Experimental turbulent mixed convection behind a heated cylinder

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Abstract. Turbulent mixed convection around a horizontal cylinder at constant temperature exposed to a cross-flow is experimentally investigated by means of flow visualizations, 2D particle image velocimetry and thermocouple measurements. This paper analyses the effect of buoyancy when the wake of the cylinder is 3D and fully turbulent. Within this investigation the Reynolds number was chosen to be 1000 and the Richardson number is taken as 2.77 and 0 for comparison with the isothermal case. Results show that buoyancy effects strongly disturb the wake which becomes asymmetric and undergoes an upward deflection. Flow visualizations show the presence of two kinds of structures in the wake with heating of the cylinder. At the rear of the cylinder, the ambient fluid is subject to a high buoyant force due to the great temperature gradients. These significant gradients allow typical mushroom-like structures to emerge in the near wake region but also several diameters downwards the cylinder. In the lower shear-layer, heating is responsible of the generation of Kelvin-Helmholtz instabilities that usually exist at higher Reynolds numbers under isothermal conditions. Moreover comparison of velocity and temperature fields exhibits an opposite behaviour between velocity and temperature fluctuations in the free shear-layers.

1. Introduction

Flow analysis behind bluff bodies is of great importance from a fundamental or industrial point of view, with outstanding applications in nuclear engineering, external aerodynamics and environmental sciences for instance. Under isothermal conditions, the flow behavior downwards a horizontal cylinder is relatively well-known, see Zdravkovich [1] for a complete review. When temperature between fluid and the cylinder differs, the Richardson number reveals the relative importance between buoyancy and inertia:

\[ Ri = \frac{g \beta (\Delta T) D}{U_\infty^2} = \frac{\text{Buoyancy}}{\text{Inertia}} \]

(1)

where \( g \) is the gravity acceleration, \( \beta \) the volumetric expansion coefficient, \( \Delta T \) the temperature difference between the cylinder and the fluid, \( D \) the cylinder diameter and \( U_\infty \) the flow velocity.

For small temperature difference, the convective flow is known as the forced convection regime. Although buoyant forces are negligible, temperature still modifies the thermo-physical properties of the fluid in the close vicinity of the cylinder. For \( Re < 200 \) and \( Ri < 1 \), Patnaik et al. [2] shed light on
the laminarisation effect downstream from a heated cylinder. They showed that the eddy roll up mechanism is weakened due to cylinder heating until the dynamic vortices degenerate into Föppl vortices, Zdravkovich [1]. Experiments conducted by Lecordier et al. [3, 4] for Re < 200 and Ri < 0.05 shown the great influence of temperature on the wake characteristics even for very low Richardson number. They particularly showed that vortex shedding phenomenon may be suppressed by applying rate of heating sufficiently strong even for Ri < 0.05. So even for small Richardson numbers, effects of laminarization occur, despite temperature is often quoted as a “passive scalar” in the literature [5].

When the Richardson number increases, the regime is known as a mixed convection flow. In such flow, buoyancy term is no more negligible and acts as a source term. Gravity is then responsible of strong flow structure modifications as shown by Bhattacharrya et al. [6] in water for Re < 200 and Ri < 2. In their paper, they numerically showed that buoyancy forces provide an increase of the vortex shedding frequency. This result was also found in air by Biswas et al. [7] who indeed underlined that for Re < 49 the thermal buoyancy brings about asymmetry in the wake and induces unsteadiness. Beyond a critical value of Ri for a given Reynolds number vortex shedding is initiated. Finally, the asymmetry of the wake is also characterized by a lower shear-layer stretched in the direction of the cross-flow and vortices developing in the upper part of the flow with a dipole-like vorticity structure. These typical structures have been clearly identified by several authors in the literature in the Ri < 2 and Re < 200 ranges (Biswas et al. [7], Steenhoven et al. [8], Kieft et al. [9-11]).

Our main target in the present paper is to experimentally study the effects of buoyancy on the turbulent wake of the cylinder for Re∞ = 1000 and Ri = 2.77 and 0 for comparison with the isothermal flow. The study is done only in the mid-plane section (z = 0) as the 3D effects in the transverse direction will be studied later. The organization of this paper is as follows; Section 2 is devoted to the description of the experimental set-up and measurements techniques. Results and their analysis constitute the next section. Finally, some conclusions and perspectives are drawn in Section 4.

