Influence of synthetic jet in crossflow configuration on heat transfer enhancement

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Abstract. A two-dimensional computational model was developed to investigate the effect of synthetic jet interaction with crossflow in channel on the cooling of heat wall. A range of parametric studies by varying membrane oscillating amplitudes and inlet velocities of channel was conducted. The resulting complex, conjugate heat dissipation was analysed. The synthetic jet interacts with the channel flow and gives rise to heat dissipation enhancement at the heated wall. The upstream heat transfer deteriorates in the jet hole, and the heat transfer in the downstream region has improved.

1. Introduction

Demands for better and more effective cooling of electronic devices have never been greater as the electronic components become more and more powerful, dissipating more heat, whereas the space around these components continues to be reduced to miniaturization trends. Channel heat sinks are the passive enhancement technology and show well recognised potential for meeting high heat dissipation needs. The impingement synthetic jet consists of two strokes for the completion of a cycle: blowing and suction strokes. The jet flow impinging on the heated surface is capable of breaking the thermal boundary layer, leading to a better mixing of the bulk flow and the flow adjacent to the heat wall. Synthetic jets are actuated using piezoelectric devices, and are employed particularly in applications that involve small scale heat transfer such as chip cooling [1, 2]. The primary advantage is that synthetic jets recycle ambient fluid and hence have a zero net mass-flux. As a result, there is no need for an external pressurized supply of fluid.

Fanning et al. [3] reported convective heat transfer study of adjacent impinging synthetic jets for the effects of orifice-to-impingement distance and orifice-to-orifice distance with varying phase difference between the jets.

Greco et al. [4] documented both time average and phase average heat transfer and flow study for single and twin circular synthetic jet with an IR camera and PIV measurements.

Jagannatha et al. [5] simulated the impingement phenomenon using the SST k-ω model in FLUENT. In their approach, the cavity was included on the computational domain in order to investigate the fluid flow inside it. They estimated a 30% enhancement on the heat transfer when compared to a continuous jet at matched conditions. It was also stated that because synthetic jets require no external plumbing in their actuation, when compared to steady jets, they offer lower levels of pressure drop.
Lee et al. [6] performed a three-dimensional investigation of synthetic jets for heat transfer enhancement in air-cooled microchannel. With the actuation of the synthetic jet and interaction of the pulsating flow with the cross-flow in the channel the heat transfer rate at the heated surface of the wafer was enhanced.

Luo et al. [7] developed an innovative cooling technology based on a vectoring dual synthetic jet (DSJ). The predicted results are validated to be in good agreement with the experimental results in the normal impingement region and the cross-flow region.

Xie et al. [8] have simulated different types turbulence of an impingement synthetic jet and employed a verified v2-f model. Three kinds of ribs are investigated. The results found the crescent ribs can enhance local heat transfer on the end wall downstream the ribs by generating longitudinal vortices, which intensify flow mixing.

Zhang et al. [9] studied various wave-forms for the purpose of heat transfer enhancement and compared to the corresponding steady air jet. The maximum heat transfer enhancement coefficient of synthetic jets is found to be 74.7% higher than that of the corresponding steady jet.

Giachetti M [10] studied the influence of their confrontation on flow structure and the roles of this frequency as well as four others on heat transfer coefficient.

The present study examines a thermal enhancement strategy by combining the benefits of highly favourable synthetic jet characteristics and the proven effectiveness of channel flows. This hybrid arrangement is envisaged to deliver excellent thermal performance for channel heat sinks without the need for additional fluid circuits and large fluid velocities.

2. Numerical model

2.1. Governing equations

Turbulent flows of incompressible Newtonian fluids are considered. Applicable governing equation for the analysis are the Reynolds-averaged Navier-Stokes (RANS) equations, the continuity equation and the energy equation subject to applied boundary conditions. The governing conservation equations are given as follows:

\[ \nabla \cdot \vec{u} = 0 \]  

(1)

\[ \rho \frac{\partial \vec{u}}{\partial t} + \rho \vec{u} \cdot \nabla \vec{u} = -\nabla p + (\mu_l + \mu_t) \nabla^2 \vec{u} \]  

(2)

\[ \frac{\partial T}{\partial t} = U_i \cdot \frac{\partial T}{\partial x_i} = \frac{\partial}{\partial x_i} \left( \alpha \frac{\partial T}{\partial x_i} - u_i T' \right) \]  

(3)

Where, the overbar “-” represents a Reynolds averaged quantity, and \( \rho, \mu, U_i, T \) and \( p \) are the density, kinematic viscosity, velocity, temperature and pressure, respectively.

