FLOW VISUALIZATION AND SIMULTANEOUS VELOCITY AND TEMPERATURE MEASUREMENTS IN THE WAKE OF A HEATED CYLINDER

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ABSTRACT
A novel optical diagnostic technique, Molecular Tagging Velocimetry and Thermometry (MTV&T), was used for qualitative flow visualization and quantitative simultaneous measurements of velocity and temperature fields in the wake of a heated cylinder. The experiment was conducted in a water channel with the heated cylinder placed horizontally in the middle of the water channel, and the flow being vertically downward to approach the heated cylinder. The temperature of the heated cylinder varied during the experiment, with the corresponding Richardson number (Ri) varying between zero (unheated) and unity. The heat transfer process around the heated cylinder changed from forced convection regime to mixed convection regime. With increasing Richardson number, significant modifications of the wake instability were revealed from both qualitative flow visualization images and quantitative simultaneous velocity and temperature fields.

1 INTRODUCTION
An understanding of the flow around a bluff body is of great importance due to its fundamental nature as well as many related engineering applications. A circular cylinder is a most commonly studied bluff body. Despite its simple shape, a circular cylinder generates a wake that is dynamically complex. By varying the Reynolds number, a variety of flow patterns and vortex shedding characteristics in the wake of a circular cylinder have already been observed and discussed in literature.

The wake behavior behind a heated circular cylinder is physically more complicated due to the buoyancy effect added to the viscous phenomena. The heat transfer from the surface of a heated cylinder to surrounding fluids can be either pure forced convection, free convection or mixed convection depending on the Richardson number (Ri = Gr/Re^2) [1]. In the forced convection regime (Ri << 1), where the effect of buoyancy is neglected, the heat transfer is a function of Reynolds number (Re = ρUD/μ) and the Prandtl number (Pr = ν/κ). In free convection regime (Ri >> 1), where forced convection is negligible, the heat transfer is a function of the Grashof
number \( (Gr = g\beta(T_w - T_f)D^3/\nu^2) \) and the Prandtl number (Pr). In the mixed convection regime, both forced convection and free convection are important, and the heat transfer is a function of the Grashof number (Gr), the Reynolds number (Re), the Prandtl number (Pr) and the approaching flow direction. Despite the fact of that mixed convection around bluff bodies is of great importance for various engineering applications (for example, electronics cooling, compact heat exchangers, etc.), the thermal effect (buoyancy effect) on the wake stability of a bluff body in mixed convection regime has received little attention compared to that in forced convection regime.

When a heated cylinder operates in the mixed convection regime, the buoyancy force can play an important role in the wake flow pattern. For a horizontal heated cylinder, the flow approaching the heated cylinder can be either horizontal, parallel (vertically upward) or contra (vertically down), and this defines the angle between the direction of buoyancy force acting on the fluids around the heated cylinder and the approaching flow direction.

In the present study, the effect of buoyancy on the wake instability of a heated cylinder exposed in a contra flow is investigated experimentally. A novel optical diagnostic technique, Molecular Tagging Velocimetry and Thermometry (MTV&T), was used for qualitative flow visualization and quantitative simultaneous measurements of velocity and temperature fields in the wake of the heated cylinder.

### 2 MOLECULAR TAGGING VELOCIMETRY AND THERMOMETRY TECHNIQUE

The Molecular Tagging Velocimetry and Thermometry (MTV&T) technique used in the present study is a novel molecule-based flow diagnostic technique. Instead of using particle tracers, MTV&T technique utilizes same phosphorescent molecules, which can be turned into long lifetime tracers upon excitation by photons of an appropriate wavelength, as tracers for both velocity and temperature measurements.

Supramolecules of phosphorescent triplex (1-BrNp-Gβ-CD-ROH) were used as molecular tracers in the present study. The phosphorescent triplex is actually the mixture of three different chemicals, which are lumophore (indicated collectively by 1-BrNp), glucosyl-β-cyclodextrin (indicated collectively by Gβ-CD) and alcohols (indicated collectively by ROH). In the present study, we used a concentration of \(2\times10^{-4} \text{ M} \) for Gβ-CD, a saturated (approximately \(1\times10^{-5} \text{ M} \)) solution of 1-BrNp and a concentration of 0.06 M for the cyclohexanol (ROH), as suggested by Gendrich et al. [2].

