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On the thermal and structural characteristics of an artificially generated young turbulent spot

Weerachai Chaiworapuek *, Chawalit Kittichaikarn

Department of Mechanical Engineering, Faculty of Engineering, Kasetsart University, Bangkok 10900, Thailand

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ABSTRACT

The unsteady heat transfer from an isothermal wall to a water flow via a turbulent spot at an early stage was investigated experimentally using thermochromic liquid crystals. With a Reynolds number of approximately 75,000 at the test area, an artificially generated turbulent spot was induced by a water injection in a low-turbulence water tunnel with a turbulent intensity of 0.93%. The ratio of the spot heat transfer rate to the heat transfer rate existing without the spot was determined to evaluate the turbulent spot effectiveness. Selected images of both the Nusselt number and the spot effectiveness were illustrated to visualize the spot development. Interesting results were obtained soon after the spot initiation, as the spot provided an averaged heat transfer up to 10% above the laminar state. The results also indicated a significant influence of the water injection consequent to the non-linear behavior during the young state of the turbulent spot. The turning point from young to mature state was reported. Moreover, the spot footprint appeared as a hand-like shape and propagated downstream with 38% of the free stream velocity.

1. Introduction

Turbulent spots occur under boundary layer transitions from laminar to turbulent flow and are responsible for the change in boundary layer properties and profile observed between the laminar and the turbulent state. The turbulent spot was first discovered by Emmons [1], who noticed a small turbulent patch on a water table. Emmons also showed that the turbulent spot could be generated directly by releasing a water droplet to strike the target surface. Later, Schubauer and Klebanoff [2] undertook experiments using a hot wire anemometer and found that the turbulent spot had an arrowhead shape, which propagated downstream with 88% and 50% of the free stream velocity at its leading and trailing edges, respectively. These researchers also found a stable state region similar to the laminar flow following the passage of the turbulent spot. This area was highly stable, and no breaking down was likely to appear. This region was "the recovery trail" or "the calmed region".

The results from many contributions [3–9] have also confirmed that the turbulent spot body has an arrowhead-like structure. Using a hot wire anemometer, Wygnanski et al. [4] suggested that the entire turbulent spot, based on the ensemble averaged analysis, was a single large vortex. However, multiple sub-structures have been detected by different measurement techniques [5,8–13]. The growth mechanism of the turbulent spot in the streamwise and heightwise directions is due to the gulping entrainment process at its front interface and the nibbling process at its trailing edge [7]. Meanwhile, destabilization is considered the primary cause of the lateral growth of the turbulent spot [7,12]. In the bypass transition process, the turbulent spot can be directly initiated by injecting fluid into the flow or increasing the level of the free stream turbulence. Haidari and Smith [12] suggested that the initial hairpin vortex generated by the injection process was the primary vortex. This vortex then induces the subsidiary vortex and the secondary vortices, which were also considered main features of the turbulent spot. However, the spot would take some time to develop to a linear or mature state. This time becomes shorter with increasing Reynolds number [4].

The thermal structure of the turbulent spot was first investigated using a cold wire by Van Atta and Helland [18]. When it was compared with the contour of velocity perturbation, yielded by Zilberman et al. [19], the temperature and velocity fields were found to be strongly anti-correlated. Van Atta and Helland [18], Antonia et al. [20], and Chong and Zhong [21] were all in agreement that the near wall temperature inside the turbulent spot was below the local temperature before the spot arrival. This finding is consistent with the results reported by Zhong et al. [22],

* Corresponding author.
E-mail address: fengwcc@ku.ac.th (W. Chaiworapuek).

