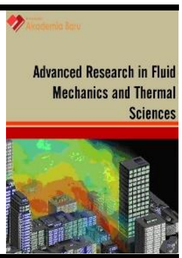
Penerbit Akademia Baru

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage: www.akademiabaru.com/arfmts.html
ISSN: 2289-7879




# Heat Transfer Performance of a Synthetic Jet Generated by Diffuser-Shaped Orifice

Open Access

Azmi Husin[1,3], Mohd Zulkifly Abdullah[2,*], Azmi Ismail[1], Ayub Ahmed Janvekar[1], Mohd Syakirin Rusdi[1], Wan Mohd Amri Wan Mamat Ali[1]

1 School of Mechanical Engineering, Engineering Campus, Universiti Sains Malaysia, 14300 Nibong Tebal, Penang, Malaysia
2 School of Aerospace Engineering, Engineering Campus, Universiti Sains Malaysia, 14300 Nibong Tebal, Penang, Malaysia
3 Faculty of Mechanical Engineering, Universiti Teknologi MARA Pulau Pinang, 13500 Permatang Pauh, Penang, Malaysia

**ARTICLE INFO**

***Article history:***
Received 23 October 2018
Received in revised form 11 December 2018
Accepted 13 December 2018
Available online 10 January 2019

***Keywords:***
Synthetic jet, diffuser-shape orifice, heat transfer, speaker actuator.

**ABSTRACT**

Synthetic jet impingement cooling has been identified to be an advanced cooling technique in a variety of applications such as turbine blade cooling, paper drying, and electronic cooling. The high heat removal capabilities with a simple construction of the device, demonstrate the advantage of synthetic jet compared to other methods. In the present work, the 3D numerical simulation using computational fluid dynamics (CFD) is carried out to predict the heat transfer performance of synthetic jet produced by speaker actuator with the diffuser-shape orifice. Numerical predictions are made for an orifice diameter of 6 mm with several opening angles. The excitation frequency of the speaker diaphragm is fixed at 100 Hz. Three vibration amplitude are used to investigate the effect of the different velocity of synthetic jet. The results showed that the opening angle of 90° is better than 45° and the heat transfer enhancement using a diffuser shaped orifice is more significant at a higher vibration amplitude. Also, the increment of vibration amplitude more than 0.6mm may not increase the cooling performance of synthetic jet.



## 1. Introduction

Synthetic jet is a flow generated by a movement of the diaphragm in an enclosure with a small opening. The vibration of diaphragm created suction and ejection of fluid into and out from a cavity through one or more orifice in one completed cycle. The ejection cycle generates positive net momentum and creates a pulsating jet moving forward direction. This unique flow has been intensively studied in thermal management field especially in electronic cooling.

Numerous investigations have been carried out on impinging synthetic jet over the last decades. Recent studies of synthetic jet have focused on heat transfer characteristics [1–6], which demonstrate the effectiveness of the cooling capability of the synthetic jet. Several of them discussed the heat transfer enhancement of synthetic jet experimentally. Most of the research

* *Corresponding author.*
*E-mail address: mezul@usm.my (Mohd Zulkifly Abdullah)*

investigated the effects of orifice sizes and shapes, orifice thickness, excitation frequency, cavity size, actuator orientation, and orifice-to-surface spacing. From the experimental results, synthetic jet shows significant improvement in heat transfer characteristics.

In addition to the experimental studies, numerous researchers have used numerical simulation to investigate the characteristics of the synthetic jet. Sila and Ortega [7] investigated the convective heat transfer while Jain *et al.,* [8] studies the flow characteristic. Both performed a two-dimensional numerical with laminar flow modelling for a single synthetic jet. Alimohammadi *et al.,* [9] work on flow vectoring phenomenon of the adjacent synthetic jet. Their two-dimension simulation results are validated with an image from particle image velocimetry (PIV). Yao Ma *et al*., [10] analyzed the cooling of the microelectronic chip by using a multiple orifice synthetic jet actuator. The multiple orifices provide more cooling area and enhanced the heat dissipation compared to single orifice configuration. Lv *et al.,* [11] simulated the effect of actuator parameters and frequency on flow characteristic of synthetic jet. They found that the diameter and depth of the cavity and orifice have influences the synthetic jet flow characteristics. A three-dimensional modeling to study the behavior of flow and heat transfer of synthetic jet in micro-channels was done by A. Lee *et al.,* [12]. The finding showed that the ejection of synthetic jet perpendicular to the micro-channels flow to enhance the heat dissipation.

