ENHANCING HEAT TRANSFER IN CHANNEL FLOW USING SYNTHETIC JETS

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ABSTRACT

Synthetic jet's effectiveness in flow control, fluid mixing enhancement, and cooling has been established. The current study aims to examine the improvement of fluid blending and heat dissipation rate of two water inlets with varying temperatures in a channel that is disturbed by a synthetic jet at different excitation frequencies. The simulation analysis predicts the temperature distributions and the fully develop the velocity profile along symmetrical plane of the channel with interference of synthetic jet using establish CFD software. The RNG k- ε turbulence model was employed to compute the turbulent flow produced by the synthetic jet. A moving mesh approach was employed to replicate the movement of a synthetic jet diaphragm. The results indicate that the fluid flow behavior in the channel disrupted by the synthetic jet flow. Hence, indicating to an enhance in both the fluid flow velocity and the heat transfer rate. A higher frequency of the actuator enhances fluid mixing and reduces the channel distance required to achieve temperature equilibrium within the channel in comparison to a lower frequency of the actuator.

Keywords: *CFD, Channel flow, Fluid mixing, Synthetic jet, Heat transfer,*

1.0 INTRODUCTION

A type of fluid flow that is formed by an alternating ejection and suction of its surrounding fluid via an orifice due to a motion of an actuator inside the cavity known as a synthetic jet. The actuators to create a motion inside the cavity used in recent studies include the piezoelectric diaphragm [1], the electromagnetic diaphragm [2] and the reciprocating piston [3]. The ejection phase of the synthetic jet cycle produces a train of circulation vortices that move out from the orifice and produce a fluid flow [4]. The flow field in the near zone of the cavity exhibits continuous vortex circulation, whereas the flow field in the far zone behaves as a continuous jet [5]. The synthetic jets research has primarily focused on fluid mixing [6, 7], the performance of heat transfer [8] and flow control [9, 10].

The behaviors of synthetic jets have been applied in numerous research to improve liquid mixing in inline flow systems. Xian and Zhong studied to investigate the synthetic jet orientations using PLIF and PIV methods. Their study encompassed a range of synthetic jet configurations, including lateral synthetic jet [11], staggered lateral synthetic jet [12] and multiple synthetic jet pairs [13, 14]. They found that the effectiveness of these synthetic jet pairs in augmenting mixing stemmed from the generation of a significantly large interfacial area. In a related, L Wang et al. [6] experimentally study the mixing behavior of the oval and the rectangular orifice synthetic jet under a low Reynolds number. Their findings illuminated that the rectangular orifice configuration generating more pronounced streamwise eddies and consequently achieving superior mixing performance. Most of the studies focused on enhancing mixing through synthetic jets have heavily on experimental investigation, while numerical simulations have been comparatively less explored. This gap emphasizes the potential for further exploration and integration of numerical simulation methodologies in understanding and optimizing the efficiency of synthetic jets to enhance fluid mixing

In recent years, several numerical simulations have investigated the flow patterns and heat dissipation capabilities of systems that combine synthetic jets with microchannels. The possibility of improving heat transfer through surface heat convection in a channel of moving air by the creation of a synthetic jet is investigated by Kim et al. [15]. The enhanced heat transfer was revealed to be significantly influenced by the vortex packets' direct contact or sweeping with the heated surface. They were found to be high-momentum regions with intense stream-wise whirling motions. Qiu et al.[16] study the effect of a synthetic jet on heat transport in a microchannel using numerical methods. The research results indicated that boundary layer’s thickness could be reduce at the impingement zone. This makes it possible for the vortex to convey fluid with a lower temperature from the middle of the channel to the surface that is heated. Lee et al. [17] examine the microchannel fluid flow interactions with the cross-flow synthetic jet for the purpose of cooling a microprocessor. They found that higher jet velocities considerably altered the shape of the flow within the channel as well as the infiltration rates at the intake and outlet. This was a result of the increased membrane oscillation amplitude.

Based on the literature, there are several turbulent models used to study the flow fields and heat transfer of the synthetic jet. The RNG (Renormalization Group) k-ε turbulence model [18], the standard k- ε turbulence model [19–21], and lattice Boltzmann method [22], SST (Shear Stress Transport) k-ω turbulent model[23–25]are the most frequently used to predict the flow of synthetic jets. Recently, the flow and heat transfer properties of synthetic jet flow impinge on flow in the channel were predicted using the RNG k- ε turbulence model[15].