#### 2.1 Flow velocity measurement

The methodology of the MTV&T technique is actually an extension of Molecular Tagging Velocimetry (MTV) technique [3, 4], which can be thought as the \textit{molecular} counterpart of the Particle Imaging Velocimetry (PIV) technique for the velocity field measurement of a fluid flow. Compared with PIV, MTV offers advantages in situations in which the use of seed particles is either not desirable or may lead to complications. MTV has been developed and extensively used to conduct investigations of fundamental flow phenomena and applied fluid engineering problems over the past several years.

Figure 1 shows an example of the MTV measurement of a vortex ring impacting a solid wall at normal incidence [2]. The figure shows both the initially tagged regions and their subsequent...
evolution after a time delay, together with the resultant velocity vector field derived from the image pair using a spatial correlation method.

For the velocity measurement, MTV utilizes only the information about the spatial distributions of the photoluminescence of the “tagged” molecules to determine the displacement vectors of the “tagged” regions between the two interrogations. The simultaneous temperature distribution of the fluid flow can be extracted from the information about the photo-luminescence intensity decay of the “tagged” molecules.

![Typical MTV image pairs and the resultant velocity field.](image)

2.2 Flow temperature measurement

According to quantum theory [5], for a diluted solution and unsaturated laser excitation, the decay of phosphorescence emission intensity follows an exponential law, and can be expressed as:

\[ I_p = I_i C \varepsilon \Phi_p e^{-t/\tau} \]  

where \( I_i \) is the local incident laser intensity, \( C \) is the concentration of the phosphorescence dye, \( \varepsilon \) is the absorption coefficient of the phosphorescence dye, \( \Phi_p \) is phosphorescence quantum yield, and \( \tau \) is the lifetime of the phosphorescence emission, which refers to the time when the intensity drops to 37% (i.e. \( 1/e \)) of the initial intensity.

For some phosphorescent dyes like the phosphorescent triplex (1-BrNp-Gβ-CD-ROH) used in the present study, the phosphorescence quantum efficiency (\( \Phi_p \)) and the lifetime of the phosphorescence emission (\( \tau \)) are temperature dependent. Therefore, the phosphorescence intensity may be considered, in principle, to depend only on temperature if the excitation laser intensity is uniform and the phosphorescent dye concentration remains constant in the measurement region.

By referring phosphorescent emission intensity directly to temperature, Thomson and Maynes [6] have demonstrated the possibility of fluid temperature measurement by measuring the phosphorescence intensity of the phosphorescent triplex (1-BrNp-Gβ-CD-ROH). It should be noted that since the phosphorescence intensity is also the function of incident light intensity, therefore, the spatial and temporal variations of the incident light intensity would have to be corrected for
separately in order to extract quantitative temperature data from phosphorescence images by using the method suggested by Thomson and Maynes [6]. However, in practice, it is very difficult, if not impossible, to ensure a non-varying laser illumination intensity distribution, especially for unsteady flows with index of refraction variations. This may cause significant error in the temperature measurement.

In order to overcome this problem, a novel ratiometric technique, named as lifetime imaging technique, was developed recently by the authors [7, 8], which achieves the quantitative temperature mapping of a fluid flow by taking advantage of the temperature dependence of the phosphorescence lifetime of the phosphorescent triplex (1-BrNp-Gβ-CD·ROH).

Figure 2 shows the calibration curve of the phosphorescence lifetime of the phosphorescent triplex (1-BrNp-Gβ-CD·ROH) changing with temperature. It can be seen that the phosphorescence lifetime of the phosphorescent triplex (1-BrNp-Gβ-CD·ROH) varies significantly with increasing temperature. The relative temperature sensitivity of the phosphorescence lifetime ranges about 5.0% per degree at 20.0 °C to about 20.0% per degree at 50.0 °C. The temperature sensitivity is much higher than those of most commonly used LIF dyes. Further information about the calibration experiment and procedure is available at [7, 8].

