The wake behaviour behind a heated horizontal cylinder

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Abstract

The behaviour of vortex structures shed from a heated cylinder is experimentally investigated by means of 2-D particle tracking velocimetry. Within this investigation the \( Re_D \) number was chosen to be 73. The \( Ri_D \) number, the dimensionless number which presents the relative importance of the induced heat, varies between 0 and 1. The experiments were carried out in a large towing tank where the disturbances caused by boundary layers could be minimised. The results show that for small \( Ri_D \) numbers the induced heat results in a deflection of the vortex street in negative y-direction. Within the vortex street a linking of two subsequently shed vortices occurs where the vortex shed from the lower half of the cylinder rotates around the vortex shed from the upper half. These phenomena are assumed to be caused by a strength difference between the vortices shed from the upper half of the cylinder and the lower half. For \( Ri_D \geq 1 \) the effect of the induced heat and buoyancy becomes even more pronounced resulting in a more upwards directed vortex street.

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1. Introduction

The behaviour of the wake behind a heated bluff body is mainly determined by the shed vortices. An early breakdown of these wake vortices for example, strongly influences the mixing behaviour of this wake. Therefore, the cooling performance of another heated component positioned in this wake improves due to a more effective mixing with the relative cold outer region. The fundamentals of this behaviour is investigated by considering the effect of heat on a single cylinder wake. Knowledge of the behaviour of the wake vortices and their influence on the wake properties may lead to a more effective design of compact heat exchangers and small electronic devices.

Most of the work done on the stability of the wake and the behaviour of the shed vortices concerns isothermal cylinder flows. The effect of vibrations [1] and splitter plates [2] on the wake behaviour are studied experimentally, numerically as well as theoretically. The effect of heat on the wake behaviour is one of the topics which recently has been given more attention. Already in the early 1970s it was pointed out that the heat, induced during hot wire velocity measurements, influenced the heat transfer coefficient and the near wake behaviour. Therefore, the induced heat leads to a significant error in the measured velocity for small fluid flows [3]. These investigations, mainly experimental, only dealt with the global effect of the induced heat on the heat transfer coefficient. Much attention was given to the problem under which the flow could be assumed to behave as a forced convection flow. The detailed effects of heat on the cylinder wakes were almost not investigated. In the eighties some numerical calculations were presented which showed the effect of heat on the wake of a horizontal cylinder exposed to an upward cross flow [4,5]. The results show that for increasing heat input the vortex shedding process could be suppressed. Lately these results were verified experimentally [6], where the suppression of the vortex shedding was assumed to be caused by a take over of the buoyant force over the effect of the viscous force as induced by the purely forced convection flows.

The problem discussed in this paper deals with experiments on a heated cylinder positioned horizontally in a cold horizontal uniform cross flow (Fig. 1). In contrast to the problem discussed in [6] the induced heat will cause an asymmetry in the problem.

The flow is assumed to behave according to the Boussinesq approximation, meaning that small density variations, which give rise to a vertical velocity, are

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linearly dependent on the temperature and are only taken into account in the buoyancy forces. All other fluid properties are not affected by the temperature differences, a valid assumption if the temperature variations are not too large. The dimensionless conservation laws for respectively, mass, momentum and energy, now read:

$$\nabla \cdot \tilde{u} = 0,$$

$$\frac{\partial \tilde{u}}{\partial t} + \tilde{u} \cdot \nabla \tilde{u} = -\nabla p + \frac{1}{Re_D} \nabla^2 \tilde{u} + \nabla \tilde{T},$$

$$\frac{\partial \tilde{T}}{\partial t} + \tilde{u} \cdot \nabla \tilde{T} = \frac{1}{Pe_D} \nabla^2 \tilde{T},$$

with $Re_D = Gr_D/Re_D^2$ the Richardson number, $Re_D = \frac{U_0 D}{v}$ the Reynolds number based on the cylinder diameter, $Gr_D = \beta g (T_H - T_C) D^3/v^2$ the Grashof number, $Pe_D = Re_D \cdot Pr = \frac{D}{\nu}$ the Peclet number, $Pr = \nu/\alpha$ the Prandtl number, $\beta$ the expansion coefficient, $g$ the absolute value of the gravity vector, $\alpha$ the thermal diffusivity, $\tilde{g} = (0,1,1)^T$ the gravity vector, $\tilde{T} = (T - T_C)/(T_H - T_C)$ the dimensionless temperature, $\tilde{u}$ the velocity vector and $p$ the pressure.