The orifice is one of important parameter in the synthetic jet studies. Most of numerical simulation used a straight wall types orifice with various geometry and size. Lingbo *et al.,* [13] used sharp edge circular shape orifice with diameter of 50mm and thickness of 40 mm. Also, Hatami *et al.,* [14] used round orifice with diameter of 5mm and thickness of 10mm. A limited number of studies have considered the diffuser-shape orifice in numerical investigation. This types of orifice will enlarge the spread area of synthetic jet in a short distance.

In present work, a three-dimensional simulation of the speaker driven synthetic jet impinges on a square surface and spread out randomly is numerically studied. The effect of the opening angle of the diffuser-shape orifice and vibration amplitude of speaker cone on the convection heat transfer performance are the main concern of this research. The air is used as a working fluid. The synthetic jet actuator is constructed by the round speaker with 74 mm diameter. The speaker diaphragm is cover with an enclosure to create a cavity. The orifice with a diameter of 6 mm and a thickness of 3 mm is created at the center of the device cavity. The effect of two opening angles (45$^o$ and 90$^o$) and three diaphragm peak to peak amplitude (0.3, 0.6 and 0.9 mm) are examined. The geometry and relevant parameters are shown in Figure 1. The orifice to plate distance is fixed to 15 mm. The heating surface is treated as a constant heat flux surface.

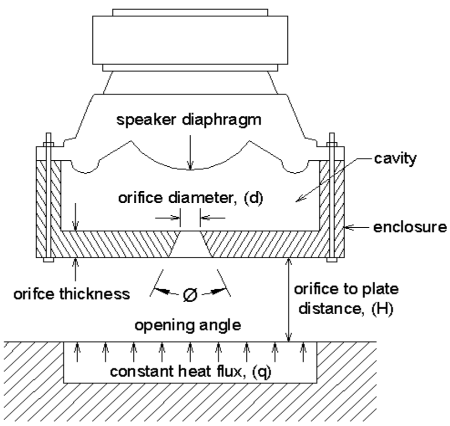



**Fig. 1.** Important geometry in impingement synthetic jet

## 2. Methodology

The unsteady Reynolds-average Navier-Stokes (RANS) equations are chosen as governing equations for the synthetic jet problems. The flow is assumed to be incompressible and turbulent. The governing equations describing the fluid flow are conservation of mass, conservation of momentum and conservation of energy. The general form of the mass conservation equation for incompressible flows can be written as

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

The conservation of momentum in the $i$-th direction in an inertial (non-accelerating) reference frame is described by

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial P}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho \mathrm{g}_i + F_i \tag{2}$$

where $P$ is the static pressure, $\tau_{ij}$ is the viscous stress tensor and $\mathrm{g}_i$ and $F_i$ are the gravitational acceleration and external body force in the $i$ direction respectively. The energy equation cast in terms of $h$ (static enthalpy) can be written as

$$\frac{\partial}{\partial t}(\rho h) + \frac{\partial}{x_i}(\rho u_i h) = \frac{\partial}{\partial x_j}\left(k \frac{T}{\partial x_i}\right) \tag{3}$$

where $T$ is the temperature, $k$ is the thermal conductivity. The turbulent model for the current study is shear-stress transport (SST) $k - \omega$. The selection of the turbulent model is based on the research finding by Bazdidi-Tehrani *et al.,* [15]. The transport equations for the turbulence kinetic energy $(k)$ and the specific dissipation rate $(\omega)$ are represented by Eq. 4 and 5, respectively. For more details on the SST $k - \omega$ turbulence model referred to the reference [16] and [17].

