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Heat transfer and fluid flow characteristics of impinging jet using combined device with triangular tabs and synthetic jets

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ABSTRACT

The fluid flow and heat transfer characteristics of an impinging jet with a combined active–passive device were investigated. The combined device consisted of triangular tabs and a synthetic jet array that provided periodic disturbance to the jet's shear layer. The Reynolds number based on the nozzle diameter (D) was 3.9×10^4, and the nozzle-to-wall spacing (L/D) was 2. Four triangular tabs were attached to the nozzle outlet. The synthetic jets were issued at an angle of 30° against the primary jet. Under the triangular tab operation, the longitudinal vortices were generated and the transverse vortex of the primary jet collapsed. Moreover, the velocity of the primary jet increased because of contracted flow. Under the synthetic jet operation, the development of the transverse vortex was promoted due to the increased instability of the shear layer. The jet's periodic disturbances strengthened because of the use of synthetic jets. The combined device operation led to increased velocity magnitude and periodic disturbance of the primary jet; thus, the peak RMS value of the velocity fluctuation was enhanced and the peak local Nusselt number near the stagnation point increased by 35% compared with cases where the device was not used. Additionally, the area-averaged Nusselt number was 10% larger than that obtained without the device. The heat transfer was governed by the jet's velocity, RMS, and periodic velocity fluctuation. These results indicate that the fluid flow and heat transfer characteristics of an impinging jet could be controlled by optimizing the actuation conditions of the combined active–passive device.

1. Introduction

Impinging jets are used for many purposes, such as in high-temperature gas turbines, paper drying, and steel or glass processing, to obtain high heat transfer coefficients. Particularly, impinging jets have become a subject of great interest because more efficient cooling techniques, which are necessary for future advanced electronics, are required. Indeed, because of the increased heat flux in recent devices [1], requirements for thermal management in electronics have grown stricter, leading to increased research into the heat transfer and fluid flow characteristics of impinging jets [2].

The flow characteristics of a circular jet have been extensively studied with emphasis on large-scale vortex structures; for example, periodic vortex rings were investigated using flow visualization [3], velocity and pressure fluctuation spectra [4], and vorticity distribution [5]. At moderate Reynolds numbers, vortex formation occurs due to Kelvin–Helmholtz instability in the region closest to the jet nozzle exit. Zaman has shown that vortex pairing in circular jets occurs in two distinct modes: the shear layer mode at $St_\theta = 0.012$ and the jet column mode [6]. The turbulent flow structure of an impinging jet is also important for its heat transfer characteristics. Kataoka et al. revealed that the breakdown of large-scale ring-vortex structures in the jet enhances heat transfer near the stagnation region [7]. Donovan et al. revealed that the local Nusselt number on an impinging plate has two peaks, which suggests that heat transfer is affected by flow behavior in the boundary layer [8]. Violato et al. showed the interference of longitudinal and transverse vortices by considering three-dimensional vortex dynamics [9].

Convective heat transfer can be enhanced using either a passive or active flow control device. Passive control offers the benefits of a simple structure and high heat transfer enhancement [10,11]. Meanwhile, active control offers a great degree of flexibility and applicability. Many studies show that active control devices lead to the stimulation of the shear layer mode's periodicity [6] and promote the mixing and diffusion of jets [13,14]; furthermore, various

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Nomenclature

D	diameter (m)	T_w	wall temperature (K)
f	frequency (Hz)	U	axial velocity component of primary jet (m/s)
L	nozzle to impingement surface spacing (m)	U_{ref}	velocity at reference point (m/s)
Nu	local Nusselt number (–)	VR	velocity ratio (–)
$\overline{Nu}$	averaged Nusselt number (–)	x	streamwise distance from nozzle (m)
q_w	wall heat flux (W/m^2)	α	heat transfer coefficient (W/(m^2 K))
r	radial distance (m)	ν	kinematic viscosity (m^2/s)
Re_D	Reynolds number (–)	ψ	circumferential angle (°)
St_θ	Strouhal number based on momentum thickness of primary jet (–)	λ	thermal conductivity of air (W/(m K))
T_a	temperature of jet (K)	Ω_x	x component of vorticity (1/s)

flow controls are possible with active control devices by changing their operating conditions and optimizing their output.

