Effect of Flow Oscillation

on Enhancing Heat Transfer or a 3D Object

With the increase in heat dissipation of components and management of heat extraction, innovative cooling solutions are proposed on a continuous basis. The active researchers in this area are trying to come up with new technologies to increase the heat transfer and remove the heat from the component at a reasonable cost. One of the techniques that might be useful is flow induced oscillation that enhances the heat transfer. The oscillating flow promises a higher heat transfer rate than a continuous flow and is a good candidate to be deployed in thermal management systems. Even though there have been a lot of articles on the fluid dynamics of the oscillation behind an object, very little work has been done on the heat transfer part of it.

One of the few to have conducted an experiment for simulating the oscillating flow heat transfer is Tae et al [1]. Figure 1 shows the concept behind this experiment. A square-shaped object 15x15 mm is placed in a uniform flow. There is an oscillation imposed on this uniform flow. The unsteady flow can be represented as:

$$U_t = U_0 (1 + A\sin 2\pi f t)$$

Where:

U_t = instantaneous velocity, (m/s)

U_0 = time averaged velocity, (m/s)

f =frequency of pulsation, (Hz)

t = time, (s)

The goal is to compare the heat transfer before and after the oscillation.

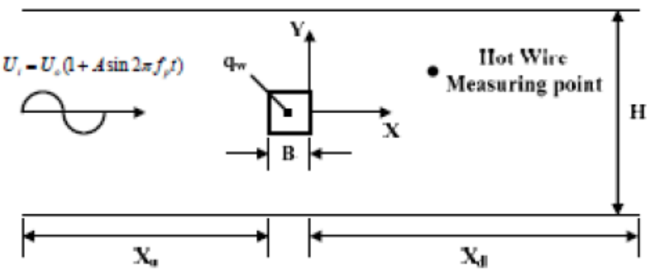


Figure 1- Concept of Oscillating Flow Experiment [1]

Figure 2 shows the schematic of the experiment in more detail

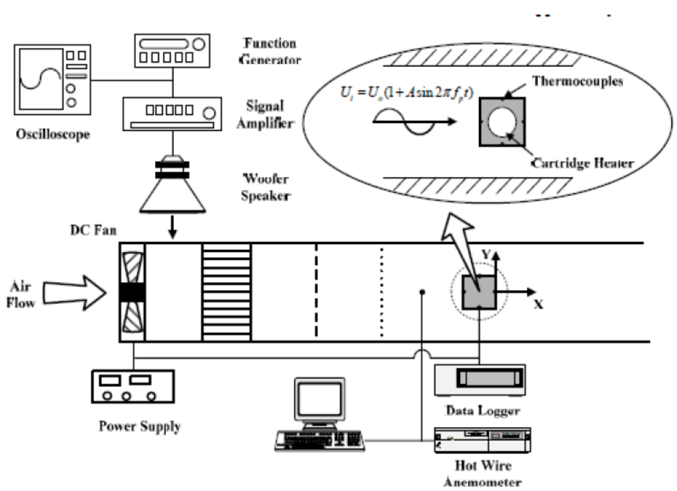


Figure 2- Schematic of the Oscillating Flow Experiment [1]

The flow was generated by a commercial fan and varied from 0.37 m/s to 0.57 m/s. To induce the oscillations, a 300 mm-woofer speaker was installed at the downstream of the fan. A function generator signal was sent to a signal amplifier and the output was fed to the speaker. A honeycomb and two screen meshes were installed at the downstream section of the speaker to make the flow uniform and to reduce the turbulence intensity. The channel width, length and height are 150 mm, 960 mm and 150 mm respectively. A cartridge heater was inserted at the center of the block to generate the heat. To ensure the periodic motion of the flow, a hot wire anemometer was inserted at the upstream of the component and the velocity was measured. Figure 3 shows the sinusoidal motion of the flow and its spectrum. The amplitude of the oscillation was kept fixed at 0.05 m/s. Figure 3a shows the velocity as a function of time at 5 Hz frequency. Its spectrum shows all the oscillation is at one harmonic of 5 Hz. Similarly figure 3b shows the flow and its spectrum at 20 Hz. This proved the flow to be clean at the upstream of the component.

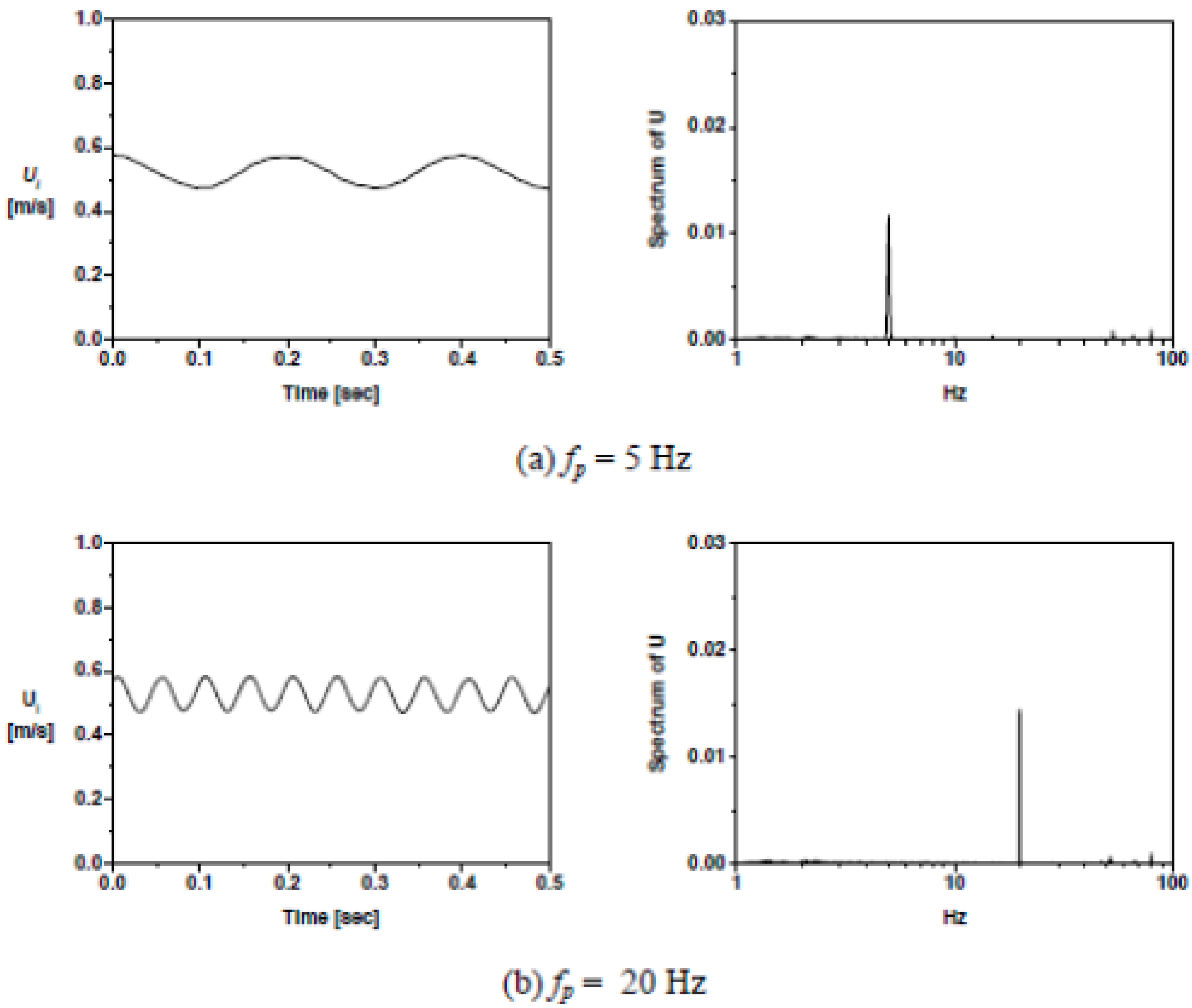


Figure 3- Periodic Motion of Flow and Its Spectrum [1]

After the surface temperature of the component reached a steady state, the speaker was turned on and the surface temperature of the component was measured after the temperature got to a steady state. A hot wire anemometer was installed at the downstream of the component to measure the time dependent velocity. Then an FFT (Fast Fourier Transform) was performed on the time dependent data to obtain their spectrum. Figure 4a shows the vortex shedding frequency which happens at the natural frequency fs_0 for the block when the speaker is off. When the speaker is on, the spectrum clearly shows that, in addition to the natural frequency of the vortex shedding, there is another component of frequency which is the frequency of the pulsations of the speaker, which occurs in the wake. This can be seen at Figures 4b, 4c, 4d and 4e for speaker frequency of 9, 10, 20 and 40 Hz. This experiment was done for a Reynolds number of 540.