$$\frac{\partial k}{\partial t} + U_j \frac{\partial k}{\partial x_j} = P_k - \beta^* k\omega + \frac{\partial}{\partial x_j}\left[(\nu + \sigma_k \nu_T)\frac{\partial k}{\partial x_j}\right] \tag{4}$$

$$\frac{\partial \omega}{\partial t} + U_j \frac{\partial \omega}{\partial x_j} = \alpha S^2 - \beta \omega^2 + \frac{\partial}{\partial x_j}\left[(\nu + \sigma_\omega \nu_T)\frac{\partial \omega}{\partial x_j}\right] + 2(1 - F_1)\sigma_{\omega 2}\frac{1}{\omega}\frac{\partial k}{\partial x_i}\frac{\partial \omega}{\partial x_i} \tag{5}$$

The averaged Nusselt Number on the impingement surface is calculated by

$$Nu_{avg} = \frac{h_{avg} d}{k} \tag{6}$$

where *d* is orifice diameter, *k* is air thermal conductivity, the averaged heat transfer coefficient is calculated using Eq. 7

$$h_{avg} = \frac{q}{(T_s - T_a)} \tag{7}$$

where $q$ is the constant heat flux, $T_s$ is the impingement surface average temperature and $T_a$ is the ambient temperature.

### 2.1 Computational Domain and Boundary Condition

The axisymmetric three-dimensional model is constructed to replicate the actual conditions of synthetic jet impinge on the heating surface. The computational domain for the simulation is shown in Figure 2. The fluid domain is divided into two regions. The upper region consists of a moving diaphragm and cavity while the lower includes an orifice, ambient air and heating surface. The upper region is meshed with unstructured tetrahedral mesh due to profile complexity and the movement of the diaphragm [10]. The lower region is meshed with structured hexahedral mesh to reduce the simulation time.