2. Experimental set-up and measurements techniques

2.1. Experimental set-up

Experiments were carried out in the low speed open wind tunnel COMIFO of the PPRIME Institute. The working section specific dimensions are: 3000, 1000 and 1000 (in mm) for the length, width and height respectively. Experiments were conducted at Re∞ = 1000, evaluated from the incoming conditions. Under these conditions, the main upstream flow corresponds to 0.3 m/s only and fluctuating intensity at inlet was found to be lower than 2.5%. Based on the cylinder diameter D, the experimental model was a piece of copper cylinder of length L = 20D which is larger than the value of [12]. An electrical cartridge of length l = 10D and an outer diameter d = D/2 provided heating to the cylinder. Due to the great thermal conductivity of the copper, temperature variations along the cylinder surface were considered negligible as the maximum observed variation was less than 3% at Ri = 2.77. End cylinders were used at each end of the cylinder to avoid oblique vortex shedding [13] as shown in Figure 1. The investigated isothermal configuration was conducted to obtain a reference case but also to validate all these flow field behaviour assumptions. Figure 1 presents all the characteristics of the heated cylinder. Three T-type thermocouples with a diameter of 3 mm are located in the cylinder to control its temperature. They were disposed beneath the cylinder surface. A first one is located in the mid-plane (z = 0) and the two other ones are located at each ends of the heating part of the cylinder (at z = -5 and z = 5 respectively). Finally to limit the thermal losses, insulating material composed of aluminium silicates was used at both ends of the heating element. Temperature in the heating source is monitored with time and allows checking the heating stability in time and space.
2.2. PIV measurements

A 2D-PIV system was used to investigate the wake structure behind the cylinder. Figure 2 shows a schematic diagram of the experimental set-up and measurement plane. The standard PIV system consists of a pulsed laser, a camera and a synchronization board - which is located in the Flow Map processor as shown in Figure 2. This unit synchronizes the illumination system and the camera [14]. The Nd:YAG laser (NewWave Solo II) generates laser pulses with a wavelength of 532 nm and light intensity of 2 x 50 mJ. The Hisense camera has a 1080 x 1200 pixels resolution. Standard PIV measurements were performed for 2 cases to examine the effect of buoyancy on the wake flow structure from mixed convection configuration ($Ri = 2.77$) to isothermal configuration ($Ri = 0$).

Particle images were captured at a rate of 4 Hz and each pair of particle images had an interval time ($\Delta t = 32$ ms). Although the low frame rate inherent to such PIV system [15], it still allows us to describe the time-averaged flow structure in term of mean and fluctuating parts. Moreover this acquisition rate allows us to clearly detect the vortex shedding frequency under isothermal conditions. From the captured particle images, instantaneous velocity fields were obtained using a cross-correlation PIV algorithm. The interrogation window size was 32 x 32 pixels and adjacent windows were 50% overlapped. The cylinder wake was illuminated with a 2-mm-thick laser sheet and the field of view was about 180 x 140 mm$^2$. Glycol-water particles with a mean diameter of 1 µm were seeded as tracer particles. A total of 800 successive instantaneous velocity fields were obtained under each set of experimental conditions. All these data were averaged to obtain the spatial distributions of mean velocity and turbulence statistics. To better enhance our understanding, visualizations of the flow structures is directly accessible from PIV pictures and will also be used to globally describe the whole flow behavior.
2.3. Temperature measurements

In order to supplement PIV results and have access to all the scales of the turbulent flow behind the cylinder for the $Ri$ Richardson number of 2.77, temperature measurements in the wake of the cylinder were carried out using a 12.7 μm diameter type K thermocouple which corresponds to a $8.10^{-3}$ s response time for the chosen velocity $U_\infty$. The thermocouple was located on a motorized displacement system. The hot junction was placed in the wind-tunnel section at the measurement point whereas the cold junction was located in the acquisition board with a precision of +/- 1°C. Temperature measurements were carried out in the mid-plane ($z = 0$). For each measurement point temperature signal was decomposed into a mean and a fluctuating part. The signal acquisition was done at a sample rate of 100 Hz with a total of 1024 samples.

