Comparing the Influence of Synthetic jets on Cooling the Angled Plates Versus Vertical and Horizontal Plates

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Abstract

Synthetic jets besides being used in heat transfer, have also been used to control turbulence and flow separation. In the previous decade, research on the applications of a synthetic jet has indicated that by using these types of jets, flow separation can be reduced or even stopped altogether. In addition, these jets have been utilized in unmanned aerial vehicles (UAVs) (to control separation on airfoils) and flight control. In this study, the jet is located perpendicular to the flat plane with fixed heat flux and the effect of some geometric parameters including the ratio of the distance between the jet and the impact plane to the nozzle width, the ratio of the impact plane length to the jet nozzle width, the ratio of synthetic jet width to width of the nozzle, the ratio of the hole height to the nozzle width, the angle of the impact plate as well as the diaphragm characteristics such as amplitude and frequency of the jet diaphragm in heat transfer were evaluated numerically by using OpenFOAM open-source software. The findings indicate that synthetic jets have very weak efficiency for cooling vertical panels. However, they are extremely effective on angled plates. Synthetic jets have more influence on angled planes than horizontal planes.

1. Introduction

Synthetic jets in addition to their usage in heat transfer, have also been used to control turbulence and current separation. In the previous decade, studies on the applications of synthetic jets have shown that by using these types of jets, current separation can be reduced or even stopped altogether. In addition, the use of these jets has been noticed in unmanned aerial vehicles (UAVs) (to control separation on airfoils) and flight control [1].

Zero-Net Mass-Flux (ZNMF) actuators also have applications in propulsion. The jet used by mermaids, squid and octopus, and others is conceptually very similar to the used mechanism to create synthetic jets. These animals consecutively, by swallowing and expelling water jets, make a pure stream. Similar to synthetic jet applicants (SJAs), which add both energy and momentum to the stream despite zero net mass flux to energize the boundary layer current in air-shaped devices and flow control applications.

Jet flow is a type of fluid flow in which through a nozzle a fluid is injected into the ambient fluid [2]. Synthetic jets, as explained in the introduction, have a chamber, a piston or vibrating membrane, and one or more nozzles. One of the fluid characteristics of these jets is the production of vortex rings at the nozzle or orifice output. During the blowing phase, the outlet fluid separates at the edge of the nozzle to form a vortex pair or vortex ring. In the suction stage, the fluid is pulled from the environment into the chamber, but the eddy rings are far enough away from the nozzle and are not relatively influenced. Then new vortex ring is produced, and thus the cycle continues with the production of a chain of vortex rings. In the fast-growing electronics industry, effective cooling systems are necessary. However, one of the major challenges for engineers is the effective use of air to transfer heat in a confined space to electronic equipment. Considering the high-end processing and downsizing of electronic equipment, proper cooling of the components is

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important to ensure their proper operation [3]. Heat wells, fans, and heat pipes are commonly used to cool electronic components. A synthetic jet is comparatively a new option with the potential to cool electronic components effectively. The lack of need for an external fluid source makes the use of synthetic jets very attractive for many applications in heat transfer. Based on previous research, the first attempts to use synthetic jets in heat transfer were made in early 1980 by Gottmark et al.

Mangesh et al. [4] experimentally studied the heat transfer of a synthetic jet with several outlets. In this research, the variables of synthetic jet excitation frequency, the radius of rotation of synthetic jet, axial distance from the fin were studied. The maximum heat transfer coefficient has increased by 12% compared to one hole in the case of multiple holes. The radius of the pitch circle has very little effect on the heat resistance of the heat well. The central hole in the arrangement of several holes plays a vital role in increasing heat transfer. Many research indicate that the heat transfer coefficient raises by increasing the Reynolds number on the vertical plane [5]. The ratio of the nozzle size to the Nusselt number plate is not only a function of the Reynolds number but also depends on the length of the nozzle. In large dimensionless ratios, the mean to the Nusselt number plate does not change a lot. The results indicated that compared to permanent jet heat transfer with synthetic jet increased by 40%.

Tajfar et al. [6] using numerical analysis, investigated the influence of synthetic jets to control separation. In the current research, they concluded that despite the presence of synthetic jet, the drag has decreased and the separation was delayed. Numerical analysis was performed for aerodynamic evaluation of NACA 23012 airfoil with synthetic jet.

Lu et al. [7] simulated the flow field of a synthetic jet with the LUO-XIA model numerically. The results represented that the zone with lower pressure has an important role in the interaction of the two jets. The dual synthetic jet operator generates two pairs of vortices with reverse rotation. The pressure in the area includes a pair of major vortices lower than in other flow regions. In the downstream stream near the nozzles, the vortex pairs of the two jets are strong and attract the surrounding fluid, which interacts with each other, and the flow field is complex. In dual synthetic jets, there is a phenomenon of self-support between the jets because of the different pressures between adjacent nozzles.

