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Surface flow visualization using thermal tufts produced by an encapsulated phase change material

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Abstract

A new thermal tuft method for flow visualization similar to the laser thermal tuft method is described. The earlier laser thermal tuft method involved heating a spot on a surface with a laser, producing a teardrop temperature distribution on a surface coated with thermochromic liquid crystals. In the present study, thermal tufts are produced by embedding small thermal masses in a low thermal conductivity substrate. When a model is exposed to wind tunnel flow, the embedded thermal masses remain (nearly) isothermal while the thermal tufts appear downstream. The advantage of using embedded thermal masses over previous methods is that no laser or heated base is needed. Multiple tufts can easily be achieved. By using an encapsulated phase change material the phase change between solid and liquid (ice) produces isothermal spots. Images of the surface temperature distributions associated with these thermal tufts were obtained using both liquid crystal and infrared thermography. Flow visualization using these thermal tufts is demonstrated for an impinging jet and on a flat surface in a wind tunnel with crossflow.

Keywords: Tuft; Flow visualization; Phase change; Infrared; Liquid crystal; Thermal

1. Introduction and background

Surface flow visualization is useful for understanding flow in many applications and can be used to complement and validate computational studies of complex flow. A recent development in non-intrusive surface flow visualization is the "laser thermal tuft". (Baughn et al., 1995), first described this technique in a study to determine where flow separation had occurred on the suction side of a turbine blade. This technique was later patented by the USAF (River et al., 1999). The principle behind this method was to use a laser to heat a spot on a surface coated with microencapsulated thermochromic liquid crystals (TLCs). This circular heated laser spot (~3 mm) creates a distinct thermal pattern or tuft downstream by advection in the direction of surface airflow. The thermal tuft was a teardrop shape color change in the TLCs pointing in the downstream direction. Using this method, Baughn et al. (1995) were able to determine the location of boundary layer separation on a turbine blade model in a cascade wind tunnel. They pointed out that multiple spots could be obtained by using a Laser Tuft Matrix (LTM). In the location of boundary layer separation or reattachment, the thermal tuft is circular and centered around the laser spot with no hint of a teardrop shape. Further demonstrations of the laser thermal tuft were done by (Townsend, 1996). (Baughn et al., 1999), presented the results for a laser thermal tuft created by an infrared (IR) laser on the flow separation and reattachment on a turbine blade at low Reynolds numbers. The IR laser produced a clear red spot at the center of the thermal tuft. Their results are shown in Fig. 1.

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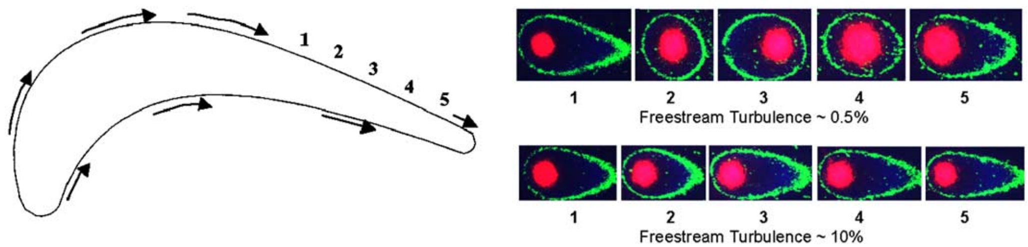

Fig. 1. Laser thermal tuft on a turbine blade (Baughn et al., 1999).

For their case where freestream turbulence was 0.5%, separation occurred at location 2, while reattachment occurred at location 4. Between location 2 and 4 was a region of recirculation, indicated by the tail of the thermal tuft pointing in the opposite direction of freestream at location 3. At high freestream turbulence, they were able to show that the flow remained attached; the laser tuft images all point in the direction of the freestream flow.

Further applications of the laser thermal tuft were done by (Butler et al., 2001), and (Byerley et al., 2003). These studies also used the laser thermal tuft to determine the location of flow separation and reattachment. In addition, (Byerley et al., 2003), introduced a dimensionless term to quantify the strength of the laser tuft called the eccentricity. Using a similar principle as the laser thermal tuft, (Batchelder and Moffat, 1998), described a surface flow visualization technique using heat sinks with "pin fins" to create an array of small hot spots on a surface.

A "cool" thermal tuft was produced by (Byerley et al., 2001), where IR heaters were used to uniformly heat a black surface with reflective spots affixed to the surface. The reflective surface remained cool while the surrounding surface heated up and produced a thermal tuft downstream of the "cool" spot.

The purpose of the present research was to develop a new thermal tuft method using an embedded thermal mass with an encapsulated phase change material. The capsules use the phase change between solid and liquid (ice in the present study) to produce isothermal spots. A matrix of embedded capsules is used, providing surface flow visualization at different locations on a model surface.

2. Principles of the thermal tufts

We define a thermal tuft here, in reference to surface flow visualization, as a teardrop shaped temperature pattern on a surface, originating from a heated or cooled spot, pointing in the direction of the surface flow. The thermal tuft is generated by advection causing the heated or cooled air to interact with the surface downstream of the thermal spot. The region surrounding the thermal tuft involves heat transfer in both convection and conduction.

For boundary layer flow, the characteristics of the boundary layer play an important role in the shape and size of the thermal tuft. The two types of boundary layers affecting the thermal tuft are the velocity boundary layer and thermal boundary layer. The hydrodynamic- or velocity boundary layer begins upstream of the thermal tuft. The thermal boundary layer begins at the heated or cooled spot and dissipates downstream of the spot, creating the thermal tuft. It is thin compared to the velocity boundary layer. The size of the heated or cooled spot is small with respect to the change in thickness of the velocity boundary layer over the distance of the spot which means that the velocity profiles at the beginning and at the end of the spot remain relatively unchanged. The shape of the thermal tuft is determined by the dissipation of the thermal boundary layer and the heat transfer to the substrate.

3. Encapsulated phase change material—model design

The materials used in the model and base must have a low thermal conductivity in order to produce a clear thermal tuft. An advantage of having a base material with low thermal conductivity is the short thermal time constant. After some analysis, polystyrene foam was selected as the base material for the present study. In order to have a smooth surface, a layer of foam filled poster board was used. It was painted with black matte finish paint then airbrushed with TLCs. The model consisted of a 3×3 matrix of capsules spaced 2.5 cm apart. This model was designed to plug into a base producing a flat plate that would be mounted in a wind tunnel. A diagram of the encapsulated phase change capsule is shown in Fig. 2.

The capsules were made from copper tubing with brass end plugs. The brass plug on the top surface of the tuft was soldered into place and machined flat to maintain a smooth model surface. A small piece of polystyrene foam was inserted into the capsule to compensate for the expansion of ice during the freezing process. The bottom of the capsules was sealed with another brass plug using epoxy cement.