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# Oscillation and heat transfer in upward laminar impinging jet flows ☆

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ABSTRACT

Upward, laminar, axisymmetric, pipe-issued, submerged impinging jets, with the water as the working fluid, are numerically investigated. The impingement surface is subjected to heating, which causes the wall jet to prematurely separate from the impingement surface and turns the following region into a dead zone where the heat transfer rate deteriorates. Effects of (1) the inlet-based Reynolds number, (2) the heating-rate dependent Grashof number, and (3) the impingement-surface height to the inlet-diameter ratio are examined in detail. It is found that the separated jet oscillates when the Richardson number of the flow is moderate, but it separates without any oscillation when the Richardson number is large. The flow oscillation also induces cyclic fluctuations in on-surface quantities, such as, the Nusselt number, the surface temperature, and the skin-friction coefficient. The flows slowly approach to statistically steady states where oscillation parameters and heat transfer properties tend to stabilize about fixed values.



## 1. Introduction

Impinging jets are extensively used in various heat and mass transfer application since long past, such as, in paper and textile industries, in metal processing units, and in cooling of turbine blades and electronic devices. Due to their widespread usage, the impinging jet flows have been a matter of constant study, with a majority of the attention paid to turbulent impinging jet flows, because they yield relatively high heat transfer rates. On the other hand, the laminar impinging jet flows are studied because they are preferred in small-sized and delicate applications, or where the viscosity of the working fluid is so large that turbulence production becomes practically infeasible. Martin (1977), Jambunathan et al. (1992), Viskanta (1993), and Zukerman and Lior (2006) carried out thorough reviews on the impinging jet flow studies available in the literature.

When laminar impinging jet flows are subjected to surface heating, the post-impingement wall jet experiences a buoyancy force due to temperature dependence of the fluid density. When the buoyancy force is large, it significantly affects the flow field and the on-surface quantities, such as, the heat transfer coefficient, the surface temperature, the surface pressure, and the skin-friction coefficient. The degree to which the buoyancy force can affect a flow is determined by the Richardson number: if the Richardson number is small, the buoyancy force is negligible compared to the inertia force, and therefore the heating does not affect the flow properties any significantly; whereas the buoyancy force dominates if the Richardson number is large. Similarly, if the Richardson number is moderate, the buoyancy and the inertial forces are of comparable magnitudes, in which case the flow behavior becomes fairly complex.

In general, the flow remains unaffected from the buoyancy force in the forced-convection region of the wall jet, which is the region within a few diameters of the radial distance from the central axis. Afterwards, the buoyancy force becomes effective when the momentum of the radially progressing wall jet diffuses significantly and the local Richardson number becomes sufficiently high.

The flow behavior under surface heating also differs with the orientation of the jet; that is, depending on whether the jet is issued in the downward direction, in the upward direction, or at some angle, the flow properties vary.

Effects of the buoyancy force on the flow behavior and on the on-surface quantities, such as, the Nusselt number, the surface temperature, and the skin-friction coefficient, are studied by many researchers, both for slot jets and for circular jets. Most of these studies considered downward impinging jet flows (that is, the jets are issued along the gravity). Yuan et al. (1988) studied downward, two-dimensional slot jets, impinging onto an isothermal flat surface. They found that the heat transfer increases with increasing Richardson number, because the buoyancy force causes the wall

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**Nomenclature**

| | |
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| $b$ | length of the inlet pipe |
| $D$ | inlet diameter |
| $C_f$ | skin-friction coefficient $\equiv -\frac{\rho_{film}\gamma_{film}}{0.5\rho_{inlet}\overline{W}^2_{inlet}}\left(\frac{\partial U}{\partial z}\right)_s$ |
| $Fr$ | Froude number $\equiv \frac{\overline{W}_{inlet}}{\sqrt{gD}}$ |
| $\vec{g}$ | gravitational acceleration; $g \equiv \lvert\vec{g}\rvert = 9.81\ \mathrm{m/s^2}$ |
| $Gr_q$ | modified Grashof number $\equiv \frac{g\beta\bar{q}_{heater}D^4}{k_{inlet}\gamma^2_{inlet}}$ |
| $H$ | height of the impingement surface from the upper end of the inlet pipe |
| $k$ | thermal conductivity of water |
| $Nu$ | Nusselt number $\equiv \frac{qD}{(T-T_{inlet})k_{film}}$ |
| $P$ | pressure |
| $Pr$ | Prandtl number $\equiv \frac{\gamma_{inlet}\rho_{inlet}c}{k_{inlet}}$ where $c$ is the specific heat of the fluid at constant pressure |
| $q$ | heat flux at the impingement surface |
| $r$ | radial distance from the central axis |
| $Re$ | Reynolds number $\equiv \frac{\overline{W}_{inlet}D}{\gamma_{inlet}}$ |
| $Ri_q$ | modified Richardson number (for a given heating rate, $q) \equiv \frac{Gr_q}{Re^2}$ |
| $t$ | time |
| $T$ | temperature |
| $T_{film}$ | film temperature $\equiv \frac{T_{inlet}+T_s}{2}$ |
| $U$ | radial component of the instantaneous flow velocity |
| $V$ | azimuthal component of the instantaneous flow velocity |
| $\vec{V}_L$ | instantaneous flow velocity; $V_L \equiv \lvert\vec{V}_L\rvert = \sqrt{U^2+V^2+W^2}$ |
| $W$ | axial component of the instantaneous flow velocity |
| $\overline{W}_{inlet}$ | bulk-mean flow velocity at the lower end of the inlet pipe |
| $z$ | axial distance from the inlet, in the upward direction |
| $z^*$ | axial distance from the impingement surface, in the downward direction; $z^* = H - z$ |