3. Results and discussion

3.1. Instantaneous characteristics of the wake structure

To directly exhibit the role of the cylinder heating on the flow field behavior, instantaneous flow visualization pictures extracted from the PIV acquisition at $Ri = 0$ and $Ri = 2.77$ are displayed in Figure 3. Velocities presented here are scaled with the main flow velocity $U_\infty$ and coordinates $x$, $y$, and $z$ are scaled with the diameter $D$ of the cylinder. The frame is centered back to the cylinder location in the $0 < x < 3.5$ zone. Under isothermal condition the instantaneous pictures reveal the development of a large roll-up arising from the upper shear-layer while no such structure is detected in the lower part of the picture at that time step. However, as soon as the upper structure is convected, a similar roll-up structure develops in the lower shear-layer region; this is the very famous Von Karman alley mechanisms [1]. The flow behavior is completely modified in the heating condition. First, PIV particles evaporate at very high temperature and lack of particles in the back of the cylinder confirms that temperature in the fluid exceeds such a threshold value of 110°C. As a consequence,
visualizations of flow pattern are awkward without particles directly in the cylinder back. However convection of hot flow structures in colder flow environment (charged with glycol particles) allows one to qualitatively detect the flow structure. Despite such difficulties, one can be easily observe that under heating condition, the large coherent von Karman structures do not organize anymore and the flow behavior sounds to be much more disorganized than for the isothermal case; in the instantaneous snapshot displayed, two different structures are detected at least. In the upper shear-layer region, a hot fluid structure (called “Type I” structure here) is deviated upward and penetrates in colder region providing from upstream flow from the cylinder almost not deviated by the presence of the cylinder. This upward motion is naturally issued from buoyancy force that competes with inertia. At the same time, characteristic Kelvin-Helmholtz structures (called “Type II” here) are identified in the lower shear-layer region. These structures are also slightly deviated in the y-positive direction.

![Type I and Type II structures](image)

**Figure 3.** Near-wake flow visualizations at $Ri = 0$ (left) and $Ri = 2.77$ (right) in the mid-plane ($z = 0$).

The presence of such structures is usually expected under isothermal conditions at higher Reynolds number [16] from $1200 < Re_\infty < 2400$. The thermal field directly plays a major role in the destabilizing process. In order to underline the strong upward deviation of the flow field, instantaneous flow field visualization was carried out in the $3.5 < x < 7.5$ and $1.5 < y < 4$ zone at $z = 0$, as displayed in Figure 4. From this visualization characteristic mushroom-like structures are clearly identified in the wake of the cylinder. In Figure 4 mushroom cap region is characterized by high temperature because of the lack of seeding particles. The existence of these structure exhibits the strong interaction between buoyancy and inertia as well as the significant unsteadiness of the cylinder wake. These structures are typical from pure thermally driven flows such as thermal plume (Pham et al. [17]) and they arise at the boundary of the wake upward oriented.

![Mushroom-like structures](image)

**Figure 4.** Far-wake region flow visualization at $Ri = 2.77$ in the mid-plane ($z = 0$).
3.2. Mean flow fields
The mean and fluctuating dimensionless velocity components were determined by 2D PIV technique for the two investigated configurations. Averaged data were estimated from 800 instantaneous velocity fields. Figure 5 shows mean and fluctuating dimensionless velocity components in the mid-plane for \( Ri = 0 \) and \( Ri = 2.77 \) at \( x = 2 \).

The most striking feature in the two presented velocity contours is the loss of symmetry in the cylinder wake. For instance, the minimum longitudinal velocity contour \((U)\) is located at \( y = 0 \) for \( Ri = 0 \) whereas it reaches \( y = 0.2 \) for \( Ri = 2.77 \), which also shows the upward deviation of the wake under buoyancy effects. The heated case favors a strong acceleration in the longitudinal direction below the cylinder with maximum velocity reaching 1.6 for \( Ri = 2.77 \) while it does not exceed 1.3 for \( Ri = 0 \). At the same time a deceleration is observed in the upper shear-layer region as the \( U\)-value reaches 0.8 for \( Ri = 2.77 \) instead of 1.2 for \( Ri = 0 \). This phenomenon was also observed experimentally in laminar regime [11]. As the flow that moves beneath the cylinder is significantly heated the buoyant force acquired is important and then the wake is deviated in the \( y\)-positive direction. Mass conservation then demands that more fluid should be transported underneath the cylinder. As the analysis of the \( V\)-mean vertical velocity component shows that the profiles are symmetrical with the point \((0; 0)\) for \( Ri = 0 \) and dissymmetrical for \( Ri = 2.77 \): a net increase of vertical velocity for \( y < 0 \) and \( y > 0 \) is observed due to buoyancy effects.