The Nusselt number Nu and heat transfer coefficient are defined as:

\[ Nu = \frac{hd_o}{\lambda} \]  

(4)

\[ h = \frac{q_{\text{conv}}}{T_s - T_j} \]  

(5)

Where, \( h \) is a convective heat flux, \( \lambda \) is the thermal conductivity, \( d_o \) is the orifice diameter, \( q_{\text{conv}} \) is the net heat flux removed by the impinging jet with cross-flow, \( T_s \) and \( T_j \) are the impingement surface temperature and the jet temperature, respectively.

2.2. Numerical procedure and boundary conditions

The governing equations are converted into algebraic ones through the finite volume technique. They are solved, in a segregated manner, using a Cartesian staggered grid, applying fully implicit time integration. In the flow domain, the hybrid differencing scheme which switches between the first-order upwind differencing and second-order central differencing based on the local Peclet number-defined
as the ratio of the rate of advection to the rate of diffusion by the fluid flow – is adopted for the advection terms. The pressure-based SIMPLE method is applied to couple velocity and pressure fields [11]. Within each time step, the converge criterion of the continuity and the energy equation are considered to be equal with $1 \times 10^{-5}$ and $1 \times 10^{-8}$, respectively and for other equations is equal with $1 \times 10^{-4}$.

At all stationary walls, the velocity of the fluid is set to the nonslip condition. The thermal boundary of the heater surface was maintained at constant heat flux of $1000\text{W/m}^2$. The boundary conditions of the vibrating diaphragm are based on the $X-L$ model, a computational model for synthetic jet actuator is adopted which considers the actuator cavity and the exit throat as a single computational domain [12].

The oscillating uniform velocity at the channel inlet obeys a sinusoidal function as follows:

$$v_{in}(t) = A \cdot \sin(2\pi f \cdot t)$$  \hspace{1cm} (6)

where $A$ is the diaphragm amplitude, $f$ is the frequency and $t$ is time.

The schematic diagram of the two-dimensional computational domain is illustrated in Figure 1. The length of membrane, $L$ (heater length), in the axial direction is $40\text{mm}$ and the depth of the cavity, $h_c$, is $46\text{mm}$. The orifice, $d_o$, is $2\text{mm}$ while the orifice height, $h_o$, is $4\text{mm}$. The channel has a length $D$, $180\text{mm}$ while the channel height, $Z$, is $30\text{mm}$.

![Figure 1. Schematic diagram of synthetic jet mounted on channel in crossflow configuration.](image1)

![Figure 2. Comparisons of simulating data with experiment data.](image2)

3. Results and discussions

3.1. Evaluation of turbulence models capabilities

Figure 2 display the variation of velocity, with the time at the middle of the orifice exit ($y=0\text{ mm}$) and downstream ($x=1\text{ mm}$). The RNG $k-\varepsilon$ turbulence model provides the most reliable prediction being generally the nearest to the available experimental data of Luo [13], displaying a similar trend to that of the experimental data. Therefore, on the basis of the results shown in Figure 2, the RNG $k-\varepsilon$ turbulence model is applied to produce the results in the following sections.

3.2. Transient results of fluid flow characteristics with different velocity

With the operation of the actuator, the general flow structures in the channel as well as in the cavity were investigated with different oscillating amplitude and inlet velocity, i.e. $0.2\text{ mm}, 0.3\text{ mm}, 0.4\text{ mm}, 0.5\text{ mm}$ of membrane oscillating and $0.5\text{ m/s}, 1.0\text{ m/s}, 2.0\text{ m/s}$ at a fixed frequency, $f=1000\text{ Hz}$.

The synthetic jet action periodically interrupts the channel flow and breaks up the developing thermal and hydrodynamic boundary layers at the heated top wall. The computed instantaneous velocity contours patterns at peak diaphragm displacement ($t=T/2$) are discussed in Figures 3-5 for
channel velocities of 0.5 m/s, 1.0 m/s, 2.0 m/s respectively. It is revealed that the channel flow was swayed downstream owing to the interaction of jet and crossflow.

**Figure 3.** Velocity contours at peak diaphragm displacement (t=1/2T) for f=1000 Hz, v=0.5 m/s and A=0.2, 0.3, 0.4 and 0.5mm respectively.

**Figure 4.** Velocity contours at peak diaphragm displacement (t=1/2T) for f=1000 Hz, v=1.0 m/s and A=0.2, 0.3, 0.4 and 0.5mm respectively.
3.3. Thermal characteristics of synthetic jet with crossflow

Figure 6 shows the predicted distribution of Nusselt numbers over the heated wall for different channel inlet velocities without affection of synthetic jet. The behavior is similar to flow over a flat plate, which is noted to decay from its peak value at the leading edge of the heated wall.

