International Journal of Heat and Mass Transfer 105 (2017) 196–206

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Thermal flows around a fully permeable short circular cylinder

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ARTICLE INFO

Article history:
Received 18 August 2016
Received in revised form 28 September 2016
Accepted 28 September 2016

Keywords:
Endwall heat transfer
Horseshoe vortex
Porous media
Through-flow
Wakes

ABSTRACT

Secondary flows and corresponding endwall heat transfer around a fully permeable (porous) short circular cylinder differ from those around an impermeable (solid) cylinder. There exists a through flow which is portion of the mainstream entering the front of the cylinder and exiting at the rear of the cylinder, and the alteration of an adverse pressure gradient along the plane of symmetry that causes three-dimensional boundary layer separation (or forms horseshoe vortices). This study experimentally demonstrates how these distinctive features vary horseshoe vortices, wake patterns, and endwall heat transfer around the porous short circular cylinder. Furthermore, the fluidic effect of the extent of the through-flow that is determined by the permeability of the porous cylinder on downstream heat transfer is discussed.

1. Introduction

Fluid stream that approaches an object protruded from a surface experiences an adverse pressure gradient due to its eventual stagnation on it. At a certain location upstream from the object, the boundary layer separates from the surface. The separated boundary layer rolls up and forms a series of vortices, between the object and the point of separation. In accordance with Kelvin's circulation theorem, the boundary layer vorticity cannot be destroyed. Instead, it is convected around each side of the object to form the two legs of the "horseshoe vortex" (see Fig. 1(a)).

Due to the engineering significance of the horseshoe vortex, its numerous aspects have been studied [1–25]. Fig. 1(b) exemplifies the laminar horseshoe vortex that is composed of three counter rotating pairs. Each pair consists of a larger primary vortex, rotating in a clockwise direction – for the case of the flow moving from left to right – and a smaller secondary vortex that rotates in the opposite direction. It is necessary for the vortices to form in counter rotating pairs in order for the streamline topology, within the separated region, to be preserved [1]. The kinematics of these horseshoe vortices were explained by Baker [2] who detailed how each vortex illustrated in Fig. 1(b) moves and is fed by the freestream.

The minimum number of vortices that can form is two (i.e., a single pair). A single vortex pair (V_1 and V'_1) reported by Visbal [4] was observed at the Reynolds number of $Re_D = 500$. As the Reynolds number increases to $Re_D = 1500$, two vortex pairs are formed until three vortex pairs are formed for the higher Reynolds number of $Re_D = 2500$. The existence of more than 3 vortex pairs is unlikely due to the limited space between the point of boundary layer separation and the cylinder leading edge.

Baker [2] showed that the number of vortex pairs depends on not only the Reynolds number but also the boundary layer displacement thickness for a short cylinder as summarized in Fig. 2. As the Reynolds number is increased, the primary vortex (V_1) becomes unstable, followed by its break-up into two vortices; each with a more stable vortex core [5]. If the Reynolds number is fixed, an increased displacement thickness acts to move the boundary layer separation point further upstream [6]. It is possible that increasing the distance between the separation point and cylinder leading edge, would in some way either delay the instability in the primary vortex or allow for a vortex to remain stable at a higher Reynolds number at its core [6]; resulting in fewer vortex pairs forming.

It has been shown that the horseshoe vortices will not form at all if a cylinder span-to-diameter ratio (or an aspect ratio, l/D) is too small. Akkoka [7] and Mendez et al. [8] both conducted numerical and experimental studies for aspect ratios of $0.116 \leqslant l/D \leqslant 0.265$ and Reynolds numbers of $1200 \leqslant Re_D \leqslant 1460$. They showed that under these conditions, no horseshoe vortices would appear at the juncture. For any $l/D < 0.28$, the boundary layers of the upper and lower endwalls would intersect, likely preventing the formation of the horseshoe vortices. For $l/D > 1.0$, the effect of the cylinder aspect ratio ceases to have a noticeable effect on the separation point or any of the other flow features [9].