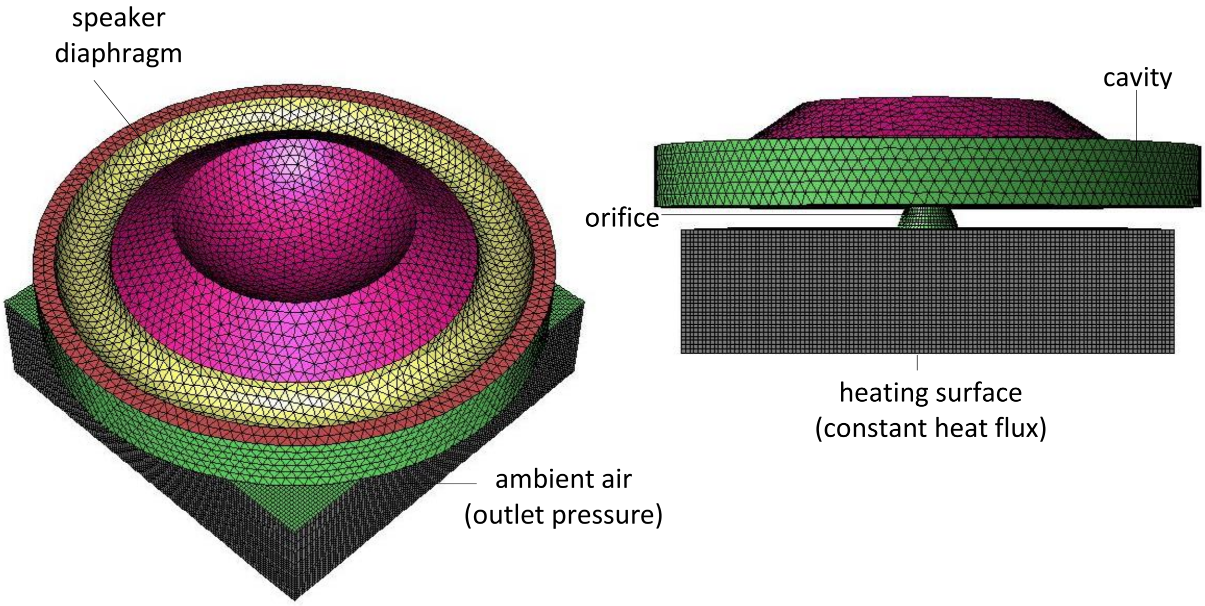



**Fig. 2.** Meshing and the boundary conditions of the computational fluid domain

The outlet pressure boundary condition (relative pressure is assumed as zero) is applied to the ambient air as this allows the flow to enter and exit the domain. The diaphragm, cavity surfaces, and heater surface are considered as an impermeable wall with additional conditions are applied to the diaphragm and heater surface. A constant heat flux of 2000 W/m$^2$ is applied over an area of (0.05x0.05) m$^2$ heating surface. The surrounding area of the heating surface was assigned with zero heat flux. The crucial part is to set up the moving boundary of the speaker diaphragm. The diaphragm is a module with dynamic mesh technique and user-defined function (UDF) to imitate the movement of the speaker diaphragm. For the present study, the sinusoidal function of 100 Hz has been employed to simulate the vibrating profile of the speaker diaphragm. The amplitude of the vibration (peak to peak) is varied from 0.3 mm to 0.9 mm. The time-varying profile of a moving diaphragm is expressed as

$$y(t) = \frac{a}{2} sin(2\pi f t) \tag{8}$$

the instantaneous logarithmic diaphragm velocity is derived by differentiating Eq. 9

$$v(t) = \frac{dy}{dt} = a\pi f \cos(2\pi f t) \tag{9}$$

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences
Volume 53, Issue 1 (2019) 122-128

where $y$ is the displacement of the rigid diaphragm, $a$ is the amplitude of vibration (peak to peak), $f$ is the frequency, $t$ is the time and $v$ is the velocity.

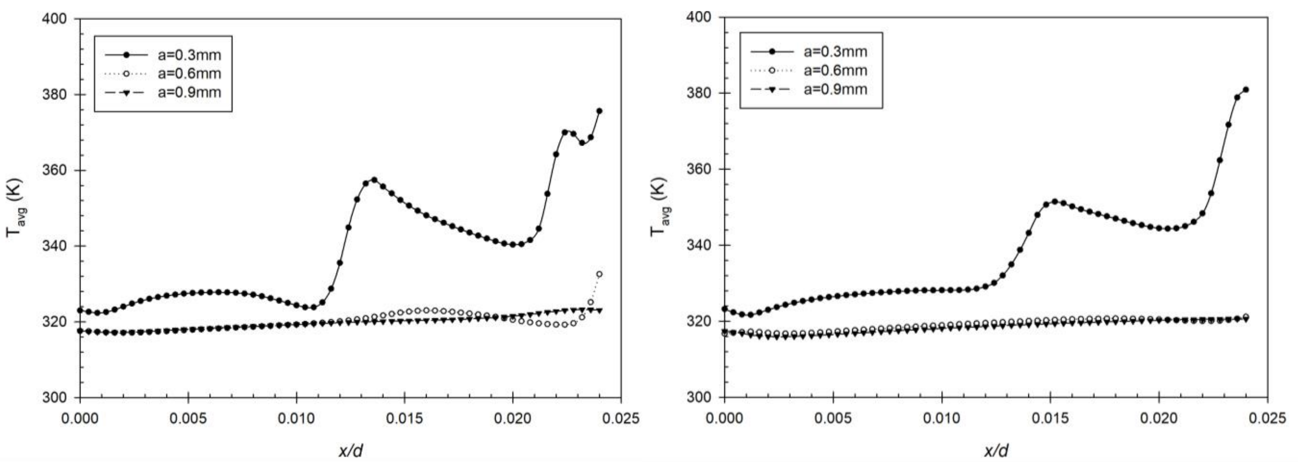
*2.2 Solution Procedure*

The pressure-velocity coupling was solved using a couple scheme. The second-order upwind spatial discretization was used for the momentum, energy, turbulent kinetic energy, and turbulent dissipation rate. Under-relaxation factors were left as default values.

