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Heat transfer under composite arrangement of pulsed and steady turbulent submerged multiple jets impinging on a flat surface

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ABSTRACT

A numerical study has been conducted to seek an optimized arrangement of steady and pulsating impinging multiple submerged slot jets. A composite design consisting of steady as well as intermittent (on/off) or sinusoidal jets in different combinations of four slot jets was simulated. Effect of large temperature differences between jets and the impingement surface was examined by considering fluid properties to be dependent on temperature. In addition, the effect of frequency, phase angle for both types of pulsation as well as amplitude of the sinusoidal pulsing jets was examined on the time-averaged local Nusselt number distribution on an isothermal planar target surface. Results indicate that the combination of pulsed jets with steady jets provide the most uniform and enhanced Nusselt number distribution for the array of four jets. Furthermore, due to the alternating pulsating flow patterns, an increase in the convective heat transfer is observed around a secondary stagnation point. Significantly higher heat transfer can be obtained by the combinations of intermittent-steady jets rather than the sinusoidal-steady ones.

1. Introduction

Jet impingement is an effective technique which provides higher heat transfer rate in comparison with other methods through the formation of a thin thermal layer on the impingement surface [1–3]. Because of this characteristic, it is used in many industries such as cooling of turbine blades and electronic components, drying of paper and textiles, etc. [4–6]. In practice, the fluid flow rates and dimensions of the nozzles are such that the flow is typically steady and turbulent so as to provide high heat and mass transfer rates. In some special applications the temperature difference between the heating or cooling fluid and the target surface is large so that account must be taken of the effect of temperature on fluid properties. In this study the potential of a novel way for enhancing impingement heat transfer under steady or pulsed turbulent jets is examined by combining them in a suitable arrangement in an array. No prior work exists in this area.

Many studies have appeared in the literature aimed at enhancing jet impingement heat transfer. One proposed technique is related to use of a pulsed jet instead of a steady jet. Some experimental results on effect of pulsed flow on impingement heat transfer have been reported by Zumbrunnen and Aziz [7]. In their study, a pulsed water jet was used to cool a hot flat surface subjected to a constant heat flux. Sheriff and Zumbrunnen [8] in a later study analyzed the effects of using sinusoidal and square form waves in impingement of a water jet on a flat surface. Their experimental results show that the local Nusselt number in the stagnation region decreases for a sinusoidal pulsed jet. Lewkongsataporn et al. [9] reported that pulsed square-shaped waves in impinging jets increase the heat transfer rate in comparison with steady jets. They showed that for the same value of the mean Reynolds number, the increase of pulse amplitude or reduction of nozzle-to-surface distance enhances impingement heat transfer considerably. Hofmann et al. [1] investigated the influence of a pulsation on flow structure and heat transfer with experiments, and determined the threshold Strouhal number for small nozzle-to-plate distances to be in order of 0.2. According to their results at moderate frequencies heat transfer is only affected by the pulsation when nozzle-to-plate distance and amplitude are large

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enough. Behera et al. [10] investigated the effects of jet Reynolds number, shape of the pulsed waves, pulse frequency and nozzle-to-surface spacing on the heat transfer rate. They, through using intermittent pulsations in the inlet jet, increased the time-averaged Nusselt number by 12% and 35% in the impinging zone and wall jet region, respectively, compared to the steady jet under the parameter values tested. The maximum enhancements of those values in these areas were about 5 and 10 percent for sinusoidal waves. Liewkongsataporn et al. [11] investigated the effect of pulse velocity on heat transfer for a confined jet impinging on a flat surface. Based on their results, the increase of the velocity amplitude leads to the time-averaged Nusselt number enhancement. Due to the acceleration effect of pulsed jets, the recirculating flow produced in the impingement zone has been reported as the key factor in the heat transfer process. Recently, Xu et al. [12] examined numerically the effect of large temperature difference between a sinusoidal impinging jet and a flat target surface. Their results show that for heating of the target, the Nusselt number decreases with higher temperature differences for gas as the viscosity of gases increases with temperature in the vicinity of the wall. More research on sinusoidal waves in impinging jets on flat surfaces was reported by Demircan et al. [13]. They showed that, although the general flow field structures in pulsed and steady jets are nearly the same, due to the formation of circulating flow in the pulsed jets on the target surface, the Nusselt value oscillates with time in the wall-jet region. They also indicated that the Nusselt number is enhanced by increase of the jet Reynolds number and oscillation amplitude. Mohammadpour et al. [14] numerically investigated the effect of intermittent and sinusoidal pulsed flows on the heat transfer rate from a slot jet impinging to a concave surface. They reported that increasing the velocity, frequency and pulse amplitude values at the inlet jet can create much stronger vortices which enhance the rate of impingement heat transfer. Xu et al. [12] studied the variation of heat transfer rate for a flat surface when the velocity of the square-shaped pulsed jet varies intermittently. It was shown that intermittent pulsation can result in higher turbulence, larger vortices, increased entrainment and mixing promoted by fluid instabilities as well as by reduced instantaneous hydrodynamic and thermal boundary layer thicknesses in the flow domain. Bovo et al. [15] reported three sets of measurements of a single pulse jet impinging on a temperature controlled flat target at different angles experimentally to serve as a reference for CFD validation. Their results show the heat transfer effects are highest for the jet impinging normally on the target. Medina et al. [16] investigated the effect of Reynolds number variations on the fluid dynamics and turbulence statistics of pulsed jets impinging on a flat surface. They showed that the influence of the Reynolds number may be somewhat different for a jet subjected to pulsation when compared to an equivalent steady jet.

