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Vortex dynamics-driven heat transfer and flow regime assessment in a turbulent impinging synthetic jet

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A B S T R A C T

Synthetic jets gained attention in the last decade as a thermal management solution, especially in the electronic cooling community. Under certain conditions, they can remove heat more efficiently than conventional steady jets. In this work we aim to further the knowledge on the fundamental behavior of such flows and their role in heat transfer enhancement. A numerical canonical geometry was developed to de-couple the impinging flow from possible artifacts, such as actuator and geometry resonance. The unsteady flow was assumed in turbulent regime, which was approximated via the Finite Volume Method through the software ANSYS Fluent™. The turbulence was modeled using the SST $k-\omega$ model, which accurately agreed with experimental data. Synthetic jets generate a train of counter-rotating vortices that, when impinged onto a stationary wall, give rise to secondary vortices that cause a colder fluid downwash into the heated zone. We proposed an alternative definition of the Reynolds number (Re_Γ) that characterizes the strength of the generated vortices, consequently representing the strength of the jet. We found that to increase the jet thermal efficiency: (1) Having close consecutive vortices is as important as producing strong vortices, and (2) the jet-to-surface distance should be modified such that the vortex finds its peak intensity nearest to the heated wall. Compared to the classic definition of Re, the Stroke Length based Reynolds number (Re_{L_0}) appears as a more suitable definition to establish flow regimes, with the data suggesting $Re_{L_0} \approx 10,000$ as a threshold where the flow fully transitioned to turbulence. Silva-Llanca et al. (2015) proposed three hypotheses to explain some disagreement found in their data: Turbulent flow at large Re_{L_0}, significant heat losses in the experiments at low Re_{L_0} and unaccounted three-dimensional effects. We proved that the first two explained their entire data disagreement, thus rendering the third hypothesis unnecessary.

1. Introduction

Impinging Synthetic Jets popularized in recent years as a suitable thermal management solution, especially in confined small scale electronics. Due to their oscillatory nature and the particular way they interact with solid boundaries, they generally remove heat more effectively than conventional steady jets. Synthetic Jets generate from the periodic intake/outtake of fluid into-and-from a confined volume that spawns an outwardly advecting train of vortices. The actuation of these jets is divided into two main stages: (a) The Forward Stroke in which the fluid is expelled, and (b) the Back Stroke wherein the same amount of fluid is returned at equal rate into the delivering volume.

During the Forward Stroke of a slot Synthetic Jet, two counter-rotating vortices form a vortex pair at the orifice edges as schematically depicted in Fig. 1; each vortex induces a downward translational velocity onto its counterpart [1]—this being the principal mechanism that sustains a coherent flow with positive momentum. The vortices detach from the channel edges before the forward stroke completes, and are sufficiently far from the nozzle when the back stroke takes place, thus suffering negligible impact from the flow intake.

The convective heat transfer generated by the impinging synthetic jets has been studied numerically and experimentally [1–27]. The flow generally finds optimum heat transfer within the

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so-called "intermediate zone", where the ratio between the jet-to-wall distance and the jet diameter ranges between 4 and 11 [4,7,9–11,16,20]. Pavlova and Amitay [4] concluded that for a fixed Reynolds number, this optimum distance decreases when the jet frequency increases, and that augmenting the frequency improves the heat transfer at close jet-to-wall spacings.

Various numerical studies exist in the literature, differing in their approaches and level of accuracy: laminar [7,24], k–ε [25], SST k–ω [23,26] and Large Eddy Simulation (LES) [22]. In order to liberate the flow from possible actuator artifacts, Silva and Ortega [7] introduced an idealized geometry, thereby conducting a fundamental study of pure impinging flow; laminar regime was assumed throughout. Those data agreed with subsequent experiments for a given range of frequencies, Reynolds numbers and jet-to-wall distances [8], where the remaining unmatched data were hypothesized to disagree due to unaccounted conduction losses in the heated surface, flow in turbulent regime and three-dimensional phenomena. Bazdidi-Tehrani et al. [26] used available experimental data on a confined axisymmetric impinging synthetic jet to compare the accuracy of three turbulent models, selecting the SST k–ω since it presented the lowest deviations with respect to the experiments, with an estimated 19% difference on average.

Silva-Llanca and Ortega [1] studied the complex interaction between the vortices and the stationary heated surface, and its influence on the heat transfer, observing that when the vortex approaches the wall, a secondary vortex with opposite sense of rotation emerges near the surface, becoming the principal enhancer of heat transfer in the wall jet region. Greco et al. [28,29] observed similar behavior by locating and measuring secondary vortex rings in axisymmetric synthetic jets, using PIV in air and water. Rohlfs et al. [30], via Direct Numerical Simulations, identified near-wall secondary vortices in a periodically perturbed axisymmetric conventional jet.

