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Simulation of synthetic jets with non-sinusoidal forcing functions for heat transfer applications

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Abstract: Effective techniques for cooling electronic devices are essential for dealing with increasing heat loads associated with higher density manufacturing processes. Many conventional cooling techniques are reaching the limits of their effectiveness, and more novel methods of heat transfer are necessary to cope with these higher cooling demands.

Devices based on zero net mass flux jets (or synthetic jets) show promise in this area and are being actively investigated by a number of researchers. Typically in these devices the piston or diaphragm creating the synthetic jet is driven by a sinusoidal motion. In the present work the effect of using a non-sinusoidal forcing function was investigated using Computational Fluid Dynamics (CFD). A synthetic jet consisting of a channel, cavity and moving piston was modelled in order to capture accurately the flow and heat transfer from a heated surface.

The open-source CFD software OpenFOAM was used for the simulations, and in particular its moving dynamic mesh libraries. Custom modifications were implemented to create the non-sinusoidal motion of the piston. Within OpenFOAM, mesh motion is facilitated by applying suitable boundary conditions for the displacement(s) at each boundary, while at each timestep a Laplace equation is solved for the displacement of the internal mesh nodes based on the displacement of the boundary nodes. Within this framework the non-sinusoidal motion of the piston was modelled by creating a custom boundary condition to give the desired piston displacement at each timestep.

The piston motion was described by a phase modulated sinusoidal function, with the operating frequency of the modulator and carrier kept the same. The modulator phase was selected so that the piston motion exhibited a rapid discharge stroke, followed by a slower intake stroke. This motion increased the momentum of the fluid that impinged on the heated surface, while keeping the operating frequency constant. Behaviour of the system with sinusoidal motion of the piston was also simulated to allow the heat transfer enhancement due to the non-sinusoidal motion to be determined.

A two dimensional synthetic jet was considered, with the k-ω SST turbulence model used to account for turbulence in the flow. An additional transport equation was solved for the energy, and heat transfer, in the system. The synthetic jet system investigated had a cavity width of 10 mm and a mean depth of 10 mm. The orifice had both a width and depth of 1 mm, while the heated surface was located 10 mm from the orifice discharge. Oscillating frequencies of 250, 500 and 1000 Hz were investigated.

Comparison of the heat transfer results between sinusoidal and non-sinusoidal operation showed heat transfer to be between 5 and 10 percent higher for non-sinusoidal results.

Keywords: *Synthetic jet, CFD, OpenFOAM, Non-sinusoidal synthetic jet*

1. INTRODUCTION

Recent developments in semiconductor manufacturing techniques are allowing higher component densities in microchips, and their associated devices. Consequently, significantly higher rates of heat dissipation are required for these devices in order to avoid failure through thermal breakdown. Cooling techniques involving synthetic jets have been identified by a number of researchers as a suitable means to replace or complement conventional cooling methods to provide high heat fluxes and localised cooling to 'hot-spots' in devices and on chips. (Gillespie et al. 2006, Pavlova & Amitay 2006, Campbell et al. 1998, Mahalingam & Glezer 2002)

A synthetic jet is formed when a fluid is forced to flow back and forth though a small orifice. This motion is usually achieved by creating a cavity beneath the orifice where one wall is an oscillating diaphragm or a piston. The geometry of the cavity, orifice and piston causes the fluid to be expelled from the cavity with higher momentum than it is has when drawn in. Over one cycle there is no net change in mass of fluid in the cavity, and hence these devices are also known as 'Zero-Net-Mass-Flux' jets. For heat transfer applications the synthetic jet is directed towards a surface, and the impingement of the fluid on this surface causes the convective heat transfer rate to be increased. While a similar flow can be achieved by periodic interruption of a conventional impinging jet, synthetic jets have a significant advantage in terms of their space requirements, and the fact that they require almost no moving parts. Figure 1 shows a schematic of a synthetic jet actuator impinging on a heated surface.

