

DEVELOPMENT OF A TEMPERATURE MEASUREMENT TECHNIQUE USING MOLECULAR TAGGING VELOCIMETRY

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Abstract

A summary of the development of a method of measuring fluid temperature with a laser is presented. The method is based on molecular tagging velocimetry (MTV), an established technique of obtaining spatially-resolved fluid velocity profiles by analysis of laser-induced molecular phosphorescence emitted by photoluminescent chemicals. In aqueous solutions the intensity of the phosphorescent emission is inversely related to the temperature of the fluid. Research into quantifying the relationship between the solution temperature and emission intensity has resulted in the development of a calibration curve which may be used for subsequent temperature measurements. Error analysis shows that temperatures may be determined over a range of nearly 30°C with a typical error of less than ±2.66%, or ±0.8°C, with a 95% confidence level. A discussion of the technique development, including experimental methods, calibration curve development, and error analysis, is here presented.

Nomenclature

κ	Thermal diffusivity
I'	Normalized beam intensity
T	Fluid temperature
T'	Normalized fluid temperature
t	Time
u_j	j^{th} velocity component
x_j	j^{th} directional component

Introduction

Many situations involving fluid flow require that temperature and velocity data be known in order for the flow to be understood. This understanding is necessary in both model development and validation. Situations requiring this data include mixing applications and systems involving heat transfer. The governing equations – consisting of the momentum, continuity, and heat transfer equations – contain all of the details of

such flows, both laminar and turbulent. The heat transfer equation is given in tensor notation by Eq. (1).

$$\frac{\partial T}{\partial t} + u_j \frac{\partial T}{\partial x_j} = \kappa \frac{\partial^2 T}{\partial x_j \partial x_j} \quad (1)$$

For turbulent flow no analytical solution has been found to Eq. (1), making numerical analysis the necessary solving tool. In turbulent flow, however, there becomes a significant problem with even numerical solutions. The challenge comes from the range of length and time scales involved in turbulence. In typical turbulent pipe flow, for example, the spatial resolution required for numerical analysis of these equations depends on the turbulent length scale, which ranges from the order of the diameter of the pipe down to the size at which the turbulent kinetic energy is dissipated into heat by viscosity – a difference of many orders of magnitude. Because of this, the computational demands for all but the simplest of turbulent flows are far too great for even the fastest computers currently available.

A widely used method of dealing with this difficulty is to average the governing equations in such a way that the mean quantities of interest (temperature, pressure, and velocity) are solved for, rather than the instantaneous values. This is done by decomposing the variables of interest into mean and fluctuating components, and then time averaging them. This significantly reduces the computational resources required for solution while at the same time retaining useful information about the mean behavior of the flow. Equation (2) shows the heat equation, Eq. (1), decomposed and averaged in this way:

$$\frac{\partial \bar{T}}{\partial t} + \bar{u}_j \frac{\partial \bar{T}}{\partial x_j} = \kappa \frac{\partial^2 \bar{T}}{\partial x_j \partial x_j} - \frac{\partial}{\partial x_j} (\overline{u'_j T'}) \quad (2)$$

As can be seen from Eq. (2), upon averaging a new temperature-velocity correlation term $\overline{u'_j T'}$ arises (where the overbar and prime correspond to the averaged and fluctuating values, respectively), while no new

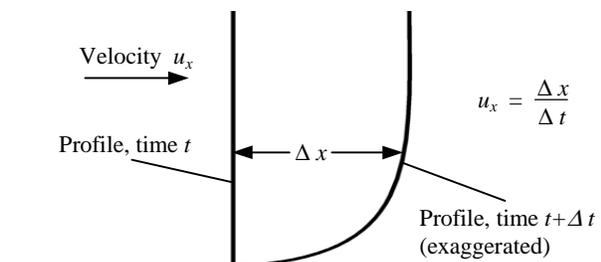


Figure 1. Velocity calculation using MTV.

equations have been added. This leads to the fundamental “closure” problem of turbulence – there are more unknowns than there are equations – and this will continue to be the case upon subsequent decomposition and averaging; thus this new velocity-temperature correlation term must be modeled. Experiments then become necessary to determine the model’s validity.

Experimentally obtaining this data is not trivial; the velocity and temperature measurements must coincide in both space and time and must be obtained throughout the flow field in order to be of significant benefit. High spatial resolution is also necessary. Much research over the last few decades has explored various methods of obtaining this data, such as combination hot- and cold-wire probes (Yao et al., 1994) and laser-based methods such as laser doppler velocimetry with thermocouples (Gould et al., 1994; Brdlik and Filimonov, 1989).

An alternative to these methods is found in molecular tagging velocimetry (MTV), a recently established non-intrusive method of obtaining velocity profiles which is also capable of producing temperature information.

