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International Journal of Heat and Mass Transfer 47 (2004) 4285–4292
International Journal of HEAT and MASS TRANSFER
www.elsevier.com/locate/ijhmt

A laser induced diagnostic technique for velocity measurements using liquid crystal thermography

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Received 24 February 2004; received in revised form 27 April 2004

Abstract

Wind tunnel experiments were performed to show that wind velocity could be correlated to thermal patterns generated on a model surface. The idea makes use of the thermal patterns generated by a laser thermal tuft that was originally developed and patented (Patent #5,963,292) by researchers at the USAF Academy and the University of California, Davis. The present study quantifies this flow visualization idea by correlating the length of the thermal tuft to velocity and demonstrates that this measurement is strongly dependent on laser power. Until now, the laser thermal tuft has been used only to qualitatively characterize flow fields. By quantifying flow velocity, this extension of the patented idea may promote increased usage of this laser thermal tuft technique.

1. Introduction

Tracer techniques such as buoyant bubbles, and surface visualization techniques such as porous oil dispensers, photochromic materials, and temperature-sensitive paint are all methods used to understand fluid behavior [1,2]. Sometimes seeding the flow can be messy and lead to inaccuracies resulting from the intrusive nature of the tracer gas or liquid in the free stream. These methods can also pollute the free stream and damage the model. Non-intrusive flow visualization techniques will preserve the test model for future experimentation.

The need for surface flow visualization creates opportunities to apply liquid crystals to the investigation of interesting heat transfer and fluid flow problems. Liquid crystals are temperature-sensitive microencapsulated crystals that respond to a change in temperature by changing colors [3].

A study by Batchelder and Moffat [4] visualized the surface flow field by heating a series of spots on a panel coated with liquid crystals. A pin fin connected to the base of an aluminum heat sink generated the heated spots. The fins were mounted to the back of the model so that heating through the model triggered the thermal spot. The results demonstrated that a thermal wake is produced from the heated spot and the local flow direction can be inferred from the thermal wake. For many applications, the incorporation of pin fins behind a test model may be difficult.

This study will utilize an external radiant heat source (diode laser) to generate a heated spot as described in [5]. The first description of the laser thermal tuft was presented by Baughn et al. [6] in which they used the tuft to characterize flow separation around a turbine blade. The idea was then patented by Rivir et al. [5] and further used to qualitatively characterize the flow around turbine blades [7,8]. In these studies [5–8] the patterns generated from heated spots on a liquid crystal coated surface enabled visualization of regions of flow separation and reattachment, as well as flow reversal and transition from laminar to turbulent flow. Their approach employs an external laser to heat a spot on a liquid crystal coated surface [5]. As flow advects over

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doi:10.1016/j.ijheatmasstransfer.2004.04.026

Nomenclature

A	surface area of heated spot (m^2)
g	acceleration due to gravity (m/s^2)
h	convective heat transfer coefficient ($W/m^2 K$)
k	thermal conductivity (W/m K)
L	length of the plate (m)
q	power produced by the laser (W)
q''_o	constant surface heat flux (W/m^2)
T_s	temperature of the projected spot (°C)
T_i	initial temperature (°C)
T_∞	ambient temperature (°C)
T_{hot}	temperature of the region heated by laser beam
t	time duration laser beam is impingent on the plate (s)
u	free stream velocity (m/s)
z	depth into model (m)
L_w	length of thermal wake with airflow
L_{wo}	length of thermal wake with no airflow
Greek symbols	
α	thermal diffusivity (m^2/s)
β	coefficient of thermal expansion (K^{-1})
ε	emissivity of the substrate
ν	kinematic viscosity (m^2/s)
σ	Stefan Boltzmann constant (5.67×10^{-8} $W/m^2 K^4$)
Non-dimensional parameters	
Gr_L	Grashof number $= g\beta(T_s - T_\infty)L^3/\nu^2$
Nu_L	Nusselt number $= hL/k$
Re_L	Reynolds number $= uL/\nu$
Pr	Prandtl number

the spot an airfoil shaped pattern forms (this pattern is referred to as a tuft by [5–8]) and is indicative of the type of flow present (i.e., laminar or turbulent). The idea has been previously applied to better understand the aerodynamics associated with flow over turbine blades [6–8]. Butler et al. [7] correlated flow direction to transitions from laminar to turbulence by generating a thermal tuft with an IR laser. Byerley et al. [8] further applied this idea to understand flow separation and reattachment over turbine blades by determining the strength of the flow direction and calculating an eccentricity factor. The eccentricity factor is a ratio of the downstream tuft length to the upstream tuft length and is related to the wall static pressure distributions. For an incompressible flow, the wall static pressure is directly related to the square of the velocity distribution.