The main aim of this investigation is to determine experimentally the effect of heat on the 2-D stable wake and the behaviour of the shed vortices as a function of the induced heat. The $Re_D$ number is chosen to be 73 where the $Re_D$ number is varied between 0 and 1. From visualisation experiments it is found out that for these dimensionless parameters the flow does not develop into a 3-D and turbulent flow within the domain of interest. For the investigation an experimental device is developed in which particle tracking velocimetry (PTV) techniques are used to determine the velocity in the wake. First, the experimental set-up and the experimental technique used will be explained. Then the obtained results and the drawn conclusions will be presented.

2. Measuring device and techniques

2.1. Experimental set-up

For the experiments a towing tank is used. By towing the cylinder through the test section a relative velocity of the cylinder with respect to the fluid is generated. The main advantage of this device is a minimal creation of boundary layers and an almost uniform inflow velocity distribution [7]. The specific dimensions of the water tank are for the length × width × height = 500 × 50 × 75 cm³ (Fig. 2).

The test section windows are made out of 15 mm thick glass where special attention has been given to the variation in the glass wall thickness. Those thickness variations can give rise to local lens effects as one moves along the test section window. These lens effects can finally lead to an error for the calculated particle locations and therefore to an error in the calculated velocity. For that reason the thickness variations are not allowed to be more than 50 µm.

Both the camera, used for the PTV experiments, as well as the cylinder are connected to a stiff construction which carries the cylinder and measuring equipment. The carrier is translated along two rails which are mounted on top of the water tank. The cylinder which has a diameter of 8.5 mm and a length of 495 mm, is connected to the construction by two perspex plates (Fig. 3(a)) with specific dimensions for the length × width × height = 50 × 0.4 × 65 cm³. These plates are constructed such that during their translation a minimum of disturbances is created. Besides, these plates also act as end plates which suppress oblique vortex shedding [8] and which insulate the cylinder at the ends.

![Fig. 2. Measuring device.](image)

![Fig. 3. Details of the experimental construction: (a) the carrying construction; (b) configuration of the cylinder.](image)
resulting in an almost uniform temperature of the cylinder wall.

To obtain the desired cylinder wall temperature a rod cartridge heater (Kurvall) is used with a maximum heat density of 8.0 W/cm² and a diameter of 6.35 mm. Around this heating element two copper shields are mounted, the inner shield (Fig. 3(b)) has an outer diameter of 8.0 mm and the most shield an outer diameter of 8.5 mm where the surface roughness of the outer surface is 0.5 µm. The purpose of these shields is to suppress fast temperature fluctuations and to make it possible to position three thermocouples inside the cylinder in order to measure the cylinder wall temperature. These thermocouples are placed at the positions 1, 2, 3 as indicated in Fig. 3(b). All the thermocouples are positioned about 0.250 mm below the outer surface. The thermocouples positioned in 1 and 2 are used to measure the wall temperature and the difference in wall temperature over the cylinder wall. The temperature of the cylinder is kept constant in time by controlling the heat input with the help of the measured wall temperature at position 3.

A characteristic time signal of the thermocouples in positions 1 and 2 (Fig. 4) shows that the temperature difference between the two positions did not exceed 0.2 K. The time variation of the temperature had a typical amplitude of 0.4 K and a typical time scale of 25 s.

The translation of the construction is obtained by an electronic motor which is corrected for its variation in rotational speed by means of a closed circuit, resulting in a variation in the rotational speed of less than 0.2%. The motor is coupled to the drive wheel by using a 1:100 gear. Around the drive and the idle wheel of the translation system an almost inelastic fibre based tape is looped which is finally connected to the camera/cylinder construction.