Jane et al. [8] conducted numerical simulations to analyze the influence of different chamber parameters and orifice/chamber shapes on the flow of the synthetic jet. A synthetic jet with a circular orifice was simulated supposing axial symmetric behavior and the findings were validated with accessible experimental and numerical data. Movable diaphragms were modeled with velocity condition, movable piston condition, and also movable wall boundary condition. The findings obtained from using these methods were compared and it was concluded that the boundary condition of the movable wall allows the most real representative of the diaphragm motion. Simulation results showed that synthetic jets are more influenced by changes in the geometric parameters of the orifice than the chamber. The most obvious parameters were the radius of the orifice and the chamber and the length of the orifice. Two new parameters of volume efficiency and Orifis productivity coefficient were introduced; different types of apertures can be compared with the help of these parameters. The findings of the current study are considerable because they provide fundamental design guidelines for the chamber and orifice and can be used to optimize the shape.

Omidreza Ghaffari et al. [9] experimentally analyzed the heat transfer of an impact miniature synthetic jet. Heat transfer findings indicated that the maximum cooling performance occurs in the distance from the jet to the plate $H/D_h \leq 10$, which is related to the flow consisting of coherent vortex structures. There is a drop in heat transfer intensity for distances closer to the jet, such as $H/D_h = 2$, which is because of the incomplete growth of the vortices, followed by the re-drawing of hot air back from the impact plane into the jet stream. Also, some hot air is sucked back into the jet during the suction phase of the synthetic jet. For a constant Reynolds number, cooling at high Stokes numbers improved, but was accompanied by a decrease in performance.

Lu et al. [7] determined an innovative cooling technology according to the synthetic jet vector and then experimentally studied the characteristics of the flow field and heat transfer. The deflection angle of the DSJ velocity vector can be changed bilaterally and linearly with adjustable slider motion. This new feature greatly expands the level of effective heat transfer compared to a conventional DSJ. The ability to sweep the stream can prevent the fringe areas from working continuously at high temperatures. This cooling technology is expected to have significant practical implications for the cooling of confined spaces and the vast electronics industry. Meanwhile, they developed a prediction model of the heat transfer influence area based on the DSJ vector angle. The predicted findings were in good agreement with the experimental results in the vertical collision zone and the cross-flow zone. This can provide a guide to an appropriate arrangement of electrical equipment to improve heat transfer.

A semi-analytical finite strip method is successfully applied to the thermal, mechanical, thermo-mechanical buckling and thermal post-buckling of SMAHC plates by Rostamijavani et al. (2021). The first-order shear deformation theory, as well as the von Karman strain–displacement relation, has been used, and the convergence investigations are carried out with respect to the number of implemented strips for both buckling and post-buckling analysis. By obtaining some numerical results and comparing them with those available in the literature, the capability of semi-analytical FSM is
approved. The effects of various terms such as volume fraction, pre-strain values, boundary conditions and the amplitude the imperfection on the thermal post-buckling of SMAHC plates have been studied. It is noted that the comparatively small number of degrees of freedom has been used in the FSM in comparison with other finite element analysis [10].

2. Methods and materials

In this research, the influence of some geometric parameters such as plate length, plate angle, plate-to-jet distance, cavity diameter, and cavity height, and aperture characters such as amplitude and frequency of the jet diaphragm on the Nusselt number numerically using text software The OpenFOAM is analyzed.

![Figure 1. Schema of the research problem](image)

The method of cooling the contact plate is this way that by vibrating the diaphragm, the current is periodically (suction and blowing) injected from the nozzle into the environment and hits the hot plate. After hitting the hot plate, this current is transformed from both sides of the plate to the outside of the area between the jet and the plate, and this process is being repeated. Figure 1 shows the research schema. It should be mentioned that the flow simulation is two-dimensional, and the cross-section of the jet is rectangular.

