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Computational Fluid Dynamic (CFD) Simulation of Synthetic Jet Cooling: A Review

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ABSTRACT

Synthetic jet which is also known as pulsed jet is a mechanism that is applied in many industries, such as manufacturing, automotive, and electronics. It is used in the industries as a cooling device. There have been many products developed and experimental data gained in the previous decade from synthetic jet technology. Interestingly, the expansion in computational fluid dynamic (CFD) simulation for synthetic jet analysis becomes important due to the technical advantages in reducing the analysis time and cost of the test rig. Therefore, this paper reviews the parameters in the CFD simulation which affects the synthetic jet performance. The parameters involved are synthetic configuration, numerical method modelling, and cavity. The numerical methods employed are Shear Stress Transport, Reynolds Averaged Navier-Stokes (RANS), k-ε, and Lattice Boltzmann. The investigation on synthetic jet via CFD analysis still needs further enhancement, especially on numerical method selection and modification. In certain conditions, the results of CFD simulation perform very close to the real experimental data. Therefore, the CFD technology is crucial to expedite the synthetic jet product enhancement.

1. Introduction

Air cooling is traditionally employed in many devices for cooling purposes. The new challenge in electronic devices is the density part that is difficult for air-fan to meet with the cooling requirements. Besides, the volume of components that need to be cooled down is increased. The fact is that the fan power is proportional to the airflow rate. Therefore, it will increase the fan speed, thus resulting in more noise and reduced fan reliability. Besides that, the current electronic devices are becoming

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smaller and need a better cooling system. It is a big challenge to dissipate away from the heat from a small hotspot device [1-2]. The synthetic jet is also called a pulsed jet, and air cooling thermal management solution was proposed to significantly replace the air fan cooling technique, especially for high-density electronic [1–6] products and other applications, such as in manufacturing [7-8] and automotive [9-10].

The idea of synthetic jet first appeared over a century ago in a renown study. The effect of synthetic jet had been explored by Lord Rayleigh. It reported that a tiny pulsed air jet was capable of extinguishing a candle [11]. Extensive research had been undertaken to understand in detail the sciences and principles of synthetic jet, such as in terms of operating parameters [12-13], vortex rings [14-15] thermal management application [5,16], and pulsed air jets [4]. Furthermore, more application of the acoustic streaming model on heat transfer and the history of the technology was reported as well [9,11,17–19].

The synthetic jet operation is different as compared to the fan blower. Entrainment flow is the main process which is delivered by the external pulse to the air jet actuator. This permits the actuator to perform a better flow size than the fan blower. In addition, synthetic jet was reported to be 60 times better than natural convention in terms of heat transfer characteristics in the electronic microchannel cooling system [6]. Synthetic jet delivers pulsed air jet in high velocity, as shown in Figure 1. The oscillating changes of volume in the piston or diaphragm produce pulsed air bullets from the actuator [20]. There are various techniques to produce oscillating movement, including pistons [21], piezoceramic composite diaphragms [22–24], or electrodynamically driven diaphragms [25]. Another parameter that needs to be highlighted is the flow field that is created behind the nozzle at the outlet fluid flow. This flow field trajectory is shown in Figure 2 [26].

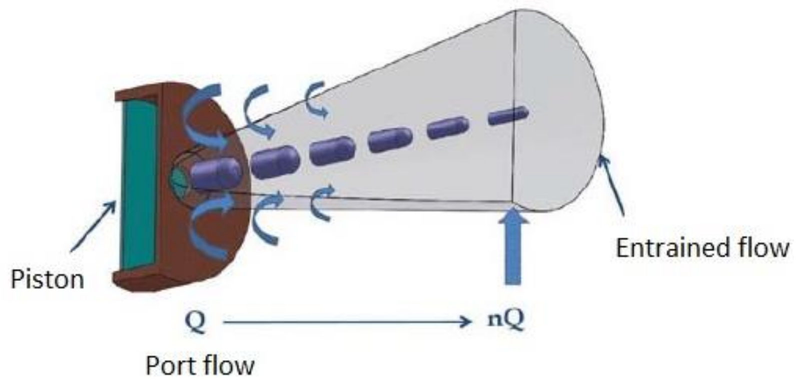

Fig. 1. Synthetic jet flow model [4]