Several studies have been done to improve the heat dissipation in channel flow, however, it is still unclear how two streams in a channel with a synthetic jet will flow and transmit the heat. In this paper, the rate of heat transfer improvement because of the fluid mixing enhancement in the channel by a synthetic jet was studied numerically.

2.0 METHODOLOGY

2.1 Numerical Method

CFD (Computational Fluid Dynamics) is a powerful and adaptable engineering technique utilized for the analysis and simulation of fluid flows in many applications. It covers from aerodynamics in aviation and automotive design to heat transfer in industrial processes and environmental modelling. The CFD combines principles of numerical analysis, fluid mechanics, and computer science to predict complicated fluid characteristics with acceptable precision. Figure 1 illustrates the sequence of the numerical simulation methodology employed in this investigation. In CFD, the sequence of three major processes is pre-processing, processing (solver), and post-processing respectively.

In the pre-processing stage, the shape of the computational domain was drawn using CAD software. The geometry was assumed to be symmetrical in the vertical plane as shown in Figure 2. The dimensions of the primary channel are 30 x 20 x 200 mm. The synthetic jet actuator is situate on the upper wall of the channel and 30 mm from inlet 1. The orifice shape is cuboid with the dimensions of 5 mm for width, length and height. There are two openings at the intake of the channel. The inlet 1 is for cold fluid with a dimension of 12 x 20 mm. The inlet 2 is for hot fluid with a dimension of 16 x 20 mm. The computational domain was meshed into smaller elements. The volume of the synthetic jet cavity was meshed using an unstructured tetrahedral mesh due to intricate geometry of the actuator profile. Tetrahedral elements are suitable for circular curvature and asymmetrical systems. The structural hexahedral mesh was used for the orifice and the main channel due to the mesh captures the flat surface with perfect accuracy. The computational time could be kept lower because the total element count was lower compared to tetrahedral mesh. The meshing techniques were crucial in maintaining the accuracy and dependability of numerical simulation.