3. Turbulence Model $SST \ k - \omega$

It is well known that the occurrence of near-wall turbulence leads to a considerable increase in the wall-normal momentum diffusion. This results in a dramatic increase in the frictional drag exerted on the wall as compared to the laminar flow. Thus, the attempt to reduce frictional drag in turbulent wall flows is of practical importance [11]. The Shear Stress Transport model of Menter (SST) changes between $k - \omega$ and $k - \epsilon$ models. The SST transfer equations for $k$ and $\omega$ are defined as follow:

- **Transitional Equation $k$**

$$\frac{\partial (\bar{\rho}k)}{\partial t} + \frac{\partial (\bar{\rho} \bar{u}_j k)}{\partial x_j} = P_k - \beta^* \bar{\rho} \omega k + \frac{\partial}{\partial x_j} \left( \mu + \sigma_k \mu_t \right) \frac{\partial k}{\partial x_j}$$

(1)

- **Transitional Equation**

$$\frac{\partial (\bar{\rho} \omega)}{\partial t} + \frac{\partial (\bar{\rho} \bar{u}_j \omega)}{\partial x_j} = \frac{\gamma \bar{\rho}}{\mu_t} P_k - \beta \bar{\rho} \omega^2 + \frac{\partial}{\partial x_j} \left( \mu + \sigma_\omega \mu_t \right) \frac{\partial \omega}{\partial x_j} + 2(1 - F_1) \frac{\bar{\rho} \sigma_\omega}{\omega} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j}$$

(2)

- **Related Equations**

$$P_k = \min \left( \bar{\rho} \frac{\partial \bar{u}_j}{\partial x_j}, 10 \beta^* \bar{\rho} \omega k \right)$$

(3)
\[
\mu_t = \frac{\bar{\rho} \alpha k}{\max(\alpha_1 \omega, SF_2)} \quad (4)
\]

\[
S = \sqrt{2S_1 S_1} \quad (5)
\]

The last wording in the equation \( \omega \) is derived from the transformation of the equation of the model \( \epsilon \) in the form of sentences \( \omega \). The coefficients of this model \( \phi(\sigma_{k}, \sigma_{\omega}, \beta, \alpha) \) are explained as follows [12]:

\[ \phi = F_1 \phi_1 + (1 - F_1) \phi_2 \quad (6) \]

So, the above relationship changes between the constant values of the \( k - \omega \) model with subtitle 1, and the \( k - \epsilon \) constants with subtitle 2. Other functions of this model are as follow:

\[ F_1 = \tanh(\text{arg}^1) \quad (7) \]

\[ \text{arg}^1 = \min \left[ \max \left( \sqrt{\frac{\gamma}{\beta^* \omega d}, \frac{500 \mu}{\bar{\rho} \beta^* d^2}} \right) \cdot \frac{4 \bar{\rho} \sigma_{\omega} k}{C D_{k \omega d^2}} \right] \quad (8) \]

\[ C D_{k \omega} = \max \left( \frac{2 \bar{\rho} \sigma_{\omega}}{\omega \partial^2 \omega}, 10^{-10} \right) \quad (9) \]

\[ F_2 = \tanh(\text{arg}^2) \quad (10) \]

\[ \text{arg}^2 = \max \left( \frac{\sqrt{\gamma}{\beta^* \omega d}, \frac{500 \mu}{\bar{\rho} \beta^* d^2}} \right) \quad (11) \]

In the above relations \( d \) is the distance from the points of the field to the nearest wall. The model constants are given in table 1 below:

| \( \alpha_1 \) | \( \beta^* \) |
|---|---|
| 0.31 | 0.09 |

| \( \sigma_{k1} \) | \( \sigma_{\omega1} \) | \( \beta_1 \) | \( \gamma_1 \) |
|---|---|---|---|
| 0.85 | 0.5 | 0.075 | 5/9 |

| \( \sigma_{k2} \) | \( \sigma_{\omega2} \) | \( \beta_2 \) | \( \gamma_2 \) |
|---|---|---|---|
| 1.0 | 0.856 | 0.0828 | 0.44 |

**Table 1. SST model coefficients**

![Image](image-url)

**Figure 2. Schema of the current research**
4. Geometric characteristics of the field

Based on the figure (2) the schematic of the synthetic jet and its external field along with the geometric parameters used in this research are shown. The investigated parameters in the current study will be geometric changes and changes related to the characteristic of the jet aperture.

| Mark | Amount (millimeter) |
|------|---------------------|
| $d_c$ | 46 |
| $h_c$ | 5 |
| $d_o$ | 2 |
| $h_o$ | 2 |
| $H$ | 20 |
| $H$ | 30 |

| Parameter | Scope of Changes |
|-----------|------------------|
| $d_c/d_o$ | 30-25-23-20-15-10 |
| $h_c/d_o$ | 3.5-3-2.5-2-1.5-1 |
| $H/d_o$ | 25-20-15-10-8-6.5-5 |
| $L/d_o$ | 30-25-20-15-10-5 |
| Plate angle | 90-60-45-30-0 |
| $f^* = f/f_b$ | 5-4-2.5-1-0.5 |
| $A_m^* = A_m/A_{mb}$ | 2-1.75-1.5-1.25-1 |

The investigated dimension of the study and the base sizes are indicated in table 2.