Although before every experiment the rails were cleaned from dust and lubricated with silicon oil, still some vibration can be found. Previous investigations showed that for certain amplitudes and frequencies these vibrations could influence the vortex shedding process [1,9]. For external vibrations which have a frequency between 0.5 and 2 times the natural vortex shedding frequency (0.15 Hz for ReD = 73), the natural shedding frequency can change into the frequency of the external vibration, a so-called lock-in process. For this process the amplitude of the external vibration needs to exceed a certain threshold which is equal to 0.05D [1]. For larger frequencies the mechanical vibration can still influence the wake, but for this interaction a larger amplitude of the vibration is necessary. In order to verify whether the occurring external vibrations could influence the vortex shedding process test experiments were carried out to measure the amplitudes and the typical frequencies of these vibrations. For these experiments a xyz-acceleration recorder was used which has its sensitivity range between 0 and 100 Hz (directions as defined in Fig. 1). This recorder was positioned on the camera position which is assumed to be a sensitive position with respect to vibration in the construction (due to the free end at which the camera is positioned). From the recorded signals the power spectra of the acceleration in x-, y- and z-directions were calculated (Fig. 5). From these spectra the frequencies and the amplitude of the vibration could be calculated. It turned out that the most significant frequency was 8 Hz for the x-, y- as well as the z-directions and also 6 Hz for the x-direction. Both frequencies had an amplitude over diameter ratio of O<sup>0</sup>10<sup>−3</sup>. In conclusion it is justified to assume that the occurring vibrations are of minor influence on the vortex shedding process.

2.2. Particle tracking velocimetry

The velocity in the wake is measured by means of a PTV method. The particles with a nominal diameter of 100 µm and a density almost equal to the water density, are illuminated in a small light sheet (about 5 mm thick) with help of a 750 W xenon light source. During the
experiments the particles in this light sheet are recorded on a video tape by a 3CCD 512 x 512 monochrome camera. From this tape the particle locations in every video frame are determined by a particle location program. From these calculated particle positions the velocity and particle trajectories are calculated by an algorithm which uses only particles which can be found in at least five subsequent video frames. The velocity \( (U_x, U_y) \) in frame \( i \) is finally calculated by

\[
U_x = \frac{x^{i+2} - x^{i-2}}{4\Delta t}, \quad U_y = \frac{y^{i+2} - y^{i-2}}{4\Delta t},
\]

where the superscript denotes the frame number, \((x^i, y^i)\) the particle location in frame number \(i\) and \(\Delta t\) the time step between 2 subsequent frames. By using this method about 750–1250 velocity vectors per frame can be calculated. The error in the measured velocity vector exists out of two parts; a part which involves the error made during the particle location procedure and an error which occurs due to the inability of particles to follow the flow. The particle location error is determined by the scope of the field (20 x 10 cm²) and the camera resolution. The particle position, which is defined as the volume centroid, is measured on sub-pixel accuracy \[10\]. For the camera used it means \((512 \times 512\) pixels, 25 Hz) that the centroid of the particle is determined with an accuracy of about 6 \(\mu\)m. The error in the velocity vector is therefore 0.015 cm/s, which is about 2% of the main velocity. The incapability of the particles \(D = 100 \text{ \mu m}, \rho \approx 1000 \text{ kg/m}^3\) to follow the flow, leading to a velocity error, is determined by the density difference between the fluid medium and the particles. For the particles used it turned out that this error is at least one order lower than the velocity error due to the particle location error.

The unstructured field of vectors is transformed onto a regular grid which is necessary to calculate the vorticity distribution, and other derived quantities. For this transformation a Gaussian weighting method is used, \[11\] Eq. \(5\):

\[
U_{x,y}(x,y) = \sum_{j=1}^{n} \frac{z_j(x,y) U_x(x_j,y_j)}{\sum_{j=1}^{n} z_j(x_j,y_j)},
\]

\[
z_j(x_j,y_j) = \exp\left(\frac{-(x-x_j)^2+(y-y_j)^2}{4\sigma^2}\right),
\]

where \(n\) denotes the amount of unstructured data points, \(z_j\) the weighting parameter which describes the weighted contribution of a velocity vector on position \((x_j,y_j)\) on the interpolated velocity in a grid point at position \((x,y)\). \(H\) determines the width of the weighting function and is for that reason of strong influence on the obtained interpolated field. It is shown \[12\] that the error made by the weighting procedure has a minimum value if \(H\) is chosen to be according to Eq. \(6\).

\[
H = 1.25 \cdot \delta, \quad \delta = \frac{1}{\sqrt{n}} \sqrt{\frac{A}{N}}
\]

where \(\delta\) describes the average minimum distance between two closest neighbouring points and is calculated by using the total area covered by the test section \(A\) and the total amount of velocity vectors \(N\). This error is strongly dependent on the spatial velocity fluctuations in the domain of consideration. In this experiment the interpolation error for this ratio is estimated to be about 5% of the main velocity \[12\].