This work expands on the development of the thermal tuft by demonstrating that it can also be used to quantify flow velocities. Current methods for measuring the velocity of the flow field include using a standard thermal anemometer. However, anemometers are actually positioned inside the flow which could be disruptive to the flow field. The intrusive nature of an anemometer also makes velocity measurements difficult on or very near the surface of an object. In this study, the free stream velocity is determined based on the length of the thermal wake produced by heat advected downstream from the heated spot. By developing a relationship between thermal wake length and free stream velocity, this diagnostic technique has potential to be increasingly useful to researchers. Methods of applying this technique are discussed and ideas for further diagnostic developments are also presented.

2. Experimental

As described by [5–8], when a flat plate is placed in a wind tunnel and flow advects over a heated spot, the motion of the air above the spot causes a temperature variation around the heated region and the shape of the thermally affected region is altered from that of the original heated spot. A schematic of the thermal tuft is illustrated in [5]. The schematic illustrated in Fig. 1 is uniquely different in that it diagrams the three main thermal mixing zones downstream from the heated spot. This concept is analogous to mixing zones downstream of a turbulent jet in a surrounding uniform air stream [9]. For a uniform free stream laminar flow, the temperature advects in the direction of flow causing a symmetrical, relatively isothermal airfoil shaped thermal wake pointing in the direction of the flow (i.e., Zone 3 in Fig. 1). The direction of flow immediately above the surface can determined by the direction of the thermal wake (Zone 3). The magnitude of the velocity is related to the length of the thermal wake (Zone 3).

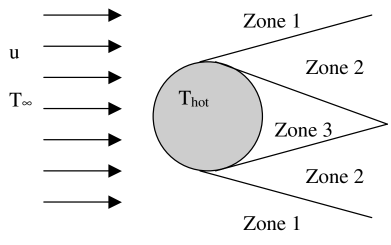

Fig. 1. Schematic of thermal zones downstream of heated region.

The experimental setup described here is similar to that detailed in [5] with exceptions that will be noted. Similarities include the type of camera and liquid crystals, the choice of a polystyrene model and the use of a laser [5]. Our experiments using this similar setup showed a strong dependence of the thermal tuft length on the laser power. For this reason, this study incorporates a power meter to monitor and control the laser power impingent on the substrate. We also note that the distance from the start of the laser beam to the model surface can also influence the tuft length. Applying this technique for the purpose of measuring flow velocity requires the position of the laser with respect to the model surface to be carefully monitored and controlled. A more detailed discussion of the experimental components follows.

Images of the thermal wake are captured and processed using a Sony DXC390 3-chip R-G-B color CCD camera with 580×472 effective pixel resolution and stored as a bitmap (.bmp) file. Any color camera or video camera can be used to record the thermal wake images. Black and white images can also be captured. However, the temperature gradient within the heated region will not easily be observed due to the absence of the color spectrum. As an estimate of the cost for this measurement technique, assume a camera can be purchased for approximately $500.00.

The thermochromic liquid crystals (TLCs) fall into the cholesteric form and can be destroyed by exposure to ultraviolet light and excessively high temperatures. For this reason, a UV laser should not be used as the external heat source. The TLCs exhibit visible color change in response to changes in their thermal environment. The wavelength of light reflected by the crystals is equal to the pitch of the grating formed by the rotated layers of TLC molecules. The pitch of the TLCs is dependent on temperature and color is dependent on wavelength so that the temperature can be determined by a change in color. In the microencapsulated form, the TLCs are, for the most part, insensitive to effects of pressure and surface shear. Some advantages of TLC coatings over techniques involving other surface coatings are that illumination only in the visible spectrum is required, images can be recorded by a camera without need for special optics or filters, and the color changes that occur are reversible and repeatable. The temperature-sensitive type of liquid crystals as compared to the shear stress sensitive type of liquid crystals is more optimially suited for deducing flow characteristics in the following experiments. Two separate types of TLCs were used in this study. The first exhibits the full color spectrum within a one-degree temperature band (i.e., from 35 to 36 °C, R35C1W). The second exhibits the full color spectrum within a five-degree temperature band (i.e., from 35 to 40 °C, R35C5W). Both were purchased from Hallcrest, Inc for approximately $120.00 for 50 g.