**Figure 5.** Mean and fluctuating velocity components in the mid-plane section \((z = 0; x = 2)\).

Analysis of \( u'\) profiles shows two peaks corresponding to the shear-layers region (at \( y = 0.9 \) and \( y = -0.8 \)). The \( u'\)-values is larger in the lower shear-layer \((u' = 0.65)\) than the \( u'\)-value for \( Ri = 0 \) \((u' = 0.35)\). For the upper shear-layer the \( u'\) value increases from 0.35 for \( Ri = 0 \) to 0.55 for \( Ri = 2.77 \). In the recirculation zone a diminution of the fluctuating activity is observed for \( Ri = 2.77 \) for \(-0.6 < y < 0.6\). The fluctuating activity is also greater in the lower shear-layer than in the upper one for \( Ri = 2.77 \). Analysis of \( v'\) profiles shows that there is a decrease of the values at the rear of the cylinder \((-0.6 < y < 0.6)\) for \( Ri = 2.77 \) going from 0.38 at \( Ri = 0 \) to 0.25 for \( Ri = 2.77 \). There is also the apparition of two peaks in the shear-layers region (at \( y = -0.7 \) and \( y = 0.7 \)). Decrease of vertical velocity fluctuations...
with heating of the cylinder is also observed in Figure 5. This phenomenon may be linked with the increase of kinematic viscosity as observed by Lecordier et al. [4] in laminar forced convection ($Ri < 0.05$ and $Re < 200$) or with a redistribution of vertical velocity fluctuations ($v'$) towards transversal fluctuations ($w'$) due to 3D effects.

To better understand this wake behavior under significant buoyancy effects, temperature measurements in the wake of the cylinder were carried out for the configuration $Re_\infty = 1000$ and $Ri = 2.77$. Mean temperature was scaled according to the relationship $T = (T^*-T^*_{\infty})/(T^*_{p}-T^*_{\infty})$ where * is the dimensional value and fluctuating temperature $T'$ was scaled by $(T^*_{p}-T^*_{\infty})$. Figure 6 shows the dimensionless mean and fluctuating temperature profiles for three positions: $x = 1; 2$ and $3$.

![Figure 6](image.png)

**Figure 6.** Profiles of mean (A) and fluctuating (B) temperature in the mid-plane ($z = 0$) for $Ri = 2.77$.

From these profiles it is showed that the previous dissymmetry observed on velocity fields still exists. In Figure 6-A, one observes that the upper shear layer is warmer than the lower one and the thermal wake is strongly deviated in the $y$-positive direction. The imbalance between upper and lower rows is observed with a maximum temperature reaching almost 0.19 for the upper shear-layer and 0.11 for the lower one at $x = 2$.

Analysis of fluctuating temperature profiles shows that maximum temperature fluctuations are observed in the upper shear-layer region with the value of 0.09 at $y = 0.8$ and 0.03 at $y = -0.8$ for $x = 1$. Maximum fluctuating level is reached for $x = 2$ and start to decrease for $x > 2$. Under buoyancy effects the location of the maximum fluctuating temperature in the upper shear-layer is deviated upward: from $y = 0.8$ for $x = 1$ to $y = 1$ for $x = 2$ and $y = 1.16$ for $x = 3$. In the same time the temperature fluctuations in the lower shear-layer seem to be constant and located at the same positions ($T' = 0.03$ and $y = -0.8$).

The high degree of temperature fluctuations may be due to the great interaction between the upper shear-layer and the secondary that develop at the rear of the cylinder, Boirlaud et al. [16]. Contrary to velocity fluctuations (Figure 5) temperature fluctuations are greater in the upper shear layer region. That shows that velocity fluctuations are not correlated with temperature fluctuations. This is an unusual but comprehensive result as for such regime temperature is supposed to be not a passive scalar. This particular phenomenon would need to pay more attention and will be the object of next coming studies.

4. Conclusion

Our study focused on the experimental investigation of the turbulent wake of a horizontal cylinder under buoyancy effects. The Reynolds number chosen was equal to 1000 and a Richardson number was equal to 2.77. PIV and temperature measurements in the wake of the cylinder were provided only in the mid-plane section to determine dynamic and thermal effects on the wake structure.

Results show that under buoyancy effects the wake becomes asymmetric, as it is deviated upwards. In the upper shear-layer region, mushroom-shaped structures emerge in the wake of the cylinder. Such structures were already identified in laminar mixed convection flow but not yet in the regime studied. These structures develop not only in the upper shear-layer region but also several diameters.
downwards along the cylinder. Results also show that longitudinal velocity fluctuations are strengthened by thermal field whereas vertical velocity fluctuations are weakened. Such asymmetry is accentuated by the opposite behavior between upper and lower shear-layers. The lower shear-layer is stretched in the main flow direction due to a strong acceleration of the fluid beneath the cylinder, responsible for the appearance of Kelvin-Helmholtz instabilities. The most striking observed phenomenon concerns the loss of correlations between temperature and velocity fluctuations as maximum temperature fluctuations were detected in the upper shear-layer whereas maximum velocity fluctuations were located in the lower shear-layer.

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