For the considered flow the particle density and therefore the local value of \(\delta\) differs strongly in the flow field, especially in the cylinder near wake. From calculation of this local value from the PTV data, it turned out that the local value of \(\delta\) in the cylinder near wake was about 10–15% larger than the value of \(\delta\) if the entire domain was considered. Therefore, the value of \(\delta\) is taken from this local area. The z-component of the vorticity (the only component in a 2-D flow) is calculated on the interpolated regular grid by using a first order central difference scheme.

In order to minimise the effect of random errors the vorticity fields are averaged over 6 samples. For the 2-D problems where the typical time scale is about 6 s this averaging does not influence the observed results.

2.3. Measurements

Before every experiment the tracer particles were suspended and uniformly distributed by stirring the water tank. The experiments were started at least 1.5 h after these particles were added, allowing all fluid motions to damp out.

Although most of the fluid motion vanished during this period still a fluid velocity could be detected. This fluid motion seems to be created by the temperature difference between the fluid inside the tank and the laboratory which give rise to the formation of small convection cells inside the tank. The resulting velocity has a maximum magnitude of about 0.5 mm/s. The spatial size of the observed background motion is relatively large and was observed to be of the same order as the dimensions of the test rig’s cross-section. These observations are in agreement with the results of Anagnostopoulos which are obtained from a similar set-up \[7\].

About 5 min before the actual measurement started the heating element was turned on allowing to stabilise the cylinder wall temperature. As soon as a stable temperature was reached the cylinder was towed through the water tank. Due to this movement the heat transfer coefficient changes resulting in a temporally decrease of the cylinder wall temperature. Therefore, the particle tracking measurements were started after a stable temperature was reached which took about a few minutes. The tracking experiments finally were done for approximately 20 periods of the natural time scale which turned out to be 120 s.

3. Results

The effect of heat on the shed vortices is analysed by comparing the iso-vorticity contours for the different \(R_{iD}\)
numbers (Figs. 6(a), 7(a), 8(a) and 9(a)). For increasing \( \text{Ri}_D \) number the regular pattern of vortices which occurs for \( \text{Ri}_D = 0 \) (Fig. 6(a)) changes into a pattern where two subsequent shed vortices seem to form a linked structure which exists of a lower vortex followed by an upper vortex. Within such a structure the vortex shed from the lower half of the cylinder rotates around the vortex shed from the upper half during the downstream convection.

Fig. 6. Results for \( \text{Ri}_D = 0, \text{Re}_D = 73 \): (a) iso-vorticity contours; (b) trajectories of the vortices analysed for 120 s.

Fig. 7. Results for \( \text{Ri}_D = 1/2, \text{Re}_D = 73 \): (a) iso-vorticity contours; (b) trajectories analysed for 120 s.

Fig. 8. Results for \( \text{Ri}_D = 3/4, \text{Re}_D = 73 \): (a) iso-vorticity contours, (b) trajectories analysed for 120 s.
For increasing $Re_D$ number this rotation effect becomes even more pronounced as can be concluded from Figs. 7(a), 8(a) and 9(a).