It is important to pick a liquid crystal with an activation temperature only a few degrees higher than the ambient. In this way, less energy is required to heat the spot and the thermal influence on the flow field remains negligible. Using an external heat source applied to the model could potentially induce temperature gradients significant enough to disturb the flow field. To determine the non-intrusive nature of measurement technique, the Grashof and Reynolds numbers were evaluated to compare the role of free and forced convection. When the inequality in Eq. (1) is satisfied, buoyancy effects resulting from heating of the air directly above the heated spot on the model can be neglected.

$$\frac{Gr_L}{Re_L^2} \ll 1 \tag{1}$$

As a worst case scenario, the influence of buoyancy was assessed assuming that the entire plate was heated to a temperature of 35 °C instead of the small spot which actually occupies less than 1% of the plate's total surface area. For a free stream air temperature of 28 °C, velocity of 5.0 m/s and a 61-cm plate length, the Grashof number divided by the square of the Reynolds number is 0.0086 and buoyancy effects are negligible.

The flat plate model was made from polystyrene foam with a thermal conductivity of 0.027 W/mK and a thermal diffusivity of 4.06×10^{-7} m^2/s. Polystyrene is representative of commonly used materials in wind tunnel modeling applications and has isolative properties that minimize the effects of heat transfer through the model [5].

Some high-power laser beams could potentially burn through the model. For this reason, the temperature distribution through the model resulting from laser heating was calculated assuming transient conduction through a semi-infinite solid. Eq. (2) is the one-dimensional heat equation and Eq. (3) is the closed-form solution for a constant surface heat flux boundary condition and pre-specified initial condition [9].

$$\frac{\partial T}{\partial t} = \frac{1}{\alpha}\frac{\partial^2 T}{\partial z^2} \tag{2}$$

$$T(z,t) = T_{\mathrm{i}} + \frac{2q''_{\mathrm{o}}(\alpha t/\pi)^{1/2}}{k}\exp\left(\frac{-z^2}{4\alpha t}\right) - \frac{q''_{\mathrm{o}}z}{k}\operatorname{erfc}\left(\frac{z}{2\sqrt{\alpha t}}\right) \tag{3}$$

Eq. (3) predicts that the surface temperature reaches 35 °C in 2 s. This is a reasonable time interval for common flow visualization studies. Also, the thickness of the model is 2.0 cm and heating is confined primarily to a thin surface layer (0.2 cm) such that the back surface of the model remains at ambient temperature.

The laser used in this study is a Power Technology 150-mW infrared diode laser (830 nm wavelength) consisting of a diode module (Model Number PPM (830-150B) G4T11) and a laser diode (Model Number LD1362). The cost estimate for this type of laser is approximately $2000. The laser is powered by a turnkey, stand-alone power source (Model Number LDCU12) and controlled by five potentiometers, located inside the outer casing. A seven-pin connector allows the output parameters to be observed using a voltmeter. The laser has two operating modes: constant current mode and constant power mode. The constant power mode is used for this study because it provides a constant heat source which was monitored by the power meter (Molectron Power Probe).

In choosing an adequate laser, it is important to estimate the minimum amount of power required by the laser to produce a thermal pattern. The temperature required to initiate the TLC color play is 35 °C and the free stream temperature is 28 °C. For these conditions the necessary power from the laser is determined by applying an energy balance at the surface of the model.

$$q = -kA\,\mathrm{d}T/\mathrm{d}z + hA(T_\mathrm{s} - T_\infty) + \varepsilon\sigma A(T_\mathrm{s}^4 - T_\infty^4) \qquad (4)$$

In this equation, A refers to the area of a heated spot (i.e., approximately 6 mm in diameter). The heat required includes heat absorbed by conduction through the substrate, convective cooling, and radiation exchange between the surface and the surroundings. As an upper limit for radiation, the emissivity is assumed to be 1.0. For convective cooling, the surface is modeled as a flat plate and h is estimated from the Nusselt number expression for laminar flow over a 61-cm long flat plate [10].

$$Nu_L = 0.332 Re_L^{1/2} Pr^{1/3} \qquad (5)$$

For this calculation an upper estimate of 10 m/s is assumed for the free stream velocity. Using the properties for air at 28 °C, h is 6.3 W/m^2 K. In Eq. (4) the temperature gradient through the model is calculated by differentiating Eq. (3) with respect to position (z). The properties for polystyrene and t equal to 2 s are used. The necessary power from the laser is calculated to be 7.0 mW per spot. Therefore, a 150 mW laser is sufficient for this application.

