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Heat transfer under turbulent double pulsating jets impinging on a flat surface

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ABSTRACT

In the present study the turbulent flow and heat transfer of double pulsating jets impinging on a flat surface were numerically analyzed. The unsteady two-dimensional numerical solutions for two similar and dissimilar jets was determined using the RNG k-ε model. Results showed that the RNG k-ε model generates satisfactory predictions of Nusselt number distribution. Comparisons indicated that for two identical jets with a constant frequency and amplitude, an increasing Reynolds number considerably increases the time-averaged Nusselt number. The averaged Nusselt number of the flat surface increases with rising oscillation amplitude. Increasing the phase difference angle of the pulsating jets leads to an augmentation in mixing between jets, thereby increasing the Nusselt number in this zone. For two jets of equal frequency and phase angle, increasing the oscillation amplitude of one jet leads to an asymmetric distribution of Nusselt number. In this case, the Nusselt number averaged between two jets increases. Furthermore, the array of double jets with different types of oscillation (intermittent and sinusoidal) considerably increases the averaged Nusselt number in the stagnation region between the jets.

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1. Introduction

Cooling is an important influencing factor for ensuring suitable temperatures in industrial processes. Among different methods, impingement cooling is one of the most commonly applied techniques for surface cooling. This technique has found numerous industrial applications, including the cooling of gas turbine blades and combustion chamber walls, material cutting, and paper drying; it has also been extensively employed in the food, electronics, and chemical industries. The advent of novel technologies in recent decades has resulted in the reduction of the size of electronic equipment, thereby remarkably increasing the heat produced per unit of volume. This development has attracted researchers' attention. Effective and abundant heat transfer is enabled by the use of impinging jets and the thinning of the hydrodynamic and thermal boundary layers on the surface of a stagnation region [1].

Previous studies showed that intermittent and pulsating jets increase heat transfer from a surface [2]. This increase depends on parameters such as the temperature difference between a surface and flow, Reynolds number, flow turbulence, jet flow frequency, oscillation amplitude, and oscillation type. Geometric characteristics, such as the shape of a nozzle hole, the type of jet array, and the distance between a nozzle and a surface, are also influential on heat transfer. To date, many studies have been devoted to these parameters, and for more than three decades, numerical and experimental flow analyses and descriptions of individual or multiple impinging jets have been carried out to improve heat transfer. A considerable stream of research has focused on identifying a numerical simulation model of heat

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transfer to derive improved correlation with experiments. Some numerical and experimental initiatives concentrated on the effects of intermittent flow and local Nusselt number on heat transfer. The results showed that flow pulsation exerts different effects on flow and heat transfer. In some cases, generating intermittent flow remarkably increases heat transfer [1, 2], whereas in other cases, the influence of such flow is negligible [3].

The first study on pulsating impinging jets was that conducted by Zumbrunnen and Aziz [4], who indicated that heat transfer can be increased by intermittent impinging jets. Marzouk et al. [6] examined two-dimensional numerical solution methods to investigate intermittent impinging jets and develop solutions. In their analysis, the authors assumed that in the outlet of a nozzle, temperature is constant and outer velocity is in the form $u = u_0(1 + A\,sin(\omega t))$. They considered two issues: (1) a freely flowing jet and a jet constrained to walls and (2) walls that may be adiabatic or characterized by uniform heat. Mujumdar et al. [7] numerically explored the effects of intermittent jets on the flow of impinging jets. The authors showed that the separation point of flow on a wall, which affects jets, depends on the point of flow that has a constant Nusselt number. Kamaruzzaman et al. [8] compared the local Nusselt numbers of steadily flowing and intermittent jets and found that flow with high velocity and high turbulence causes strong local heat transfer.

