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Unsteady heat transfer and flow structure of a row of laminar impingement jets, including vortex development

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ABSTRACT

Considered is a cylindrical channel with a single row of 10 aligned impinging jets, with exit flow in the axial direction at one end of the channel. For the present predictions, each jet is laminar with a Reynolds number of 200. An unsteady FLUENT solver is employed for predictions of flow characteristics within and nearby the 10 impingement jets. Instantaneous, local surface Nusselt numbers oscillate as time progresses, such that the local Nusselt number signature from one individual vortex diminishes in intensity, as the opposite vortex in the same pair then produces an increase in the local, instantaneous Nusselt number signature. Spectrum analysis of different flow quantities shows frequencies associated with laminar jet and vortex oscillations, and evidence more orderly flow for $Re = 200$, without the chaos and broad-band mixing associated with the turbulent flow when $Re = 15{,}000$. Laminar flow spectra also evidence increased flow unsteadiness as cross-flows accumulate within the impingement channel with streamwise development as Z/D increases. In some cases, this increased unsteadiness manifests itself through the formation of multiple spectral peaks, in place of single peak spectra. Similar with turbulent jet arrangements, the unsteady, local static pressure gradient variations along interfaces between laminar jets and cross flow are also a key flow feature, which is connected to the initiation and development of the Kelvin–Helmholtz instability induced vortices.

1. Introduction

The present laminar impingement jet arrangement is selected for investigation because information on important impingement mechanisms are provided, without the complications of turbulent flow. Of particular interest are phenomena associated with each impingement jet, regardless of jet Reynolds number. For example, as each jet exits its supply hole, it is associated with an axisymmetric region of flow separation, and a shear layer interface with fluid having different momentum. Such effects result in an unsteady flow field, and Kelvin–Helmholtz vortices, which are difficult to predict numerically. Note that information on single jet behavior is provided by the first jet at the smallest Z/D location. As a result, the present data provide new physical understanding of impingement cooling and related flow instabilities, and new design information for a variety of low Reynolds number industrial applications. Low Reynolds number industrial applications include millimeter-scale and micro-scale environments for electronics cooling applications, where the impingement arrangements always involve laminar jets. With these arrangements, both single jets, rows of jets, and arrays of cooling impingement jets are employed.

Recent related impingement cooling investigations consider the influences of different parameters such as jet diameter, jet pitch and nozzle to target distance, and present a variety of different results, including flow structural characteristics, visualizations of flow characteristics, as well as distributions of surface shear stress rates, surface heat transfer coefficients, surface heat transfer rates, and/or surface friction factors. Such data are provided for both single jet and showerhead jet arrangements [1–8]. Other recent impingement investigations consider unsteady flow characteristics and the resulting Kelvin–Helmholtz instabilities [9–12]. In several cases, the influences of liquid and vapor phases of the experimental medium are also considered [10,11]. Of particular significance are results presented by Lugt [12], who describes the origin of unsteadiness and Kelvin–Helmholtz instabilities. According to this author, local flow streamline separations for a variety of different impingement configurations can result in Kelvin–Helmholtz instabilities. Discrete vortices develop when the shear flow is unstable. Unsteady separation in a boundary layer produced by an impinging

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Nomenclature

A	amplitude
A^*	amplitude normalized by root-mean-square value, $A^*(x) = A(x)/\mathrm{RSM}(x)$
c_p	specific heat
D	impingement hole diameter
f	frequency
L	impingement hole length
N	vector length for DFT input
P	jet hole pitch
p	static pressure
p^*	static pressure normalized by inlet and outlet static pressure, $p^* = (p - p_o)/(p_i - p_o)$
R	target curvature radius
Re	Reynolds number based on jet diameter and spatially-averaged jet velocity
S_w	local swirl strength of flow field
t	time
t^*	time normalized by D/V, $t^* = (tV)/D$
T	temperature
T^*	temperature normalized by temperature difference between jet supply air and target wall $T^* = (T - T_o)/(T_i - T_o)$
V	impingement jet spatially-averaged velocity at impingement hole exit
V_x	velocity component in X direction
V_y	velocity component in Y direction
V_z	velocity component in Z direction
X	coordinate in the target length direction
Y	coordinate from the jet exit to the target surface
Z	coordinate in the axis direction of channel