The flat plate polystyrene model was cut into a rectangle (61×46 cm) and the leading edge was tapered to a 4:1 elliptical ratio to ensure laminar flow over the plate. Mylar film was adhered to the foam in order to reduce surface roughness and create a smooth laminar flow field. The thickness of the mylar film is estimated on the order of microns and is not thought to affect the thermal conductivity of the substrate or the thermal wake length of the heated spot. Black primer paint was applied using a Badger Air-Brush (Model Number 175, cost approximately $80). The black primer paint was purchased from Cole-Parmer Instrument Company and designed specifically for use with liquid crystals. The test section was coated with liquid crystals, which were applied using the Badger Air-Brush. Two separate models were prepared, one using R35C1W and the other using R35C5W liquid crystals. During the application of liquid crystals a hair-dryer test was performed to determine the amount of liquid crystals needed. The quality of the color spectrum increases as the thickness of liquid crystals increase. Once the section was coated to a satisfactory level, the color play appeared brilliant and the coating of the substrate was complete.

Fig. 2 illustrates the experimental setup. The wind tunnel has an aerodynamic test section that is 1.8-m

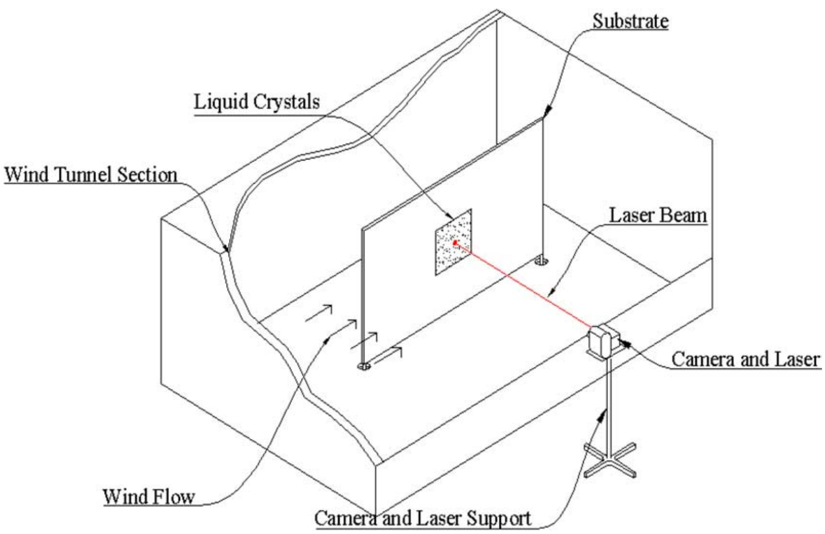

Fig. 2. Experimental test setup.

wide, 1.2-m high, and 2.1-m in streamwise length. The laser module was clamped to a standard camera tripod for stability and placed directly in front of the model on the outside of the wind tunnel. Testing was conducted for free stream velocities ranging from 2 to 10 m/s. The velocity was monitored using a Pitot tube and TSI thermal anemometer. The free stream velocity readings between these two instruments compared within 0.5%. The free stream flow was uniform across the wind tunnel with a standard deviation of 0.5% and the turbulence intensity was measured as 0.1% with a standard deviation of 0.18% [11]. It is noted that above 10 m/s the flow begins to transition to turbulence and the thermal wake no longer has an airfoil shaped pattern. Therefore, 10 m/s is the upper limit for correlating thermal wake length to velocity.

