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# Characteristics of the wake behind a heated cylinder in relatively high Reynolds number

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ABSTRACT

Thermal effects on the dynamics and stability of the flow past a circular cylinder operating in the forced convection regime is studied experimentally for Reynolds numbers ($Re_d$) between 1000 and 4000, and different cylinder wall temperatures ($T_w$) between 25 and 75 °C by means of Particle Image Velocimetry (PIV). In each experiment, to acquire 3000 PIV image pairs, the temperature and Reynolds number of the approach flow were held constant. By adjusting different temperatures in different Reynolds numbers, the corresponding Richardson number was varied between 0.0 and 0.2. With increasing temperature of the wall cylinder, significant modifications of the wake flow pattern and wake vortex shedding process were clearly revealed. By increasing the Richardson number, the high temperature gradient in the wake shear layer creates a type of vorticity with opposite sign to that of the shear layer vorticity. This temperature gradient-vorticity weakens the strength of the shear layer vorticity, causing delay in reaching the recreation point. In addition to the wake characteristics, it is found that, as the Richardson number is increased, the organization of the vortex shedding is altered and the relative position of the first detached vortices with respect to the second one is changed. This change varies the frequency of the shedding process.



## 1. Introduction

The dynamics and stability of flow over a cylinder, in spite of a wide variety of studies remains a challenging task as a result of the complexity of the flow inside and behind the wake, see e.g. Norberg [1] and Williamson [2] as two extensive reviews on the subject. This turbulent flow is also of great importance due to its widespread practical applications such as heat exchangers [3–5], automotive design [6], and stack towers [7], to name just a few. It is also important on the forces induced by flow on the solid object, heat transfer to or from the object and pollution transfer by fluid flow.

In this flow field, a range of turbulent structures in both the wake region and the region characterized by vortex shedding phenomenon, have been reported before (see e.g. [8,9,2,10,1]), where most of their results were collected in sub-critical flow. Sub-critical flow by definition is the condition at which the boundary layer over the cylinder remains laminar and transition takes place at some points after separation. An excellent review of the vortex dynamics of cylinder wakes and its dependence to the Reynolds number has been provided by Williamson [11]. It was shown that the flow over the cylinder is highly dependent on Reynolds number. At $Re_d = 5000$, the three-dimensionality of characteristics of the wake is changed. This is coupled with rapid structural changes in the wake and large-scale phase dislocation of vortices along the span [1]. This Reynolds number plays a key role in structural analysis as the change-over from the "high-quality" vortex shedding ($Re_d < 5000$) to "low-quality" vortex shedding ($Re_d > 5000$) takes place here. This variation is as a result of the change in the process of transition. In addition to the characteristics of the wake, the shedding process is also of great interest due to the fact that these vortices are detached from the wake, and the characteristics of them are correlated with those in the wake. Detached vortices become stronger and larger by increasing Reynolds number. With $Re_d > 1000$, the shear layer separating from the cylinder surface becomes unstable and well before reaching the supercritical regime, $Re < 3 \times 10^6$, transition to turbulence takes place in the shear layers.

This turbulent flow behind a cylinder becomes more complex when heat is added to the cylinder body. This is because the added heat is carried away by the flow leading to buoyancy-induced instabilities which will interact with the cold (unheated) portion of the flow. High temperature gradient in the wake shear layer