Due to their suitability for cooling electronic devices, synthetic jet actuators have been the subject of a number of experimental studies. These studies have included both fundamental investigations, such as those reported by Utturkar & Holman (2005) and Smith & Swift (2003), as well as application examples, such as those by Campbell et al. (1998), Mahalingam & Glezer (2002) and Mahalingam & Rumigny (2004). In particular, Utturkar & Holman (2005) identified the formation criteria for a synthetic jet based on the Reynolds number, Stokes number and Strouhal number. They found jet formation occurred when $1/\mathrm{Sr} = \mathrm{Re}/\mathrm{S}^2 \geq K$, where K, a constant, is approximately 1 for two-dimensional jets, and 0.16 for axi-symmetrical jets.

Numerical studies have included those by Mittal & Udaykumar (2001) and Utturkar et al. (2002). For numerical modelling of a synthetic jet actuator, two approaches have generally been reported in the literature. The first approach is to model the jet as an imposed oscillating velocity at the exit of the orifice (Wang et al. 2006, Fugal & Smith 2004, Kral et al. 1997), while the second approach includes a complete model of the cavity as well (Rizzetta et al. 1999, Lee & Goldstein 2002).

The key defining factor of the above works is that only sinusoidal oscillation of the cavity membrane or piston has been considered. This paper extends this work to investigate the effect on heat transfer if a non-sinusoidal forcing function is used to drive a synthetic jet actuator. In particular the heat transfer from a two-dimensional piston driven planar synthetic jet is modelled.

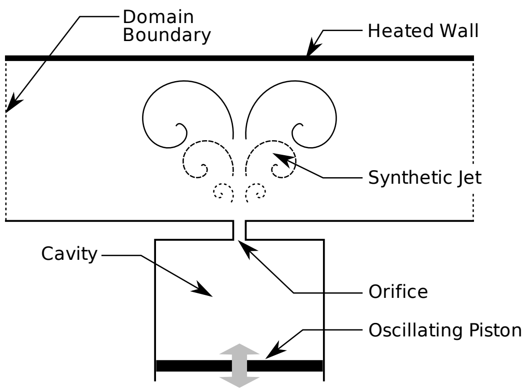


Figure 1: Planar synthetic jet

2. APPLIED PISTON MOTION

In this paper two cases of piston motion for a synthetic jet are presented, firstly for sinusoidal motion of the piston, and secondly for a specific non-sinusoidal motion of the piston. For the sinusoidal synthetic jet the piston displacement is defined as:

$$y = A_0 sin\left(\omega t - \phi\right) \tag{1}$$

where A_0 is the amplitude, ϕ is a phase shift (nominally zero) and the piston operates at a frequency of

$$f = \frac{\omega}{2\pi} \tag{2}$$

This configuration forms the reference case and many results for this mode of operation are reported in the literature.

For the second case, a suitable non-sinusoidal forcing function must be selected. In choosing this function it was important to consider the characteristics of the resulting jet. It was desirable that the jet impinged on the heated surface with as high a momentum as possible in order to increase the heat transfer rate at the surface. Higher momentum of the jet was achieved by increasing the velocity of the piston during the ejection phase. Consequently, to maintain the same operating frequency for the jet, the velocity of the piston during the suction phase needed to be reduced. This variation in the speed of the upstroke and downstroke was the key constraint on the selected forcing function, while at the same time it was desirable to have a function which was unlikely to cause numerical instability. A simple equation identified to meet these requirements was

$$y = A_0 sin\left[\omega t - \phi + \frac{1}{2} sin\left(\omega t - \phi - \psi\right)\right] \tag{3}$$

This equation consists of a phase modulated sinusoid where the carrier and modulator frequencies are the same ($f = \omega/2\pi$). As for the sinusoidal function, A_0 is the amplitude of the piston displacement oscillations and ϕ is the primary phase shift. By setting the modulator phase shift, ψ, to an appropriate value it was possible to achieve a forcing function with the desired short duration upstroke and longer duration downstroke. A suitable value for ψ was found to be $\pi/3$, while ϕ was set to zero. Figure 2 shows a comparison of the sinusoidal and non-sinusoidal forcing functions over one period of oscillation.