Despite the fact that some studies of impinging jets with passive control devices have demonstrated that such schemes have some drawbacks such as less applicability to dynamic flow changes [12], considerable interest has been demonstrated for investigating the use of both passive and active control of an impinging jet to improve heat transfer. Hayashi et al. have shown that fluid flow and heat transfer characteristics are affected by the transverse vortices generated from triangular tabs attached to the nozzle exit [15], thus clarifying that heat transfer is promoted by the large velocity fluctuation induced by such tabs. Tamburello et al. have shown that the longitudinal vortex structure generated by a synthetic jet is effective at improving heat transfer performance similarly to the flow structure made by passive tabs for free jets [12]. These researchers also mention that a jet injection angle of 30° to the primary jet is optimal for flow control. A synthetic jet has no net mass flux and can introduce periodic jet injection disturbance and suction into the flow system [16]; such synthetic jets have recently been referred to as "vestigial synthetic jets" because of their nature [17]. The periodic disturbance thus induced is beneficial to exciting the instability of the shear layer. Moreover, it is possible to downsize the device because of its simple structure. Periodic disturbance generated by tabs can be further stimulated by synthetic jets when the remaining periodic disturbance matches the synthetic jet disturbance. In addition, apparently, mixing and diffusing the jet is promoted because of the similar longitudinal vortex structures that are generated by either tabs or synthetic jets. Therefore, combining an active device with a passive device should have the synergetic effect of improving the heat transfer of an impinging jet.

In this work, we investigate the flow and heat transfer characteristics of an impinging jet controlled by triangular tabs and synthetic jets. First, we conducted velocity measurements and flow

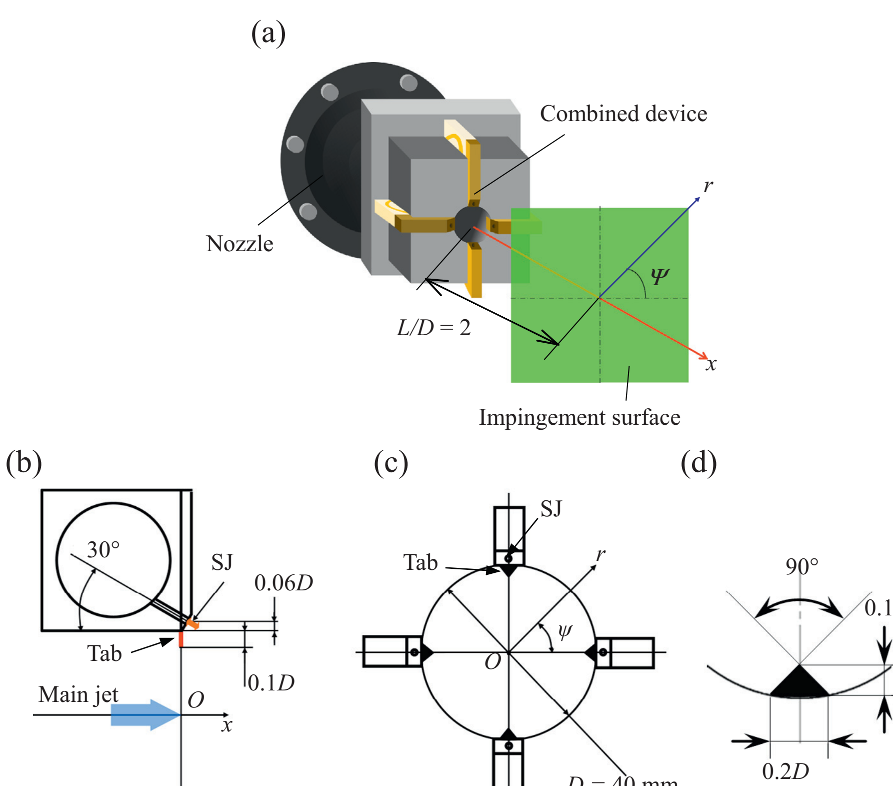

Fig. 1. Experimental setup. (a) Jet nozzle and impingement surface, (b) cross-sectional view of the combined device in the x–r section at ψ = 90°, (c) the r–ψ section, and (d) tab geometry.