**3. Results**

*3.1 Effect of Vibration Amplitude*

The importance of vibration amplitude of the speaker diaphragm on heat removal is address in this subsection. Figure 3 represents the variation of time-averaged temperature, $T_{avg}$ with *x/d* for three different values of diaphragm amplitude at fixed diffuser-shape orifice opening angle. The results from Figure 3(a) and 3(b) demonstrate that the time-average temperature on the heated surface impinge by synthetic jet with the vibration amplitude of 0.6mm and 0.9mm are more uniformly distributes compare to 0.3mm. The increased in vibration amplitude means increment in velocity of synthetic jet. Event through there is a raise of the velocity but there is no significant change in temperature distribution along x/d between $a$=0.6mm and $a$=0.9mm. The results may due to the limitation of air to absorb heat from the heated surface.




(a) (b)

**Fig. 3.** Time-averaged temperature distribution on heater surface for (a) $\emptyset = 45$ and (b) $\emptyset = 90^o$

*3.2 The Effect of Orifice Opening Angle*

The orifice opening angle effect on heat transfer of an impinging synthetic jet is investigated using different values of opening angle. Figure 4 illustrates the variations of the time-averaged Nusselt number, $Nu_{avg}$, with respect to the dimensionless axial distance, $x/d$ for variation of opening angle. Figure 4(a) displays the distribution $Nu_{avg}$ of at lowest vibration amplitude ($a$=0.3mm), the overall trends of $Nu_{avg}$ decrease with the increase of $x/d$. The wave effect of $Nu_{avg}$ distribution is due to the characteristics of synthetic jet flow with sinusoidal function input. The effect of opening angle is not clearly seen. However, the enhancement of heat dissipation due to the opening angle is showed in Figure 4(b). At the vibration amplitude of 0.6mm, Ø=90$^o$

dominate the higher values of $Nu_{avg}$. The increment of vibration angle also helps to delay the fluctuation values of the $Nu_{avg}$ distribution along $x/d$. The significant of heat transfer enhancement due to opening angle is presented in Figure 4(c). At highest amplitude ($a$=0.9mm), the orifice opening angle of 90$^o$ show the highest heat transfer followed by 45$^o$ and 0$^o$ respectively.