Rozli et al. [9] compared the Nusselt numbers of steadily flowing and intermittent jets under a Reynolds number of 1600. The authors conducted their investigation under radial distances of 2, 4, 6, 8, 10, and 12 cm and frequencies of 10, 30, 50, and 70 Hz. The results indicated that for a Reynolds number of 1600, the Nusselt number in the stagnation point of the steady jet in all frequencies is higher than that of the intermittent jet. For locations with large distances from the stagnation point, however, the intermittent jet registers a higher Nusselt number than does the steady jet. Peng et al. [10] inquired into the use of alternating pulsating jets on the increase in heat transfer of intermittent jets with turbulent flow. The numerical results showed a considerable increase in heat transfer from the heated flat surface at a wide range of flow oscillation. The authors also revealed that heat transfer highly depends on hydrodynamic and thermal boundary layers. Mujumdar et al. [11] investigated the heat and mass transfer properties of some intermittent impinging jets. To this end, the authors looked into two adjacent intermittent jets with a high temperature difference between the jets and the aluminum target surface. Peng Xu et al. [12, 13] experimentally studied intermittent single pulsating jets and numerically investigated intermittent flow in impinging jets. They concluded that an increase in Nusselt number during sinusoidal oscillation is negligible but that intermittent pulsation (on–off cycles) can dramatically influence the local heat transfer ratio.

Zhou et al. [14] performed experiments on heat transfer over smooth and rough surfaces for sinusoidal and intermittent pulsating jets. They found that on smooth surfaces, sinusoidal and intermittent pulsating jets increase heat transfer by up to 10% and 40%, respectively. Mohammadpour et al. [15] delved into the combination of configurations of four impinging jets on a flat surface for steady and intermittent jets. The authors compared combinations of pulsating steady and sinusoidal steady jets. The results indicated that for four adjacent jets, the combination of intermittent pulsating and steady jets yields better heat transfer than that achieved with the combination of sinusoidal and steady jets. Mohammadpour et al. [16] analyzed the heat transfer of intermittent pulsating impinging and sinusoidal jets on a concave surface. They considered the effects of amplitude, phase, and Reynolds number variations on the average increase in Nusselt number. Given that the complexities of the flow structure and shape of a formed boundary layer are affected by flow oscillation, a pulsating jet and its heat transfer properties are worth investigating. A considerable proportion of previous studies concentrated on optimizing the heat transfer of a steady single impinging jet and a single intermittent jet.

In the current work, the Nusselt number distributions of dissimilar double pulsating jets (with two common square-shaped and sinusoidal waveforms) were numerically investigated. The numerical results for the pulsating jets were then compared with available experimental data. The effects of oscillation amplitude and Reynolds number on the distribution of Nusselt number were also explored.

2. Governing equations

Governing equations include continuity, momentum, and energy equations, expressed in equations (1) to (3), respectively.

$$\frac{\partial(\rho)}{\partial t} + \frac{\partial(\rho u_i)}{\partial x_i} = 0 \quad (1)$$

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

$$\left(\frac{\partial(\rho T)}{\partial t} + \frac{\partial(\rho u_i T)}{\partial x_i}\right) = \frac{\partial}{\partial x_j}\left(\frac{\mu}{Pr}\frac{\partial T}{\partial x_i} - \rho\,\overline{\theta'_i u'_j}\right) \quad (3)$$

In these equations, $\overline{u'_i u'_j}$ and $\overline{\theta'_i u'_j}$ are the stress tensor and heat flux that require modeling. The RNG k-ε method was used for such modeling. Yakhot et al. [17] introduced a novel k-ε state, which exhibits an operational performance superior to that of a standard model. The authors' proposed model was based on the renormalization group and was therefore termed RNG. The RNG model has an additional term in its ε-equation that significantly improves the accuracy of modeling for rapidly strained flows [17]. The corresponding equations are presented as follows:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_j}(\rho U_j k) = \frac{\partial}{\partial x_j}\left[(\mu + \frac{\mu_t}{\sigma_k})\frac{\partial k}{\partial x_j}\right] + P_k - \rho\varepsilon \quad (4)$$

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_j}(\rho U_j \varepsilon) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + \frac{\varepsilon}{k}(C_{\varepsilon 1}P_k - C^*{}_{\varepsilon 2}\rho\varepsilon) \quad (5)$$

The local Nusselt number is defined on the basis of equation (6):

$$Nu = \frac{q}{\Delta T}\,\frac{w}{k(T)} \quad (6)$$

In the current analysis, Nusselt number varies with time and location. Therefore, the time average of the local Nusselt number and the total average Nusselt number (time–location) are computed using equations (7) and (8).