It should be mentioned that the dimensions in Table 3 are in millimeters and frequency in hertz. In this research, changes in hole diameter and height, distance and dimensions, heater plate angle, frequency, and amplitude of oscillation have been analyzed. The extent of these changes is represented dimensionless in the table 3.

4.1. Boundary conditions

There is a boundary condition for the plate which is a constant heat rate of 1000 watts per square meter and the initial temperature of the plate is 300 Kelvin. The field output is also in the form of a pressure outlet. The border condition of the wall is also without slip. But the most challenging border condition is the velocity input in the synthetic jet. For different types of synthetic jets, researchers have chosen different approaches, which three types are mentioned here:

- A wall-normal velocity boundary condition with the supposed profile at the aperture or nozzle output
- Movable piston border condition
- Vibration diaphragm border condition

In this research, the input border velocity condition with a specific profile in the diaphragm is used. The advantage of this method comparing to other methods is the high speed of problem-solving along with its relatively good accuracy, which is the most proper method of problem-solving in this study because of the high number of assumed parameters and accessible computer facilities. The output is considered at stable atmospheric pressure and for the most important part of the simulation, the aperture, as noted before, the input velocity limit condition is used. To determine the appropriate velocity profile to simulate aperture motion, a model called the $X - L$ model is applied to the software with a code. $X - L$ model is as below:
\[
\begin{align*}
\begin{cases}
u_x &= 2\pi f A_m \left(1 - \left(\frac{r}{r_c}\right)^2\right) \sin(2\pi f t + \varphi_0) \\
u_y &= v = 0
\end{cases}
\end{align*}
\]

Where \( r \) is the distance from the center of the aperture, \( r_c = 23 \text{mm} \) is the radius of the aperture and \( \varphi_0 = 0 \) is the initial phase of the aperture. In addition, the air is used as the operating fluid in this simulation. The dimensionless time and phase of the synthetic jet aperture are defined as below [13]:

\[
t^* = \frac{t - nT}{T}, \quad n = \left\lfloor \frac{t}{T} \right\rfloor \text{(correct part)}, \quad T = \frac{1}{f}
\]

\[
\varphi^* = t^* \times 360^\circ
\]

5. Results

5.1. Velocity, pressure, and temperature counters

Dimensions and basic working conditions are discussed in the previous chapter. In this section, the fields of temperature, pressure, and velocity in the zero-degree phase are shown. Figure 4, 5 and 6 shows the temperature field in the zero degrees phase.

Figure 3. Temperature field (K) base state at time \( t^* = 0 \) (zero diaphragm phase)

Figure 4. Instantaneous collision plate temperature (\( t^* = 0 \)) for different values of \( H/d_c \)
As indicated in the figure, the effect of the synthetic jet on the edges of the collision plate is insignificant. This is also particularly shown in figure 1. This is very important in practical applications because electronic components have a certain tolerable temperature range. In baseline mode, after 4 seconds, the maximum temperature of the collision plate (with a power of 1000 watts per square meter) has reached 365 Kelvin.

5.2. The effect of changing geometricp

5.2.1. Ratio of jet distance to impact plane to nozzle width \( (H/d_o) \)

In this section, the effect of the ratio of the jet distance to the impact plane to the nozzle width \( (H/d_o) \) on the Nusselt number is studied. In addition, a temperature diagram of the collision plate for different values \( (H/d_o) \) is also represented.

Figure 4 shows the temperature of the collision plate in terms of the dimensionless variable. As expected, in the central regions the temperature of the impact plate is lower and the heat transfer is more intense. For \( H/d < 5 \) the heat transfer ratio has decreased while for \( H/d > 6.5 \) we see an increase in heat transfer rate. Another important point is that with increasing this ratio (within the research area), the temperature profile has become more uniform, which is a desirable point.

5.2.2. Projection ratio of nozzle width to nozzle width \( (L/d_o) \)

In this section, the influence of the ratio of the impact plate length to the nozzle width \( (L/d_o) \) on the Nusselt number is investigated. In addition, a temperature diagram of the collision plate for different values \( (L/d_o) \) is also determined.
Figure 7. Temperature field (K) base state at time $t^* = 0$ (zero diaphragm phase) for a ratio of 25

Based on figure 5 with increasing the length of the hot plate, the ability of the synthetic jet to cool the outer areas is greatly reduced. In general, it can be mentioned that a synthetic jet with fixed specifications can cool a limited plate. Interestingly, the synthetic jet was able to keep the temperature of the plate with the ratio of the length of the plate to the width of the nozzle 5 relatively uniform, which prevents the creation of thermal stresses due to the temperature gradient on the plate. As the length of the plate increases, the temperature gradient along with the plate increases, and the difference between the maximum and minimum temperature along with the collision plate increases. According to figure 3, with increasing the length of the impact plate for a synthetic jet with fixed characteristics, the temperature range increases and causes thermal stresses in the considered part.