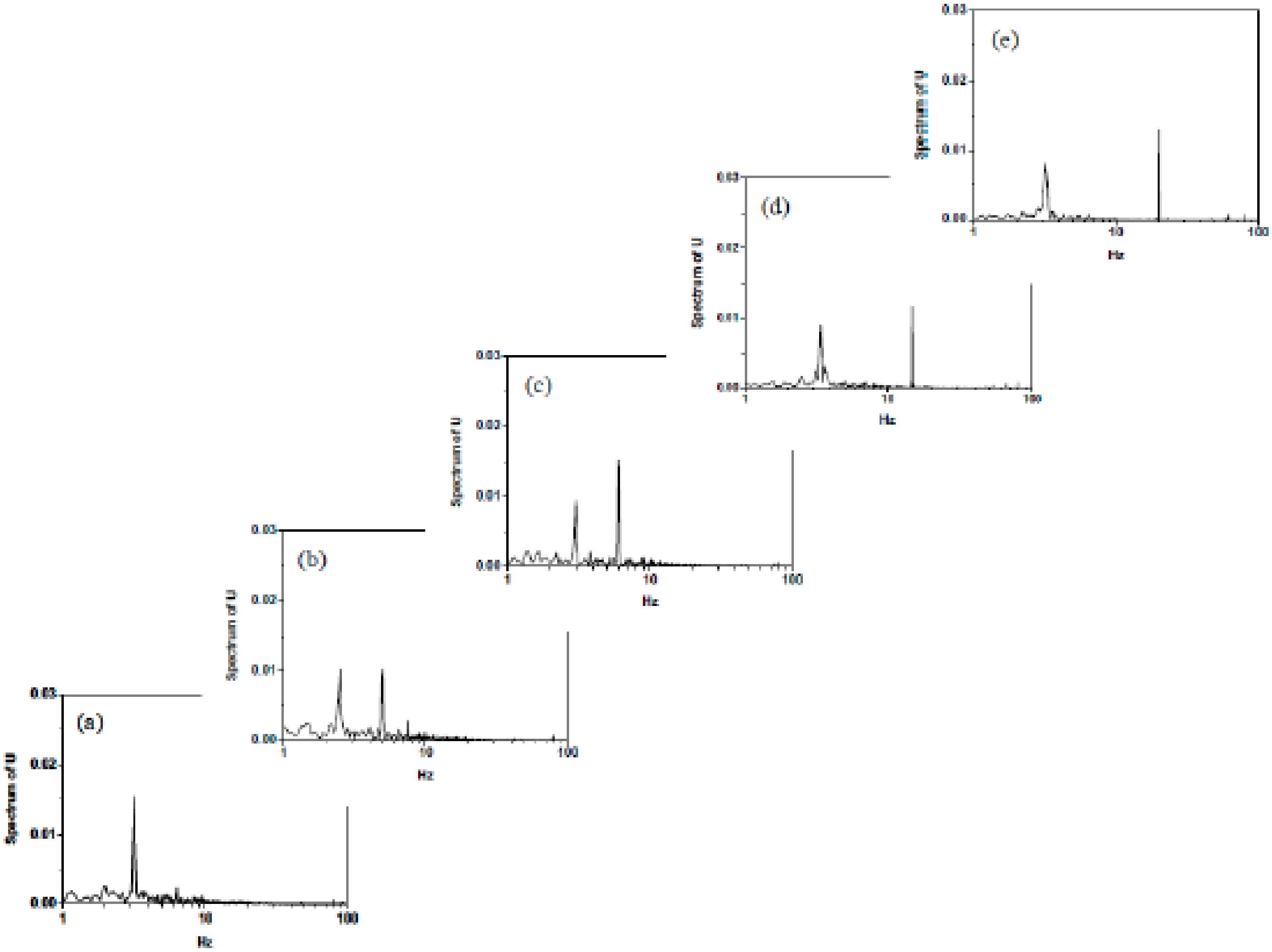


Figure 4- Spectrum of The Flow Induced Oscillations [1]