Molecular Tagging Velocimetry

MTV is an established method of obtaining spatially resolved velocity profiles over either a planar or 3-dimensional domain of interest. It is based on the ability to image the phosphorescence of a tracer molecule in either liquid- or gas-based flows; for water-based flows, the molecular complex 1-BrNp•Gβ-CD•ROH, developed by Ponce et al. (1993), is used. Upon excitation by ultraviolet light, the molecule 1-BrNp exhibits both fluorescence and phosphorescence. The phosphorescence of 1-BrNp is useful for measurement purposes, but is quenched by both oxygen and water. To shield it from the quenching effects of water, the cup-shaped molecule glucosyl-β modified cyclodextrin (Gβ-CD) is added; to shield it from the quenching effects of oxygen, an alcohol is added to the solution. Various alcohols can be used and a thorough

discussion of their behavior is given by Hartmann et al. (1996).

Because the addition of glycerin causes no adverse effects on the phosphorescence, a large range of fluid viscosities can be studied with glycerin-water solutions. Spatial resolution of MTV measurements is adjustable via lens magnification; for example, Webb and Maynes (1999) report spatial resolutions of up to 2 μm/pixel.

To obtain velocity measurements in water, an ultraviolet beam (308 nm) is directed into an aqueous solution of 1-BrNp•Gβ-CD•ROH. The electrons in the molecules of the chemical become excited (“tagged”) by the photons and then gradually return to their unexcited state. As they do so, they give off energy in the form of light; in aqueous solutions, a bright green light is emitted and a profile appears in the fluid and travels with the flow for a short period of time before decaying. The lifetime of the phosphorescence depends on factors including the alcohol used for the shield and the imaging equipment utilized and is typically on the order of 15-20 ms. The delayed transitioning of the electrons in the molecules is what allows for velocity measurements.

The simplest excitation configuration for MTV consists of a single UV beam that is directed into a flow field. By comparing the displacement of this line over a given time interval, the velocity component perpendicular to the line can be obtained at each location along the line (see Fig. 1). By directing multiple lines through the fluid, the velocity in the direction of the flow can be calculated at multiple locations throughout the flow field. This method of acquiring only the velocity component perpendicular to the line profile is referred to as the “line” method. Another approach known as the “grid” technique involves the use of a beam splitter to direct multiple lines through the fluid such that a grid pattern is formed in the flow field. This technique allows for two components of velocity to be determined by tracking the grid intersections. This technique and its image analysis methodology are discussed in detail by Gendrich et al. (1997). Additionally, three-dimensional measurements of a flow field have been suggested using stereo imaging (Koochesfahani 1999).

MTV has been demonstrated in boundary layer flows in both gases (Thurlow and Klewicki, 1996) and liquids (Lee 1994; Maynes 1997), and in jet flows in gases (Stier and Koochesfahani, 1999). MTV has also been successfully employed in turbulent flows (Hill and Klewicki, 1996) and rotating unsteady flows (Maynes et al., 1997). Typical errors are on the order of 3.5%-6.0% for instantaneous velocities (Hill and Klewicki, 1996). These errors can be reduced to 1.1%-1.9% when ensemble averaging over 10 images in laminar flow.

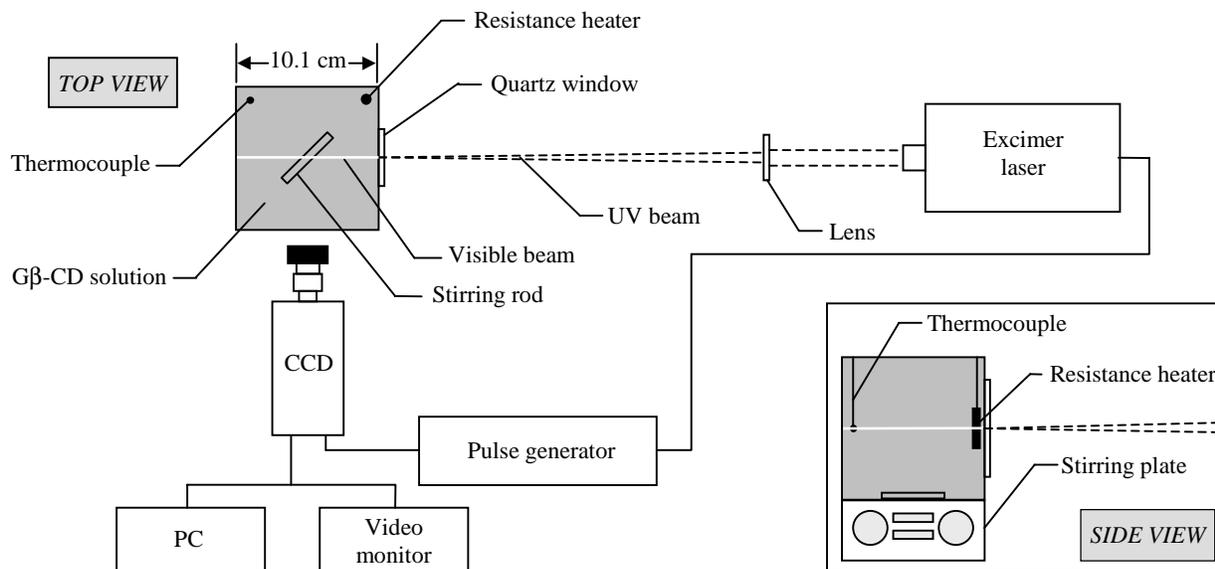


Figure 2. Setup used in the development of MTT.