Figure 7 indicated the distribution of Nusselt numbers over the heated wall for several time steps during one cycle of operation. The shifting and breaking of the vortex pairs impinges on the heated surface. The distribution of the Nusselt number off center peaks near the impinging surfaces.
Figure 8. Distribution of Nusselt number at the heated wall with one cycle f=1000Hz, A=0.5mm, Vi=1.0 m/s.

Figure 8 shows a distribution of Nusselt numbers at the heated wall over one cycle for the case of fluid flowing (Vi=1.0 m/s) in the channel. It is indicated that the distribution now shifted downstream and the peak value of the Nusselt number is reduced to about 2.0. And this is because the channel flow interacts with the impinging jet and drags it with flow, for Figures 3-5. Thus, the temperature and velocity gradients at the heated wall are reduced along with the heat transfer rates.

In the upstream region, the heat dissipation effect of no crossflow is better than that of the crossflow, and the higher the inlet velocity of the crossflow, the faster the attenuation of the heat dissipation. In the downstream region, the expelled fluid flow from the orifice is observed to interact the thermal boundary layer region where heat transfer occurred as the jet reached the upper boundary of the channel. It is revealed that the effect of synthetic jet is dominant, and the heat dissipation effect without crossflow is better than that of crossflow.

4. Conclusions
In this paper, the numerical results for heat transfer within a channel with synthetic jet had been presented. A pulsating fluid generated by a “Synthetic jet” that injects net positive fluid momentum with zero averaged jet mass flow into the channel crossflow. The use of synthetic jet actuator was shown to be able to remove the hot regions in heated wall. The synthetic jet interacted with the channel flow, which altered the channel flow structure and flow entrainment at both inlet and outlet. This technique is capable of delivering a two-fold increase in channel heat transfer, which does not require the deployment of additional fluid flow circuits to achieve such high heat transfer rates.

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References
[1] Bhapkar U S, Mohanan S, Agrawal A and Srivastava A 2014 Interferometry based whole-field heat transfer measurements of an impinging turbulent synthetic jet Int. Commun. Heat Mass Transf 58 118-124
[2] Tan X M and Zhang J Z 2013 Flow and heat transfer characteristics under synthetic jets impingement driven by piezoelectric actuator Exp.Thermal Fluid Sci 48 134-146
[3] Fanning E, Persoons T and Murray D B 2015 Heat transfer and flow characteristics of a pair of adjacent impinging synthetic jets Int. J. Heat Fluid Flow 54 153-166
[4] Greco C S, Ianiro A and Cardone G 2014 Time and phase average heat transfer in single and twin circular synthetic impinging air jets Int. J. Heat Mass Transf 73 776-788
[5] Jagannatha D, Narayanaswamy R and Chandratilleke T T 2009 Analysis of a Synthetic Jet-Based Electronic Cooling Module *Numerical Heat Transfer Part A: Applications* **56** 211-229

[6] Lee A, Timchenko V and Yeoh G H 2009 Three-dimensional modelling of fluid flow and heat transfer in micro-channels with synthetic jet *Int. J. Heat and Mass Transf* **55** 198-213

[7] Luo Z B, Deng X, Xia Z X, Wang L and Gong W J 2016 Flow field and heat transfer characteristics of impingement based on a vectoring dual synthetic jet actuator *Int. J. Heat Mass Transf* **102** 18-25

[8] Xie G, Liu X, Yan H and Qin J 2017 Turbulent flow characteristics and heat transfer enhancement in a square channel with various crescent ribs on one wall *Int. J. Heat Mass Transf* **115** 283-295

[9] Zhang Y Y, Li P and Xie Y H. 2018 Numerical investigation of heat transfer characteristics of impinging synthetic jets with different wave forms *Int. J. Heat Mass Transf* **125** 1017-1027

[10] Giachetti B, Fénol M, Couton D and Plourde F 2018 Influence of Reynolds number synthetic jet dynamic in crossflow configuration on heat transfer enhancement *Int. J. Heat and Mass Transf* **118** 1-13

[11] Patankar S V 1980 *Numerical Heat Transfer and Fluid Flow* Hemisphere Publishing Corporation

[12] Luo Z B, Xia Z X, Hu J X, Zhao J M, Miu W B and Wang D Q 2004 Numerical simulation of synthetic jet flow field and parameter analysis of actuator *J. Propulsion Technology* **25** 199-205

[13] Luo Z B 2004 Ph. D. Thesis, Principle of synthetic jet and dual synthetic jets, and their applications in jet vectoring and micro-pump National University of Defense Technology