MODELING OF SYNTHETIC JET EJECTORS FOR ELECTRONICS COOLING

Raghav Mahalingam
Nuventix, Inc.
4301 Westbank Dr., Suite 150A, Austin, TX
raghav@nuventix.com

Abstract

This paper presents the modeling results for prediction of thermal performance using synthetic jets ejectors. A synthetic jet is an intense, small-scale turbulent jet synthesized directly from the fluid in which it is embedded. A jet ejector consists of a primary high momentum jet inducing a secondary flow within a channel. In the work presented here, a 2-D synthetic jet is used as the primary jet causing secondary flow to be induced in a channel. The flow entrainment prediction for the model is based on the solution of mass and momentum equations within the channel. A resistance network model is used to predict the thermal performance. The modeling results are compared with data from past tests of synthetic jet cooling within channels as well as a completely integrated synthetic jet heat sink module.

Keywords

Synthetic jets, jet ejector, modeling, cooling

1. Introduction

Heat dissipation levels of electronics continue to increase. Consumer-oriented systems still focus on air cooling approaches due to simplicity and ease of implementation (Bar-Cohen [1]). In order to achieve increased local power dissipation levels with fan-heat-sink configurations, designers are forced to use higher-speed fans, resulting in noise and reliability issues. Another challenge in electronics cooling is the packaging of compact systems such as portables, where in many cases there isn't enough room to even use fans. Previous approaches to thermal management of portable devices have focused primarily on using heat spreaders to distribute the heat to the skin of the portable.

Over the last several years synthetic jets have been researched as an alternative to fans as air moving devices and have been shown to be highly effective for cooling of electronics in a very small form factor. Synthetic jets are formed by time-periodic, alternate suction and ejection of fluid through an orifice bounding a small cavity, by the time periodic motion of a diaphragm that is built into one of the walls of the cavity. Unlike conventional jets, synthetic jets are "zero-mass-flux" in nature and produce fluid flow with finite momentum with no mass addition to the system and without the need for complex plumbing (Smith and Glezer, [2]). Because of their ability to direct airflow precisely along heated surfaces in confined environment and induce small-scale mixing, these jets are ideally suited for cooling applications at package and heat sink levels.

The principle of jet ejectors or pumps ([Gosline et al. [3]) has been known for several decades. In conventional jet ejectors, the primary jet is formed by ducting net mass flow from a continuous jet into the entry region of a channel. The low pressure created by the primary jet as it discharges into the channel results in the entrainment of ambient fluid, thus creating an increase in overall flow rate through the channel. The synthetic jet ejector consists of a primary, high momentum "zero-mass-flux" synthetic jet driving a secondary airflow through a channel. The use of synthetic jets as the primary jet is an attractive option since the only input to the primary jet is electrical, requiring no plumbing and flow sources. As shown in Figure 1, the high momentum primary jets (shown as block arrows) issue along the channel walls. A low-pressure region is formed at the inlet region of the channel during the ejection stroke of the synthetic jet resulting in the entrainment of ambient fluid. Additional flow entrainment is achieved during the suction stroke of the jet. The secondary flow (shown in dashed arrows) is entrained and driven through the channel between the fins. The primary synthetic jet is comprised of coherent vortices that break up the thermal boundary layer and enhance the heat transfer from the surface of the fins. The pulsating flow creates efficient mixing between the boundary layer and mean entrained flow.

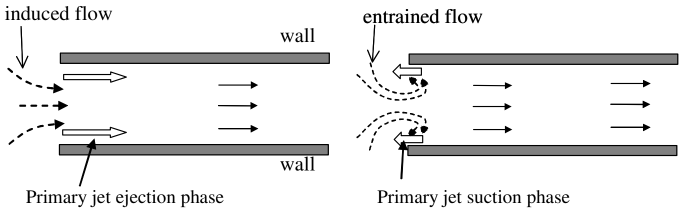


Figure 1. Basic principle of operation of a synthetic jet ejector.

Mahalingam et al.[4] showed that synthetic jet ejectors have much higher Nusselt numbers than steady flows of same Reynolds numbers based on the mean channel flow. Mahalingam and Glezer[5] also showed that the concept of Synthetic jet ejector arrays can be used to design active heat sinks for cooling integrated circuits. The present paper is an effort to model the performance of synthetic jet ejector cooling in a channel in a configuration similar to Figure 1. Experimental data is used from Ref[4] for validation of the modeling results. Then, the model is used to predict the and compare the performance of a heat sink built and tested at Georgia Tech.