The measured Nusselt number was calculated based on the heat input and the temperature data as follows:

$$Nu = \frac{hB}{K} = \frac{\dot{q}B}{K(T_s - T_f)}$$

Where:

q = heat flux (W/m^{2}k)

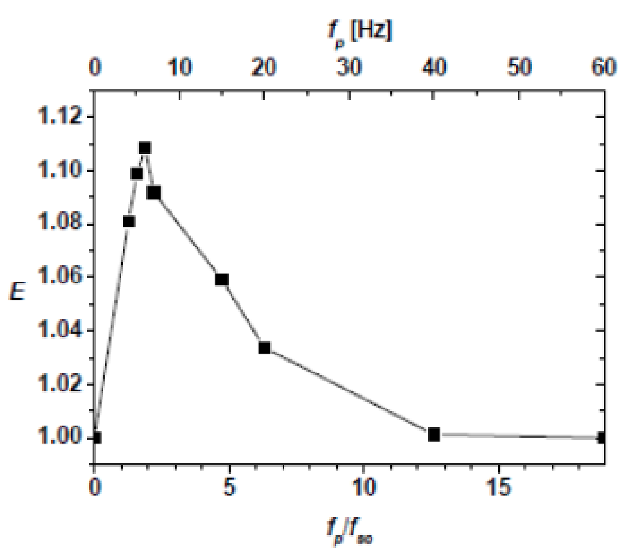
K = air thermal conductivity (W/m.k)

B = side length of component (m)

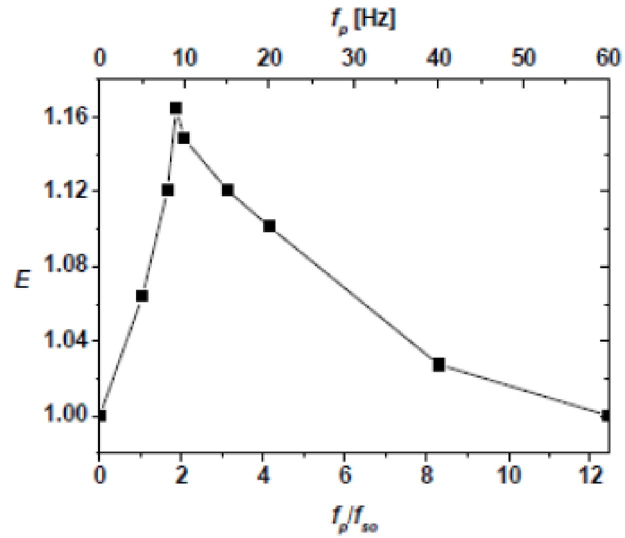
T_s = component surface temperature (ºC)

T_f = air inlet temperature (ºC)

Figure 5 shows the ratio of the Nusselt numbers before and after the imposed oscillation of the speaker, as a function of speaker frequency at two Reynolds number. The data was taken for two Reynolds numbers of 350 and 540. It is interesting to see that the improvement peaks at twice the natural frequency of the vortex shedding. It also can be observed that, as the Reynolds number increases, the improvement also increases. At a Reynolds number of 350 a 10% improvement in heat transfer was realized, while at a Reynolds number of 540 a significant 16% improvement in heat transfer was obtained.



(a) $Re = 350$



(b) $Re = 540$

Figure 5- Heat Transfer Improvement Due To Flow Induced Oscillations [1]

In a recent paper, Sung et al [2] conducted an experiment on a natural convection micro fin structure enhanced by acoustic vibration. Figure 6 shows the schematic of the experiment. They placed two micro fin heat sinks back to back and rested it in a rectangular chamber covered on top by a mesh screen. A 50 mm woofer loud speaker was placed at 10.25 mm from the fin structure. Thin film resistive heaters were attached to the backside of the heat sinks using a metal deposition and etching process.