$$Nu_{avg}\,(x) = \frac{1}{\Delta t}\int_0^t Nu\,(x,t)dt \quad (7)$$

$$Nu_{avg} = \frac{1}{\Delta x}\frac{1}{\Delta t}\int_0^x \int_0^t Nu\,(x,t)dt\,dx \quad (8)$$

For sinusoidal intermittent jets, the velocity profile in a nozzle exit is defined using equation (9) and applied to jet exit (Figure 1).

$$u_{avg} = u_{avg} + Au_{avg}\sin(2\pi f t) \quad (9)$$

For intermittent pulsating jets, such velocity profile is defined thus:

$$u_{jet} = 2u_{avg} \rightarrow (2n)\frac{\tau}{2} < t < (2n+1)\frac{\tau}{2} \quad (10)$$

$$u_{jet} = 0 \rightarrow (2n)\frac{\tau}{2} < t < (2n+1)\frac{\tau}{2} \quad (11)$$

3. Geometric characteristics and boundary conditions

Figure 2 shows that for the single jet, only half of the flow domain were modeled and discretized because of the aim for symmetry. The geometric characteristics were selected on the basis of [18]. The distance between a nozzle and a surface was set at 37 mm, and the nozzle diameter and aluminum target surface were 5 mm and 20 cm, respectively. The temperature of the wall was kept at 400 K, and the temperature of the intermittent impinging jets was assumed to be 300 K. As indicated in Figure 2, the distribution of the predicted average Nusselt number correlates well with experimental results [18].

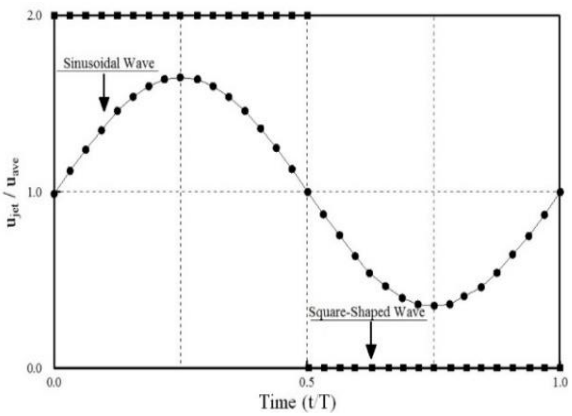


Fig. 1. Velocity profiles at inlet jets

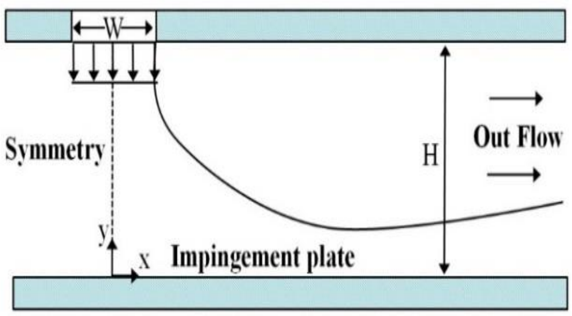


Fig. 2. Computational domain and schematic of slot–jet impingement over a flat surface

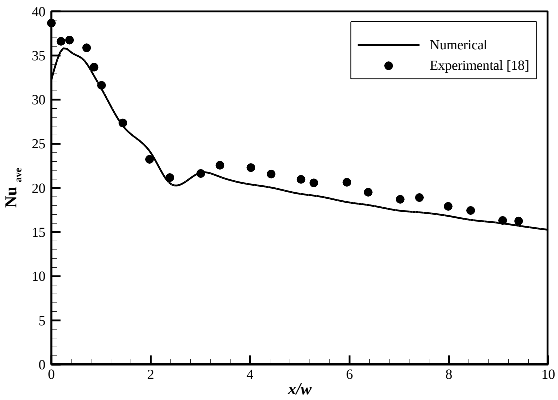


Fig. 3. Comparison of numerical results for sinusoidal jets with experimental data [18]

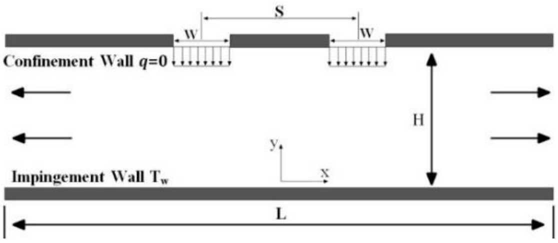


Fig. 4. Computational domain and schematic of two jets adjacent over a flat surface.