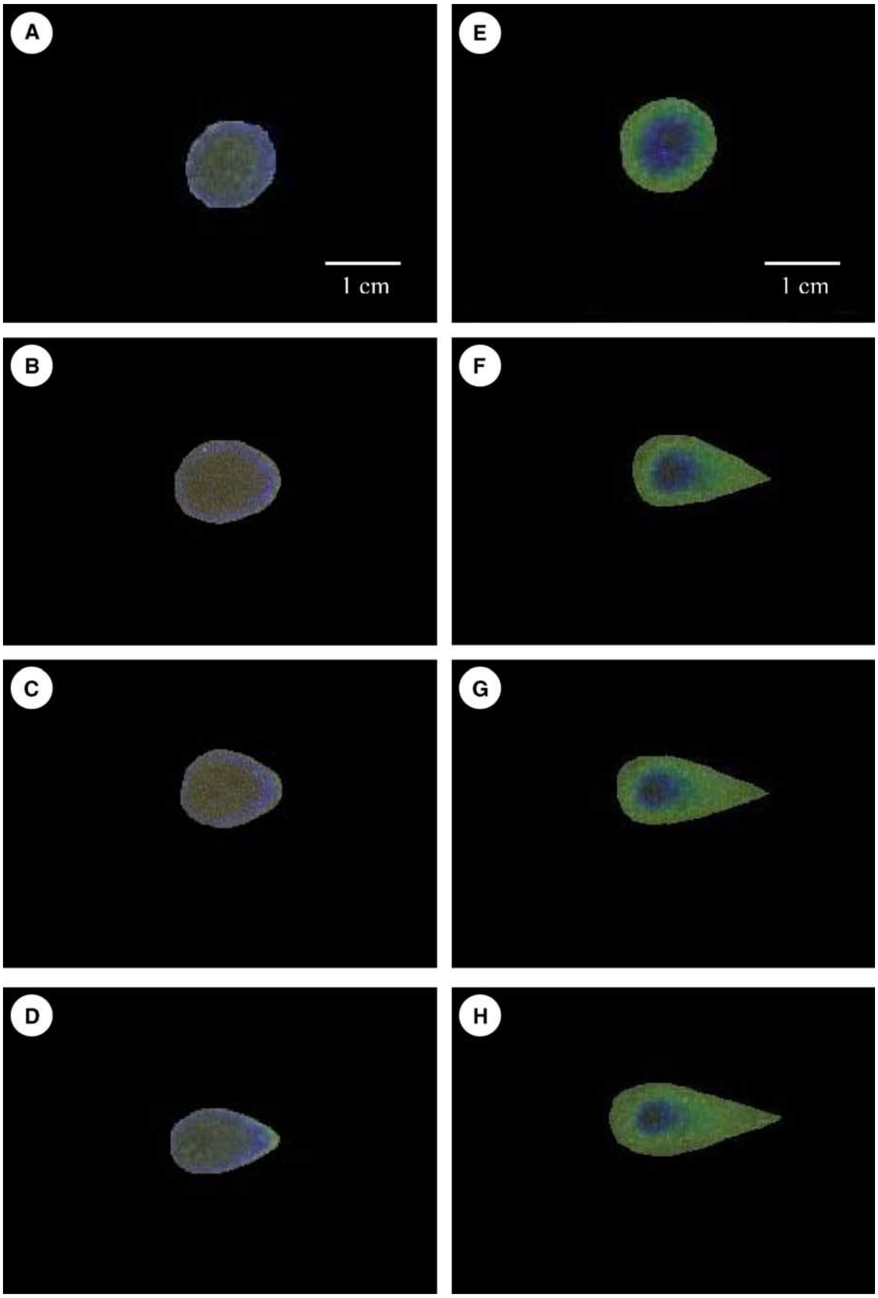

Fig. 3. Thermal patterns produced with increasing free stream velocities (50 mW). (A) 0 m/s, (B) 2 m/s, (C) 5 m/s, (D) 10 m/s (R35C1W/one-degree bandwidth); (E) 0 m/s, (F) 2 m/s, (G) 5 m/s, (H) 10 m/s (R35C5W/five-degree bandwidth).

3. Results

Images of a thermal tuft on the suction surface of the cascade turbine blade are presented by Butler et al. [7] and demonstrate the changes in tuft appearance with oncoming flow conditions around an airfoil. Fig. 3 presents tuft images that were captured in this study for flow over a flat plate and for the purpose of demonstrating the relationship between tuft length and flow velocity. In the present study all experiments were conducted for a fixed location 14 cm from the leading edge and along the center line of the plate. Fig. 3A illustrates the heated spot (diameter 6 ± 0.5 mm) generated on R35C1W TLCs exposed to no flow. The spot appears violet [1] in the center and transitions to bright blue around the perimeter. This is consistent with the Gaussian distribution of the laser beam in which the center is slightly hotter than the perimeter of the spot. Fig. 3B–D illustrates the thermal wake when the model is exposed to flow. Fig. 3E illustrates the heated spot on R35C5W TLCs exposed to no flow. This image shows more color play than the one-degree bandwidth liquid crystals (Fig. 3A). Fig. 3F–H illustrates the thermal wake at progressively higher free stream velocities. Based on Fig. 3E–H, the five-degree bandwidth (R35C5W) TLCs appear better for measuring velocity. Both types of TLCs are functional, but the five-degree bandwidth produces greater color play and thermal wake length.