*Greek symbols*

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| $\beta$ | thermal expansion coefficient of a fluid |
| $\gamma$ | kinematic viscosity of a fluid |
| $\rho$ | density of a fluid |
| $\psi$ | Stokes stream function |
| $\theta$ | azimuthal direction |

*Subscripts*

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| *inlet* | a physical quantity defined at the lower end of the inlet pipe |
| *film* | a physical quantity defined at the film temperature, $T_{film}$ |
| *s* | a physical quantity defined at the impingement surface |
| *stag* | a physical quantity defined at the stagnation point of the impingement surface |

*Conventions*

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| $\bar{a}^{(t)}$ | time-averaged value of any physical quantity, $a$, over the time-interval 0–$t$ |
| $\bar{a}_{(r)}$ | area-averaged value of any physical quantity, $a$, over the horizontal circle of radius $r$, whose center lies on the central axis |
| $\{a\}$ | a physical quantity, $a$, that is represented in its dimensional form |
| $\bar{a}_{heater}$ | area-averaged value of any physical quantity, $a$, over the entire heater surface |
| $\lvert\vec{a}\rvert$ | magnitude of a vector quantity, $\vec{a}$ |
| $\vec{a}_1 \cdot \vec{a}_2$ | scalar product of any two vector quantities, $\vec{a}_1$ and $\vec{a}_2$ |

*Abbreviations*

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| PIV | Particle Image Velocimetry |

jet to separate from the impingement surface and moves the local fluid in the upward direction. Chuo and Hung (1994) studied similar slot jets, by examining effects of the Reynolds number, the impingement surface distance from the inlet, and the inlet velocity profile, on the heat transfer rate. Sahoo and Sharif (2004) studied upward and downward impinging jets, both, and presented the velocity and the temperature fields. Seban et al. (1978) studied the temperature distribution along the axis of symmetry and the penetration depth of downward, heated air jets discharging into a colder ambient. All these studies examined only the average flow fields and the average heat transfer properties of the flows, without paying any attention to their transient characteristics.

In order to understand mechanism of the flow separation due to the buoyancy force, Chen et al. (1977) studied a simplified configuration of a flow parallel to a horizontal heated surface. They found that the heating affects the flow by inducing a pressure gradient in the streamwise direction. Mori (1961) studied a similar flow, analytically, and found that the skin-friction coefficient in a decelerated flow decreases sharply when the surface is subjected to heating, indicating that the flow might have separated from the surface. These results suggest that a flow in the wall-jet region of an impinging jet configuration is also prone to separation.

There are only a few studies that focused on unsteady flow behavior of heated impinging jet flows. It is known that, in general, a high degree of unsteadiness is induced when the Kelvin–Helmholtz vortices generated in the shear layer of the pre-impinging jet impinge onto a heated surface and then interact with the stratified fluid in the wall-jet region. In fact, these vortices cause the flow to temporarily separate from the impingement surface, even when the impingement surface is not subjected to any heating. Didden and Ho (1985) investigated such flow separations in detail, after creating large Kelvin–Helmholtz vortices by forcing the inlet jet at different pulsing frequencies. Liu and Sullivan (1996) studied unsteady heat transfer behavior of a circular impinging jet flow after forcing the jet in a similar manner, and found that the vortices cause the heat transfer coefficient to fluctuate. Olsson and Fuchs (1998) studied unsteadiness in a circular impinging jet flow, again by exciting the jet at different frequencies. Rohlfs et al. (2012) examined forced axisymmetric flows and suggested that when the Kelvin–Helmholtz vortices generated in the pre-impingement region impinge onto the surface, they induce secondary vortices in the wall-jet region, which separate from the surface about the radial location $r = 2.1$ and yield a local heat-transfer peak similar to that observed in turbulent impinging jet flows. Chung and Luo (2002) studied the unsteadiness in an unforced compressible slot jet where the Kelvin–Helmholtz vortices generated naturally. They observed organized temperature fluctuations at locations very close to the impingement surface when the Reynolds number of the flow was relatively small. However, the fluctuations became less regular, but remained approximately periodic, when the Reynolds number was increased, because it produced stronger vortices. For a smaller impingement surface distance from the inlet, the fluctuations became organized again, because the shear layer vortices remained weak and underdeveloped when they impinged onto the surface, due to the short traveling distance before the impingement.

All the aforementioned studies considered downward impinging jets, except the brief study of upward slot jets by Sahoo and