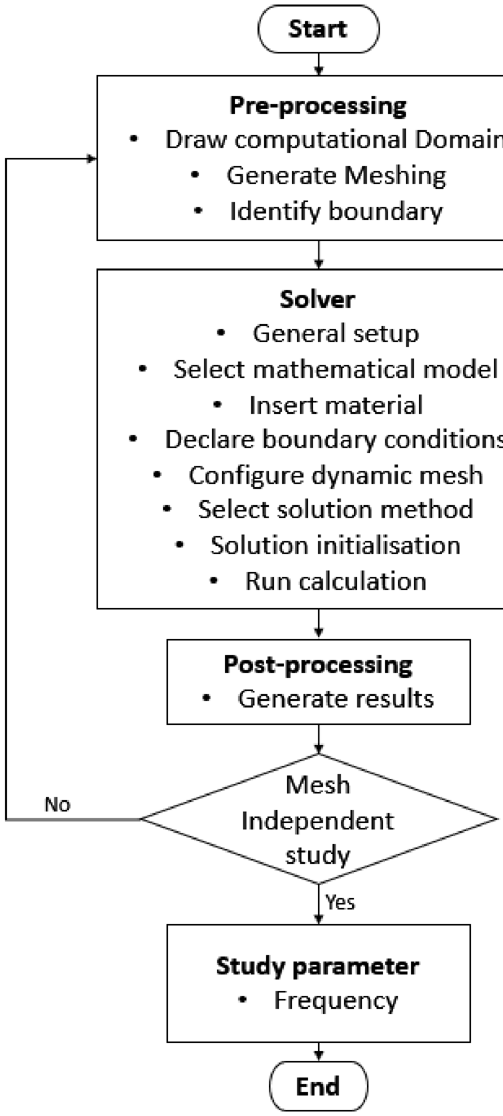


Figure 1: The methodology flow chart

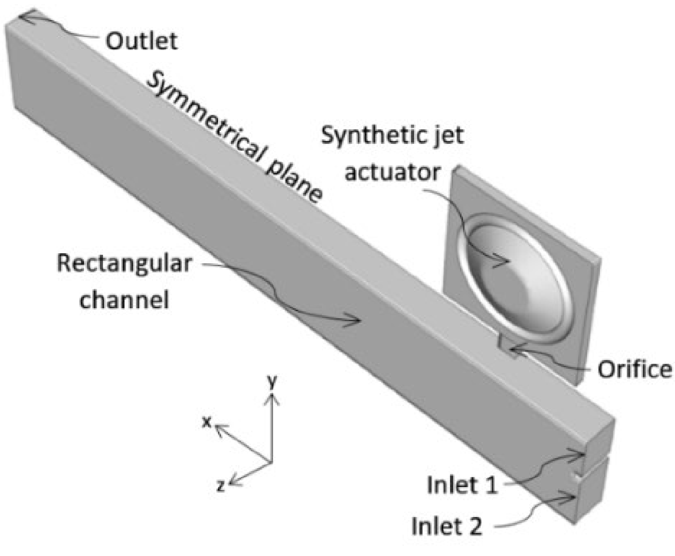


Figure 2: The computational domain of the current study.

In the solver stage, the selection of the mathematical model and the materials of the computational domain was done. The simulated flows in three dimensions are assumed to be turbulent, incompressible, and unsteady. The latest research demonstrated that the RNG k-ε model accurately depicted the streamlined structures and vortex formation observed in channel flow [15]. In this study, the turbulent viscosity produces when a synthetic jet activate is replicated using RNG k-ε turbulent model. Next, define the model's boundary conditions. All walls are configured as no-slip condition except a symmetrical plane. The mesh motion method is used to mesh the boundary of the actuator. This technique allowed the mesh to deform according to the motion of the actuator. Equation 1 defines the displacement function of the actuator, where z represents the diaphragm's displacement in the z-direction. The variables f corresponds to the and frequency of the diaphragm while a is the amplitude (peak to peak) and. The t denotes as time. Both inlets have a velocity of 0.5 m/s. The inlet temperatures for water have input of 275 K and 300K at inlets 1 and 2 respectively. The PISO methodology was employed to address the pressure-velocity coupling, while the turbulent dissipation rate, momentum, and turbulent kinetic energy were determined using the second-order upwind spatial discretization method.

$$z(t) = a/2\ sin(2\pi f t) \tag{1}$$

During the post-processing stage, the results that are expected to be produced are made available. The primary aspects of the results that need to be analyzed are the patterns of streamlines and the contours of temperature distributions. This portion of the research is where all the data that are reported in this study were obtained.

The investigation parameters of the synthetic jet configurations are tabulated in Table 1. For Case 1, the actuator of the synthetic jet has been deactivated. In Case 2 and 3, the operating frequencies for the synthetic jet were 10 Hz and 25 Hz respectively with the same amplitude of 1.0 mm.

Table 1: The present study parameters

Case	Amplitude (*a*)	Frequency (*f*)
1	-	-
2	1.0 mm	10 Hz
3	1.0 mm	25 Hz

2.2 Mesh Independent Study

The mesh-independent study had to be accomplished before using the model to perform an analysis of the research parameters. This step is crucial for determining the appropriate number of elements for the computational model to minimize the computational resources required. Figure 3 illustrates the velocity profile obtained at 50 mm away from the inlet for varying mesh elements numbers. The number of elements for Mesh 1 is 67396 elements, Mesh 2 is 144485 elements, Mesh 3 is 520513 elements and Mesh 4 is 716677 elements. The distance (y-axis) refers to the high of the channel. 0 value refer to the datum while 30 mm refer to top of the channel. Table 2 list all of the elements in each mesh configuration. The study reveal that the velocity profile of Mesh 3 closely matched the result from Mesh 4. This indicates that the mesh has achieved its optimal number of elements. As a result, the number 520513 elements are an adequate number of elements for the present investigation.