Besides the effect described above, a downward movement of the vortex street can be observed. This movement can be seen more clearly by analyzing the trajectories formed by the shed vortices. During a period of about 12 s the movement of the vortices is analyzed by calculating their position every second. The position is defined as

$$X = \frac{\int_\alpha \omega_z (x,y) x \, da}{\int_\alpha \omega_z \, da},$$

$$Y = \frac{\int_\alpha \omega_z (x,y) y \, da}{\int_\alpha \omega_z \, da},$$

with $(x,y)$ a certain position inside the area $\alpha$ which is formed by a closed contour around a vortex. The contour which forms the area $\alpha$ is chosen to be an iso-vorticity contour of value 0.3 (1/s). A larger value should lead to larger errors in the calculated vortex position while a lower value should lead to a stronger influence of the noise on the calculated vortex position. The latter can already be seen in the calculated positions where unphysical vortices are found far outside the vortex street (for example, at $(12,4.5)$ and $(7,5)$, Fig. 8(b)). The obtained accuracy in the calculated vortex position by this choice for the iso-vorticity value, is estimated to be $0.5D$. The large spreading which can still be found in the trajectory plots might be caused by an oscillating behaviour of the entire vortex street. This oscillating behaviour might be caused by the small background motions which occur in the water tank.

The vortex paths, formed by the calculated vortex positions, show for $Re_D = 0$ (Fig. 6(b)) an almost symmetric profile with respect to the $y = 0$ axis. During the downstream convection the vortex paths show only a widening between the paths from the upper and lower vortices. This widening of the vortex street is assumed to be caused by the mutual interaction of the vortices which takes place as soon as their vortex cores, spread out by the viscous effects, reach each other [13]. Although not very clear one can see in the trajectories that the widening starts approximately at $X/D = 10$. For $Re_D = 1/2$, $Re_D = 3/4$ and $Re_D = 1$ the vortices move in negative $y$-direction during their downstream convection, resulting in a bend-off of the vortex street (Figs. 7(b), 8(b) and 9(b)). For $Re_D = 1/2$ both the upper vortex row and lower vortex row are equally deflected in negative $y$-direction, while for $Re_D = 3/4$ and $Re_D = 1$ the lower vortex row is deflected stronger than the upper vortex row. For $Re_D = 1$ the paths of the upper vortices are almost directed horizontally again and a second deflection of the lower vortex row can be observed at $X/D = 15$. Besides, for $Re_D = 3/4$ and $Re_D = 1$ a severe widening of the vortex street takes place.

The relative movement of the shed vortices is analysed by attaching a reference frame to a vortex shed from the upper half of the cylinder (vortex 2, Fig. 10). During the downstream convection the movement of a vortex shed from the lower half (vortex 3, Fig. 10) within the reference frame is presented. These results are only shown for $Re_D = 0$ and $Re_D = 1$ (Fig. 11) in order to emphasise the observed behaviour. The figures present the relative $x$- and $y$-distances ($(X - X_0)/D$ and $(Y - Y_0)/D$) between two subsequently shed vortices (Fig. 10(a)) and two subsequently shed upper vortices Fig. 10(b). In these figures the the first shed vortex is positioned in $(X_0, Y_0)$. For both $Re_D = 1/2$ and $Re_D = 3/4$ a similar but less severe behaviour can be observed.

For $Re_D = 0$, the relative position of the lower vortex with respect to a subsequently shed upper vortex does not change during the downstream convection (Fig. 11(a), +-marks). The centre of the scattered data is approximately $(2.8–1.5)$ which gives a ratio between $x$ and $y$ spacing of $0.5$. This ratio is close to the ratio predicted by von Karman [14] who predicted on the basis of stability of the point vortex street a ratio of 0.56.

For $Re_D = 1$ (Fig. 11(a), *-marks) during the downstream convection a relative movement between the lower and upper vortex was observed (denoted with the arrow in Fig. 11(a)). The lower vortex more or less
rotates around the upper vortex during its downstream movement. This can be seen by the decreasing $X$ distance and increasing $Y$ distance.

From the comparison with the results for $Ri_D = 0$ (Fig. 11(a), +-marks) it can be observed that the relative $x$-distance of a lower vortex with respect to a subsequently shed upper vortex is smaller, even just after the structures are shed. Therefore, one can conclude that those two subsequently shed vortices form a linked structure. This becomes even more clear when the relative movement of two subsequently shed upper vortices is analysed (Fig. 11(b)). Here it can be seen that the relative position of two subsequently shed upper vortices does not change during the downstream convection. Therefore, two subsequently shed vortices form one combined structure while the distance between two of those subsequently shed combined structures remains constant. This behaviour can also be observed in the vorticity contour plots (Figs. 7(a), 8(a) and 9(a)). Remarkable is that the distance between two subsequently shed upper vortices differs only slightly for $Ri_D = 0$ and $Ri_D = 1$ (Fig. 11(b)).

