interact crosswise with the free stream flow. A dual role of the thermal buoyancy can be apprehended depending on the type of interactions. Sometimes, it provides stability to the flow under the aiding buoyancy condition which is established through the suppression of flow separation occurring at relatively low Reynolds numbers (Re) (10–40) [1] and the suppression of vortex shedding at a moderate range of Re (50–150) [2–6]. While acting opposite to the flow direction, the buoyancy destabilizes the flow as established through the initiation of the vortex shedding at relatively lower Re under opposing buoyancy condition [7–9]. For the case of cross-buoyancy, a steady symmetric flow at relatively low Re may become unsteady periodic with vortex shedding by the introduction of thermal buoyancy [10–21], showing once again a destabilizing nature of the buoyancy. Accordingly, there is a dual

* Corresponding author. Tel.: +91 343 6510455; fax: +91 343 2548204.
E-mail address: d_chatterjee@cmeri.res.in (D. Chatterjee).

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Nomenclature

B	buoyancy force, N
C_f	skin friction coefficient, $2\tau_w/\rho v_\infty^2$
C_p	pressure coefficient, $2(p_s - p_\infty)/\rho v_\infty^2$
d	object size, m
f	vortex shedding frequency, Hz
g	gravitational acceleration, ms^{-2}
Gr	Grashof number, $g\beta(T_W - T_\infty)d^3/\eta^2$
h	local heat transfer coefficient, W m^{-2} K^{-1}
H	width of computational domain, m
L_d	downstream length, m
L_u	upstream length, m
k	thermal conductivity, W m^{-1} K^{-1}
L	height of computational domain, m
L_r	dimensionless recirculation length, l_r/d
n_s	direction normal to the cylinder surface
Nu	local Nusselt number, $-\partial\theta/\partial n$
p	pressure, Pa
P	dimensionless pressure, $p/\rho v_\infty^2$
Pe	Péclet number, $Re\ Pr$
Pr	Prandtl number, η/α
Re	Reynolds number, $v_\infty d/\eta$
Ri	Richardson number, Gr/Re^2
St	Strouhal number, fd/v_∞
t	time, s
T	temperature, K
u	cross-stream velocity, ms^{-1}
U	dimensionless cross-stream velocity, u/v_∞
v	stream-wise velocity, ms^{-1}
V	dimensionless stream-wise velocity, v/v_∞
x	cross-stream coordinate, m
X	dimensionless cross-stream coordinate, x/d
y	stream-wise coordinate, m
Y	dimensionless stream-wise coordinate, y/d

Greek symbols

α	thermal diffusivity, m^2/s
β	blockage ratio, d/H
β_T	volumetric expansion coefficient, K^{-1}
η	kinematic viscosity, m^2/s
θ	dimensionless temperature, $(T - T_\infty)/(T_w - T_\infty)$
ρ	density, kg/m^3
τ	dimensionless time, $v_\infty t/d$
τ_w	local wall shear stress, N/m^2

Subscripts

avg	average
cr	critical
w	cylinder wall
∞	free stream

role of the superimposed thermal buoyancy in controlling the boundary layer separation around bluff objects [22]. Such duality cannot be observed in cases of other agents such as rotation [23] and magnetic forces [24] which also influence the boundary layer separation around bluff objects.

It should be emphasized that the low Re laminar flow is always at a high risk of boundary layer separation since the laminar boundary layer can support only a very small adverse pressure gradient without the occurrence of separation. Apart from some real applications in microfluidics and MEMS and some liquid metal flows in nuclear and semiconductor applications, such low Re flows are extremely important fundamentally. Keeping in mind that the boundary layer separation, being a detrimental flow phenomenon in many engineering applications, causing increase of drag, loss of lift and pressure recovery which pose serious challenges to practical engineering applications, a lot of attention is directed to control the flow separation. Application of thermal buoyancy is unarguably a possible way to control the separation. As demonstrated in a recent article by Chatterjee and Mondal [1] the buoyancy can effectively be used to control the flow separation around bluff obstacles such as square and circular objects. For such geometrical shapes, the unconfined flow is steady and separated in the low Re range $10 \leqslant Re \leqslant 40$. Below and above the lower and upper limits, the flow may behave like an attached flow or unsteady periodic flow. With the inception of aiding (object is hotter than the free stream) thermal buoyancy, the recirculation region behind the objects reduces gradually and eventually vanishes completely at some critical strength of the buoyancy. Hence, the separated flow gradually turns into an attached flow due to the application of the aiding thermal buoyancy. The opposed (object is colder than the free stream) buoyancy, on the other hand, can lead to the initiation of the vortex shedding even at such low Re range [7]. We intend here to understand the effect of the aiding/opposing thermal buoyancy on the boundary layer separation over a triangular object. One important difference among the circular/square objects and the triangular one is that the orientation of the triangular object with respect to the incoming flow may offer intriguing fluid dynamics which has already been elucidated in few contemporary articles [25–27]. Hence, the flow which is suppressed or is characterized by vortex shedding for one particular configuration of the triangular object may behave differently for another configuration. We specifically aim to compute the critical heating parameters for suppression of flow separation under the aiding buoyancy condition and the initiation of vortex shedding under opposing buoyancy condition for the two different configurations of the triangular

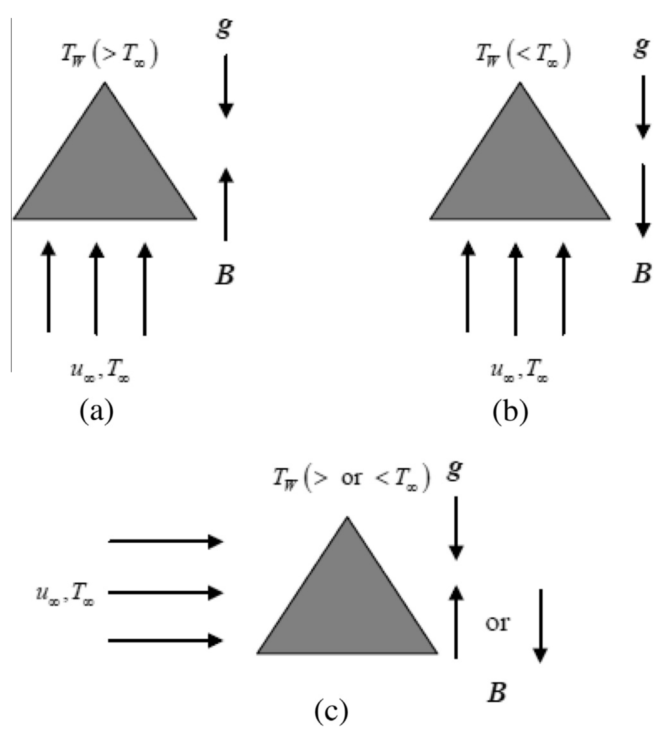

Fig. 1. Interaction between thermal buoyancy and free stream flow, (a) aiding, (b) opposing and (c) cross buoyancy [***g***: gravity, ***B***: buoyancy].