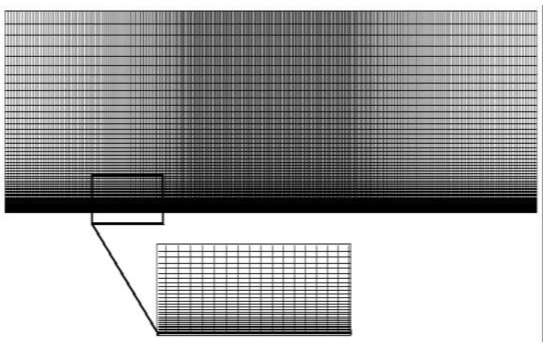


Fig. 5. Sample mesh for numerical analysis

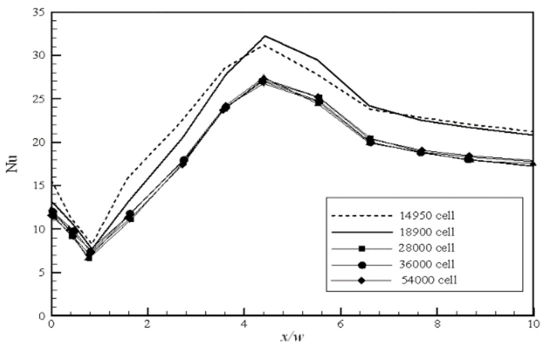


Fig. 6. Effects of grid size on the predicted local Nusselt number

For the analysis of two jets, an array of jets with a distance of 25 mm from the aluminum surface was considered on the basis of the data in Figure aluminum 4, where the width of the impinging jets and the distance between the centers of two jets are denoted by *w* and *S*, respectively.

The fluid (air) in this analysis was assumed to be incompressible and Newtonian. A pulsating velocity profile was applied to the entrance of the jets, and the flow and temperature distribution were calculated using the finite volume computational method. In pulsating impinging jets, flow parameters (i.e., frequency and velocity oscillation amplitude) increase the complexity of jet interactions and heat transfer. The RNG k-ε turbulence model is a powerful and fast model for the analysis of the complicated flow in an intermittent jet [15]. In this work, therefore, the RNG k-ε model was used to represent the behavior of turbulence flow in the impinging jets. The impinging surface was assumed to have a constant temperature of 400 K, and upper surfaces were considered to be adiabatic. On the impinging wall, a no-slip condition was assumed. The relationship between speed and pressure were selected using the SIMPLE (Semi-Implicit Method for Pressure Linked Equations) algorithm. The time step was 0.0001 s, and the convergence criterion was a relative residual of $\mathbf{10^6}$ for energy and $\mathbf{10^4}$ for other variables.

As seen in Figure 5, mesh grids were accurately produced and then analyzed with the use of rectangular cells. The produced meshes are well organized, thus enabling the production of finer meshes near the walls. Consequently, $\mathbf{Y^+}$ is located in an acceptable range. This quantity for low Reynolds models is about unity ($\mathbf{Y^+ < 1}$).

To ensure that the solutions are independent of the meshes, these meshes were refined in five stages. The variations in Nusselt Number in the direction of flow in a turbulence low Reynolds model for some mesh grids is depicted by a Reynolds number of 5500 (Figure 6). On the basis of Figure 6, the grid with 28000 computational cells was selected because of the effects of the number of meshes on Nusselt number prediction. Note that in this research, mesh independence is sophisticated for all analyzed geometries.

4. Results and discussion

To confirm the validity of the numerical analysis, the Nusselt number distribution obtained in this study was compared with experimental data. The results are presented in Figures 2 and 3. Figure 7 compares the findings of the analysis of two steady and sinusoidal pulsating jets with ratios of H/W = 5 and S/W = 5 at a Reynolds number of 5000. At the steady state, the external flow of the nozzles hits the surface, and the flow moves upstream via a horizontal movement. This phenomenon decreases the Nusselt number in the central zone of the static point. The comparison of the steady and pulsating jets visibly indicated that no significant increase in Nusselt number occurs in the sinusoidal pulsating jet. In other words, a slight change in heat transfer is occurs in pulsating jets.