At the calculated vortex position also the vortex strength $\Gamma$ is calculated which is defined in the present study as

$$\Gamma = \int_a \omega_z \, da.$$  \hfill (9)

For the calculation of $\Gamma$ the area $a$ is enclosed again by the vorticity contour $\omega_z = 0.3$ (1/s). Due to viscous effects the vortex cores spread out during their downstream convection. This spreading effect causes the integrated vorticity $\Gamma$, Eq. (9), to decrease while the vortex may be of a constant strength. As it is expected that the viscous diffusion will be hardly affected by buoyancy effects, this definition gives at least an indication of the difference in vortex strength between the upper and lower vortices at different $Ri_D$ numbers.

Although the scatter of the measured strength is quite large (standard deviation of about 15%), the calculated vortex strength shows that for $Ri_D > 0$ (Figs. 12(b) and 13) the vortices shed from the upper half of the cylinder seems to be slightly stronger (negative circulation) than the vortices shed from the lower half. From
the fitted exponential functions (Table 1) it can be concluded that the vortices of both the upper and lower vortex rows are almost equal just after the vortex formation region ($X/D \approx 5$). The measured decay coefficient shows that during the downstream convection of the vortices the strength decay of the lower vortices is larger than for the upper vortices, resulting in a strength difference between the vortex rows.

This can also be seen if the average strength of the vortices over the entire domain ($X/D = [5-20]$) is considered (Table 2). For $Ri_D = 0$ the average strength of both the upper and lower vortices are about equal, while for $Ri_D > 0$ the strength of the upper vortices (negative circulation) is larger than that of the lower vortices.

In order to obtain some knowledge of the occurring time scales the $y$-component of the velocity on the horizontal axis at a downstream position ($x/D, y/D = (7, 0)$) is measured. The power spectrum of this signal (Fig. 14) shows clearly the typical natural frequency ($f$) occurring in the flow field. For $Ri_D = 0$ the Strouhal number (dimensionless natural frequency $Sr_D = fD/\nu$) turned out to be 15.3. For $Ri_D = 1/2$ the $Sr_D$ changes to 16.9 while for $Ri_D = 1$ the $Sr_D$ number was found to be 18.3.

4. Discussion

The presented results show that for moderate $Ri_D$ numbers ($0 < Ri_D < 1$) an increasing heat input results in a deflection of the vortex street in negative $y$-direction and a relative movement of two subsequently shed vortices. These two vortices, one negative and one positive vortex, seem to form a combined linked structure where a strong mutual interaction takes place. This results in a relative rotation of the lower vortex around the

Fig. 12. Vortex strength of the upper vortices (negative circulation) and lower vortices (positive circulation) for $Ri_D = 0$ and $Ri_D = 1/2$: (a) $Ri_D = 0$; (b) $Ri_D = 1/2$.

Fig. 13. Vortex strength of the upper vortices (negative circulation) and lower vortices (positive circulation) for $Ri_D = 3/4$ and $Ri_D = 1$: (a) $Ri_D = 3/4$; (b) $Ri_D = 1$. 
upper vortex. For a relatively large rotation \((\text{Ri}_D = 3/4\text{ and } \text{Ri}_D = 1)\) the mutual interaction of the vortices seems to cause a larger widening of the vortex street. The observed rotation suggests that the upper vortex is slightly stronger than the lower vortex. Measurements of the vortex strength show, though not very pronounced, that a small strength difference occurs for \(\text{Ri}_D > 0\) where the upper vortices are slightly stronger.