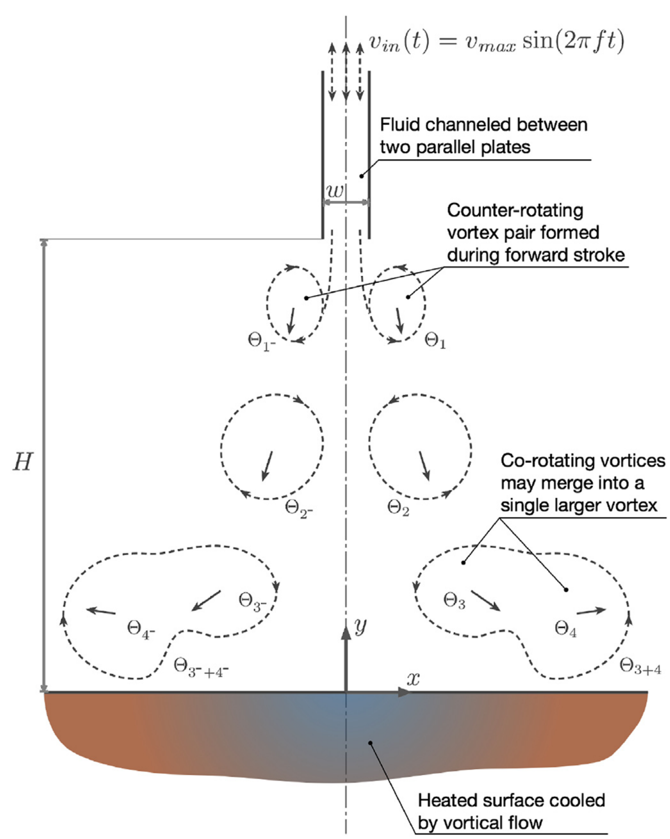

Fig. 1. Schematic of the problem and its relevant phenomena.

Vortex merging happens when two consecutive co-rotating vortices coalesce into a larger vortex, represented schematically in Fig. 1. This phenomenon, whose appearance is more likely to occur at higher frequencies and/or lower Re [1], correlates to an overall decrease in the heat transfer [7] as it reduces the number of secondary vortices "sweeping" the heated wall [1]. Two competing effects arise when the jet frequency augments: (1) The higher production rate of secondary vortices increases the heat transfer, and (2) the onset of vortex merging diminishes the heat transfer. Silva-Llanca and Ortega [1] deconstructed vortex coalescence, detecting three distinguishable stages during its evolution. This allowed them to develop a formulation that can optimize the heat transfer by avoiding merging at the highest possible frequency.

2. Motivation and goals

Previous studies focused on the formulation and experimental validation of an idealized canonical geometry that freed the flow from artifacts and elucidated the physics of a pure impinging synthetic jet flow [1,7,8]. Such an approach unraveled the complex vortex dynamics generated by the interactions between the vortices and the stationary impinging heated surface [1]. This work intends to deepen this prior understanding of the phenomena and its impact on the instantaneous and overall heat transfer.

The specific goals of this paper are:

1. Using empirical data to thoroughly validate a range of numerical simulations at low and intermediate Reynolds numbers and frequencies.
2. Testing and proving the hypotheses proposed in a previous work to explain the disagreement observed between numerical and experimental data.
3. Establishing flow regimes based on a modified and better suited definition of the Reynolds number.
4. Studying the evolution of the vortex-to-vortex and the vortex-to-wall interactions during the jet impingement.
5. Finding the relationship between the jet capacity to remove heat and the intensity (strength) of the vortices it generates.

3. Physical situation and mathematical model

The flow fluctuates periodically between two inviscid parallel plates (Slot Jet) separated by a distance $w = 4.2$ mm (Fig. 1), forming a train of counter-rotating vortex pairs that translate toward a heated surface. This idealized "Canonical Geometry" liberates the flow from artifacts and allows for a study of the fundamental convective heat transfer phenomena.

The assumptions in the physical situation establish the following: (a) Two-dimensional flow, (b) turbulent regime, (c) insignificant viscous dissipation and (d) temperature independent thermophysical properties. The mathematical model proposed to represent the physics yields:

Continuity:

$$\frac{\partial \overline{u_i}}{\partial x_i} = 0 \tag{1}$$

Momentum:

$$\rho\left(\frac{\partial \overline{u_i}}{\partial t} + \frac{\partial \overline{u_i}\,\overline{u_j}}{\partial x_j}\right) = -\frac{\partial \overline{p}}{\partial x_i} + \frac{\partial}{\partial x_i}\left[\mu\left(\frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i}\right) - \rho\overline{u_i' u_j'}\right] \tag{2}$$

Energy: