Analysis performance of forced convection cooling using synthetic jets with wave variations (sine, square, and triangular)

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Abstract. Cooling effectiveness using a cooling fan on an electronic device becomes a benchmark. Speaker-based synthetic jets that are becoming innovations today work on the principle of zero input mass, producing air in the cavity with an oscillating membrane which results in the suction phase occurring in the orifice hole. The generated air then flows through the orifice to pound the heat source as a forced convection cooler. Speakers used as oscillating actuators resemble waveforms using sine, square, and triangular wave functions with frequencies of 80, 100, and 120 Hz. Air flow simulation created using Fluent CFD. The use of wave variations has different characteristics. Triangular waves indicate the final test temperature reaches 27°C, with an optimum frequency of 80 Hz. Air flow created in the form of vortex flow with a type of turbulent flow. The electric power consumption of cooling fans reaches ten times the consumption of synthetic jet power.

1. Introduction
The rapid development of technology facilitates almost all human activities today. Electronic equipment is a tangible manifestation of technological development that greatly helps all human activities. Every day and every human being can not be separated from electronic equipment that has become a necessity in undergoing work.

Electronic equipment developed today still has some shortcomings. When operating, electronic equipment does not rule out the possibility of not generating heat transfer. Heat transfer that occurs can reduce the efficiency of the performance of the tool in operation, to create a solution to reduce heat transfer by using a cooling fan (fan).

The cooling fan which has been the solution so far has been working with the electromagnetic principle of copper wire windings so it requires large space and power to cool the heat transfer[1]. The level of effectiveness that is lacking in cooling is also a
benchmark that encourages the creation of new innovations in cooling heat sources from electronic equipment.

One innovation that is currently being developed is a cooling system using synthetic jets. With the working principle that drains air from a narrow gap, allows synthetic jets to be the optimum cooling system with less space and power compared to conventional cooling fans. The air flowed through this narrow gap is produced by the oscillation movement of the elastic membrane in the cavity of the synthetic jet generated by a vibrating wave \[^1,^2\].

The integration of synthetic jet cooling schemes is carried out on the surface of a full-sized heat sink with due regard to the heat transfer that occurs\[^3\]. The synthetic jet design used is the same as the general one that existed at that time to avoid interference with jet flow with the fan used to direct the flow directly towards the heat sink\[^4-^6\].

The synthetic structure of the jet actuator adopts a loudspeaker as its mechanism\[^7\]. The air cavity (cavity) and the output nozzle are square shaped made of material made from acrylic\[^8\]. The loudspeaker used has the same surface boundary as the diaphragm surface that resonates to produce air flow in the cavity\[^9-^11\]. Assumptions regarding synthetic jets as a cooling system for electronic equipment are getting stronger. Numerical approach is used by considering various wave forms\[^12-^14\]. The aim is to increase heat transfer and compare with steady flow\[^15,^16\]. Synthetic jets that use wave variations simulated in two dimensions adopt a turbulence flow model SST - \(k\omega\) and pay attention to the value of Reynolds number\[^17-^20\].

Each wave and frequency used has different characteristics. To determine the optimum value of the effectiveness of synthetic jets as coolants, it is necessary to do research and testing based on the limits and formulation of the problem specified. Therefore, this study focuses on the characteristics of the wave variations used with the aim of obtaining the optimum value of frequency, type of air flow produced, and the amount of synthetic jet power requirements when used as a heat source cooler on a flat plate.

2. Literature Review

2.1. Wave

Based on its shape, waves are divided into two types namely sinusoidal waves and non-sinusoidal waves. Sinusoidal waves or sine waves, have the same curve as the curve function \(\sin \theta\) against \(\theta\). Sinusoidal waves are simple waves that can be used for more complex waves. Sinusoidal waves can also be a mathematical function in the form of repetitive fine oscillations. This function often appears in mathematics, physics, signal processing, and electrical power engineering. Joseph Fourier, in 1822, discovered that sinusoidal waves could be used to form (at least close to) all periodic waves, including square waves. Fourier uses this invention as a tool to analyze waves and heat transfer. This analysis is used in signal processing and time series statistical analysis.

2.2. Fluid Flow

Fluid is part of changes in the shape of objects, including liquid, gas, plasma, or solid objects. Fluid has the ability to flow (or follow the shape of a place). The nature of the fluid that can follow the shape of the place due to the inability to withstand the influence of shear forces\[^21,^22\]. Fluid gas does not have a fixed shape or volume. Gas will develop to fill all places. Because the liquid and gas phases do not maintain a fixed form, both have the ability to flow. Thus both are often collectively referred to as fluids\[^23\].

2.3. Heat Transfer

Heat transfer can be defined as the transfer of energy from one region to another due to differences in temperature from these regions from higher fluid temperatures to lower fluid temperatures. If seen as a branch of science, heat transfer is the science that predicts energy transfer that occurs due to temperature differences between objects or materials. The science of heat transfer not only tries to explain how heat energy moves from one object to another, but it can also predict the rate of heat transfer that occurs under
certain conditions. As in thermodynamics, the rules of experiment used in the problem of heat transfer are quite simple, and can be easily developed so that they cover a wide variety of practical situations\[24\].

2.4. CFD (Computational Fluid Dynamic)
Computational Fluid Dynamic (CFD) is a method that can be used to study, estimate, and predict fluid properties, reactions, heat transfer, and fluid phenomena using mathematical equations. CFD is a way of modeling complex fluid flows by describing geometric shapes into cells consisting of discretion\[25\]. Fluid flow prediction using CFD is based on three things namely the Mathematical model (Navier-Stokes), numerical methods, and tools or software usage. The use of software in analyzing the characteristics of a fluid is needed, the software application used is CFD FLUENT®.

2.5. Synthetic Jet
Synthetic jets are fluid jets that appear to be generated from periodic motion of a closed diaphragm in an open cavity from one or more walls\[26\]. Synthetic jets are streams with zero net net (zero-mass) input produced by the harmonic motion of the membrane and out through the orifice gap\[26\]. Synthetic jets operate simply, flexible membranes or called diaphragms forming one end of a partially enclosed space\[27\]. Opposite the vibrating membrane, is the jet nozzle or orifice plate.

2.6. Electrical power
The energy absorbed or generated in a series of electronic equipment is electric power. Energy sources or electric voltage will generate electricity, while the load connected to the electricity voltage will absorb the power. In simple terms, electrical power can be interpreted as the level of energy consumption in an electric circuit circuit of time.

3. Research Methodology

![Flow chart of synthetic jet research](image)

**Figure 1.** Flow chart of synthetic jet research
3.1. Data Collection Procedure

Data was collected for 3600 seconds recorded using a TM-946 digital thermometer connected to a laptop with the Lutron801 application. The limits of the problem specified in conducting data retrieval are as follows.

1. Using sine, square and triangular wave variations in the Test Tone Generator application.
2. Frequencies used are 80, 100, and 120 Hz.
3. Height of synthetic jet with a heat source of 3 cm.
4. The environmental temperature interval shows 26-28°C.
5. The state of the closed door.
6. The temperature of the heat source is 60°C.
7. Air flow simulation is carried out using Fluent CFD.

Simulations using CFD Fluent are performed to obtain the type of air flow created from synthetic jets. This study focuses on the use of CFD Fluent to display the vorticity contours of synthetic jet flow and the turbulent intensity contours that are formed. The Boundary Condition in the simulation is as follows.

| Table 1. Boundary conditions in the Fluent CFD |
|-----------------------------------------------|
| Model Setting                  | 2D Unsteady                     |
| Fluid                          |                                |
| Density                        | 1.2225 kg/m^3                  |
| Viscosity                      | 1.7894×10^{-5} kg/m.s          |
| Cp                             | 1006.43 J/kg.K                 |
| Thermal Conductivity           | 0.0242 W/m.K                   |
| Velocity Inlet                 | UDF                            |
| Pressure Outlet                | 0 Pascal                       |
| Heater                         | 60°C                           |
| Frequency                      | 80, Hz 100 Hz and 120 Hz       |
| Amplitude                      | UDF                            |

4. Analysis and Discussion

A decrease in temperature due to natural convection occurs due to temperature differences from the heat source to the ambient temperature. The use of fans as cooling media can accelerate cooling from heat sources. However, the final temperature of using a fan is still higher than natural convection. The trend of temperature reduction is shown in Figure 4. below.

4.1. Sine Wave Characteristics

The vibration of the speaker membrane that moves harmonically as if it resembles a sine wave form has the same curve shape to the function sin θ to θ. The increase and decrease in the deviation to the time unit of the sine wave have a relatively equal time range. Based on the final temperature value, 80 Hz frequency is lower than the frequencies of 100 and 120 Hz. The frequency of 80 Hz has experienced a relatively stable temperature change at 1200 seconds. The significant difference is shown by the frequency of 80 Hz which shows the final temperature touching the figure of almost 27.1°C.

The greatest temperature drop during the first 10 minutes of each frequency. The frequency of 80 Hz has decreased temperature faster than the frequencies of 100 and 120 Hz. But experienced a slight
fluctuation at 35 minutes the test took place. As for the frequencies of 100 and 120 which appear to have a similarity in the trend of temperature reduction is more stable than the 80 Hz frequency.

4.2. Square Wave Characteristics
Square wave or square wave has a shape like its name, which is square. This wave has a symmetrical waveform with the same duration in the other half-box cycle (having regular intervals). Square waves experience a longer time interval at the peak point and the valley point, but experience a very short time when oscillating from the peak point to the valley point and vice versa.

Based on the final temperature of the test using a square wave variation, a frequency of 80 Hz indicates a lower final temperature compared to frequencies 100 and 120 although it looks relatively the same from each frequency. Both 80, 100 and 120 Hz have relatively small fluctuations. So that in Graph 4.5 shows a stable temperature decrease trend after the first 600 seconds until the test ends at 27.4°C for 80 Hz frequency. The fastest temperature reduction occurs at a frequency of 80 Hz compared to frequencies 100 and 120 Hz. The frequencies of 100 and 120 Hz show a trend of relatively similar temperature changes of the two frequencies. The stability of temperature decrease is also shown by each frequency variation for square wave. The greatest temperature drop occurred during the first 10 minutes of testing.

4.3. Triangular Wave Characteristics
Triangular waves or triangular waves are waves that have a linear rise and decrease in the X axis. Requires a longer time interval to the maximum peak point and towards the maximum valley point. Triangular waves are also non-sinusoidal waves obtained from the transformation of sine waves so that they resemble the shape of a triangle based on the value of the amplitude with respect to time units.

Based on the final temperature of the test, the frequency of 80 Hz reaches 27°C, however, a faster trend of temperature reduction is indicated by a frequency of 120 Hz. The large fluctuating values of each frequency variation cause the graph shown does not look stable. The biggest temperature drop occurred during the first 600 seconds.

4.4. Optimum Frequency
Determination of the optimum frequency is done in order to get the best frequency for cooling the heat source. Based on the characteristics of each wave variation, then we get a comparison of each frequency variation of each wave. Based on Figure 8. 80 Hz frequency comparison of each wave, the final temperature of the triangular wave shows the lowest temperature compared to sine waves and square waves. The final temperature of the triangular wave reaches 27°C, which has a difference of 0.1°C to the sine wave. As for the Square wave, the final temperature reaches 27.4°C.

By comparing synthetic jets and fans as a source of heat, the comparison is done carefully with the same testing limitations. The variations determined as a comparison between synthetic jets and fans are as follows:

1. Distance. The influence of the distance in cooling is quite large, so in testing comparing the fan with a synthetic jet the distance is determined as far as 3 cm.
2. Dimensions. The size or dimensions of the heat source are determined to be the same on a flat plate in order to obtain the same heat transfer value under the same conditions during the test.

3. Nozzle. The use of a nozzle or a narrow gap is used as a cooling channel. Aside from being an air outlet out of a synthetic jet, the nozzle is analogous to a wall or case on an electronic device that uses a fan as a cooling medium.

4. Electric power. Seeing the value of effectiveness and efficiency, power is one of the things that is quite important to be used as a benchmark for fan and speaker-based synthetic jets. The need for electrical power from the fan that has been quite large, will be compared with the need for speaker-based synthetic jet power in cooling. So that the power used is as great as seeing the trend of temperature drop during testing.

4.5. Airflow Simulation Using Fluent CFD

The simulation stage with the CFD Fluent application can display the contours of the fluid flow from the velocity, vortex flow, turbulent intensity, pressure, and temperature that occur during the test interval. This research focuses on CFD Fluent simulations to show the broadcasts created from synthetic jets.

Table 2. 80 Hz Sine Turbulent Vorticity and Intensity

Table 3. 100 Hz of Turbulent Sine Vorticity and Intensity

Table 2. shows the vortex flow and turbulent intensity created on synthetic jets using sine waves with a frequency of 80 Hz. Interval of the first minute, vorticity occurs around the orifice with turbulent intensity created around the membrane and on both sides of the environment on a flat plate. This is because at 60 seconds, the membrane undergoes a suction phase. Whereas the blowing phase was recorded to occur at 240 seconds with a vortex flow that occurred around the orifice, the membrane to reach a heat source. The value for the largest turbulent intensity for sine 80 Hz shows the number 5.45e+00 at 300 seconds which is seen at the end of the right side environment of the heat source.

Table 3. shows the vorticity and intensity of the turbulent created by the jet architect using a sine wave with a frequency of 100 Hz. Interval of one minute, vorticity formed around the cavity with a little out of the orifice with a value of 1.53e-02. As for the turbulent intensity, it shows the number 3.65e+00 formed at the ends of the environment. The greatest vorticity reaching 2.37e-02 occurs at 240 seconds, and for the largest turbulent intensity reaches 8.60e+00 at 300 seconds.