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Nomenclature

A_s	turbulent spot area (m^2)
C_{LE}	turbulent spot velocity at leading edge
C_m	propagation rate of the turbulent spot centroid
C_{TE}	turbulent spot velocity at trailing edge
E_{in}	energy inflow (W)
E_g	energy source (W)
E_{st}	energy storage (W)
H	Hue signal value
h_x	heat transfer coefficient (W/m^2 °C)
k	thermal conductivity (W/m °C)
Nu_x	local Nusselts number
$\overline{Nu}$	average Nusselts number
Pr	Prandtl number
Q	rate of heat transfer (W)
Q_{ns}	heat transfer rate of heated plate through the area of turbulent spot (W)
Q_s	rate of heat transfer through turbulent spot (W)
q	heat flux (W/m^2)
$\overline{q}$	average heat flux (W/m^2)
q_{ns}	heat flux of heated plate through the area of turbulent spot (W)
q_s	heat flux through turbulent spot (W)
Re_x	local Reynolds number
T	temperature (°C)
t	time, counted after spot initiation (s)
T_{al}	temperature on aluminum plate (°C)
T_α	free stream temperature (°C)
U	velocity (m/s)
U_α	free stream velocity (m/s)
W	turbulent spot half width (m)
X	dimensionless streamwise distance
x	streamwise distance (m)
x_0	streamwise location of the spot generator (m)
Δx	streamwise length of each pixel (m)
Y	dimensionless spanwise distance
y	spanwise distance (m)
Δy	spanwise length of each pixel (m)
Δz	heightwise length of each pixel (m)
Greek symbols	
α	half spreading angle (°)
δ_L	laminar boundary layer thickness (m)
δ^*	boundary layer displacement thickness at the spot generator (m)
τ	dimensionless time
ε_s	turbulent spot effectiveness
$\overline{\varepsilon_s}$	average turbulent spot effectiveness
ξ	unheated starting length (m)
σ	non-dimensional spot propagation parameter

Sabatino and Smith [23], Chaiworapuek et al. [24], who employed the technique of temperature mapping using thermochromic liquid crystals. Typically, the shape of the turbulent spot's footprint can be directly examined via the region of heat transfer [22]. Its foremost edge is defined as the leading edge, as shown in Fig. 1. The trailing edge and the half spreading angle can also be obtained as shown in the figure. The footprint underneath the turbulent spot propagates downstream with velocities in the range of 74–83% and 53–57% of the free stream velocity at the leading and trailing edges, respectively [16,17,25]. Additionally, the spreading half angle of the spot footprint was reported to be between 4° and 6.8° [14–17,25]. Chaiworapuek et al. [17] found that the arrowhead-like shape was first found when the leading edge reached the streamwise distance of $x/\delta^* = 94.54$ from the location of the spot generator. Before that, a hand-like structure was observed [17]. Sabatino and Smith [23] found that a peak in heat transfer at approximately 15% above the laminar condition occurred in the calmed region. This peak is caused by the cooler fluid entering from the upstream higher level, following Johnson [26].

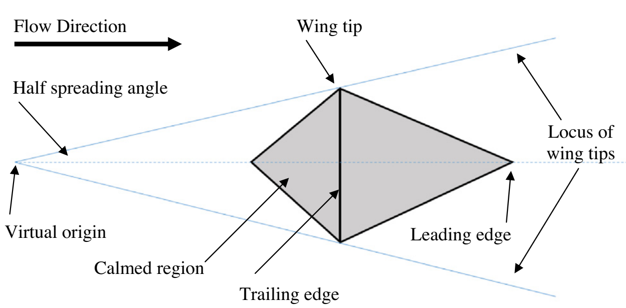

Fig. 1. Schematic of a turbulent spot on a flat plate.

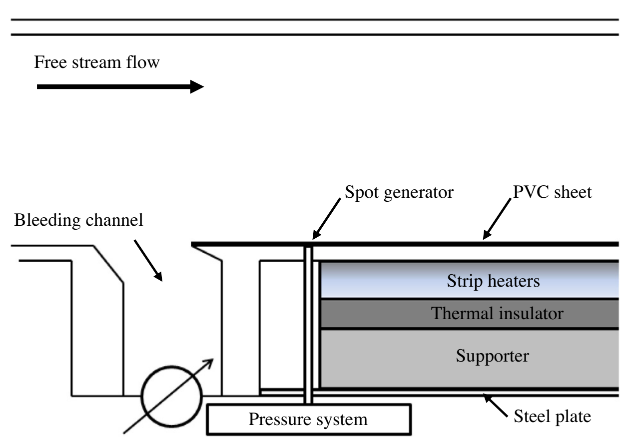

Fig. 2. Schematic of the test section in the low free stream turbulence water tunnel.

Hence, this study experimentally investigates the thermal and structural characteristics of a turbulent spot footprint. The test was conducted in a low free stream turbulence water tunnel with a Reynolds number of approximately 75,000 at the test area. To obtain all spot parameters, including the Nusselt number, the heat flux, the spot effectiveness, the velocities, the half spreading angle, and the non-dimensional spot propagation parameter, the thermochromic liquid crystals are used together with an analytical solution derived from the energy balance, following Chaiworapuek et al. [24]. All presented results provide valuable insight into the growth and heat transfer process of the turbulent spot footprint under the bypass transition.

2. Experimental setup

Fig. 2 shows a schematic diagram of the test section of the closed-loop low free stream turbulence water tunnel used in this