Section 2 describes the experiments briefly as well as the modeling principles. Section 3 presents results from the modeling effort in comparison with the experimental results. Finally, conclusions are presented in Section 4.

2. Experimental setup and modeling

The experiments were performed in a channel that is fabricated of two heated walls having a variable distance in order to change the channel width and aspect ratio (Figure 2). The synthetic jets were placed alongside the walls as illustrated in the top view. Each jet spans the entire height of the channel and its orifice width is 500 µm. The channel walls are made of an aluminium plate heated with a flat foil heater that provides a constant heat flux along the wall. The wall length and height are fixed resulting in varying channel width and aspect ratio. The backside of the heated surfaces as well as the narrow top and bottom surfaces are fabricated out of high temperature machinable glass ceramic with embedded air pockets. The temperature at several points in the setup is monitored using T-type thermocouples. Full data acquisition details are presented in Ref. 4.

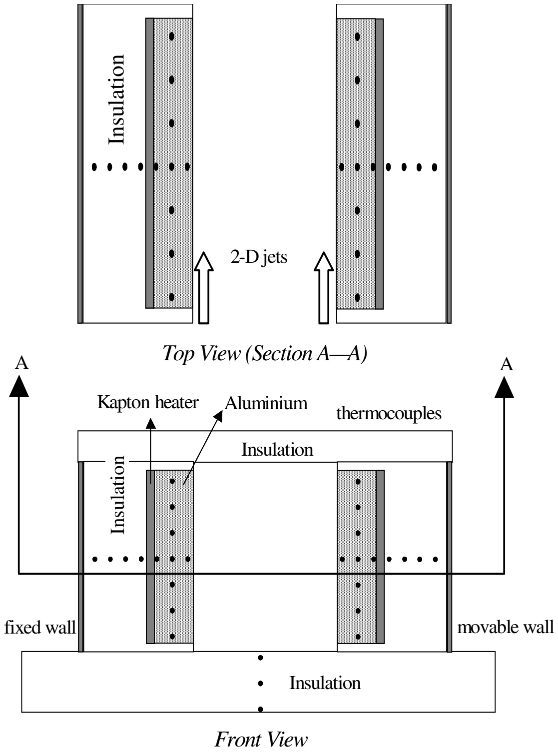


Figure 2. Schematic of the setup for measurements of jet ejector channel cooling.

Prediction of the overall thermal performance of the jet flow within the channels requires calculation of the induced flow rate due to jet ejector action, calculation of the heat transfer coefficient followed by addition of the component resistances to obtain the overall thermal resistance. The jet ejector model predicts the flow rate by solving mass and momentum conservation equations for the flow within the channel. The pressure drop and heat transfer coefficients are modeled using modified correlations found in heat transfer literature. The overall thermal performance prediction is based on resistance network analysis. For the complete heat sink model, the spreading resistance is calculated as shown by Lee et al[6].

The jet velocity used for the calculations is based on measurements of the synthetic jet prior to mounting in the channel. Figure 3 shows the streamwise decay of the time-averaged (normalized) centerline velocity for the free synthetic jet actuators (i.e., prior to their insertion into the channel). The data shows that the jets (which are almost identical) decay rapidly from about 10 to 3 m/s within 40 mm from the jet exit. (The decay rate for conventional 2-D jet is shown for reference.)

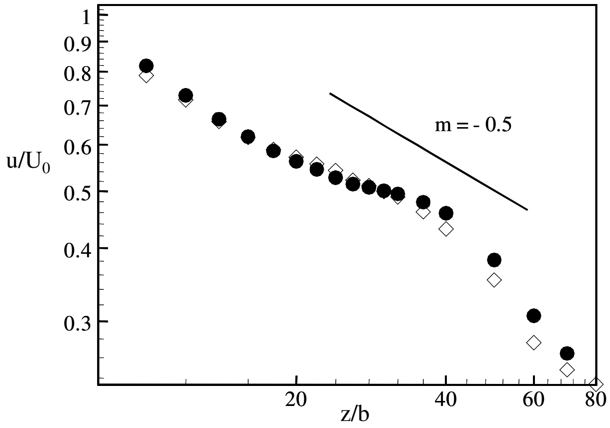


Figure 3. Streamwise variation of the free jet centerline velocity (U_0 = 11 m/s, b = 0.5 mm). The open and closed symbols are for the two individual jets.

3. Results and discussion

The effect of channel width on the induced flow through the channel is shown in Figure 4. The experimental volume flow rate is calculated based on the centerline velocity and exit area of the channel, which increases monotonically with channel wall spacing from about 0.8CFM at 7.5mm spacing to ~1.8CFM at 22mm. The flow rate is accurately predicted, with the experimental points being well within 10% of the predicted data points.