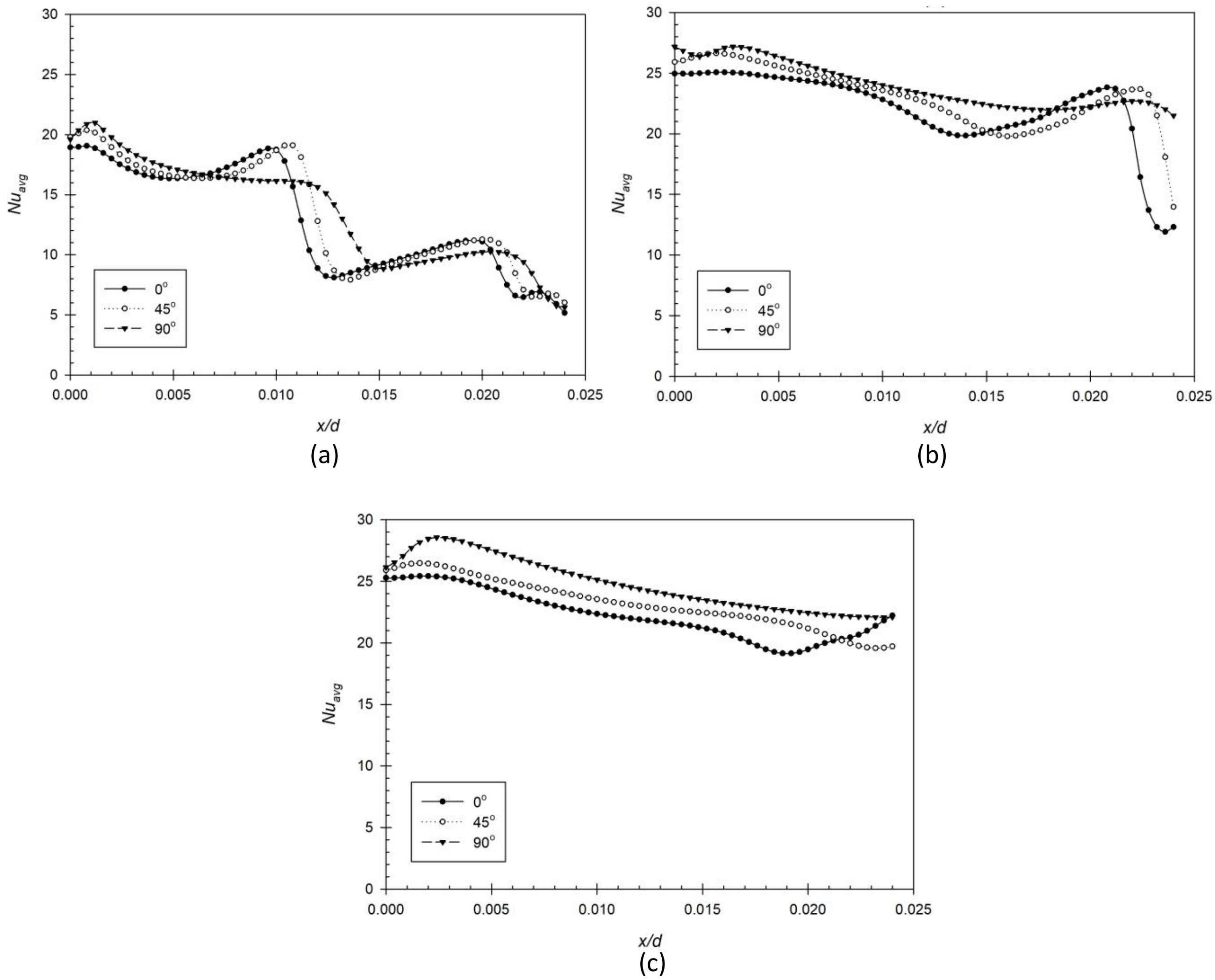



**Fig. 4.** Time-averaged Nusselt number distribution over $x/d$ for different vibration amplitude (mm): (a) 0.3, (b) 0.6, and (c) 0.9

## 4. Conclusions

In this paper, the numerical simulation of synthetic jet produced by a single speaker diaphragm impinge on the heating surface has been performed. From the finding, it can be concluded that the heat transfer performance for opening angle of 90$^o$ is better than 45$^o$ at a higher vibration amplitude. Also, the increment of vibration amplitude more than 0.6mm may not improve the cooling performance of the synthetic jet.

**Acknowledgement**

This paper was funded by Universiti Sains Malaysia, grant code 600 304/PMEKANIK/6316099 and 304/PMEKANIK/6315150.

## References

[1] Yuan, Shuai, Wen-Long Cheng, Yong-Le Nian, Qi Zhong, Yu-Feng Fan, and Jiang He. "Evaluation of prediction methods for heat transfer coefficient of annular flow and a novel correlation." *Applied Thermal Engineering* 114 (2017): 10-23.

[2] Deng, Xiong, Zhenbing Luo, Zhixun Xia, Weijie Gong, and Lin Wang. "Active-passive combined and closed-loop control for the thermal management of high-power LED based on a dual synthetic jet actuator." *Energy Conversion and Management*132 (2017): 207-212.

