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Vortex dynamics and mechanisms of heat transfer enhancement in synthetic jet impingement

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ABSTRACT

When confined flow is oscillated from and into a quiescent volume, a periodic coherent flow that resembles that of a conventional jet can be generated. Such a jet, termed a synthetic jet, has been investigated for thermal management by causing it to impinge onto a heated surface. Because of its fluctuating nature, the impinging jet thus formed is dominated by vortices that are advected towards the surface. This surface-vortex interaction is key to understanding the fundamental mechanisms of convective heat transfer by the impinging synthetic jet, which motivates this work along with the search for the improvement of the system thermal efficiency. A canonical geometry was developed to investigate the flow and heat transfer of a purely oscillatory jet that is not influenced by the manner by which it is produced. The unsteady two-dimensional Navier-Stokes equations and the convection-diffusion equation were solved using a finite volume approach in order to capture the complex time dependent flow field. The Q-criterion (Hunt et al., 1988), which defines vortices as connected fluid regions with positive second invariant of the velocity gradient tensor was utilized to identify vortices without ambiguity. A definition of the jet characteristic velocity was developed rigorously based on the vortex dynamics produced by the jet. It is equivalent to the common definition accepted in the literature, which has been successfully used to match the dynamics of synthetic and steady jets, but which was developed using heuristic reasoning. When the primary vortex advects in a direction parallel to the target surface it gives rise to a secondary vortex with opposite net vorticity. This secondary vortex is largely responsible for enhancement of the heat transfer within the wall jet region. Under certain conditions, vortex coalescence occurs, leading to degradation in the heat transfer enhancement due to the reduction in the number of secondary vortices interacting with the heated surface. By understanding, quantifying and predicting the mechanisms that drive the phenomenon of vortex merging, optimum conditions of operation are demonstrated, ultimately leading to higher efficiencies by maximizing the heat transfer at similar pumping costs.

1. Introduction

Synthetic jets are generated by the ejection and injection of fluid from or to an exiting orifice (e.g. a nozzle), resulting in the spawning of a counter-rotating vortex pair with each cycle, and consequently forming a downward moving train of vortex pairs, as seen in Fig. 1. Even though they induce zero net mass flow per cycle, positive net momentum is produced due to the difference in the dynamics of the fluid between the first part of the cycle (forward stroke) compared to the second part (back stroke). This flow can be used as the basis for a cooling method by impinging the unsteady vortical flow onto a heated surface.

The formation and evolution of a slit synthetic jet was investigated by Smith and Glezer [1]. They showed that at the end of the forward stroke, a pair of vortices is generated at the jet exit. Impelled by its own positive momentum, this vortex pair advects away rapidly enough to be only weakly affected by the suction part of the cycle. Analytical and experimental comparisons between synthetic and steady jets have been presented [2,3]. Smith and Swift [2] matched the Reynolds numbers within the range $695 < Re < 2200$, finding correspondent flow characteristics, where

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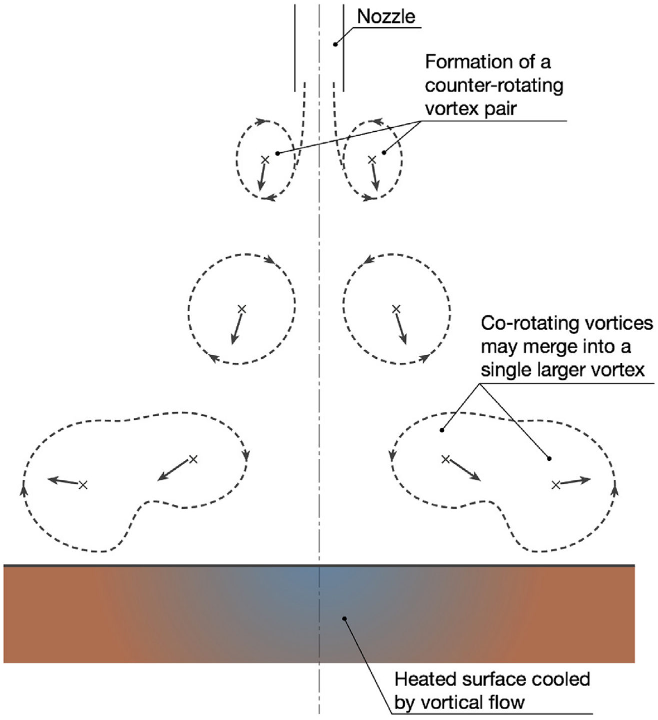

Fig. 1. Schematic representation of the vortex dynamics during synthetic jet impingement.

the normalized time mean velocity data were similar for both cases. They reported that the synthetic jet width grows linearly with respect to the downstream direction, just as in a steady jet, although it spreads more rapidly. Agrawal and Verma [3] used similarity analysis to compare synthetic and conventional jets, finding similar streamwise variation of velocity and spread rate; their conclusions were corroborated with empirical data.