Table 2: Number of elements

Mesh	No of elements
1	67396
2	144485
3	520513
4	716677

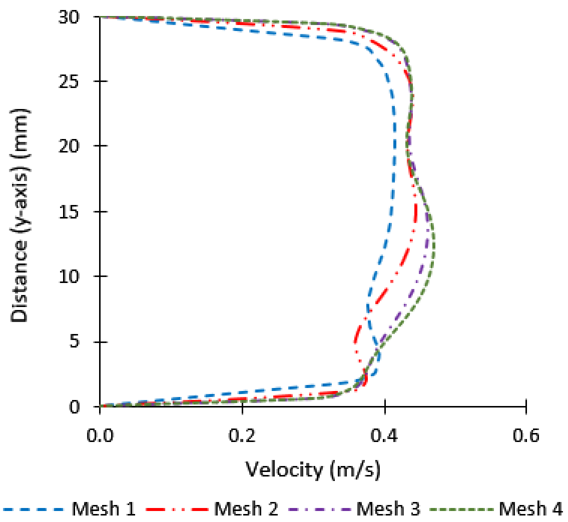
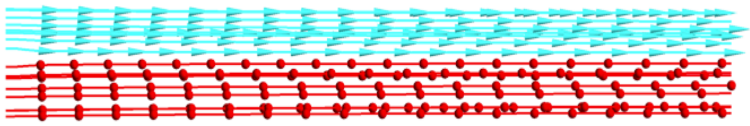


Figure 3: The velocity profile at 50mm away from inlet.

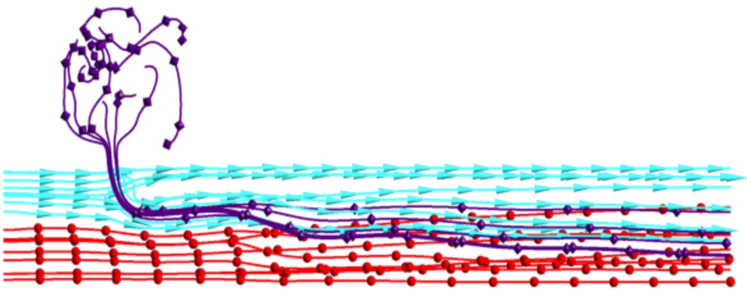
3.0 RESULTS AND DISCUSSION

3.1 The flow field in the channel

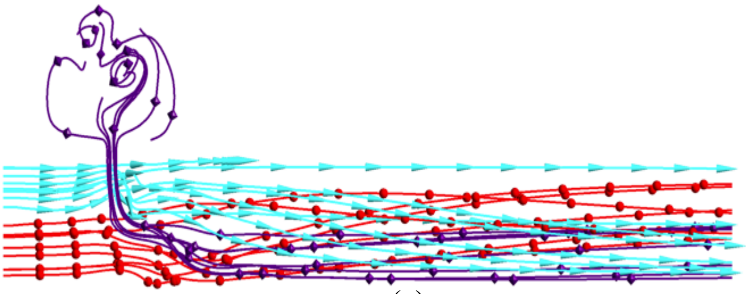
The streamlines pattern in the channel for three different parameters is shown in Figure 4. Figure 4(a) displays the streamline patterns seen at the symmetrical plane in the absence of synthetic jet activation. The flow remains laminar with a uniform streamline across the channel. This indicates a steady-state flow without significant disturbances. Figure 4 (b) shows a clear disturbance in the pattern of streamlines when synthetic jet is configure at amplitude of 1.0 mm and an excitation frequency of 10 Hz. The synthetic jet introduces vorticities into the channel flow, causing mixing and turbulence downstream of the injection point. The presence of these vortices indicates that the synthetic jet is effectively altering the flow characteristics and enhancing mixing within the channel. Figure 4 (c) demonstrates the effect of increasing the actuator frequency to 25 Hz while maintaining the same amplitude. The higher frequency results in more pronounced and frequent vorticities compare to Case 2. The increased turbulence and mixing are evident from the more chaotic streamlined pattern. Thus, suggesting that the higher frequency enhances the capability of the synthetic jet to disrupt stream and promote mixing more effectively. The comparison of these three cases illustrates the significant impact of synthetic jets on flow behavior within a channel. The introduction of synthetic jets, particularly at higher frequencies can substantially alter the flow dynamics by generating vortices and enhancing turbulence. These findings are consistent with recent studies on synthetic jet flow control, which have shown that increasing the frequency of the actuator can enhance its effectiveness in mixing and flow modification [26].