In summary, the MTV&T technique achieve the simultaneous measurements of velocity and temperature in fluid flows by using a pulsed laser to “tag” the regions of interest. The tagged regions are interrogated at two successive times within the lifetime of the photoluminescence of the tracer molecules. The measured Lagrangian displacement vector of the “tagged” molecules between the two interrogations provides the estimate of velocity vector. The simultaneous temperature measurement is achieved by taking advantage of the temperature dependence of phosphorescence lifetime, which is estimated from the phosphorescence intensity ratio of the two interrogations.

Fig. 2 Phosphorescence lifetime versus temperature profile
3 EXPERIMENTAL SETUP AND FLOW CONDITIONS

A schematic of the experimental setup used in the present study is shown in Fig. 3. The experiment was conducted in a small vertical water channel. A constant head tank with an overflow system was used to maintain a constant flow condition in the water channel during the experiment. The aqueous solution of the phosphorescent triplex (1-BrNp-Gβ-CD-ROH) in the constant head tank was filled from a reserve tank by an electric pump. Honeycomb and mesh structures were used at the inlet of the water channel to insure a uniform flow condition at the upstream of the test cylinder. A copper tube with outer diameter of 4.76mm ($D = 4.76\text{mm}$) and inner diameter of 4.00mm was used as the test cylinder in the present study. A rod cartridge heater (Watlow Firerod™) with the outer diameter of 3.1mm was stuffed inside the copper cylinder to obtain the desire cylinder temperature. High thermal conductivity paste (OMEGATHERM 201) was pressed in to fill the gap between the cartridge heater and the inner wall of the test cylinder. Two J-type thermocouples were embedded in the gap at mid-span of the heated cylinder. The thermocouples were connected to a two-channel thermometer (Omega HH23), which has a resolution of $\pm 0.1 \, ^\circ\text{C}$, to monitor the temperature of the test cylinder.
A Lambda-physik XeCl Excimer UV laser (wavelength $\lambda = 308$ nm, energy 100 mJ/pulse, pulse width 20ns) with a set of optics was used to generate illuminating grids in the measurement region to achieve qualitative flow visualization and simultaneous quantitative measurements of velocity and temperature fields in the wake of the test cylinder. A 12-bit ($1280 \times 1024$ pixels) gated intensified CCD camera (PCO DICAM-Pro) was used in the present study to conduct image recording. The camera was operated in the dual-frame mode, where two full-frame images of phosphorescence were acquired in quick succession from the same laser excitation pulse. The laser and the camera were synchronized using a digital delay generator (SRS DDG535), which controlled the timing of the laser illumination and the CCD camera data acquisition.

In the present study, the heated cylinder was placed horizontally in the middle of the water channel, and the approaching flow is vertically downward. Such arrangement makes the heated cylinder operates in a contra flow, i.e. the direction of the approaching flow opposes the direction of the buoyancy force acting on the fluid around the heated cylinder. The velocity of the approaching flow was $U_\infty = 0.0255$ m/s. The temperature of the approaching flow in the constant head tank was $T_0 = 24.0$ °C. The corresponding Reynolds number is $Re_D = \frac{\rho U_\infty D}{\mu} = 130$. During the experiment, the temperature of the test cylinder was changed at several temperature levels, which varied from 24.0 °C (unheated cylinder) to 85.0 °C. The corresponding Richardson number ($Ri_D$) changes from 0.0 to 1.05. With increasing Richardson number, the heat transfer process around the heated cylinder changes from force convection regime to mixed convection regime.

4 EXPERIMENTAL RESULTS AND DISCUSSIONS

Figure 4(a) and 4(b) show a typical pair of phosphorescence images for the qualitative flow visualization and simultaneous quantitative MTV&T measurement in the wake of the heated cylinder when the temperature of the heated cylinder was $35.0$ °C ($Ri = 0.19$). The resultant velocity vectors derived from the image pair by using a cross-correlation method is shown in Fig. 4 (c).

