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Multi-plane visualization of an artificially initiated young turbulent spot using liquid crystals

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ABSTRACT

In this paper, the temperature inside an artificially generated young turbulent spot in a low free stream turbulence water tunnel were measured experimentally, using a digital particle image thermometry (DPIT) method by seeding slurry thermochromic liquid crystals to the flow. The measurements were conducted on both an elevation view at distances of 0, 10, 20 mm from the central plane, and a plan view at distances of 3, 6 mm from the flat plate at times of 0.8, 1.2, 1.6, and 2 s after the spot initiation. During the test, the Reynolds number, turbulence intensity, and temperature of the mainstream was maintained at 75,000, 0.93%, and 23.6 °C, respectively. Meanwhile, the temperature of the heated plate, considered as the heat source of the turbulent spot, was kept at 25.4 °C. The results showed that this technique provides both an instantaneous temperature distribution throughout an entire spot structure and the spot parameters such as the spot celerities, the half spreading angles, and non-dimensional spot propagation parameter simultaneously. Moreover, the mechanism of the upward heat diffusion was observed and discussed. Finally, when the obtained structures were coincided with the temperature contour of the turbulent spot footprint, the heat convection characteristics of turbulent spot were, then, further clarified.

1. Introduction

It is a well-known fact in scientific circles that the concept of a turbulent spot under the boundary layer transition was first proposed over 50 years by Emmons [1]. A turbulent spot is a small turbulent patch, propagating downstream with a uniform growth rate and having a sharp boundary between a turbulent field inside itself and the surrounding laminar flow. The shape of a turbulent spot, on the plan view and the elevation view, is schematically shown in Fig. 1. By investigating using a hotwire anemometer, Schubauer and Klebanoff [2] reported that a turbulent spot, generated by electrical sparking, has an arrowhead shape and propagates downstream with velocity of $0.88U_\alpha$ and $0.5U_\alpha$ at its leading edge and trailing edge, respectively. With this difference in the velocities, the turbulent spot stretches in the streamwise direction. In the meantime, it spreads laterally with a half angle of 11.3°. The becalmed region, having a laminar-state-like laminar flow and following the passage of the turbulence spot, was also discovered in this study. The spot hump height increases with the thickness of a turbulent boundary layer, starting from a thickness of laminar boundary layer at a spot generator location. Wygnanski et al. [3] showed that the turbulent spot is a large single eddy, having no way to escape as long as the spot retains its shape. They found that some fluctuations appear at the overhang tip and the flow inside its body characterizes as the turbulent boundary layer at a low Reynolds number. Meanwhile, the stagnation-point flow behavior was found at the trailing edge. This part of the spot was followed by the becalmed region, having more stable velocity profiles when it was compared with the Blasius profile. Then, the characteristic of a Blasius boundary layer was found farther downstream. However, the flow within the turbulent spot comprises 2 large eddies [4]. There are 2 types of entrainment processes that result in the spot growth. More than 80% of whole entrainment occurs by the nibbling process, mostly appearing along the spot rear, while the gulping entrainment process is found at the near wall front of the spot.

Sankaran et al. [5] remarked that the number of vortex structures inside the turbulent spot body increases along the streamwise direction, corresponding to the results of Wygnanski et al. [6], Sankaran et al. [7], Sabatino and Smith [8], Schröder et al. [9], Strand and Goldstein [10]. The hairpin vortex was found to be the primary structure of turbulent spot [11]. Haidari and Smith [12] proposed that the first hairpin vortex, initiated from the injection process, is the primary vortex. It is followed by a group of hairpin vortices, termed as the secondary vortices. In the meantime, the subsidiary vortices, responsible for the spot lateral growth are influenced by the primary vortex legs. Not only an experimental visualization technique but also a direct numerical simulation

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Nomenclature

A	turbulent spot area (m^2)
A_i	area of a pixel (m^2)
B	blue signal value
C_m	fractional propagation rate of the turbulent spot center
G	green signal value
H	hue signal value
I	intensity signal value
R	red signal value
S	saturation signal value
T	temperature (°C)
T_s	surface temperature (°C)
T_∞	free stream temperature (°C)
t	time (s)
U_∞	free-stream velocity (m/s)
W	spot half width (m)
X	dimensionless streamwise distance
$\bar{X}$	streamwise centroid of a turbulent spot
x	streamwise distance (m)
$x_0 = 0.3$	streamwise location of spot generator (m)
$\bar{x}_i$	streamwise centroid of a pixel (m)
Y	dimensionless heightwise distance
y	heightwise distance (m)
z	spanwise distance (m)
Z	dimensionless spanwise distance
Greek symbols	
α	half spreading angle (°)
δ_0	thickness of laminar boundary layer at the spot generator (m)
θ	dimensionless temperature
τ	dimensionless time
σ	non-dimensional spot propagation parameter