[3] McGuinn Alan, Daniel I. Rylatt, and Tadhg S. O'Donovan. "Heat transfer enhancement to an array of synthetic air jets by an induced crossflow." *Applied Thermal Engineering* 103 (2016): 996-1003.

[4] Silva-Llanca, Luis, and Alfonso Ortega. "Vortex dynamics and mechanisms of heat transfer enhancement in synthetic jet impingement." *International Journal of Thermal Sciences* 112 (2017): 153-164.

[5] Ghaffari Omidreza, Stephen A. Solovitz, and Mehmet Arik. "An investigation into flow and heat transfer for a slot impinging synthetic jet." *International Journal of Heat and Mass Transfer* 100 (2016): 634-645.

[6] Luo Zhen-bing, Xiong Deng, Zhi-xun Xia, Lin Wang, and Wei-jie Gong. "Flow field and heat transfer characteristics of impingement based on a vectoring dual synthetic jet actuator." *International Journal of Heat and Mass Transfer* 102 (2016): 18-25.

[7] L. A. Silva and A. Ortega, "Convective heat transfer due to an impinging synthetic jet: A numerical investigation of a canonical geometry," *2010 12th IEEE Intersoc. Conf. Therm. Thermomechanical Phenom. Electron. Syst. ITherm (*2010), vol. 135, no. August 2013, pp. 7–9.

[8] Jain, Manu, Bhalchandra Puranik, and Amit Agrawal. "A numerical investigation of effects of cavity and orifice parameters on the characteristics of a synthetic jet flow." *Sensors and Actuators A: Physical* 165, no. 2 (2011): 351-366.

[9] Alimohammadi Sajad, Eoin Fanning, Tim Persoons, and Darina B. Murray. "Characterization of flow vectoring phenomenon in adjacent synthetic jets using CFD and PIV." *Computers & Fluids* 140 (2016): 232-246.

[10] Ma Yao, Zhi-Xun Xia, Zhen-Bing Luo, Xiong Deng, and Xuan Ma. "Numerical investigation on microelectronic chip cooling using multiple orifice synthetic jet actuator based on theory field synergism." *Procedia Engineering* 126 (2015): 602-606.

[11] Lv, Yuan-wei, Jing-zhou Zhang, Yong Shan, and Xiao-ming Tan. "Numerical investigation for effects of actuator parameters and excitation frequencies on synthetic jet fluidic characteristics." *Sensors and Actuators A: Physical* 219 (2014): 100-111.

[12] Lee, A., V. Timchenko, G. H. Yeoh, and J. A. Reizes. "Three-dimensional modelling of fluid flow and heat transfer in micro-channels with synthetic jet." *International Journal of Heat and Mass Transfer* 55, no. 1-3 (2012): 198-213.

[13] Geng Lingbo, Zhiqiang Hu, and Yang Lin. "Numerical investigation of the influence of nozzle geometrical parameters on thrust of synthetic jet underwater." *Sensors and Actuators A: Physical* 269 (2018): 111-125.

[14] Hatami Mohammad, Farzad Bazdidi-Tehrani, Ahmad Abouata, and Akbar Mohammadi-Ahmar. "Investigation of geometry and dimensionless parameters effects on the flow field and heat transfer of impingement synthetic jets." *International Journal of Thermal Sciences* 127 (2018): 41-52.

[15] Bazdidi-Tehrani, Farzad, Mahdi Karami, and Mehdi Jahromi. "Unsteady flow and heat transfer analysis of an impinging synthetic jet." *Heat and mass transfer* 47, no. 11 (2011): 1363-1373.

[16] Menter Florian R. "Two-equation eddy-viscosity turbulence models for engineering applications." *AIAA journal* 32, no. 8 (1994): 1598-1605.

[17] Jehad, D. G., G. A. Hashim, A. K. Zarzoor, and C.S. Nor Azwadi. "Numerical Study of Turbulent Flow over BackwardFacing Step with Different Turbulence Models." *Journal of Advanced Research Design* 4, no. 1 (2015): 20-27.