In the phosphorescence images, well defined structures in the form of “dark clusters” can be seen clearly in the wake region of the heated cylinder. The “dark clusters” are actually the warmer fluid shedding periodically from the hot boundary layer around the heated cylinder. As mentioned above, the phosphorescence intensity of the phosphorescent triplex (1-BrNp-Gβ-CD-ROH) is temperature sensitive, the warmer phosphorescent triplex molecules from the hot boundary around the heated cylinder served as tracers to visualize the alternative shedding of “Karman” vortices in the wake of the heated cylinder. Since the phosphorescence intensity of the warmer phosphorescent triplex molecules decays faster than that in ambient fluid, the “dark clusters” are revealed more clearly in the second phosphorescence image than those in the first image.

In order to construct simultaneous temperature field from the phosphorescence images, small interrogation windows were chosen in the first phosphorescence image. The corresponding positions of the interrogation windows in the second phosphorescence image were determined based on the measured velocity vectors as shown in Fig. 4(c). The phosphorescence lifetime of the “tagged” phosphorescent triplex molecules contained in each interrogation window was calculated based on the intensity ratio of the interrogation windows in the first and the second phosphorescence images. Then, the simultaneous temperature field was constructed by using the calibration curve of
phosphorescence lifetime versus temperature shown in Fig. 2. The resultant temperature distribution extracted from the phosphorescence image pair is shown in Fig. 4(d).

Corresponding to the “dark clusters” in the phosphorescence images, two sets of “warm blobs” at the two sides of the heated cylinder can be seen clearly in the temperature distribution, which are generated by the periodical shedding of the warmer fluids from the hot boundary layer around the heated cylinder. The “warm blobs” and the heated cylinder were connected by “braids” at the two sides of the heated cylinder. The “warm blobs” were found to grow in size as they traveled downstream. It should also be noted that even although the difference of the fluid temperature in the wake of the heated cylinder is quite small for this case (only about 2.0 °C), the shedding of the warmer fluid in the form of “warm blobs” can still be revealed very clearly in the simultaneous temperate distribution by using the present MTV&T technique.

Based on 360 frames of instantaneous measurement results, the ensemble-averaged velocity and temperature distributions in the wake of the heated cylinder were calculated, and the result is shown in Fig. 4(e) and Fig. 4(f). A recirculation zone at the downstream of the heated cylinder with a length of about 3 diameters is revealed clearly in the ensemble-averaged velocity field. The ensemble-averaged temperature field reveals that high-temperature regions exist at the two sides of the wake region, which are corresponding to the shedding paths of the “Karman” vortices and “warm blobs” revealed in the instantaneous measurement results.

Figure 5 shows the phosphorescence images and the corresponding MTV&T measurement results in the wake of the heated cylinder when the temperature of the heated cylinder increased to 53.0 °C (Ri = 0.50). Compared with the case of smaller Richardson number (Ri=0.19) described earlier, the shedding process of the “Karman” vortices and “warm bulbs” in the wake was found to change greatly due to the stronger buoyancy effect. Although the shedding of the “Karman” vortices and the “warm blobs” still occur alternatively at the two sides of the heated cylinder, the shedding process was found to be “delayed”, and the location of the first appearance of the concentrated “Karman” vortices and the “warm blobs” was pushed further downstream. The “braids”, which are the connection between the “warm blobs” and the heated cylinder, were found to become much longer and thicker. The ensemble-averaged velocity and temperature distributions revealed that the recirculation zone at the downstream of the heated cylinder become much wider and longer compared that of the $Ri_p = 0.19$ case.