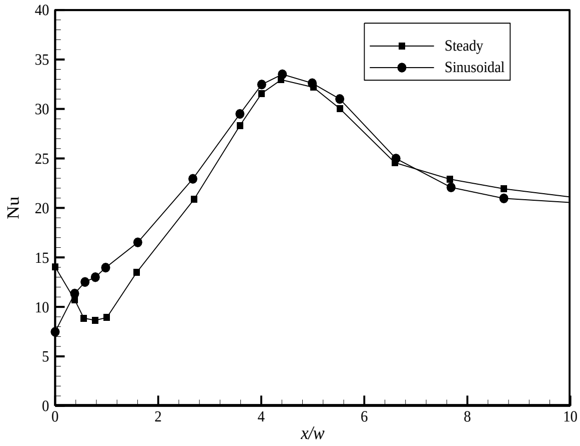


Fig. 7. Comparison of Nusselt number distribution for steady impinging jet with sinusoidal oscillation, Re = 5000

Figure 8 illustrates the effects of increasing the oscillation amplitude from 20% to 80% of the averaged velocity on the time-averaged Nusselt number of the flat surface. The oscillation frequency of two adjacent jets was set at 50 Hz. Elevating the oscillation amplitude of the jet increases the Nusselt number, especially around the impinging zone. Comparing with the cross flow in a single jet, that impinging between jets causes source flow formation and increases heat transfer. These phenomena increase when amplitude rises.

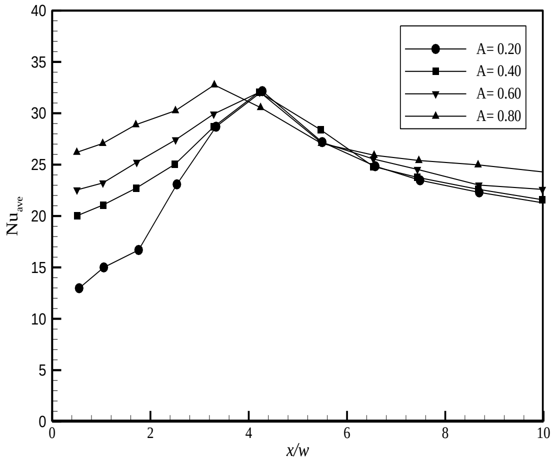


Fig. 8. Effects of pulse amplitude on averaged Nusselt number for similar jets

The effects of Reynolds number on the distribution of the averaged Nusselt number are presented in Figure 9. Increasing the Reynolds number results in an increase in the outlet flow velocity of the nozzle and impinging velocity toward the surface. Hence, the Nusselt number noticeably increased along the impinging zone, particularly in the impinging point.

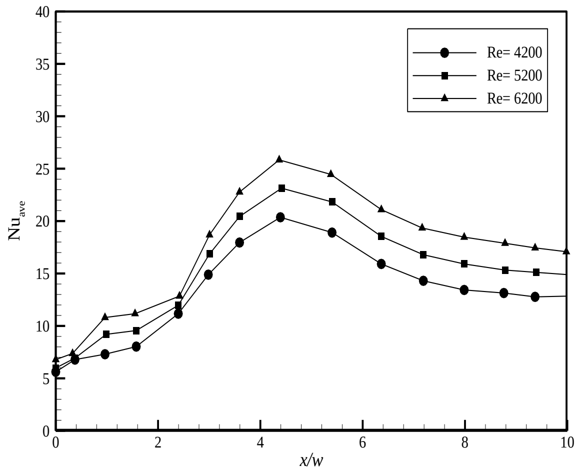
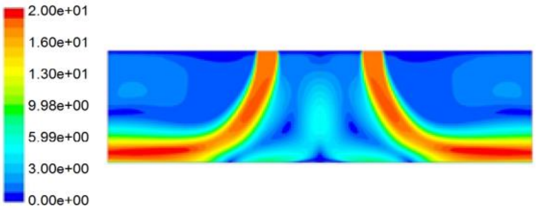