(a)



(b)



(c)

Figure 4: The streamlines pattern in the channel. (a) Case 1, (b) Case 2 and (c) Case 3

The velocity profile observed at different distances along the symmetrical plane of the channel display in Figure 5. The velocity profile at 5 mm from the inlet surface is shown in Figure 5 (a). Based on the depicted picture, the velocity profile can be seen to be remain consistent for all cases. This may be because the synthetic jet does not exert any visible influence on the first stage of the flow. In Figure 5 (b), the velocity profile at a distance of 30 mm is compared, with this particular point being aligned with the centerline of the orifice. The increased speed exhibited in the upper portion of the figure is due to the synthetic jet's ejection phase. The ejection velocity observed in case 3 is about three times greater than the velocity seen in case 2. The synthetic jet imparts supplementary momentum to induce fluid flow within the channel. This assertion is supported by the examination of Figure 5 (c) and Figure 5 (d), which definitely show that case 2 and case 3 have faster velocities that case 1. The case 2 and case 3 velocities exhibited fluctuations of approximately 80 mm before reaching a more stable state towards the end of the channel. In Case 1, the velocity profile remains consistent with the maximum velocity occurring at 0.5 m/s across the channel. Overall, the findings from the numerical simulation indicate that the flow dynamics of two streams in the channel are greatly affected by the synthetic jet flow. More precisely, synthetic jet improves the blending of liquids and results in a rise in the mean velocity. Moreover, the amplification of this phenomenon is observed with the escalation of the excitation frequency of the actuator. This research work has the potential to enhance the comprehension of fluid dynamics and their manipulation techniques in order to grasp the mixing goals. This phenomenon has the potential to generate novel perspectives and advancements within the realm of fluid mechanics.

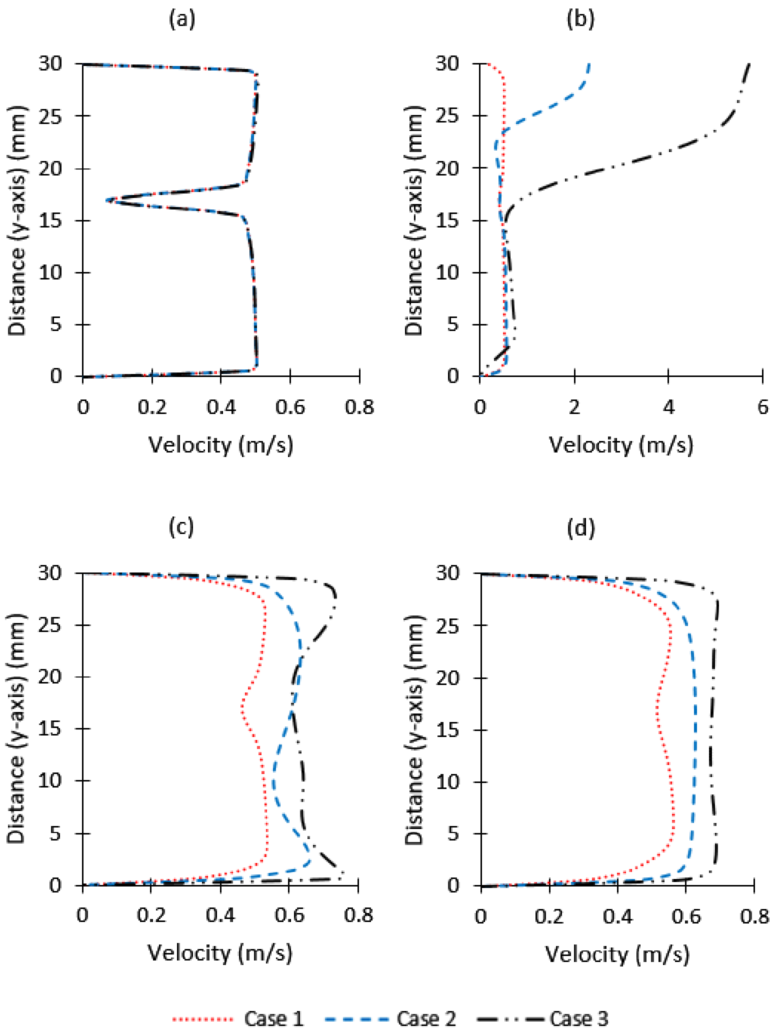


Figure 5: The velocity profile along the channel.