4. Discussion

All thermal wake lengths are measured from the leading edge to the longest point (trailing edge) which is determined from the sharp intensity variation of the color pattern of the TLCs. For fixed T and T_{hot}, Fig. 4 shows that the length increases linearly with increasing free stream velocity and is indicative of decreased lateral mixing with the free stream. The diameter of the heated region at its thickest point does not vary significantly from the original spot diameter and ranges from 7 to 6 mm for the highest wind speed. The lack of lateral heat conduction on the surface suggests that the thermal pattern downstream from the original spot results from convection to the surface from the heated air advected downstream from the beam path. This heated air pocket advects downstream, mixes with the cooler free stream flow and heats the model surface. Fig. 1 illustrates the three main thermal zones that describe the heat distribution downstream from the beam. For a uniform free stream, the segment of air flowing over the heated region

[1] For interpretation of color in Fig. 3, the reader is referred to the web version of this article.

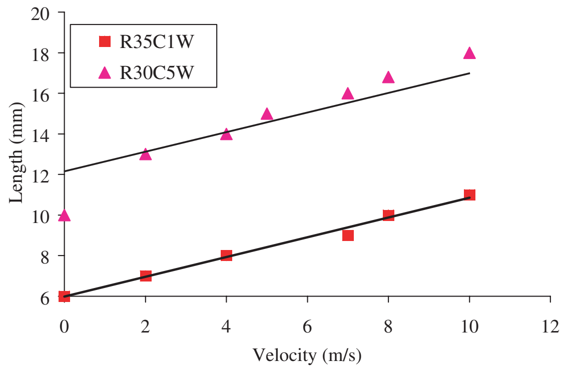

Fig. 4. Thermal wake length as a function of free stream velocity (50 mW laser power).

mixes with higher temperature air in the heated region and flows into Zone 3 at a temperature T_{hot}. The segment of the free stream air flowing outside of this heated region flows into Zone 1 and remains at T_∞. However, between Zones 1 and 3, a thermal mixing region (Zone 2) develops with increasing thickness as shown leaving a relatively symmetrical, isothermal, airfoil shaped thermal wake (i.e., Zone 3 in Fig. 1). The rate at which heat dissipates from Zone 3 determines the length of the thermal wake and heat is almost completely dissipated outside the colorplay of the thermal pattern. Therefore, the thermal patterns in Fig. 3 result from heat transfer from the air to the surface.

Because the thermal wake length is also dependent on laser power, calibration of the thermal wake length with respect to velocity at the specific laser power is imperative. Fig. 5 shows that the thermal wake length increases linearly with increasing free stream velocity. Laser power clearly affects the magnitude of the thermal wake length such that calibration at a single power is essential to estimating the velocity of the flow field based on thermal wake length.

A dimensionless thermal wake length parameter is introduced as L_w/L_{wo} in Fig. 6 and plotted as a function of Reynolds number. L_w denotes the length of the thermal wake with airflow over the heated spot, and L_{wo} denotes the length of the thermal wake without airflow over the heated spot. This was done in order to remove the need for tuft length calibration at different laser powers. Fig. 6 displays a linear increase that is on the same order of magnitude for 50 and 90 mW.