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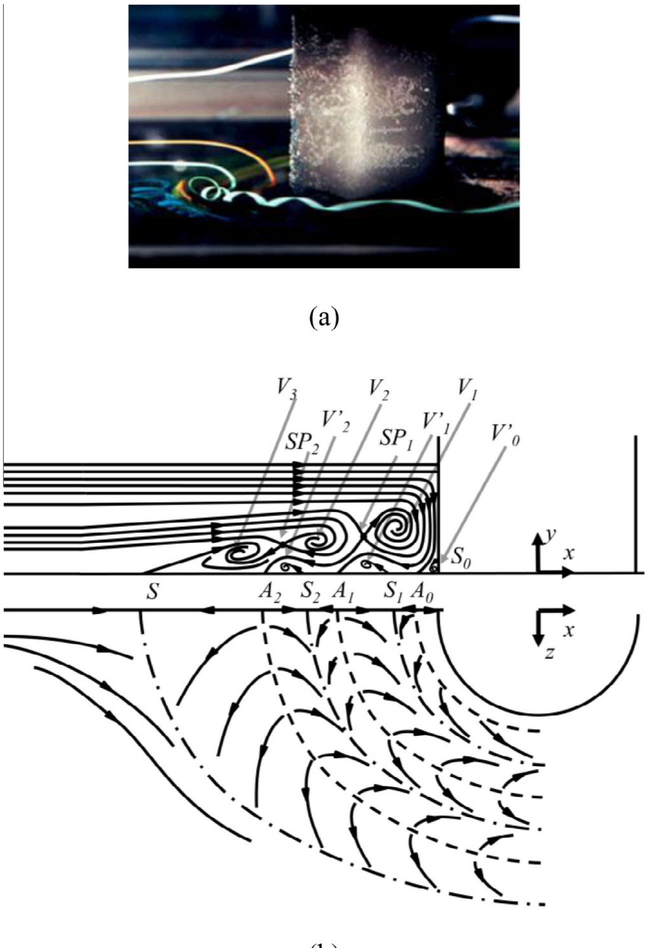
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.09.089
0017-9310/© 2016 Published by Elsevier Ltd.

Nomenclature

A	attachment point
C_p	pressure coefficient
D	cylinder diameter, m
h	convective heat transfer coefficient, W/(m^2 K)
H	channel height, m
l	cylinder length (or span), m
Nu_D	Nusselt number
Re_D	Reynolds number
S	separation point
SP	saddle point
T	endwall surface temperature, K
U	mainstream velocity, m/s
u	local axial velocity, m/s
U_c	centerline velocity at $y = H/2$, m/s
V	vortex
W	channel width, m
x	a longitudinal axis coinciding with fluid stream direction
y	an axis coinciding with the channel height, protruded cylinder span, and normal to the endwall surface
z	a transverse axis coinciding with the channel width
Greek symbols	
τ	wall shear stress, N/m^2
ρ	air density, kg/m^3
δ^*	boundary layer displacement thickness, m
x_s	position of boundary layer separation, m



(a)

(b)

Fig. 1. Horseshoe vortices: (a) visualized horseshoe vortices [1], (b) three vortex pair streamline pattern on the plane of symmetry and endwall for a laminar horseshoe vortex system where V denotes the vortex, S denotes the separation point, A indicates the attachment point, and SP is the saddle point (adapted from Baker [2,3]).

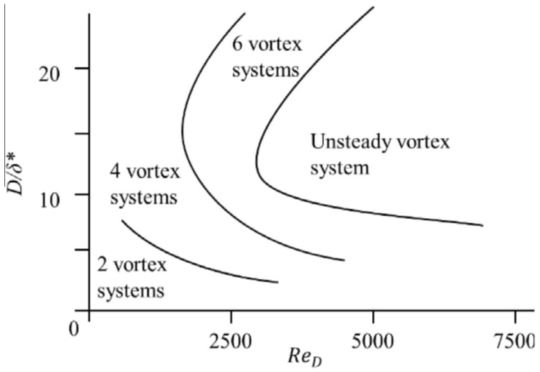


Fig. 2. Variation in number of vortices with a change in Reynolds number and boundary layer displacement thickness where $l/D = 0.5$ [2] and l is the span of the cylinder.

For higher Reynolds numbers, the boundary layer displacement thickness would be smaller and the minimum aspect ratio required for horseshoe vortices to form would, therefore, be smaller as well. Akkoka [7] showed that for aspect ratios of $l/D \geqslant 0.35$, the horseshoe vortex system around the cylinder juncture becomes stable. This was taken as an indication that the vortex system was fully formed with no interaction occurring between the horseshoe vortices forming at the upper and lower endwalls. For this reason, most studies on the horseshoe vortices and corresponding heat transfer effects, make use of obstacles with $l/D > 0.35$, with many using $l/D > 0.5$ [2,10].

The topology and kinematics discussed so far refer to stable horseshoe vortices whereby the vortices do not move or oscillate. Once the Reynolds number increases above a certain value, typically $Re_D \approx 3000$, the vortices begin to oscillate [2]. A splitting and shedding of the vortices downstream of the cylinder is also reported to occur during these oscillations.

There are conflicting reasons given for why the vortices begin to oscillate. It has been concluded, however, by Baker [2], Thomas [11], Agui and Andreopoulos [12], and Fu and Rockwell [13] that the unsteady process is produced by a natural instability of the horseshoe vortex system and not by Karman-vortex shedding in the wake of the cylinder.

Higher Reynolds numbers of the approaching flow result in the approaching boundary layer becoming turbulent, the transition occurring for $400 < Re_{\delta^*} < 1000$ with the flow being accepted as fully turbulent for any Reynolds number $Re_{\delta^*} > 1000$ [9]. When the system becomes turbulent, the flow structure becomes irregular. Time averaged flow visualization on the plane of symmetry has been stated to either indicate no vorticity occurring [14] or form only a single vortex pair [18,19]. Praisner and Smith [17] visualized