Based on figure 4 it is clear by increasing the length to diameter ratio of the nozzle temperature at the side points of the plate has increased sharply. Generally, it can be deduced from the findings of this legal section for designing a cooling system. Each synthetic jet in stable operating conditions can cool the plate to a length of 5 times the diameter of its nozzle. By increasing this ratio for optimal cooling, the number of synthetic jets should be increased.

5.2.3. The effect of the ratio of the width of the cavity to the width of the aperture $D/d_o$

In this part, the influence of the width of the synthetic jet cavity on the cooling of the collision plane is analyzed and local temperature and Nusselt number diagrams are indicated for different modes.

Figure 8. Instantaneous collision plate temperature in Second($t^* = 0$) for different values $D/d_o$
The diameter of the synthetic jet cavity is a very important variable in cooling. The diameter of the synthetic jet cavity is directly related to the speed of the synthetic jet. By decreasing the diameter of the cavity, an appropriate current does not hit the plate and causes a sharp rise in temperature in the middle of the impact plate. This trend is evident for the ratio of diameters 10 and 15. However, by increasing this ratio, the plate temperature decreases, and a uniform profile of temperature is created along with the collision plate. In general, increasing the diameter of the cavity has a significant effect on cooling, but on the other hand causes problems such as increased power required for vibration, construction costs, and problems caused by the space needed for installation.

Figure 9 indicates the local Nusselt number for the length of the collision plane. The Nusselt number has increased with the increment of the pore to diameter ratio. Generally, the ratio of hole width to groove width in synthetic jets should be more than 20.
Based on figure 10 the average Nusselt number raises terms of the ratio of the width of the cavity to the width of the orifice. So, by increasing it, the heat transfer rate can be raised. Figure 6 also indicates that by increasing this ratio, the temperature profile has become more uniform.

5.2.4. The effect of the ratio of cavity height to orifice width (\(h_c/d_c\))

In this section, the influence of the height of the synthetic jet cavity on the cooling quality is studied and the findings are shown in the diagrams. Based on figure 5, it can be noticed that the depth of the hole does not have a considerable effect on the cooling of the plate. The optimal state for this variable is the ratio of 2, which causes the best cooling.

![Figure 12. Instantaneous collision plate temperature (\(t^* = 0\)) for different values of \(h_c/d_o\)](image)

![Figure 13. Local Nusselt number of collision plane at the moment (\(t^* = 0\)) for different values of \(h_c/d_o\)](image)

5.2.5. The influence of impact plate angle

In this section, the effect of the angle of the impact plate on its cooling is analyzed. In this section, the research results for 0, 30, 45, 60, and 90 degrees are indicated. The distance of the collision plane from the jet remains stable and the plane rotates around its central point.
Based on figure 14, synthetic jets have a very weak performance for the vertical plane. The temperature on the vertical plate is much more than the rest of the plates. An angle of 30 degrees does the best cooling. Generally, the performance of the synthetic jet on the plates 30, 45, and 60 degrees is optimal and the temperature curve is relatively uniform.
According to the diagrams above, the performance of the synthetic jet is much more influential for diagonal planes than for vertical planes. The considerable point is that at angles of 30, 45, 60 degrees the temperature curve of the plate is a uniform collision and the temperature jump is prevented in areas far from the center of the plate. This prevents temperature gradients from forming on the cooling plate and cooling is performed more uniformly. The performance of the synthetic jet in angled planes was better than the horizontal plane.

6. Conclusions

The synthetic jet can cool the plate with limited dimensions in stable situations. By increasing the ratio of the length of the plate to the width of the aperture, the temperature on both sides of the plate raises and leads to thermal stresses. This problem can be solved by increasing the number of synthetic jets. By reducing this ratio, the temperature dispersion becomes uniform. Determining the diameter of a synthetic jet is very effective in its performance. If this diameter is not enough, cooling will not be done appropriately. As the diameter of the cavity increases, the temperature of the impact plate decreases, and the temperature curve becomes more uniform. Synthetic jets have very poor efficiencies for cooling vertical panels. However, it can be very influential on angled plates. Synthetic jets have a greater effect on angled planes than horizontal planes.

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