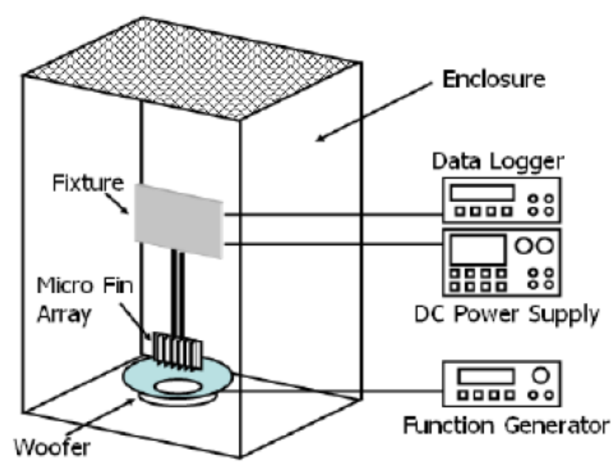


Figure 6- Natural Convection Experiment with Loud Speaker Excitation [2]

The size of the box was 300 mm height, 200 mm width and 200 mm depth. The dimensions of the microstructure are shown in table 1.

	H [μm]	S [μm]	L [mm]	W [mm]	Total area [m^2]
Array 1	100	160	10	16	0.0006712
Array 2	200	260	10	16	0.0007752
Array 3	200	160	10	16	0.0009912

Table 1- Dimensions of the Microstructure Heat Sink [2]

Where H is the height of the fins perpendicular to the flow, L is the length of the fins and S is the spacing between fins. Figure 7 shows the enhancement of the heat transfer coefficient as a function of excitation frequency. The figure shows that at a non-dimensional frequency of 0.011, the enhancement has peaked. The authors argue this might be due to the damping effect of the woofer rather than resonance effect.

Where

$h_c = h_t - h_r$ where h_c is convective heat transfer coefficient
h_t = total heat transfer coefficient
h_r = radiation heat transfer coefficient

And the non-dimensional frequency is defined as:

$$\omega = \frac{fH^2}{\alpha}$$

Where

f = frequency of vibration
α = Thermal diffusivity of air (m^2/s)

Figure 8 shows the enhancement of the heat transfer coefficient as a function of amplitude. The figure shows that the enhancement increases monotonically with amplitude.

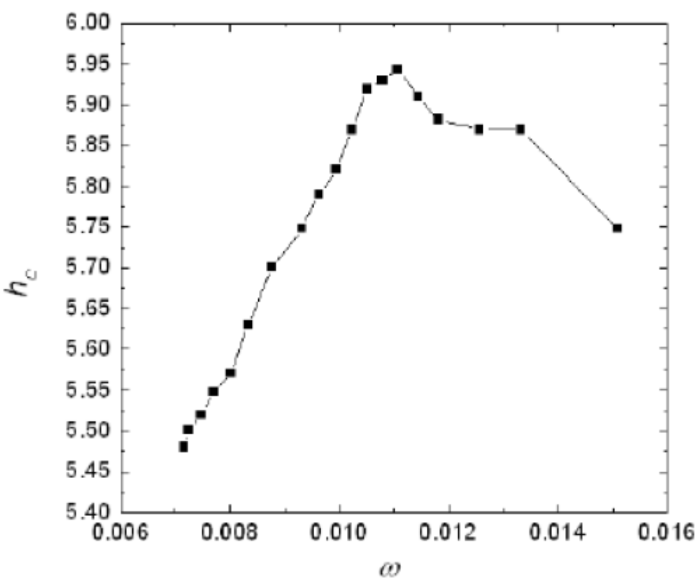


Figure 7- Heat Transfer Enhancement as a Function of Frequency[2]

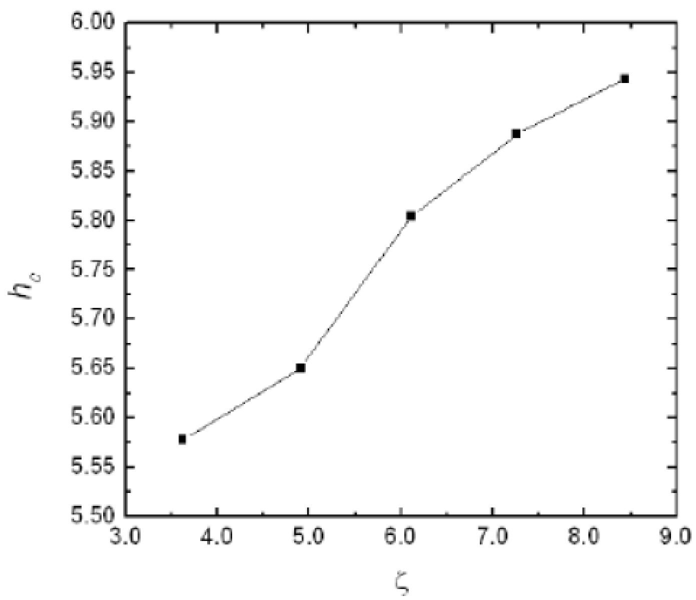


Figure 8. Heat Transfer Enhancement as a Function of Amplitude [2]