Many investigations have been conducted, namely experimental study exploring the factor influence the flow performance, such as boundary layer [27], actuator [3,17,21–25,28], heat mass transfer [17,29–31], and jet mixing [32]. Brakmann *et al.,* [33] reported that heat transfer performance using finned target was improved by 135% to 142% as compared to the smooth target. The synthetic jet application was performed on a flat plate. On the other hand, experimental and 3D numerical analyses on the synthetic jet was conducted to study the effect of the target to the plate length and hole arrangement. The report exhibited that the experimental and simulation results showed a close agreement with each other [8]. Besides that, a hybrid synthetic jet which is an improved variant of the synthetic jet was investigated as well [34]. This variant gives advantages in terms of volumetric efficiency, especially in the heat or mass transfer potential applications [34]. From this analysis, most of the investigations were conducted in the experimental analysis. Simulation analysis in the computational fluid dynamic (CFD) can give a clear understanding regarding the science of flow in this synthetic model. Besides that, the experimental facilities or apparatus can be eliminated, thus reducing the cost and analysis time. Therefore, this paper will review on the CFD numerical modelling, numerical method, and cavity analysis of synthetic jet technology in order to understand the crucial parameter involved in the studies.

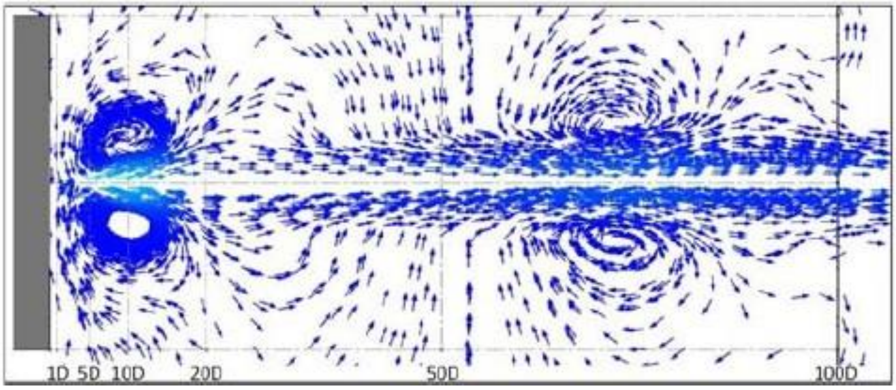

Fig. 2. Trajectory flow in synthetic jet [4,26]

2. Numerical Method Analysis

The attempt to investigate the synthetic jet effect via numerical simulation analysis had been conducted earlier. The biggest challenge is to predict and simulate the synthetic jet effect in turbulent flow. Interestingly, the cooling performance of synthetic jet in the turbulent flow is better than the laminar flow. This is due to the transient vortices movement that expelled the heat rapidly from the hot surface [35]. Three common modelling techniques are employed in turbulent conditions, which are Large Eddy Simulation (LES), Reynolds Average Numerical Simulation, and Direct Numerical Simulation (DNS) [35]. In history, Kral had initiated the investigation of synthetic jets via computational fluid dynamics analysis [36] whereby 2D Reynolds Averaged Navier-Stokes (RANS) simulations were conducted without cavity computational model in the early attempts. Then the enhancement via 3D DNS was employed by Rizzetta *et al.,* [37]. Besides that, a comparison between two open-source CFD software packages (Nek5000 and OpenFOAM) were performed via DNS modelling system to investigate the synthetic jet flow effect in turbulent conditions [38]. In addition, the combination of the LES model and the equation of vorticity stream function (in the turbulent equation) were solved by using the Lattice Boltzmann numerical method [35]. The Lattice Boltzmann model successfully improved the accuracy of the simulation and overcame the problem in a small Mach number. Fischer and Sharma [39] reported that the Scale Adaptive Simulation-Shear Stress Transport (SAS-SST) is a potential turbulence model as compared to the k-ε and the Shear Stress Transport (SST). It shows a close result in the experimental analysis. On top of that, NASA Langley Research Centre continued the effort to clarify the optimisation on the CFD method and modelling issues [38]. Table 1 shows the summary of the synthetic jets' computational studies. The numerical methods employed in each study are reported in Table 1 as well.