Molecular Tagging Thermometry

There are two primary factors which affect the phosphorescence intensity: the concentration of the different constituents of the molecular complex and the temperature of the solution. As the temperature of a solution of constant concentration rises, the intensity of the emitted light decreases. It is this relation that enables us to obtain temperature data from the same images used in the velocity measurements. This is significant in that temperature and velocity can be measured using a single technique and imaging system. When used to obtain temperature measurements, we call it molecular tagging thermometry (MTT). Advantages of MTT include non-intrusive measurement capability and high spatial resolution. The range and resolution of MTT can be adjusted by modifying equipment settings and species concentrations.

The following sections describe the development of MTT, including the experimental setup, data acquisition and analysis, calibration curve development, and error analysis.

Temperature-Intensity Relationship Study

To quantify the relationship between the emitted light intensity and the solution temperature, images of the beam as it traveled through a fluid of known temperature were analyzed.

Equipment Setup

The equipment setup used in quantifying the temperature-intensity relationship is shown in Fig. 2. A small apparatus measuring approximately 10 cm on a side was filled with 0.7 L of a solution of 1-BrNp•Gβ-CD•ROH. Various alcohols were used, including *tert*-butanol (*t*-buOH), cyclohexanol (*cyc*OH), and neopentanol (*neop*OH). A thorough discussion of their various properties is given by Hartmann et al. (1996). A pulsed UV beam (308 nm wavelength, 60 Hz pulse rate) was directed from an excimer laser and focused into the center of the apparatus. A thermocouple was placed near one side inside of the apparatus and a resistance heater near another side. A small stirring rod was placed at the bottom and the apparatus was then placed on a stirring plate. A quartz window was inserted into one side of the apparatus to allow passage of the UV light. An 8-bit light-intensifying charge-coupled device (CCD) was synchronized with the laser and transferred images of the beam to a PC for analysis.

Image Acquisition and Analysis

The heater was used to heat the fluid to a predetermined temperature and the UV beam was directed through the fluid. The CCD acquired 50 sequential images of the resulting line profile and transferred these images to the PC. The fluid was then heated slightly at a relatively slow rate (i.e. approximately 2-3 minutes per °C) so that with stirring, the assumption of a uniform fluid temperature could be made (which was reasonable considering the small fluid

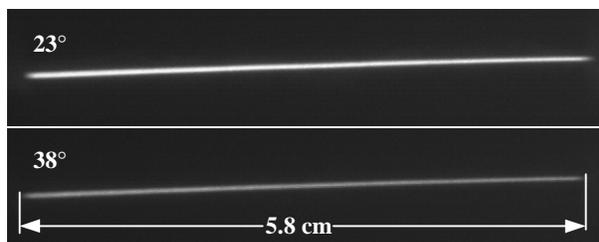


Figure 3. MTT lines at two different temperatures.

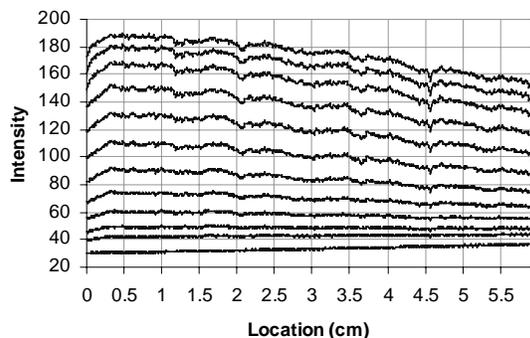


Figure 4. Intensity vs. location for multiple temperatures. The uppermost curve corresponds to a temperature of 23°C and each subsequent line represents an increase in 3°C.

volume). More images were acquired at this increased temperature, the fluid was heated again, and so on until the intensity of the beam was nearly undetectable. Figure 3 shows images of the beam at two different temperatures.

The intensity of each pixel in the image was stored as a value between 0 and 255, 0 being black and 255 being white. For each of the temperatures, the intensity of the line profiles at each location along the length of the line was determined by finding the pixel of maximum intensity at that location. The intensities of the profiles at different temperatures were then plotted as shown in Fig. 4.