3.2 Heat transfer Characteristics

Figure 6 depicts the contour of temperature distributions within the symmetric plane along the channel. The temperature of the fluid within the channel varies from 275 K to 300 K. The temperature contour for case 1 is depicted in Figure 6 (a). The phenomenon of heat transfer is limited to the interface between the cold and hot streams, and this region gradually spreads throughout the channel with a slight gradient. The majority of the fluid exits the channel with a temperature equivalent to that of the inlet. The temperature distributions exhibited fluctuations, and the rate of heat transfer was found to be superior for case 2, as illustrated in Figure 6 (b). The outcomes prove that the heat transfer rate can be effectively increased using a synthetic jet. The temperature distributions are influenced by the oscillation between the intake and expulsion phases of the synthetic jet cycle, resulting in a wave-like pattern. The effect is more pronounced in Figure 6 (c). This effect arises due to the increased excitation frequency observed in case 3 compared to case 2. The frequency is a measure of the number of cycles that are completed within a given time frame, typically expressed as the number of cycles per second. An increase in frequency results in a greater number of ejection and suction phases taking place within a given period. The implementation of a synthetic jet enhances fluid mixing, thereby causing the rate of heat transfer to rise. A comparative analysis of Figure 6 (b) and Figure 6 (c) shows that the heat transfer rate in instance 3 surpasses that of case 2. The area experiencing the highest temperatures undergoes a significant decrease, while the distribution of equilibrium temperature becomes dominant throughout the channel's topography. Therefore, increasing the excitation frequency leads to a higher heat transfer rate by forced convection.

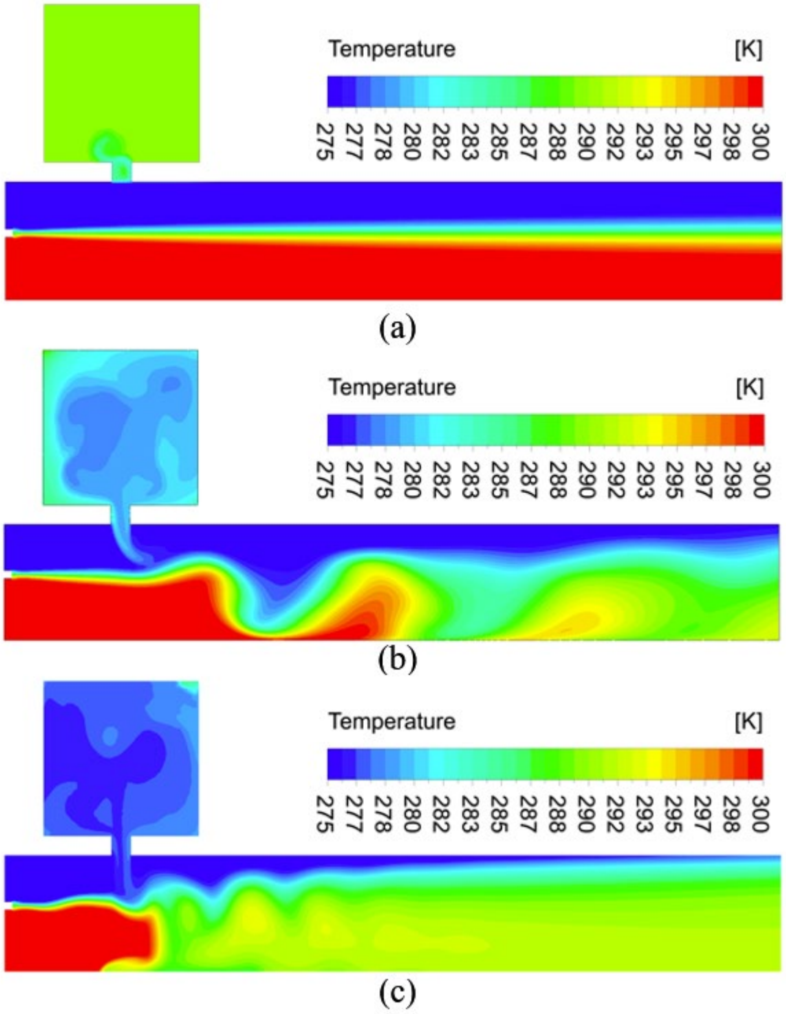


Figure 6: The contour of temperature distributions on the symmetrical plane. (a) Case 1, (b) Case 2 and (c) Case 3

The temperature distribution along the y-axis within the channel is depicted in Figure 7 at a number of different positions along the channel. Generally, the temperature at the top channel is lower than the bottom temperature. Figure 7 (a) displays the temperature profiles at a distance of 5 mm, whereas Figure 7 (b) displays the temperature profiles at a distance of 30 mm. It is possible to draw the conclusion, that none of the evaluated possibilities resulted in a temperature distribution that was significantly different from the others. This behaviour can be related to the absence of impact exerted by the synthetic jet on the heat transmission. Figure 7 (c) and Figure 7 (d) illustrate the changes in temperature distribution that occur between case 3 and 2 and 1 at the distance 80mm and 180mm respectively. The data indicates that case 3 exhibits a greater degree of temperature uniformity and a faster attainment of the mixture's equilibrium temperature compared to case 2 and case 1. The findings of the study can be put to use to improve mixing operations by determining ideal operating conditions with regard to temperature and velocity profiles. This can be done by applying the information gained from the study. This phenomenon has the potential to lead to monetary savings as well as improved operational efficiency.

