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Flow structure and heat transfer of a sweeping jet impinging on a flat wall

Tongil Park [a], Kursat Kara [b], Daegyoum Kim [a,*]

[a] Department of Mechanical Engineering, KAIST, Daejeon 34141, Republic of Korea
[b] Department of Aerospace Engineering, Khalifa University, Abu Dhabi 127788, United Arab Emirates

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ABSTRACT

While an impinging jet has been widely investigated because of its remarkable convective heat transfer performance, the impingement of a sweeping jet which undergoes periodic oscillation has drawn little interest. We experimentally examined the heat transfer of a sweeping jet impinging on a flat wall for several Reynolds number and nozzle-to-plate spacings and discovered unsteady flow structure to characterize heat transfer capability. Local Nusselt number on the wall was evaluated by measuring temperature with thermocouples, and a flow was visualized quantitatively using particle image velocimetry. The distribution of the Nusselt number is different from that of a round jet, exhibiting two distinct regions. Near the center of a sweeping jet, a high Nusselt number zone is formed without a noticeable peak commonly observed in a round jet. Away from the central region, the Nusselt number decreases monotonically. The trends of the Nusselt number at the two regions are correlated with the first mode of the flow structure obtained by proper orthogonal decomposition (POD). The boundary of the two regions is a local minimum of the first POD mode near the wall, and the magnitude of the first POD mode is large in the central region of high Nusselt number. It was also found that the distributions of mean lateral velocity and lateral velocity fluctuation were clearly different between the two regions, which implies that both quantities should be considered for the analysis of heat transfer performance.

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1. Introduction

An impinging jet, liquid or gas vertically discharged on a solid surface, has received a lot of attention in the past decades due to its compelling characteristics of enhancing heat transfer [1–11]. The impinging jet has been used in various applications including heat treatment of steel, drying of papers, and cooling of gas turbine blades and electric devices [12–15].

The impinging jet has been mainly investigated for a simple configuration, a steady jet with a simple geometry of a nozzle exit. Martin [3] presented an extensive review on the heat and mass transfer of an impinging jet for three standard types: single circular jet, array jet, and slot nozzle jet. In addition, the empirical relationships that account for nozzle geometry, confinement, turbulent intensity, and nozzle-to-plate spacing have been established by many studies [5,6,11,16].

Besides the simple jet types mentioned above, special types of jets have been introduced: synthetic jet, air-assisted jet, and annular jet. A synthetic jet, a quasi-steady jet generated by periodic suction and squirting motions in a cavity, was used to improve cooling efficiency [14,17]. It was reported that an air-assisted jet, a two-phase flow of liquid and gas bubbles, could enhance heat transfer efficiency as well [18]. Terekhov et al. [19] studied the effect of geometric variables of an annular nozzle and found that the annular jet could increase a heat transfer rate, compared to a basic round jet.

Although past studies on impinging jets have suggested many techniques to enhance heat transfer performance, only recently have studies regarding the effect of unsteady oscillating jet flow on heat transfer emerged. Here, we introduce a fluidic oscillator to generate an unsteady oscillating jet, i.e., a sweeping jet. The fluidic oscillator is an apparatus that produces a bi-stable pulsating jet of sweeping motion [20]. The fluidic oscillator can be generally categorized into feedback and feedback-free oscillators [21], and a feedback-type fluidic oscillator was chosen in this study. Fig. 1 depicts the geometry of a fluidic oscillator with two feedback loops. The mechanism generating a sweeping jet is as follows. At start, pressurized flow from the inlet of the apparatus spontaneously adheres to either wall of an interaction zone inside due to the Coanda effect. At the same time, a jet at the exit is deflected to the opposite side (Fig. 1(a)). The attached primary flow of the

* Corresponding author.
E-mail address: daegyoum@kaist.ac.kr (D. Kim).

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Nomenclature

A	surface area of the heated plate (m^2)
d	width of the nozzle exit (m)
H	nozzle-to-plate spacing (m)
h	convective heat transfer coefficient (W/m^2 K)
I	current through the heated plate (A)
k	thermal conductivity of air (W/(m K))
k_p	thermal conductivity of the heated plate (W/(m K))
Nu	local Nusselt number, hd/k
$\dot{m}$	mass flow rate drained into the fluidic oscillator (g/s)
q	rate of heat transfer (W)
R	electrical resistance of stainless steel foil (Ω)
Re	Reynolds number, Ud/ν
T_j	temperature of a jet at the nozzle exit (K)
T_s	local temperature of the heated plate (K)
t	thickness of the heated plate (m)
U	mean velocity of a jet at the nozzle exit (m/s)
$\bar{u}$	mean lateral velocity (m/s)
u'_{rms}	root mean square of the lateral velocity fluctuation (m/s)
$\overline{V}$	mean velocity magnitude (m/s)
w	width of the heated plate (m)
x	lateral coordinate (m)
ϵ	emissivity of the heated plate
ν	kinematic viscosity of air (m^2/s)
σ	Stefan-Boltzmann constant (5.670×10^{-8} W/(m^2 K^4))

interaction zone increases the pressure of the feedback loop in the same side (upper loop in Fig. 1(a)). The increase in pressure pushes the primary flow to adhere to the other side and causes the jet at the exit to change its direction (Fig. 1(b)). This process is repeated, leading to an oscillating sweeping jet.