It can be seen that the intensity of the line decreases with location; this is due to attenuation of the incident beam as it travels through the fluid. Other irregularities are present such as the small dip in intensity just past $x=4.5$ cm. These are thought to be due to contamination on equipment surfaces and variation in pixel response of the CCD because they are present at each temperature; upon normalization their presence is not significant.

This image acquisition and analysis process was repeated a number of times with different settings (i.e. variations in intensifier gain, CCD shutter duration, species concentration, temperature range, etc.).

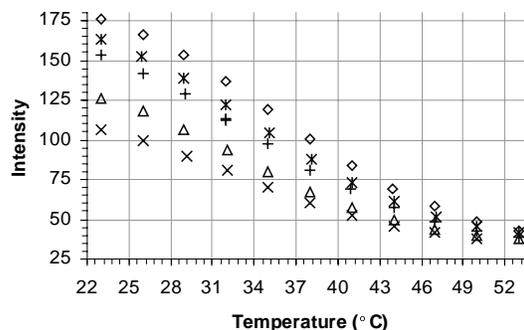


Figure 5. Temperature vs. intensity for 5 sets of data.

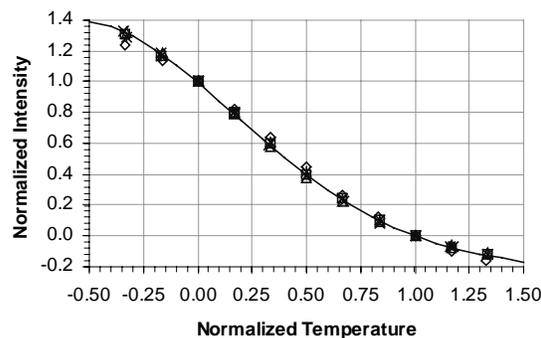


Figure 6. Normalized temperature vs. intensity for the data shown in Fig. 5.

By averaging the intensities of a few pixels surrounding a given location along the beam length, the intensity could be plotted versus temperature. This is shown in Fig. 5 for five sets of data, each obtained on separate days and using neopOH as the alcohol, at $x \approx 2.85$ cm.

While the initial intensity varied (most likely because of quenching due to exposure to air over a period of days), the shape of the curves are all generally the same and seem to have two inflectional points. These occur at about $T_A = T_i + 1/5(T_f - T_i)$ and $T_B = T_i + 4/5(T_f - T_i)$, so that normalizing could be done as $T' = (T - T_A)/(T_B - T_A)$. Normalization of the intensity was done in a similar manner with $I' = (I - I_B)/(I_A - I_B)$ where I_A and I_B correspond to the intensities at T_A and T_B , respectively. Figure 6 is a plot of T' vs. I' for the five data sets shown in Fig. 5.

As can be seen in Fig. 6, the normalized temperature vs. normalized intensity plots all collapse on to a single curve, regardless of the initial intensity. Indeed, the data obtained for a wide variety of equipment settings, alcohol types, and temperature ranges, as well as at other spatial locations along the length of the line, have been found to follow this curve.

This curve then represents a calibration curve. To obtain temperature measurements using MTT, a curve of this nature would first be generated by obtaining intensity values at known temperatures; T_A and T_B would be identified from this data. Subsequent temperature measurements could then be obtained by measuring the intensities at T_A and T_B to allow for normalization and then comparing measured intensities at different temperatures to the calibration curve.

By generating a fourth order least squares curve fit to the data (shown in Fig. 6), an equation for T' as a function of I' was found to be:

$$T' = 1.02 - 2.22I' + 3.171I'^2 - 2.781I'^3 + 0.808I'^4 \quad (3)$$

By differentiating T' with respect to I' , an estimate of the error in T' can be obtained according to the relation (Taylor, 1982):

$$T'_e = \left(\left(\frac{\partial T'}{\partial I'} \right)^2 u'_I{}^2 \right)^{1/2} = \left(\frac{\partial T'}{\partial I'} \right) u'_I \quad (4)$$

where u'_I represents the signal rms normalized by intensity. By then relating T_e to T'_e by the relation $T_e = T'_e(T_B - T_A)$, the error in T can be determined. By using the rms values associated with the images, T_e was found to be on average approximately $\pm 0.85^\circ\text{C}$ over nearly 30°C with a 95% confidence level; Thomson and Maynes (2000) contains a more thorough treatment on the error analysis.

Conclusion

In order to accomplish closure of the mean heat equation in turbulent flows, simultaneous measurements of temperature and velocity are required. MTV has been successful in obtaining velocity profiles throughout a fluid flow and, with proper calibration, has been shown to be successful in providing temperature information as well. Equipment setup, including the alcohol used in the solution, species concentrations, and apparatus type, have a significant effect on image quality and initial intensity, but these effects are generally removed through normalization by two data points. Current research efforts are directed towards validating MTV/T as a method of measuring temperature and velocity simultaneously.

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