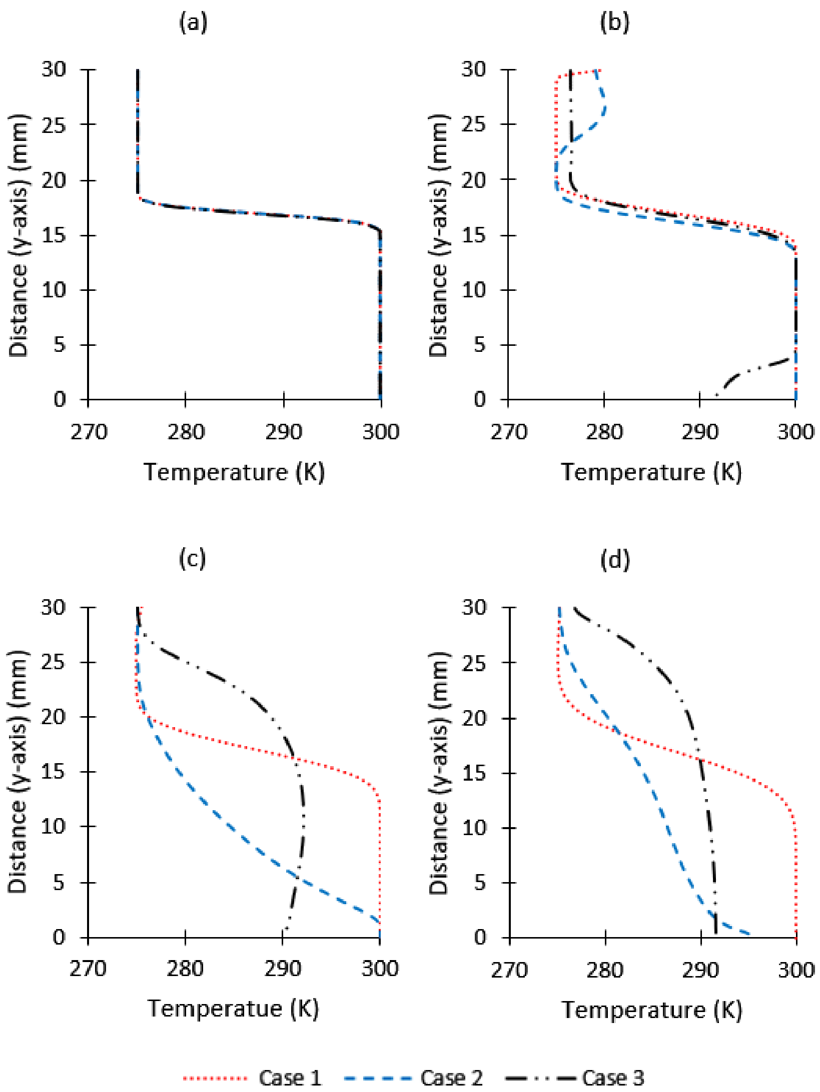


Figure 7: The temperature profile in the channel along the y-axis

4.0 CONCLUSION

The main objective of the investigation was to analyze how a synthetic jet could increase mixing and improve heat transfer between two stream flows within the channel. The conclusion drawn from the research are as follow:

- The synthetic jets have the capability to induce pronounced disturbances within the flow in channel, resulting in a significant enhancement of mixing.
- Increasing the excitation frequency while maintaining the amplitude amplifies the mixing effect and highlighting the importance of this parameter in optimizing fluid dynamics.
- The intensified fluid mixing due to synthetic jets translates into a notable acceleration in the heat transfer equilibrium.

Overall, synthetic jets offer a flexible and effective way to enhance mixing in channels and can be a valuable tool in a variety range of engineering applications.

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