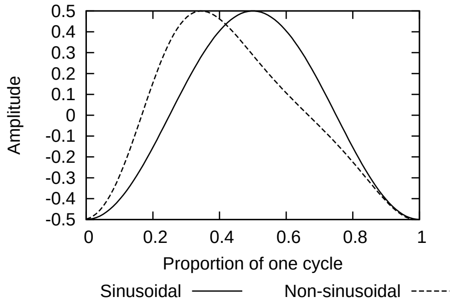


Figure 2: Comparison of non-sinusoidal forcing function and sinusoidal forcing function over one cycle

3. MODELLING CONSIDERATIONS

The open source computational fluid dynamics software package OpenFOAM was used to model the synthetic jet system (OpenCFD Ltd. 2008). OpenFOAM is a suite of C++ libraries and applications for manipulating field variables within a control volume framework. Its open source nature makes it highly extensible and it easily allows for modifications to the solvers to be made to accommodate specific problems. In this work a new solver containing two key modifications was created to model the synthetic jet. These modifications were:

- the inclusion of the energy equation to account for the energy transport and heat transfer, and
- a custom boundary condition on the mesh motion to account for the non-sinusoidal motion of the piston.

Further details on each are outlined below.

Table 1: Synthetic jet parameters

Parameter		Value(s)
Cavity width (mm)		10
Cavity depth (mm)		10
Orifice width (mm)		1
Orifice depth (mm)		1
Channel height (mm)		10
Amplitude (mm)	A_0	1.0
Frequency (Hz)	f	250, 500, 1000

3.1 Energy transport

Energy transport and heat transfer in the domain were modelled by including an additional scalar transport equation for the fluid temperature, T

$$\frac{\partial T}{\partial t} + \nabla.(\mathbf{U}T) = \Gamma \nabla^2 T \tag{4}$$

In this equation the diffusion, Γ, was determined from

$$\Gamma = \frac{k_c}{\rho c_p} + \frac{\mu_t}{\rho \mathrm{Pr}_t} \tag{5}$$

where k_c, c_p and ρ are the thermal conductivity, specific heat capacity and density of the fluid. The turbulent Prandtl number, Pr_t, was taken as 0.85 for this flow, while the effective turbulent viscosity, μ_t, is that computed for the flow from the turbulent transport equations.

3.2 Oscillating Boundary Condition

OpenFOAM has a number of mesh motion solver libraries available to distort and modify computational meshes. In this work a displacement-diffusion based mesh motion solver, by Jasak & Tukovic (2007), was used to solve the mesh deformation due to the piston motion. This solver determines the new point positions within the mesh by solving a diffusion equation for mesh displacement conditions applied at the domain boundaries. For the synthetic jet model the boundary displacements were specified to be fixed at zero on all boundaries, except for the cavity side walls and the piston. The cavity sidewalls were restricted to have a zero gradient on the mesh displacement normal to the boundary. Additionally an anisotropic diffusion coefficient was used in the mesh displacement equation to limit the diffusion of the mesh motion to the y-axis direction only.

While the above treatment is included within the OpenFOAM libraries it was necessary to construct a new boundary condition to account for the piston motion. When queried for its value, this boundary condition returned a value that indicated the piston displacement at the current simulation time, based on either Equation 1 or Equation 3.

4. PROBLEM FORMULATION

The following sections outline the formulation of the numerical problem.

4.1 Jet Parameters

The planar synthetic jet presented in this paper was treated as incompressible, unsteady and two-dimensional. Properties for the fluid were taken as those for air and were considered to be constant. Symmetry of the system about the central axis was ignored to allow any asymmetric unsteady flow features to be captured. Figure 3 shows the solution domain, while Table 1 lists the relevant parameters for the synthetic jet.

The top wall of the domain was treated as an isothermally heated wall, at a temperature of 25 °C above the inlet fluid temperature, while all other walls were treated as adiabatic. The open sides of the domain were

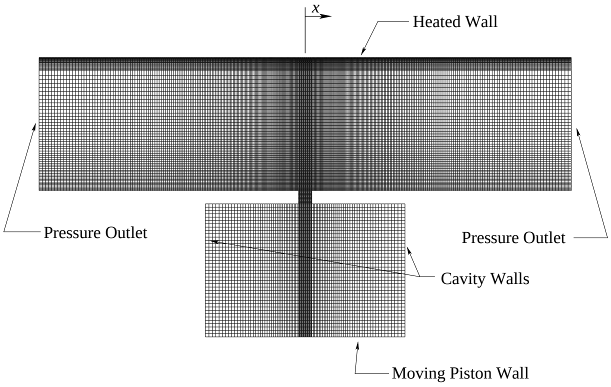


Figure 3: Mesh used for simulation

given a constant static pressure for outflow, while where inflow occurred the velocity was calculated on a face-by-face basis determined by the driving pressure difference. Modelling of the piston motion was as described in previous sections.