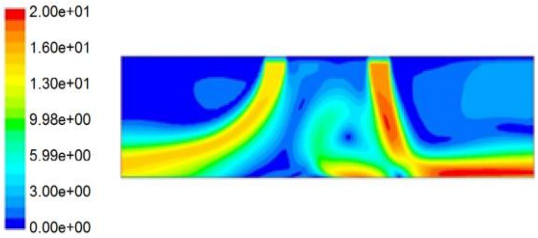
Fig. 9. Effects of Reynolds number on averaged Nusselt number distribution

The analysis of different pulsating jets is particularly important in the discussion of gas turbine blade cooling and other applications. In practical applications, providing similar jets with the same specifications in outlet flow from jet nozzles is difficult. Furthermore, in the analysis of dissimilar jets, the boundary conditions for two jets differ, and the symmetry boundary condition cannot be applied.

The contours of flow velocity for two dissimilar pulsating jets with a phase difference of $\pi/2$ are shown in Figure. 10. Despite the identically in oscillation frequency and amplitude between the jets, the phase difference causes asymmetry in the velocity field.



(a)



(b)

Fig. 10. Velocity magnitude contours: (a) similar jets, (b) dissimilar jets with a phase difference of π/2

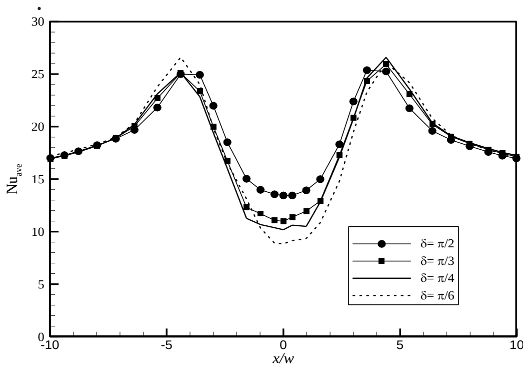


Fig. 11. Effects of oscillation phase difference on averaged Nusselt number distribution, Re = 6000

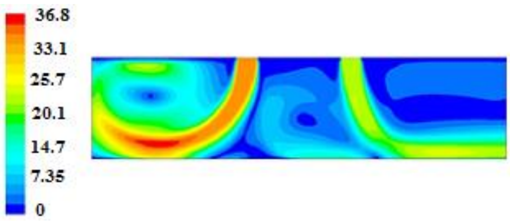


Fig. 12. Velocity magnitude contours for two dissimilar jets with oscillation amplitudes of A $_{left}$ = 0.2 and A $_{right}$ = 0.8

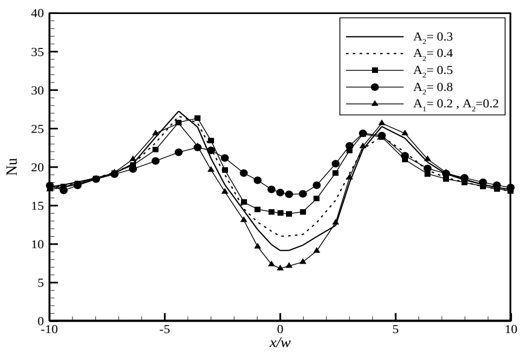


Fig. 13. Effects of differences in oscillation amplitude between two adjacent jets on Nusselt number distribution, (A_1=0.02)

Figure 11 depicts the effects of the difference in oscillation phase angle between the two impinging jets on the averaged Nusselt number distribution. The comparison of the similar and dissimilar jets showed that increasing the phase difference leads to the formation of an asymmetric flow field and an increase in turbulence between the jets. In turn, these occurrences significantly increase the Nusselt number between the jets

Figure 12 illustrates the contours of flow velocity for dissimilar pulsating jets with different oscillation amplitudes. The oscillation amplitudes for the left and right jets were 0.2 and 0.8 of the averaged velocity of the jets, respectively. As illustrated in the figure, differences in oscillation amplitude cause asymmetry in the distribution of velocity, especially between the jets.

Figure 13 indicates that differences in oscillation amplitude causes an asymmetric distribution of Nusselt number and a significant increase in the Nusselt number between the jets. The left jet was assigned a constant amplitude (A_1 = 0.2), whereas the right jet was ascribed a variable amplitude (0.3 to 0.8).