The enhancement in CFD analysis has moved rapidly. It gives a reliable result and is close to the real experimental data. These reviews show the various modelling system and the numerical method involved to simulate the synthetic jet turbulent flow. It will help the future researcher to optimise the best method for their analysis.

Table 2 presents an analysis of numerical studies on single synthetic jet evaluation. The configuration, Re and the method used for simulation were compared and assessed. The understanding of these characteristics are very important, especially during the parameter selection in order to obtain accurate and precise results. Besides that, Table 2 shows that the dynamic mesh method is employed only by a few researchers. Most of the researchers utilised inlet boundary conditions (IBC) method as compared to dynamic mesh.

Table 1
Synthetic jet CFD studies in a quiescent environment

Modeling	Numerical method	Re	References
LES	Lattice Boltzmann (2D)	400-20000	[35]
RANS	Third-order flux-difference splitting (2D)	2000	[36]
DNS	High-order compact finite-difference (3D)	1500	[37]
DNS	second-order Crank–Nicolson method high-order splitting method (2D)	1150	[38]
DNS	k-ε and the SST model, and the hybrid Unsteady RANS turbulence model –SAS-SST (2D)	18 000	[39]
LES	Lattice Boltzmann (3D)	830	[40]

Timchenko *et al.,* [41], Hong Mun Hoh *et al.,* [42] and Paul Ziadé *et al.,* [43] had employed a dynamic mesh method to analyse the flow of the synthetic jet. The dynamic mesh method allowed the researchers to view and analyse the evolution from the initial condition of quiescence. Hong Mun Hoh *et al.,* [42] reported that spatial resolution of visualisation in grid independence study improves with the higher mesh density. Wang *et al.,* [29] and Ozawa *et al.,* [43] had employed the LES turbulence modelling scheme to employ the simulations. Jain *et al.,* [44], Timchenko *et al.,* [41], Silva and Ortega [45], Hong Mun Hoh *et al.,* [42], Xia *et al.,* [46], and L. Silva-Llanca *et al.,* [13] had employed a laminar flow model on the synthetic jet flow investigation. Besides that, several researchers employed a sinusoidal wave operation to imitate the vibration in the cavity [29,45,47-48], thus reducing the model complexity and the simulation time. Most of the Re number conducted in the literature review was performed below 1000. A small Re number was employed to fit in tiny electronic devices. Therefore, the optimum Re number and numerical modelling are crucial because they give a big influence on the vortex ring stability.

Table 2
Configuration and method review in numerical analysis of synthetic jets

No	Configuration	Re	Method	References
1	Synthetic Jet into quiescent air	2400	IBC, URANS	[50]
2	Synthetic Jet based active cooling substrates	600	IBC, LES	[29]
3	Synthetic Jet in crossflow	–	IBC, URANS	[51]
4	Synthetic Jet in micro-channels	103	Dynamic Mesh laminar model	[41]
5	Synthetic Jet for active flow control	500	IBC, LES	[44]
6	Axisymmetric Synthetic Jet	167 – 1544	IBC & Dynamic Mesh laminar model	[45]
7	Impinging Synthetic Jet	1421 – 2843	IBC, SST	[49]
8	Impinging Synthetic Jet	508	IBC, laminar model	[46]
9	Impinging Synthetic Jet	2210	IBC	[48]
10	Synthetic Jet at low Re	14.8 – 553	IBC laminar model	[47]
11	Synthetic Jet at different shape	212-276	Dynamic Mesh, OpenFOAM	[43]
12	Adjacent Synthetic Jet effect	300	IBC, SST, Comparison between CFD & PIV	[52]
13	Effect of actuator parameters and excitation frequencies on SJ	-	IBC, URANS	[53]
14	Synthetic Jet at low and intermediate Re and f(Hz)	305-1000	IBC, laminar model	[13]
15	Synthetic-jet-assisted fluid mixer	83	Dynamic mesh, viscous laminar model	[42]
16	Jet impingement heat transfer	400- 20 000	Lattice Boltzmann Model	[35]

3. Cavity Analysis

The effect of cavity shape may give a significant influence on performances, such as velocity and flow regime in the synthetic jet system. Paul Ziadé *et al.,* [42] reported that three different shapes of cavities were investigated. The cavity S1 had performed the highest momentum at the exit flow [42]. S1 is the sharpest nozzle-to-cavity transition as compared to the other types. Figure 3 shows the three types of cavity shape.