4.2 Turbulence

Turbulence in the flow was accounted for using the k-ω *Shear Stress Transport* (*SST*) turbulence model. This model was chosen due to its good prediction of heat transfer when compared to other models, as well as its reasonably low overhead, due to it being a RANS (Reynolds-Averaged Navier-Stokes) model. In particular, k-ϵ models were unsuitable, having generally been shown to predict poorly heat transfer from impinging jets.

4.3 Computational Domain

A regular quadrilateral scheme was used to mesh the domain, with 26,600 cells determined to be sufficient resolution after a grid independence study. As well as ensuring grid independence it was necessary to maintain y^+ values in the near wall cell below 1 to allow accurate resolution of the boundary layer flows. Figure 3 shows the resulting mesh when the piston is at zero displacement.

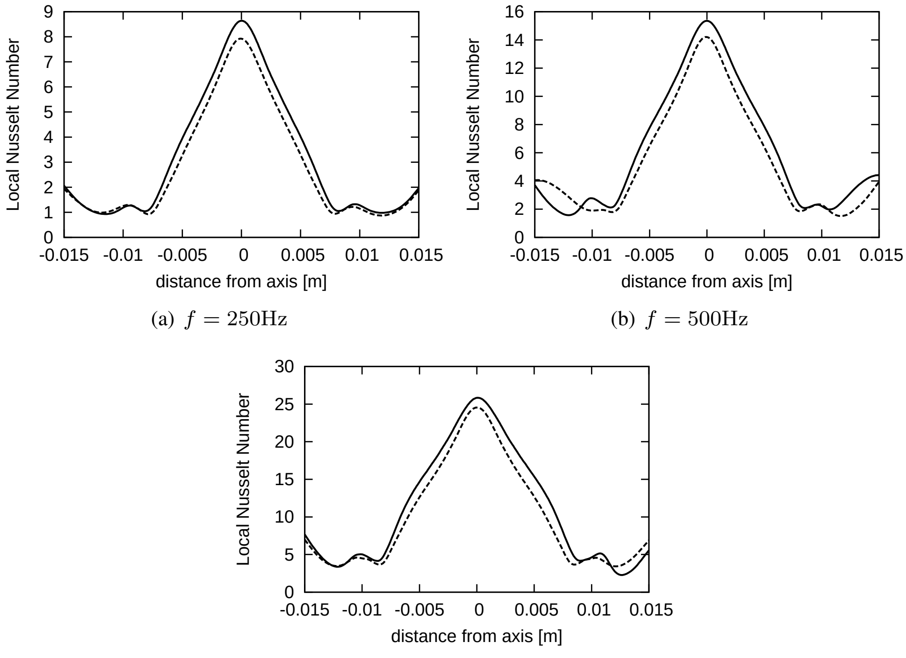
5. RESULTS

Figure 4 compares the local Nusselt number at the heated wall averaged over one cycle, for both sinusoidal and non-sinusoidal forcing functions. It can be seen that in the central region of the domain higher heat transfer is observed from the synthetic jet with the non-sinusoidal forcing function. For all the frequencies investigated the extent of this region is 10 mm either side of the orifice centreline. The increase in heat transfer ranges from 5.7 % to 9.1 %, with the highest increase observed at the lowest frequency of 250 Hz. The magnitude of the improvement decreased as the frequency increased.