The effects of two dissimilar jets with two different pulsation types on the averaged Nusselt number are presented in Figure 14. One of the jets with sinusoidal oscillation and another jet with pulse oscillation (on–off) were considered. The obtained Nusselt number distribution for the two dissimilar pulsating jets was compared with the distribution for the sinusoidal and pulsating intermittent jets.

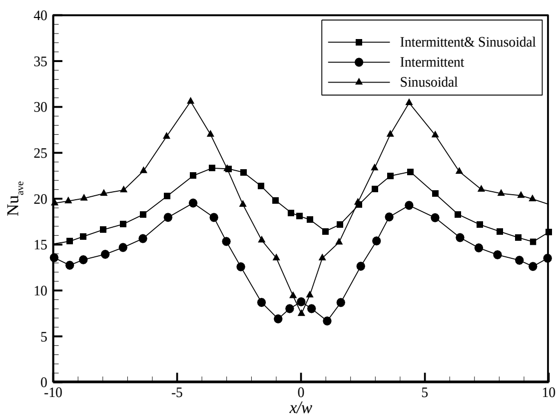


Fig. 14. Comparison of Nusselt number distribution between similar and dissimilar double pulsating jets, (Re=5500, f=50)

As illustrated in Figure 14, using two jets with different pulsation types increases the averaged Nusselt number, especially between the jets. In this condition, the maximum averaged Nusselt number is lower than that derived for sinusoidal pulsation and greater than that obtained for intermittent pulsation.

5. Conclusion

In this work, the turbulent flow and heat transfer of similar and dissimilar pulsating impinging jets were numerically analyzed. The RNG k-ε model was used to derive the unsteady two-dimensional numerical solution of governing equations. The results showed that for similar jets with the same frequency and constant amplitude, increasing the Reynolds number significantly increases the time-averaged Nusselt number. Oscillation amplitude is the effective parameter in heat transfer from the surface. The numerical findings indicated that increasing the amplitude causes an increase in surface heat transfer. Note that for two jets with equal frequency and phase angle, increasing the oscillation amplitude of one jet leads to an asymmetric distribution of the Nusselt number. Hence, the averaged Nusselt number between two jets increases. The array of double jets with different types of oscillation (intermittent and sinusoidal) leads to a substantial increase in the averaged Nusselt number in the stagnation region between the jets.

Nomenclature

Latin symbols

A	Pulse amplitude
C_p	Specific heat at constant pressure (N.m kg^{-1} K^{-1})
$C_{\varepsilon 1}$, $C_{\varepsilon 2}$	Empirical constants in turbulence model
f	Frequency of pulsation (Hz)
H	Nozzle-to-surface spacing (mm)
K	Thermal conductivity of air (w m^{-1} s^{-1})
k	Turbulence kinetic energy (m^2 s^{-2})
Nu	Nusselt number ($Nu = \frac{q}{T_w - T_{jet}} \frac{w}{K(T)}$)
Nu_{ave}	Time-averaged local Nusselt number
P	Static pressure (Pa)
P_k	Turbulent kinetic energy production
q''	Heat flux (w m^{-2})
S	jet-to-jet distance (mm)
Re	Reynolds number (= $\rho u_{ave} W / \mu$)
T_{jet}	Jet flow temperature (K)
T_w	Wall temperature (K)
t	Time (s)
u_{jet}	Jet velocity (m s^{-1})
u_{ave}	Time-averaged velocity component of pulsating jet (m s^{-1})
u_i	Mean velocity component in the x_i direction (m s^{-1})
u_i'	Fluctuating velocity component in the x_i direction (m s^{-1})
W	Slot width (mm)
x_i	Coordinates (= x, y)
y^+	Dimensionless distance

Greek symbols

ε	Dissipation rate of turbulent kinetic energy (m^2 s^{-3})
μ, μ_t	Laminar and eddy dynamic viscosities (kg m^{-1}s^{-1})
σ_k, σ_ε	Turbulent Prandtl number for k, ε
ρ	density (kg m^{-3})

Subscripts

ave	Average
w	Wall

References

[1]. D. A. Zumbrunnen, M. Balasubramanian, “Convective heat transfer enhancement due to gas injection into an impinging liquid jet”, Journal of Heat Transfer, 117 (4) (1995) 1011–1017.