(DNS) was utilized to study the flow mechanism inside the spot structure [10,13,14]. Singer [14] defined the turbulent spot at the early state after the spot initiation as a young turbulent spot. The young spot not only has a relatively narrow spreading angle, compared to the mature spot [15] but also exhibits non-linear structural behavior [2]. On the other hand, the structural characteristics such as the spreading angle and the propagation rates are constant for the mature spot. In this state, the numerous sizes of the hairpin vortices are found throughout the spot body [10]. The mature turbulent spot grows laterally with a half angle between 9° and 11.3° and propagates downstream with celerities in range of 50–57%, 88–89%, and 100% of the free-stream velocity at the trailing edge, the near wall leading edge, and the most downstream point of overhang head, respectively [2,6,16,17].

In the bypassed transition, the turbulent spot can be directly initiated by high freestream turbulence or a strong disturbance such as injecting fluid into the mainstream. The heat transfer via an artificially initiated turbulent spot under the bypassed transition was firstly investigated using a passive temperature-tagging technique by Van Atta and Helland [18]. When their results were compared with the contour of streamwise velocity, measured by Zilberman et al. [19], an anti-correlation between temperature and velocity was clearly observed. Van Atta and Helland [18], Antonia et al. [20], Chong and Zhong [21] were all in agreement that the near wall temperature inside the turbulent spot is relatively lower than the local temperature before the spot arrival. This is consistent to the results obtained by Zhong et al. [22], Sabatino and Smith [8], and Chaiworapuek et al. [23], who applied the thermochromic liquid crystals (TLCs) to construct the temperature contour of the turbulent spot footprint. The turbulent spot footprint appears as a streaky structure [22,24]. It travels downstream with celerities in the range of 74–83% and 53–57% of the free-stream velocity at the leading and trailing edges, respectively. Also, the half spreading angle of the young turbulent spot is between 6° and 6.8° [15,24,25]. When the footprint is in young state, it appears as a hand-like structure instead of the arrowhead-like shape [24,26–28]. In addition, it provides the largest heat transfer [8].

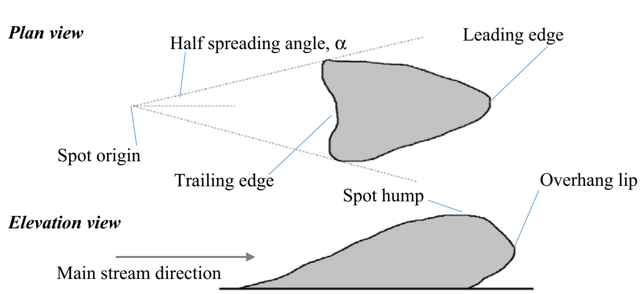

Fig. 1. Turbulent spot structure on the plan and elevation views.

Therefore, this study focuses on the investigation of the temperature change inside an artificially initiated young turbulent spot in a low freestream turbulence water tunnel using the digital particle image thermometry technique. The contours of local absolute temperature are presented on both an elevation view at distances of 0, 10, and 20 mm from the central plane and a plan view at heights of 3 and 6 mm from the test plate, at the times of 0.8, 1.2, 1.6, and 2 s after the spot initiation. However, due to the unsteadiness in the structural behavior of the turbulent spot, a centroid averaging technique is utilized within the image processing method to construct a representative spot structure. When the results are compared with the temperature contour of the young spot footprint, yielded by Chaiworapuek et al. [23], the physical process of the heat transfer mechanism inside the turbulent spot is obtained.

2. Digital particle image thermometry

Digital particle image thermometry (DPIT) is a method of temperature measurement on a two-dimensional domain using a mixture of thermochromic liquid crystal tracer particles as the working fluid [29]. Over two decades, this technique has been implemented for a variety of flow visualization applications [30]. The slurry microencapsulated thermochromic liquid crystals, used in DPIT technique are commercially available in Cholesteric and Chiral-Nematic phases. They generally appear as a thick milky matter and reflect color signals as a function of temperature [31]. Under the white light, the visible color of the liquid crystal changes from milky to red when their temperature enters the color–temperature range of the liquid crystals. Then, their color turns yellow, green, blue, and violet as the temperature is increased [32]. Beyond the range, the liquid crystals return to a milky color again. These characteristics remain repeatable and reversible during the test as long as the liquid crystals are not chemically degraded or physically damaged [31]. The response time of liquid crystals is only 3 ms, short enough for their application in fluid engineering [33]. Their working range is selectable from −30 °C to 120 °C in a bandwidth of 0.5 °C to 20 °C [34]. If the relation between the colors and the temperatures of the liquid crystals is appropriately constructed via a calibration process, the DPIT is one of the most effective