Further insight into the effects of a non-sinusoidal forcing function is gained by examining the instantaneous local Nusselt number throughout a complete cycle. Figure 5 shows this data for both sinusoidal and non-sinusoidal synthetic jets, at a frequency of 500 Hz. In Figure 5(b) the rapid upstroke due to the non-sinusoidal motion is clearly evident, with the peak local Nusselt number reaching approximately 30 at 2.8×10^{-4}s. For the sinusoidal case, the time at which the peak Nusselt number is observed is delayed, occurring at 5.7×10^{-4}s, and reaches a lower value, approximately 20, as seen in Figure 5(c).

6. CONCLUSIONS

In this paper synthetic jets with both sinusoidal and non-sinusoidal forcing functions have been successfully simulated. The selection of a phase-modulated, frequency matched non-sinusoidal motion allowed the momentum of the synthetic jet to be increased, while maintaining the same operating frequency as for sinusoidal

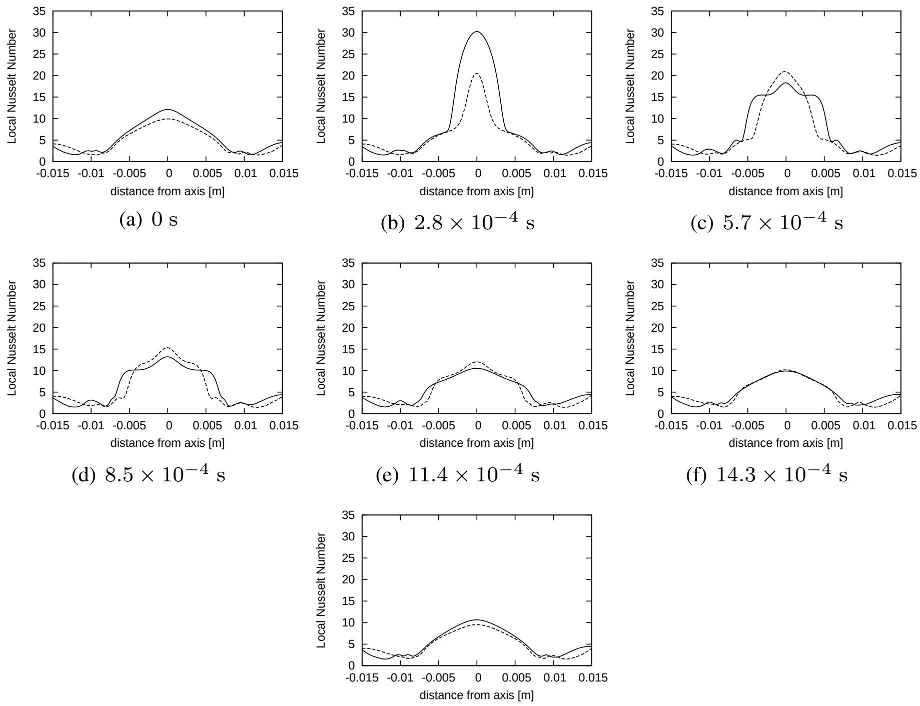


(a) $f = 250\mathrm{Hz}$ (b) $f = 500\mathrm{Hz}$

(c) $f = 1000\mathrm{Hz}$

Non-sinusoidal ——, Sinusoidal -------

Figure 4: Comparison of local Nusselt number for sinusoidal and non-sinusoidal forcing functions, time averaged over one cycle



(a) 0 s (b) 2.8×10^{-4} s (c) 5.7×10^{-4} s

(d) 8.5×10^{-4} s (e) 11.4×10^{-4} s (f) 14.3×10^{-4} s

(g) 17.1×10^{-4} s

Non-sinusoidal ——, Sinusoidal -------

Figure 5: Instantaneous local Nusselt number for one cycle at $f = 500\mathrm{Hz}$

operation. A suitable phase delay for the modulating sinusoid was identified as $\pi/3$. To model the synthetic jet system it was necessary to solve an additional transport equation for the fluid temperature and to implement a suitable boundary condition to give the required motion of the piston driving the synthetic jet.

The results from the simulations indicate that using a suitable non-sinusoidal forcing function to drive the piston motion in a synthetic jet gives reasonable increases in the heat transfer from the heated wall. For the range of parameters investigated in this work the predicted increases ranged from 5.7% at 1000 Hz to 9.1% at 250 Hz.

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