The origin of the characteristic velocity used to define Re such that the steady and unsteady jets can be compared was not established in these initial studies. The present paper shows that the characteristic velocity arises from the analysis of the self-induced velocity of the co-rotating vortex pair.

Several studies have been performed to understand the fluid flow and/or the heat transfer generated by an impinging synthetic jet [4–17]. Optimum jet operating conditions have been found for the heat transfer at certain jet-to-surface distances [4,9,11,13,14,18,19]. It has been claimed that when the wall was located within the so-called intermediate-flow regime, a more effective mixing with colder ambient air augments local heat transfer rates. When compared to conventional steady impinging jets, synthetic jets can offer higher heat transfer rates except in cases when, for example, vortex merging is present [11,12].

A notable phenomenon sometimes observed with the advection of vortices is the merging or coalescence of consecutive co-rotating vortices, as shown schematically in Fig. 1. Merging of contiguous vortex pairs has been previously reported by experimental observations [20]. The power spectrum of the instantaneous velocity near the jet exit detected the presence of a frequency equal to one half the driving frequency (sub-harmonic), which was related to vortex coalescence. Silva and Ortega [11] correlated the onset of vortex merging to a decrease in the overall heat transfer.

We note here that many if not most previous experimental investigations include actuator resonant artifacts either by intent or by mistake [4,6,7,9,13,15,17–19]. Optimum heat transfer has been found at resonance frequencies [6,7,9,15,17,19], which is an intrinsic characteristic of the actuator and the jet issuing cavity, rather than pure flow physics. In general, the experiments have been carried such that the excitation voltage is kept constant and the frequency is varied; procedure that also modifies the jet Reynolds number by maximizing it at resonance conditions. Unless a study were mainly focused on the actuator performance, this simultaneous adjustment of the Reynolds number and the frequency may obscure any conclusion regarding their individual effect over the impinging flow and the heat transfer fundamentals. Silva-Llanca et al. [12] tackled this issue in their experiment by modifying the excitation voltage when the frequency varied, so that the flow could be produced at constant Reynolds numbers. Disregarding this matter renders the data set available in the literature hard to compare, as the results are strongly related to the device utilized in each experiment.

Numerical experiments facilitate the idealization of the convective phenomena and are less prone to artifacts. Several computational studies of the heat transfer phenomenon have been presented [10–13,21]. Utturkar et al. [13] achieved good agreement between numerical and experimental data assuming laminar flow throughout. This assumption was found to be accurate due to the high effective viscosity that dampens the small vorticity scale near the jet orifice. Wang et al. [21] simulated the vibration of the diaphragm used to produce the pulsating flow as a sine wave velocity function at the inlet boundary. Large eddy simulation was the technique chosen, showing acceptable agreement with velocity and temperature distributions that were experimentally obtained. Silva-Llanca et al. [12] compared idealized numerical data from a laminar synthetic jet to large-scale experiments, up to six times the size of the previously published canonical geometry [11]. Excellent agreement was found under a given range of Reynolds numbers, frequencies and jet to wall separation. Some disagreement in the data was attributed to phenomena that were not accounted for in the numerical simulations such as: comparable conduction heat loses to convective heat transfer, transition to turbulence, and plausible three dimensional effects.

The synthetic jet, as a coherent flow, is dominated by its vortical nature, wherein the train of vortices plays an essential role in the free jet, stagnation, and wall jet zones. Locating and sizing vortices unambiguously, even when they can be identified as coherent, rotating structures in the flow, is challenging. Different Galilean invariant (frame of reference independent) definitions of a vortex have been previously proposed [22–25]. Hunt et al. [24] defined vortices as regions with positive second invariant of the velocity gradient, Q, with the additional condition that the pressure be lower than ambient. Dallmann [23], Vollmers et al. [25] and Chong et al. [22] defined vortices based on the eigenvalues of the velocity gradient $\nabla \boldsymbol{v}$ to classify the local streamline pattern around any point in a flow in a reference frame moving with the velocity of that point. They proposed that a vortex core is a region with complex eigenvalues of $\nabla \boldsymbol{v}$, which implies that the local streamline pattern is closed or spiral in a reference frame moving with the point.

2. Motivation and goals

It has been previously shown that impinging synthetic jets remove heat more efficiently than steady jets, and it has been hypothesized that the vortical nature of the flow is responsible for this enhancement in the heat transfer. However, fundamental exploration of the vortex-surface interactions that are claimed to be responsible for heat transfer enhancement has not been performed, and certainly not in a pure flow that is absent of actuator artifacts. The impinging synthetic jet flows previously studied by the authors have been created either experimentally or computationally such that they are independent to the effect of the actuator geometry