In addition, some recent investigations studied on the multiple submerged jets. The effect of submerged liquid steady jet arrays on heat transfer of impingement cooling was studied experimentally and numerically by Tie et al. [17]. Their study on the influence of dimensionless geometric parameters on the Nusselt number introduced that jets impingement cooling established best with fixed adjacent nozzle spacing and nozzle to plate distance. A computational fluid dynamic approach was used by Jiang et al. [18] to explore the effect of periodic sinusoidal pulsation multiple jets on the local Nusselt number distribution of a wet target surface being dried. The velocity and thermal fields show that the instantaneous heat transfer rate on the target surface is highly affected by the mass transfer characteristic and development of the hydrodynamic boundary layer with time. Xu et al. [2] investigated numerically the potential effect of unsteady intermittent pulsations on the heat and mass transfer rate of multiple turbulent impinging jets. Based on their results, periodic flow patterns caused by oscillatory flow lead to elimination of the stagnation point, resulting in enhanced heat transfer.

It is noteworthy that most of the aforementioned numerical studies have concentrated on prediction of enhanced impingement heat transfer from the target surface through the pulsing the flow. In the present computational fluid dynamic study, multiple impinging jet investigation was extended to cover different combinations of steady and intermittent or sinusoidal jets over a wide range of parameters. A systematic parametric study, including phase angle and frequency as well as amplitude of pulsating flow, was conducted to optimize the design of pulsating/steady jet arrays which provide more uniform and also enhanced Nusselt number distribution simultaneously. The numerical method was validated by available experimental data for single pulsed jets.

2. Problem statement

According to Fig. 1, the problem of the present study consists of a two-dimensional geometry including multiple submerged turbulent impinging slot jets. An isothermal surface ($T_w = 400$ K) with no-slip condition was considered for the impingement surface. The confinement wall was specified to be adiabatic. The jet-to-surface spacing, slot jet width and center-to-center distance between jets were defined as H, S and w, respectively.

The temperature and hydraulic diameter at the inlet jets were 300 K and $2w$, respectively. Intermittent and sinusoidal velocity pulsations with uniform velocity profiles (Fig. 2) were applied at the inlet jets as follows:

$$u_{\text{jet}} = u_{\text{avg}} + Au_{\text{avg}} \sin(2\pi f t) \tag{1}$$

$$\begin{cases} u_{\text{jet}} = u_{\text{on}} \rightarrow (2n)\frac{\tau}{2} < t < (2n+1)\frac{\tau}{2} \\ u_{\text{jet}} = u_{\text{off}} \rightarrow (2n+1)\frac{\tau}{2} < t < 2(n+1)\frac{\tau}{2} \end{cases} \quad (n = 0, 1, 2, 3, \ldots) \tag{2}$$

The values of the important parameters selected for the present study were taken based on relevant previous studies in this field [2,18]. The selected values of these parameters were $f = 10$, 25, 50, 100 and 200 Hz; St = 0.00625, 0.015625, 0.03125, 0.0625 and 0.125; $A = 0.1$, 0.5, 0.75 and 1.0 at Re = 5000, $S/w = 5$, $L/w = 30$ and $H/w = 5.0$.

In the present study, the fluid was an incompressible, Newtonian fluid (air) with temperature-dependent properties listed in Table 1 and determined from best curve-fits of data from Welty et al. [19] over temperature range 300 K < T < 400 K. The following initial conditions were applied: For $t = 0$: $u = v = 0$, $P = P_\infty$, $T = T_\infty$ and $k = \varepsilon = 0$ everywhere in the computational domain.

3. Governing equations

Numerical simulation of the flow and thermal fields in the computational domain requires solving the continuity (3), momentum (4) and energy (5) conservation equations which are expressed as follows:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_i)}{\partial x_i} = 0 \tag{3}$$

$$\left(\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial(\rho u_i u_j)}{\partial x_j}\right) = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu(2S_{ij}) - \rho\overline{u_i' u_j'}\right] \tag{4}$$