Besides that, Alimohammadi *et al.,* [52] presented that the formation of the jet is influenced by its stroke length (L_0) and Re. On the other hand, this finding supports the above report regarding the effect of cavity geometry. Figure 4 shows the single jet flow diagram conducted by Alimohammadi [52].

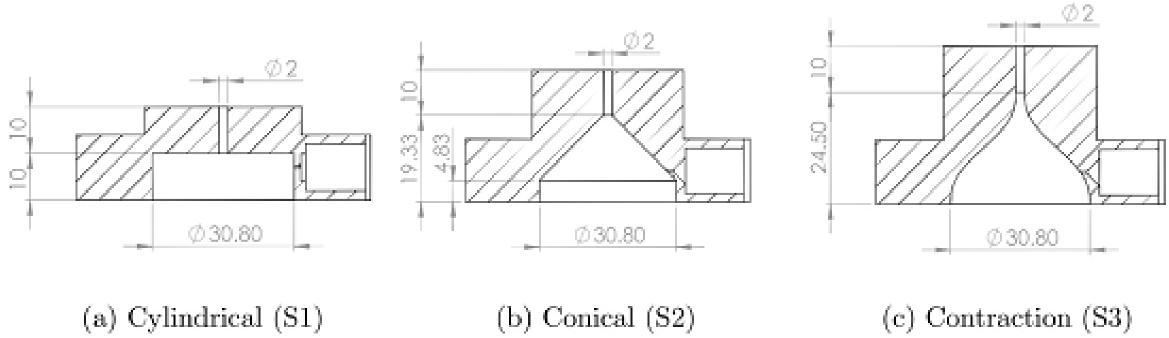

Fig. 3. Cross-section of synthetic jet cavity [18]

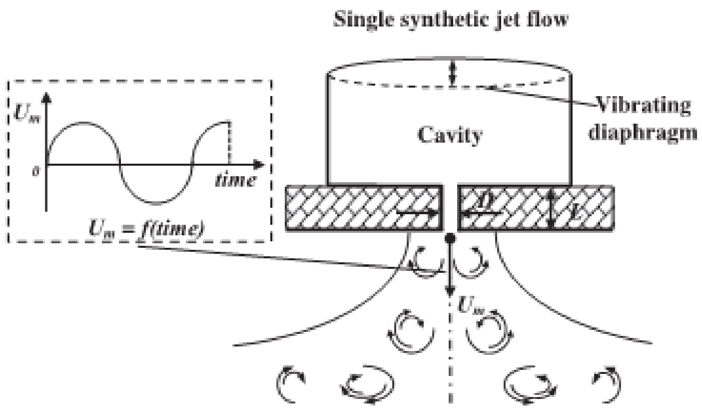

Fig. 4. Single jet flow diagram [52]

Furthermore, L. Yuan-wei *et al.,* [52] investigated the effect of cavity depth and diameter. Figure 5 shows the cavity analysis for synthetic jet flow. The results reported that the important factors influencing the performance of synthetic jet include the cavity depth, cavity diameter, orifice thickness, and orifice diameter. Besides, L. Silva-Llanca *et al.,* [13] had investigated the low performance of synthetic jets and intermediate Re and f(Hz). The analysis showed a significant understanding of the cooling management via synthetic jet mechanism operation in various applications. Figure 6 shows the heat flow analysis in computers that reported the possibilities and reliability of the results in synthetic jet application [4]. It studies the possibilities of synthetic jet mechanism to operate in compact electronic devices. The results showed an improvement up to 40% as compared to the existing fan blower cooling. The electronic cooling system has gained serious attention in today's studies. Therefore, it is worth the effort to focus on this application in the near future.