Figure 5 shows the heat transfer coefficient of the flow induced by the jet ejector. The heat transfer coefficient is slightly under-predicted with an average deviation from the measurements of about 15%. From a physical standpoint, larger channel widths result in lesser mixing between the boundary layer flow and the mean flow resulting is less efficient heat transfer from the wall.

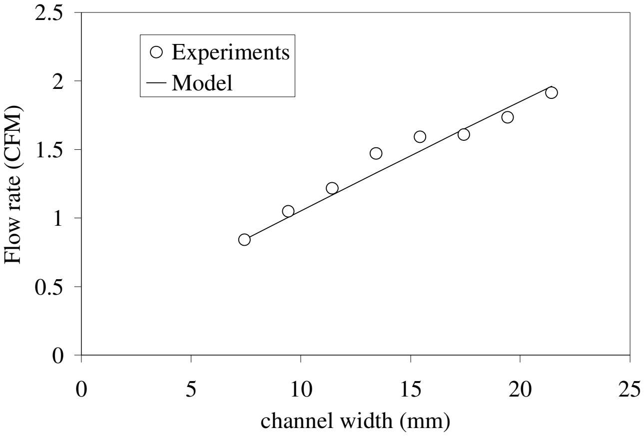


Figure 4. Induced flow rate in channel.

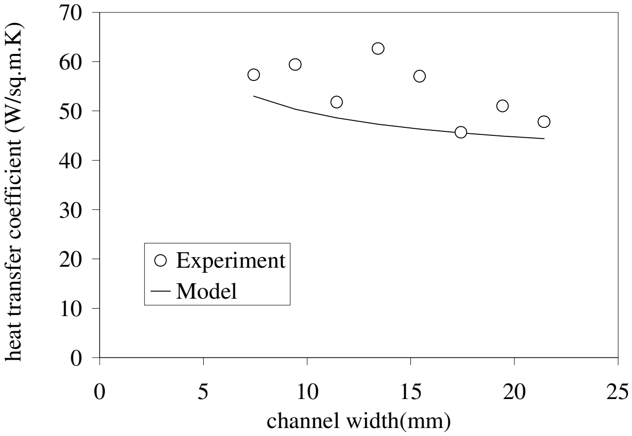


Figure 5. Heat transfer coefficient of the induced channel flow.

Figure 6 shows the wall to ambient thermal resistance in the channel. The measured data uses an average wall temperature from thermocouple measurements. The model predicts the thermal resistance based on the sum of the component resistances from the wall to the ambient including the correction for the air temperature rise from the inlet to the ambient. Again, the thermal resistance is predicted accurately with the experimental data falling within 12% of the model data.

Figure 7 shows the heat dissipated by the channel flow based on the measured wall temperature. Note that this result uses the measured wall temperature as an input to calculate the heat dissipated in the model as well as the calculated thermal resistance from the previous graph. The experimental data is based on the air temperature rise from the inlet to the exit of the channel and the mass flow rate through the channel. The experimental data all fall within 10% of the modeling results.