Greek symbols

τ	shear stress
ρ	density
ψ	the shear intensity in Y plate,
μ	kinetic viscosity
λ	thermal conduction
Ω_y	Y-component of vorticity, $\Omega_y = \frac{\partial V_x}{\partial z} - \frac{\partial V_z}{\partial x}$
Ω_y^*	normalized Y-component of vorticity, $\Omega_y^* = \frac{\Omega_y D}{V}$

jet is measured by Didden and Ho [13] for a single jet with laminar flow. Both phase-locked flow visualizations and phase-averaged hot-wire measurements are utilized. Unsteady separation is induced by the primary vortex, which produces an unsteady adverse pressure gradient, which leads to local flow separation of a local shear layer. Recent investigations by Lee et al. [14] describe several different modes of unsteadiness which develop within confined, laminar impinging slot jets of millimeter-scale. These investigators present local Nusselt number distributions measured on a constant heat flux surface to illustrate the separate effects of Reynolds number, nozzle-to-plate distance, and different unsteadiness modes for a slot nozzle width of 1.0 mm. Impingement jet unsteadiness, including flow flapping motion and intermittent oscillating motion, are observed. Lee et al. [15] provide data which illustrate cross flow effects for an impingement jet array, including the effects of varying jet-to-target plate distance and hole spacing. Chung and Luo [16] use direct numerical simulation (DNS) to simulate the unsteady heat transfer caused by a confined impinging jet. The quasi-periodic nature of the generation of the primary vortices due to the Kelvin–Helmholtz instability is tied to unsteady fluctuations in impingement heat transfer. With increasing Reynolds numbers, more chaotic and nonlinear fluctuations are observed. Janetzke and Nitsche [17] utilize time-resolved particle-image-velocimetry and surface hot wires to measure the flow field and wall shear stress distributions of a jet impingement configuration. According to these investigators, augmentation of Kelvin–Helmholtz vortices within the jet shear layer depends upon the Strouhal number and pulsation magnitude, and are associated with pairing of small scale vortices within the jet. With periodic jet pulsations, the resulting vortex rings have important effects upon the wall boundary layer, including local variations of wall shear stress and Nusselt number.

Other notable investigations, which address the development of jet cross flows, shear-layer vortices, augmented local mixing, counter-rotating vortex pairs, vortex pair development, wakes, horseshoe vortices, and unsteady oscillatory motions, are described by Mahesh [18], Ghalsasi [19], Milanovic et al. [20], Bencic et al. [21], Yao and Maidi [22], and Yang et al. [23]. According to Yang et al. [23], Kelvin–Helmholtz instability generated vortices result in highly asymmetric temperature profiles and velocity fields near and within impingement jets. A natural result is unsteady, time-varying local wall heat flux distributions beneath jet impact locations.

The present investigation is focused on laminar jets within a cylinder channel with a single row of 10 aligned impinging jets. This geometry is selected because of the influences and effects of cross flows on the development of each impingement jet, as well as the associated Kelvin–Helmholtz vortices, as impingement flow advects in the axial direction and subsequent impingement jets are encountered. Except for the investigations of Yang et al. [23,24], no previous investigation considers the present impingement channel arrangement.

For the present predictions, a FLUENT solver is employed, with a Green–Gauss cells gradient method and SIMPLEC for pressure–velocity coupling, for unsteady predictions of flow characteristics, and instantaneous surface Nusselt numbers, within and nearby the 10 impingement jets. Fast Fourier Transformations (FFT) of different flow quantities are utilized to provide data on associated frequency content. Visualizations of three-dimensional, unsteady flow structural characteristics are also included, including instantaneous distributions of Y-component vorticity, three-dimensional streamlines, shear layer parameter Ψ, and local static pressure. Kelvin–Helmholtz vortex development is then related to local, instantaneous variations of these quantities, especially instantaneous local temperature distributions. Of particular importance are complex flow interactions, developing cross-flows, and increased magnitudes and frequencies of local flow unsteadiness, as subsequent jets are encountered with streamwise development.

2. Unsteady computational procedures

Fig. 1 shows the geometry of the test configuration, including the coordinate system. Overall, the cylindrical channel is supplied by the impinging jets, with exit flow in the axial direction, at one end of the target cooling passage. The exit, for each of ten impinging jets, is located along an internal flat surface for the passage, as shown in Fig. 1. The downstream channel for impingement is