Where,

$$\zeta = \frac{AL}{\alpha}$$

A = Amplitude of velocity fluctuations (m/s).
L = length of the heat sink (m)

Figure 9 shows the ratio between heat transfer coefficients before and after the oscillation for different heat inputs (Rayleigh numbers). It also shows that the enhancement increases with the rise of heat dissipation. The acoustic interaction with the boundary layer enhances the mixing thus increasing the heat transfer.

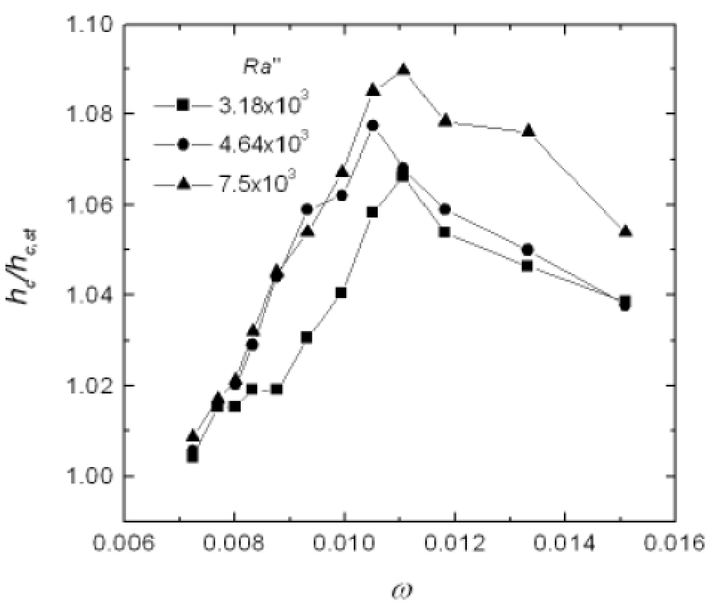


Figure 9- Heat Transfer Enhancement for Different Heat Inputs [2]

Azar [3] also conducted an experimental investigation to study the effect of forced oscillation of the fluid entering an electronic circuit pack channel on component cooling. A realistic air-cooled channel, made of two vertically mounted circuit packs containing nine components each, was employed. The experimental setup consisted of a channel with heated protrusions on one wall and a blade attached to a mechanical shaker at the inlet. Both natural and forced convection cooling were considered. The incoming fluid at the channel inlet was forced to oscillate at low frequencies.

The results showed that forced oscillation improved component flow exposure and resulted in enhanced cooling of up to 15 percent in forced convection cases. Several parameters such as angle of shaker blade, channel height, and inlet velocity were examined and their contributions were highlighted.

More experimental results are needed for acoustic excitation to decide if this is a viable technique for electronics cooling. For example, what happens when the Reynolds number increases beyond 540 for a forced convention flow? The typical flow on a PCB is about 1 m/s which is double the value of the flow in the experiment done in [1]. This corresponds to a Reynolds number of 1080.

Data is also needed to evaluate the effect of the amplitude for the forced convection flows. The amplitude in the experiment [1] was fixed at 0.05 m/s. What would be the result if the amplitude increased to 0.1 or 0.15 m/s? What are the limits before getting to a point of no return? After a more comprehensive testing, it can be determined if deploying a speaker in an electronic enclosure would contribute substantially to the cooling of components. In this process, the cost and noise implications should also be considered.

References:

1. Ji, H., Kim, Y., Hyun, M., "Heat Dissipation From a Heated Square Cylinder in an Oscillating Channel Flow", IEEE, 2006, pp 725-732

2. Sung, K., Milnes, D., Kenneth, G., Kim, S., "Enhanced Gaseous Natural Convection from Micro-scale Fin Structures Using Acoustic Stimulation", IEEE SEMI-THERM, 2010

3. Azar, K., "Effect of Forced Oscillation at the Channel Entrance for Enhanced Cooling of Components in Electronic Circuit Pack Channels", AIAA and ASME, joint thermophysics and heat transfer conference, 5th, June 1990