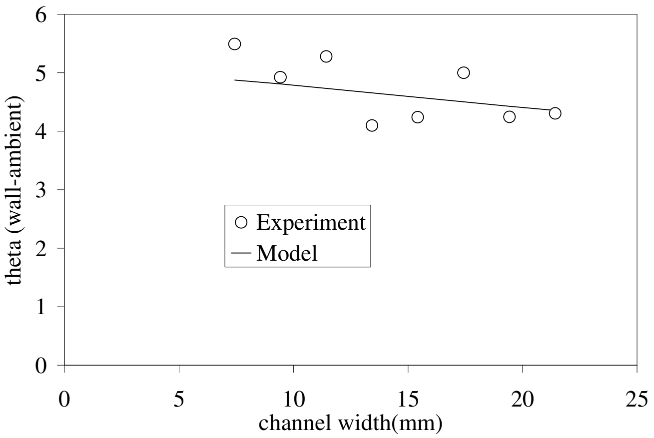


Figure 6. Thermal resistance from channel wall to ambient

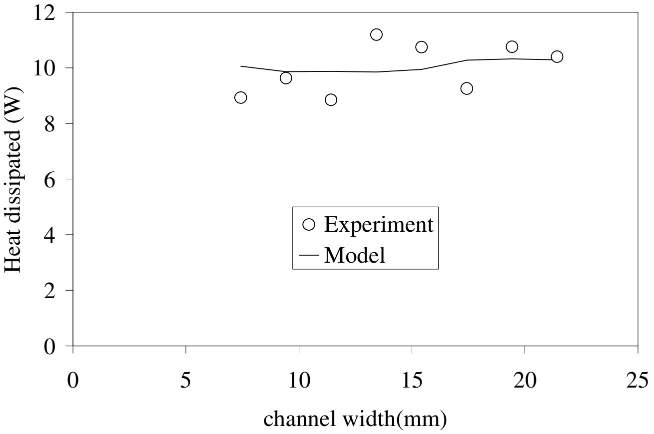


Figure 7. Heat dissipation based on measured wall temperature

Figure 8 shows a comparison between the measured and computed Nusselt numbers and an often used correlation for a turbulent channel flow. The characteristic dimension used for normalization is the channel width. While the measured and computed Nusselt numbers compare very well, it is clear that the turbulent, pulsating flow created by the Synjet ejector results in significantly higher Nusselt numbers than a hydrodynamically similar steady channel flow. A correlation developed by Gnielinski[7] for turbulent flows in channels is used for the comparison in this data. The synthetic jet driven flow has Nusselt numbers that are on average 2.5 times that of the steady flow, with higher improvement for lower Reynolds numbers.

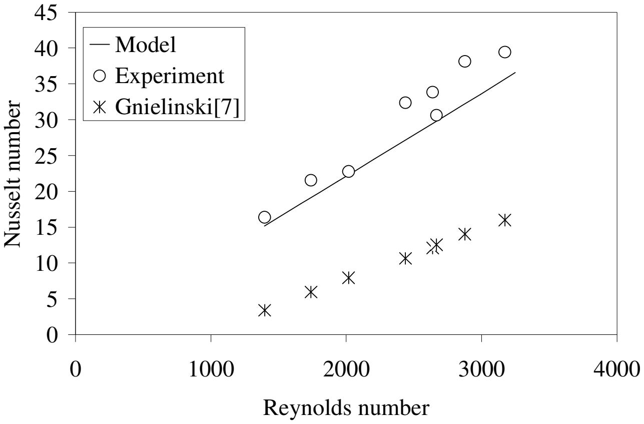
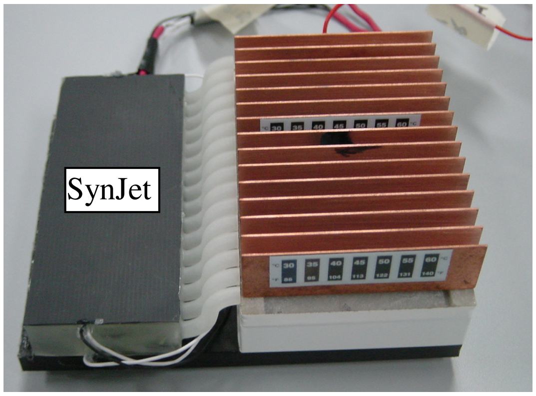


Figure 8. Comparison of predicted and measured Nusselt numbers for the Synjet driven channel flow with a correlation by Gnielinski[7]

Figure 9 shows a sample heat sink cooled by synthetic jets. The Synjet module (black with white nozzles) drives airflow through each of the channels of the heat sink. The heat sink temperature is measured with a thermocouple embedded at the bottom of the heat sink. The heat removed by the airflow is calculated by measuring the airflow rate at the end of the channels as well as the air temperature rise from the inlet to the exit. The table alongside the figure shows the results from the heat sink and comparisons with the model prediction. Again, the heat sink flow rate and the heat dissipated are predicted well.



	CFM induced	Heat dissipated(W)	Theta (C/W)
Experiment	3.03	13.83	1.01
Model	3.41	14.46	0.97
error	12.5%	4.3%	-

Figure 9. Synthetic jet cooled heat sink performance prediction.

4. Conclusions

The operation of a synthetic jet ejector is described. A model developed to predict the cooling performance of a synthetic jet ejector is validated using a simple configuration of a 2-D synthetic jet ejector in a rectangular channel. The effect of channel spacing on the induced flow rate, heat transfer coefficient, thermal resistance and overall power dissipated is modeled. All the primary quantities required to describe the performance of a synthetic jet ejector in a cooling environment are predicted within +/-15% of the experimental values. The Nusselt numbers for a synthetic jet driven flow are on average about 2.5 times that of a steady, fully-developed turbulent flow. Using the validated model, the performance of a synthetic jet ejector heat sink is predicted. Again, the experimental data falls within 15% of the prediction using the model.

Acknowledgments

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