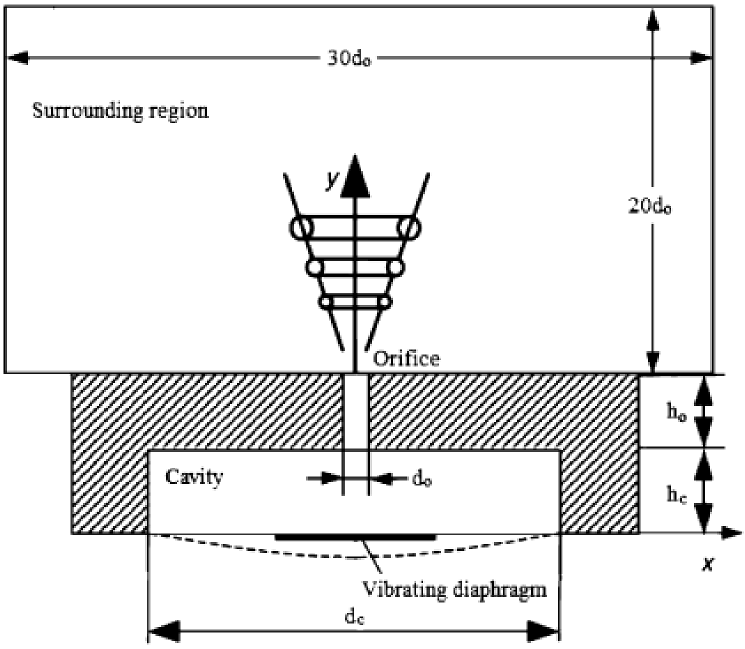

Fig. 5. Cavity analysis for synthetic jet flow [53]

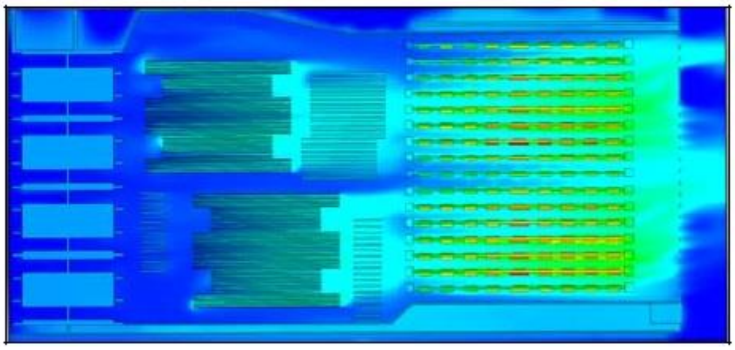

Fig. 6. Heat flow contour in the computer processor unit [4]

Besides that, Jain *et al.,* [44] reported that the pressure inside the cavity was reduced at a high cavity radius. It was due to the flow that failed to reach the orifice when the diaphragm was starting a new oscillation. Therefore, the mass flow rate was reduced as well, thus disrupting the heat transfer process. It showed that the performance of synthetic jet is influenced by the cavity size, shape, and orifice length to the surface [44,53-54]. Besides that, the diaphragm oscillation frequency exhibited a big influence as well. Firdaus *et al.,* [55] demonstrated that the excitation frequency and diaphragm amplitude had affected the heat transfer performance.

4. Conclusions

The numerical model selection and the cavity analysis were reported in this paper. The main target was to give a clear insight to the researcher about the trend of numerical and CFD analyses in synthetic jet application. Synthetic jet has the potential in electronic device application. However, there is still a gap to be explored on the heat transfer of microchannel conditions in electronic devices. The focus was on the flow field nature and the micro heat transfer characteristics.

A proper selection of Re number and numerical modelling is crucial as it has a big influence on the synthetic jet cooling performance analysis. Furthermore, the cavity size, shape, and orifice length of surface greatly affect the heat transfer performance. As a conclusion, more work is supposed to be done to improve the durability of electronic devices.

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