This work briefly describes a unique and inexpensive technique to assess velocity from the length of a thermal wake which is controlled by the growth of a thermal mixing region. Additional factors could be considered that may extend this diagnostic technique further. For example, increased moisture content within the air flow may allow more heat absorption in the laser beam path and lengthen the thermal wake. The humidity was held

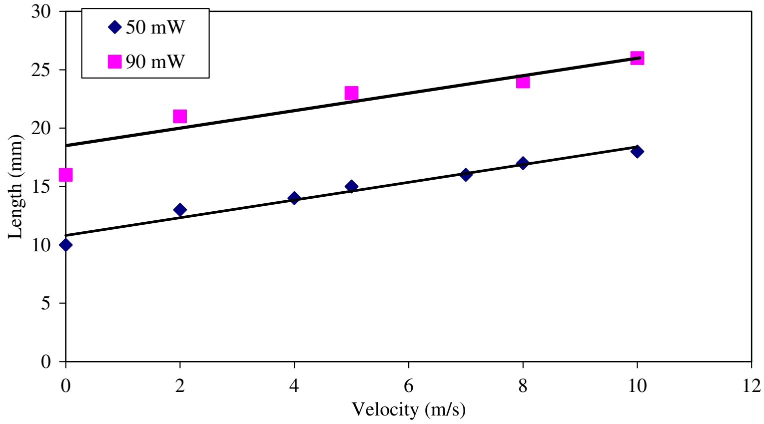

Fig. 5. Thermal wake length as a function of velocity for 50 and 90 mW laser power (R30C5W).

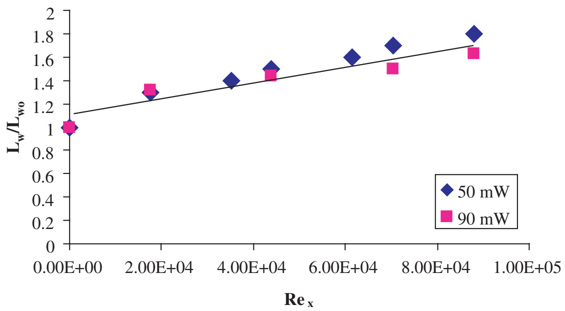

Fig. 6. Non-dimensionalized thermal wake length as a function of Reynolds number for 50 and 90 mW laser power (R30C5W). Note that L_{wo} is 7 mm at 50 mW and 13 mm at 90 mW power, respectively.

constant in this study at 10% but considerations could be made that account for variations in the moisture content of the free stream flow. It would also be of interest to allow observation of multiple thermal tufts, as described by [7] and demonstrated in [4]. This would allow visualization of a larger flow field over an object. An indepth analysis of the linear relationship between thermal wake and mixing regions and flow velocity would also benefit further development of this diagnostic technique.

5. Conclusions

This study reports that the non-intrusive laser thermal tuft originally patented by [5] can also be used for velocity measurements. Wind tunnel experiments were conducted for laminar flow conditions. An infrared (830 nm wavelength) diode laser supplied a constant heat source to a polystyrene flat plate model, coated with liquid crystals and mounted in a wind tunnel. The results show that a thermal spot on a liquid crystal coated surface will produce a thermal wake. As the wind speed increases from 2 to 10 m/s, the length of the thermal wake increases linearly and is a function of the laser power setting. The uncertainty in determining the diameter of the heated spot is 0.5 mm and the increase in thermal wake length up to 10 m/s is about 5 mm. Therefore, the uncertainty in the thermal wake length for determining velocity can be significant and a limiting factor for applying this technique to measure flow velocity. Another concern for the authors is the large number of variables affecting tuft length involved in this method. It was shown that thermal tuft length is affected by laser power, requiring self-calibration with each fluctuation in laser power, and by the distance between the heated spot and the laser diode that results from the diffusion cone of the laser beam. The type of liquid crystals was shown to also affect the thermal tuft length. The technique is limited to laminar flow conditions but has various applications described by [4–8] and could also be used as an effective teaching tool to heat transfer students. Also, the thermal wake length is related to the local heat transfer coefficient such that the relationship between thermal wake length and flow velocity is dependant on the features of the flow passage. This requires that calibration be repeated not only for laser power, type of TLC, and laser beam distance, but also for any change in the geometry of the flow channel. As a total package, the laser ($2000), any camera ($500 or less), Air-Brush ($80) and liquid crystals ($120) bring the apparatus cost to a maximum of $2700. This is an affordable and easy to implement method for measuring velocity and introducing students to the relationships between heat and mass transfer, the many variables involved may decrease its usefulness as a universal approach for other researchers to implement.

Acknowledgements

The authors would like to acknowledge the internal support provided by Texas Tech University. We are also thankful to Dr. Jessica Townsend for the initial inspiration to attempt these experiments and for detailed discussions that led to the experimental setup and ideas developed in this paper. We are also thankful to our many colleagues and friends whose thought provoking discussions have enriched this study.

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