If this strength difference which is measured in the experiments, is present it can be shown from a point vortex consideration that this difference causes the vortex street to deflect in the direction of the row with the weakest vortices. This can be understood by considering a small part of a point vortex street (Fig. 15(a)). In the street, which is situated in a potential flow with main velocity \(U_0\), the vortices are distributed regularly over the domain as defined by von Karman [14]. The strength difference \(\Delta \Gamma\) between the upper and lower vortices causes that the lower vortices move slower downstream than the upper vortices. The upper vortices move with a velocity equal to \(U = U_0 - \delta u_1\) and the lower vortices with \(U = U_0 - \delta u_2\), where \(\delta u_2 > \delta u_1\). This results in a distorted situation where the distance between two subsequent vortices (first a lower followed by an upper vortex) becomes smaller (Fig. 15(b)). From this distorted situation it can be seen that the \(y\)-velocity which all vortices induce on each other not entirely cancels out any more as it did in the initial situation. Therefore, a negative \(y\)-velocity \(\delta v_1\) remains which causes the vortex

![Fig. 14. Power spectrum of the measured \(V\)-velocity at \(x/D = 7, y/D = 0\).](image)

<table>
<thead>
<tr>
<th>(x/D = [5-20])</th>
<th>(\text{Ri}_D = 0)</th>
<th>(\text{Ri}_D = 1/2)</th>
<th>(\text{Ri}_D = 3/4)</th>
<th>(\text{Ri}_D = 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Gamma^+) (cm²/s)</td>
<td>1.9</td>
<td>1.8</td>
<td>1.7</td>
<td>1.6</td>
</tr>
<tr>
<td>(\Gamma^-) (cm²/s)</td>
<td>-1.9</td>
<td>-2.1</td>
<td>-1.9</td>
<td>-1.8</td>
</tr>
</tbody>
</table>

Table 2
Average circulation over the entire domain

![Fig. 15. Bend-off of the vortex street due to strength differences: (a) the initial situation; (b) distortion of the position in \(x\)-direction resulting in a \(r\)-velocity; (c) deflection of the vortex street.](image)
street to deflect in the direction of this velocity (Fig. 15(c)).

The deflection of the vortex street for \( Ri_D = 1/2 \) is larger than for \( Ri_D = 1 \). The larger bend-off is in agreement with the measured average vortex strength which shows for \( Ri_D = 1/2 \) a larger difference between the upper and lower vortex street than for \( Ri_D = 1 \). Besides, the trajectories of the upper vortices are less deflected for \( Ri_D = 3/4 \) and \( Ri_D = 1 \) than for \( Ri_D = 1/2 \). The smaller deflection of the upper vortex row might be induced by the increasing influence of the buoyancy forces.

5. Practical significance

Knowledge of the vortex structure behaviour inside the wake of heated objects is of practical interest to the cooling performance of downstream components. Quantities such as surface pressure and heat transfer of downstream components are directly coupled to the characteristics of the shed structures of the upstream component. Consider for example the situation where two cylinders are placed behind one another. If a vortex structure shed from the upstream cylinder collides with a downstream cylinder, a temporary decrease in heat transfer and surface pressure on the wall of the downstream cylinder occurs. The magnitude of this decrease is determined by the relative position of the downstream cylinder with respect to the upstream one. The presented results show that if the second cylinder is placed slightly lower than the first cylinder, the decrease in heat transfer will be most significant.

6. Conclusion

The experiments showed that for a positive heat input where the \( Ri_D \) numbers varied between 0 and 1, the wake behind a heated cylinder deflects in the direction of the gravity vector (negative y-direction), a rather strange phenomenon considering the effect of buoyancy which acts just the other way round. It was found that this deflection, which is strongest for \( Ri_D = 0.5 \), occurs due to a strength difference between the vortices from the upper row and the lower row, where the latter turned out to be the weakest. For higher \( Ri_D \) numbers the effect of buoyancy increases, resulting in a smaller deflection of the vortex street.

This strength difference between the shed vortices, which occurs for increasing heat input, might be caused by an additional vorticity production. From the vorticity equation for a 2-D flow problem one can see that vorticity can only be produced within the flow field due to the baroclinic term \( \nabla \rho \times \nabla P/\rho^2 \). Measurements of the pressure gradient as well as the density gradient are hard to carry out. More detailed insight into the vorticity distribution as well as the vorticity production will hopefully be acquired from numerical simulations. Besides, the future simulations will also be used to evaluate the wake influence on the local heat transfer and pressure distribution on downstream placed cylinders. The physical relationship between the vortex structures shed by the first cylinder and the heat transfer and surface pressure at the second cylinder wall can then be determined with a high order of accuracy.
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