Table 4. shows the vorticity and intensity of the turbulent created from synthetic jets using waves with a sine frequency of 120 Hz. The longest flow of vortex that is created occurs at 240 seconds, with the intensity of the turbulent formed occurring in the area around the membrane and at the tip of the left side of the heat source. The greatest value of turbulent intensity reaches 5.99e+00 for the 120th second. However, the pattern created tends to form at the ends of the synthetic jet environment.
Table 4. 120 Hz of Turbulent Sine Vorticity and Intensity

| Status | Square | Turbulent Intensity |
|--------|--------|---------------------|
| 80     | 100    | 120                 |
| 80     | 100    | 120                 |
| 80     | 100    | 120                 |
| 80     | 100    | 120                 |

Table 5. 80 Hz Vorticity and Turbulent Square Intensity

| Status | Square | Turbulent Intensity |
|--------|--------|---------------------|
| 80     | 100    | 120                 |
| 80     | 100    | 120                 |
| 80     | 100    | 120                 |
| 80     | 100    | 120                 |

Table 5. shows the vorticity and turbulent intensity created by synthetic jets using square waves with a frequency of 80 Hz. The air flow created resembles a pair of vortex rings with considerable turbulence intensity formed almost all over the surface of synthetic jets, both in cavity and on the passage of air coming out of the orifice. Interval of the first 60 seconds, the membrane undergoes a suction phase with the greatest turbulence intensity reaching 2.27e+02 around the membrane.

4.6. Comparison of Electric Power

The use of fans as a cooling system in the form of electronic equipment requires electrical power during operation. This condition has become a benchmark for fans so far as a cooling system. The amount of fan power requirements when operating, creating an innovation of a cooling system that is smaller power requirements. Comparing the level of fan power requirements with synthetic jets, Table 6. below shows the power requirements of each variable.

Table 6. Comparison of electrical power requirements

| Status | Square | Turbulent | Fan |
|--------|--------|-----------|-----|
| 80     | 100    | 120       | 80  |
| 80     | 100    | 120       | 80  |
| 80     | 100    | 120       | 80  |
| 80     | 100    | 120       | 80  |

The use of a fan as a cooling system to cool the heat source to a stable temperature or no increase is 1234 seconds. As for synthetic jets with sine wave variations of 80 Hz frequency reaching a stable temperature at 1054 seconds. Thus the magnitude of fan power requirements is ten times greater than the requirements of synthetic jet power. Innovations using synthetic jets as forced convection coolers in electronic devices can be further developed in the future.
Figure 3. Synthetic Jet Power Requirements

Figure 4. shows the electrical power requirements of synthetic jets with wave variations. Sine wave with a frequency of 120 Hz shows the frequency and waves that use the smallest electric power. This is because the 120 Hz frequency in sine waves requires a small voltage and current strength to vibrate in generating air around the speaker membrane. However, for the final temperature, the frequency of 120 Hz sine wave itself is not lower than the frequency of 80 and 100 Hz sine wave itself.

5. Conclusion
Based on the discussion that has been outlined, the following conclusions can be determined.
1. Characteristics of Sine Waves show a trend of temperature reduction occurring for 600 seconds first with a final temperature of 27°C at a frequency of 80 Hz. As for the large value of the temperature reduction reached 6.64°C at a frequency of 100 Hz.
2. The characteristics of Square Waves show a trend of temperature decrease during the first 600 seconds which then experiences a temperature stability after 1200 seconds, with the final temperature reaching 27.4°C. As for the large value of the temperature reduction reached 6.64°C at a frequency of 80 Hz.
3. Characteristics of Triangular Waves show a trend of temperature reduction during the first 600 seconds with a final temperature reaching 27°C at a frequency of 80 Hz. As for the large drop in temperature reached 6.82°C at a frequency of 120 Hz.
4. The optimum frequency obtained based on testing is 80 Hz. Because the 80 Hz frequency generates air flow at optimum speed, neither too fast nor too slow in the suction and blowing phases. If in this phase the speed is not optimum (too slow or too fast), it is possible to increase the heat during the testing process.
5. The type of flow created by synthetic jets is vortex (vortex) air flow with turbulent flow type that can be shown by the results of CFD Fluent simulations by displaying vorticity contours and turbulence intensity contours.
6. Comparison of fan power requirements reaches ten times the power requirements of synthetic jets. Thus synthetic jets are superior to fans as electronic equipment cooling systems in terms of power requirements.

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