Unsteady sweeping motion is self-sustained by the internal geometry of a fluidic oscillator without any moving element or actuator. The fluidic oscillator, therefore, is a highly durable device to shock and vibration and is not affected by electromagnetic interference [20–22]. Because of these attractive features, the fluidic oscillator has been broadly applied to many fluid engineering fields including separation control of a boundary layer, jet thrust vectoring, cavity noise reduction, and micro-bubble generation [23–27]. Meanwhile, relatively little has been investigated on the application of a sweeping jet to convective heat transfer. Thurman et al. [28] first applied the sweeping jet to heat transfer and evaluated the effect of the jet flow ejected through a hole into a cross flow on film cooling process. They discovered that a sweeping jet makes cooling performance more uniform on the surface than a jet from a spiral hole. The interaction of a sweeping jet flow and a cross flow was numerically investigated with consideration of an inclination angle to a free stream direction and a blowing ratio [29]. Moreover, Hossain et al. [30] conducted both experimental and numerical studies on film cooling performance, using an array of fluidic oscillators, and found that the array shows significant improvement in cooling effectiveness in the lateral direction because of the sweeping motion of the jet. For a jet vertically impinging on a plate, Lundgreen et al. [31] numerically investigated the thermal performance of a sweeping jet when nozzle-to-plate spacing is greater than 3 hydraulic diameters. This study demonstrated that the average Nusselt number for the fluidic oscillator is higher than that of the steady jet at small nozzle-to-plate spacing and that a fluidic oscillator can provide a more uniform heat transfer rate with a higher average Nusselt number.

In this study, we experimentally investigate the flow structure and heat transfer performance of the sweeping jet generated by a fluidic oscillator, which impinges vertically on a flat wall. Although the heat transfer of an impinging sweeping jet was suggested as a novel technique to improve heat transfer performance in the numerical study of Lundgreen et al. [31], relatively large nozzle-to-plate spacing was considered in their study, and the detailed characteristics of the flow structure and their correlation with the trend of heat transfer performance still remain unclear. By varying Reynolds number and nozzle-to-plate spacing which are known as important parameters to determine the performance of an impinging jet, we will examine noticeable characteristics of heat transfer and reveal correlations between unsteady flow structure and heat transfer performance by employing digital particle image velocimetry and temperature measurement with thermocouples.

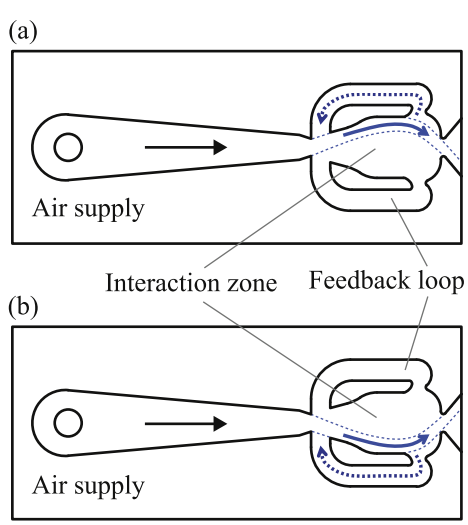

Fig. 1. Geometry of a fluidic oscillator.

2. Experimental setup

A fluidic oscillator design suggested by Stouffer [32] was used to generate a sweeping jet (Fig. 1). The nozzle exit of our fluidic oscillator has a square shape with 6.25 mm width and 6.25 mm height and an exit angle of 100°. The fluidic oscillator was fabricated using a 3D-printer (Ultimaker 2+, Ultimaker Inc.) with Polylactic Acid (PLA) material, and layer thickness in the fabrication process was 140 μm. This layer thickness was much smaller than the length scale of the fluidic oscillator (e.g., nozzle exit width 6.25 mm). Thus, we assumed that jet characteristics were not affected by the surface roughness of the device in this setup. Compressed air was supplied through a regulator integrated with a filter (W4000, CKD Co.) and injected into the fluidic oscillator. The mass flow rate of supplied air was controlled with a mass flow controller with 0.8% accuracy (F-202AV, Bronkhorst High-Tech) installed between the regulator and the fluidic oscillator.

Our experimental study consists of two measurements: convective heat transfer measurement and quantitative flow visualization, which are introduced in Sections 2.1 and 2.2, respectively.

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