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creates a vorticity with the opposite sign as the main shear layer vorticity, i.e. clockwise vorticity at the upper region of the wake where the main shear layer is counter-clockwise and vise versa in the lower region. This buoyancy-induced vorticity will weaken the shear layer vorticity causing a delay in reaching the recreation point. This type of flow has been the subject of intensive investigations for low Reynolds number flows [12,13], but there are comparatively few studies for heated cylinders at moderate Reynolds numbers [14,15]; yet limited to $Re \sim 700$. As described by Incropera [16], based on the Richardson number ($Ri_d = Gr/Re^2$), heat transfer from a heated cylinder to the ambient could be free, mixed or forced convection. This nondimensionalised number, $Ri_d$, can be thought of as the relative significance of forced or free convection in a way that very low $Ri_d$ values, $Ri_d < 1$, correspond to forced convection and high $Ri_d$ values, $Ri_d > 10$, imply buoyancy-induced flows. $Ri_d$ values falling in the range between 1 and 10, consequently, mark mixed convection flows. In some engineering applications, such as heat exchangers and electronics cooling, a mixture of free and forced convection occurs, and in such cases heat transfer is a function of the Grashof number ($Gr$), the Reynolds number and the Prandtl number ($Pr$) as well as the forced flow direction (with respect to gravity field). In spite of the importance of convection around the cylinders, the effects of the heat on the dynamics of the turbulent structures behind the bluff bodies has not received much attention. Pioneering studies on the subject mainly focused on the effect of heat input on the mean heat transfer coefficient. For instance, according to [17,18], below a critical heat flux, shedding frequency is increased compared to unheated cylinder case for a vertically upward flow past a horizontal cylinder (assisting flow). The behavior of vortex structures shed from a heated cylinder were numerically and experimentally investigated by Kieft et al. [19] and Boirlaud et al. [20]. In the former, the forced and mixed convection has been studied while in the latter study, mixed convection has been investigated. Kieft et al. [19] have shown that within the vortex street a linking between two afterward shed vortices take place where the first detached vortex rotates around the vortex shed from the other side. This pattern is assumed to be caused by a strength difference between the vortices shed from the upper half of the cylinder and the lower half. Note that this phenomenon was observed in low Reynolds number flow. When the heated horizontal cylinder is exposed to a cross-flow, the misalignment between the main flow direction and the buoyant force causes the flow pattern to become asymmetric. In this case, the upper and the lower vortices show different characteristics ([19] and references cited therein). The strength difference of the shedding vortices increased with increasing Richardson number ($Ri_d$). Surprisingly, the detached vortices were found to move down slightly; a rather unexpected behavior considering the upward buoyancy force. The angle between the flow direction and the buoyancy force direction has been studied numerically by Noto [21]. It was shown that the angle of attack has a major influence on the vortex street characteristics for low Reynolds number flows. In a notable study, Park et al. [15] performed digital Particle Image Velocimetry/thermometry at $Re_d = 610$ to obtain a simultaneous velocity-temperature field behind a circular heated cylinder. The focus of the work was, however, on uncertainty analysis and a series of the flow statistics such as temporal average and velocity-temperature correlation field was obtained using the proposed technique. The turbulence characteristics of the flow were not investigated in that study. Later on, in an interesting study, Ohta et al. [14] developed a technique for time-resolved simultaneous measurement of velocity and temperature in the wake region behind a heated circular cylinder in steady and unsteady flow. To understand the mechanism of turbulent heat transfer, the evolutions of vertical and thermal structures were analysed through the proposed technique.

To the best of the authors' knowledge, very little can be found in the literature about the thermal effects on the wake flow behind a horizontal heated cylinder at relatively high Reynolds numbers, e.g. $Re_d > 1000$, which has a wide range of industrial applications. The practical reason for our interest in this problem is our investigation of air-cooled heat exchangers in both mechanical and natural draft cooling towers where the air, moving at a velocity of up to 5 m/s, is usually colder than the cylinder wall by a maximum of 50 °C. As such, we experimentally investigate thermal effects on the turbulent structures of both the wake region and the region past the wake where vortex structures detached from the upper and the lower areas of the wake. We conducted our experiments in wind tunnel, unlike the above-mentioned low-Reynolds experiments in water tunnel. This allows for higher Reynolds numbers at the same flow velocity when compared to identical water tunnel experiments with the same cylinder diameter. The paper includes four sections. In the following section, we describe our experimental facility and provide details of the flow, PIV processing and carry out a brief uncertainty analysis. In Section 3, we show the effects of the heat on the size of the wake created behind the cylinder. Section 3 also contains detailed results from our study on the detached structures past the wake region. We introduce the linear stochastic estimation of the flow pattern around the swirling motion to investigate the relative location of the shedding vortices and to study the effect of the heat on these structures. Finally, we present our conclusions in Section 4.

## 2. Experimental setup

### 2.1. Experimental facility

Experiments were carried out in a square cross-section wind-tunnel as depicted by Fig. 1. The tunnel crosssection is $0.45 \times 0.45$ m$^2$, and the test section is 1.8 m long. Full details of the tunnel and the PIV system, including the test section, can be found in Khashehchi et al. [5].

Optical access is provided through the sidewalls and roof which are all made of glass. The laser sheet illuminated particles from the top panel, and cameras located on the side. The cylinders are positioned horizontally at $x = 300$ mm of the test section. The test section is located between the suction fan and the contraction nozzle, passing the uniform air flow towards the fan. The flow entering the contraction section passes through one honeycomb and few screens, consequently, the free-stream turbulence intensity in the absence of an obstacle (cylinder) is up to 0.5% for the stream-wise fluctuating velocity $u$ and 0.75% for the transverse fluctuating

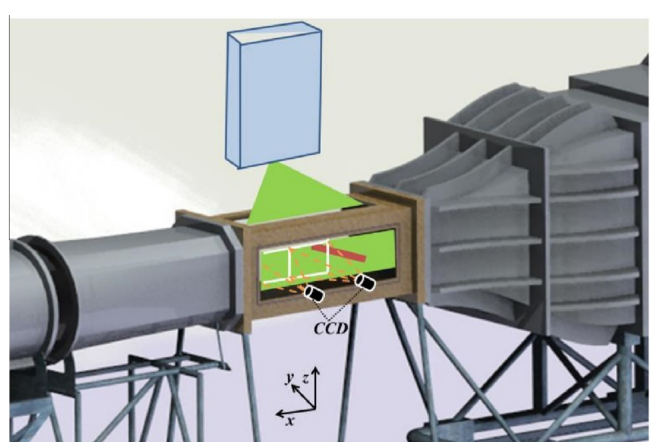


**Fig. 1.** Experimetnal setup.