[2]. D. J. Sailor, D. J. Rohli, Q. L. Fu, “Effect of variable duty cycle flow pulsations on heat transfer enhancement for an impinging air jet”, International Journal of Heat and Fluid Flow, 20 (6) (1999) 574–580.

[3]. H. S. Sheriff, D. A. Zumbrunnen, “Effect of flow pulsations on the cooling effective- ness of an impinging jet”, Journal of Heat Transfer, 116 (4) (1994) 886–895.

[4]. D. A. Zumbrunnen, M. Aziz, “Convective heat transfer enhancement due to intermittency in an impinging jet”, Journal of Heat Transfer, 115 (1) (1993) 91–98.

[5]. D. A. Zumbrunnen, M. Balasubramanian, “Convective heat transfer enhancement due to gas

injection into an impinging liquid jet", Journal of Heat Transfer, 117 (4) (1995) 1011–1017.
[6]. S. Marzouk, "Numerical study of momentum and heat transfer in a pulsed plane laminar jet", International Journal of Heat and Mass Transfer, 46 (22) (2003) 4319–4334.
[7]. Hee Joo Poh, Kurichi Kumar, A. S. Mujumdar, "Heat transfer from a pulsed laminar impinging jet", International Communications in Heat and Mass Transfer, 32 (10) (2005) 1317–1324.
[8]. Kamaruzzaman Sopian, "Comparison of Local Nusselt Number between Steady and Pulsating Jet at Different Jet Reynolds Number", WSEAS TRANSACTIONS on ENVIRONMENT and DEVELOPMENT, 5 (5) (2009) 384- 393.
[9]. Rozli Zulkifli, "Comparison of Local Nusselt Number for Steady and Pulsating Circular Jet at Reynolds Number of 16000" , European Journal of Scientific Research ISSN 1450-216X, 29 (3) (2009) 369-378.
[10]. Peng Xu, "Turbulent impinging jet heat transfer enhancement due to intermittent pulsation", International Journal of Thermal Sciences, 49 (7) (2010) 1247-1252.
[11]. Peng Xu, Shuxia Qiu, Mingzhou Yu, Xianwu Qiao, A. S. Mujumdar "A study on the heat and mass transfer properties of multiple pulsating impinging jets", International Communications in Heat and Mass Transfer, 39 (3) (2012) 378–382.
[12]. P. Xu, A.S. Mujumdar, H.J. Poh, B.M. Yu, " Heat transfer under a pulsed slot turbulent impinging jet at large temperature differences", Thermal Science, 14 (1) (2010) 271–281.
[13]. P. Xu, B. M. Yu, S. X. Qiu, H. J. Poh, A.S. Mujumdar, "Turbulent impinging jet heat transfer enhancement due to intermittent pulsation", International Journal of Thermal Science, 49 (7) (2010) 1247–1252.
[14]. J. W. Zhou, Y. G. Wang, G. Middelberg, H. Herwig, "Unsteady jet impingement: heat transfer on smooth and non-smooth surfaces", International Communications in Heat and Mass Transfer, 36 (2) (2009) 103–110.
[15]. Javad. Mohammadpour, Mohammad mehdi Zolfagharian, A. S.Mujumdar, Mehran Rajabi Zargarabadi "Heat transfer under composite arrangement of pulsed and steady turbulent submerged multiple jets impinging on a flat surface" International Journal of Thermal Sciences, 86 (2014) 139-147.
[16]. Javad Mohammadpour, Mehran Rajabi Zargarabadi, A. S.Mujumdar, Hadi Ahmadi " Effect of intermittent and sinusoidal pulsed flows on impingement heat transfer from a concave surface" International Journal of Thermal Sciences, 76 (2014) 118-127.
[17]. V. Yakhot, S. A. Orszga, S. Thangam, C. G. Speziale, "Development of turbulence models for shear flows by a double expansion technique", Fluid Dynamic, 4 (7) (1992).
[18]. E. C. Mladin, D. A. Zumbrunnen, "Alterations to coherent flow structures and heat transfer due to pulsations in an impinging air-jet", International Journal of Thermal Science, 39 (2) (2000) 236–248.