Figure 6 shows a pair of typical phosphorescence images and the resultant MTV&T measurement results in the wake of the heated cylinder when the temperature of the heated cylinder increased to 85.0 °C ($Ri = 1.05$). The flow pattern and the vortex shedding in the wake of the heated cylinder for this case were found to be very different from the cases described before. Rather than having alternative shedding of vortical structures or “warm blobs”, the shedding of the vortical structures or “warm blobs” were found to occur almost concurrently at the two sides of the heated cylinder. The sizes of these vortical structures were found to be smaller than that of the cases with smaller Richardson number, and they behaved more like “Kelvin-Helmholtz” type structures rather than “Karman” type vortical structures. The adjacent smaller vortical structures or “warm blobs” at the same side were found to merge together to form bigger vortical structures or larger “warm blobs” at further downstream. The merge process is quite similar to the “pairing process” of “Kelvin-Helmholtz” vortical structures. The merge processes of the smaller vortical structures and “warm blobs” were found to occur alternatively at the two side of the heated cylinder, which resulted in the alternative shedding of bigger vortical structures and larger “warm blobs” at far field.
Fig. 4 MTV&T measurement results ($T_c = 35.0 \degree C$, $Ri=0.19$)
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a. first image (1ms after laser pulse)  
b. second image (6ms after laser pulse)  

c. instantaneous velocity field  
d. simultaneous temperature field  

e. averaged velocity (U, V)  
f. averaged temperature (T)  

Fig. 5 MTV&T measurement results ($T_c = 53.0^\circ C$, Ri=0.50)
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Fig. 6  MTV&T measurement results ($T_c = 85.0 \, ^\circ C$, $Ri=1.05$)
The ensemble-averaged velocity and temperature distributions shown in Fig. 6(e) and Fig. 6(f) revealed that the wake region of the heated cylinder becomes even wider and longer at this Richardson number \((R_i = 1.05)\). The recirculation zone downstream of the heated cylinder become so long that its length was about 10 cylinder diameters.

Based on the time sequence of the instantaneous MTV&T measurement results, the shedding frequency of the “Karman” vortex structures in the wake of the heated cylinder can be obtained. The corresponding Strouhal number, defined as \(St = fD/U_\infty\), is shown in Figure 7. In the present study, the horizontal heated cylinder is placed in a vertically downward flow, i.e., in a contra flow. According to the results shown in Figure 7, the Strouhal number of the vortex shedding in the wake of the heated cylinder is found to decrease with the increasing Richardson number. The numerical results of Chang and Sa [9] for a cooled cylinder placed in a contra air flow at the Reynolds number of \(Re=100\) is also shown in the figure. It can be seen that both the present experimental data and the numerical simulation results of Chang and Sa [9] revealed the same decreasing trend of the Strouhal number of the vortex shedding with the increasing Richardson number when a horizontal circular cylinder is placed in a contra flow, where the direction of the buoyancy force acting on the fluids being reverse to the approaching flow.

![Fig. 7 The change of Strouhal number (St.) with Richardson number (Ri)](image)

5 CONCLUSIONS

The effect of buoyancy on the wake instability of a heated circular cylinder in a contra flow arrangement is investigated experimentally in the present study. A novel optical diagnostic technique, Molecular Tagging Velocimetry and Thermometry (MTV&T), was used for qualitative flow visualization and quantitative simultaneous measurements of velocity and temperature fields in the wake of the heated cylinder. The experiment was conducted in a water channel with the
temperature and Reynolds number of the approaching flow being held constant at $T_\infty = 24^\circ C$ and $Re = \rho_\infty DU_\infty / \mu_\infty = 130$. The temperature of the heated cylinder varied between $24^\circ C$ (unheated cylinder) and $85^\circ C$, corresponding to a Richardson number ($Ri$) varying between zero (unheated) and unity. The heat transfer process around the heated cylinder changes from the forced convection regime to the mixed convection regime over the range of Richardson number investigated.

Due to the effect of buoyancy force, the wake instability behind the heated cylinder was found to become much more complicated compared with that behind an unheated cylinder. With the increasing Richardson number, significant modifications of the wake instability were revealed from both qualitative flow visualization images and quantitative simultaneous velocity and temperature fields. The thermal effect (buoyancy effect) on the wake instability of the heated cylinder was discussed in the terms of vortex shedding pattern and vortex shedding frequency.

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