Effect of low-frequency ultrasonic waves on heat transfer of laminar water flow over a heating flat plate

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Abstract
This research investigates the effect of 40, 80, and 120 kHz ultrasound on heat transfer of laminar water flow over a heating flat plate using thin leaf thermocouples in a low turbulence water tunnel. The mainstream velocity was set at 0.127 m/s, corresponding to the local Reynolds number during 65,181 – 148,390 in the test section. The ultrasonic waves were released perpendicular to the mainstream and vertically from the upper wall at the distance of 0.15 m to the heating plate having constant heat flux of 1,040 W/m². The results show that the ultrasound, having frequencies of 40 and 120 kHz provide the maximum Nusselt number up to 15% and 31%, respectively at the most downstream position of the test region. In the meantime, the 80 kHz waves slightly affect the heat transfer over a flat plate. Hence, in an attempt to employ the ultrasound for heat transfer enhancement over a flat plate, the distance and ultrasonic frequency must be well considered.

Keywords: Ultrasound, Thin leaf thermocouple, Heat transfer, Laminar flow

1. Introduction
The active techniques of heat transfer enhancement have emerged as powerful platforms in increasing in the efficiency of the thermal system such as the use of jet, vibration, magnetic field [1-6]. The use of ultrasonic waves including the acoustic waves is one of the most widely used techniques that has a frequency above 20 kHz. The frequency range is one of the main parameters, inducing different ultrasonic phenomena such as acoustic cavitation and acoustic streaming. This leads to a different level of heat transfer augmentation [7]. On a flat plate, the 2 MHz ultrasound was found to enhance the heat transfer by increasing turbulence into the liquid flow and caused the higher convective heat transfer coefficients [8]. Meanwhile, the maximum increase in Nusselt number of laminar flows over a flat plate was 10%, 16.5%, and 20.8% under 25, 33, and 40 kHz [9]. Following the advancement of numerical simulation, the computational fluid dynamics-CFD has been employed to investigate the flow and heat transfer for many applications as well as the flow under the ultrasound [10-15]. However, the information about heat transfer under 40 – 120 kHz ultrasound is very little comparing with those from 20 – 40 kHz waves. Thus, this research investigates the heat transfer of laminar flow over a flat plate induced by 40, 80, and 120 kHz ultrasonic waves. The obtained results will be presented in form of
surface temperature and Nusselt number distributions. This work will generate fresh insight into improvement of the thermal system, and can be applied to thermal systems such as food, power plant, cleaning industries, etc.

2. Experimental setup
This experiment was carried out in a low free stream turbulence water tunnel, as shown in Figure 1. This test section had a size of 0.2 m width × 1.5 m length × 0.15 m height and was made of 10 mm acrylic plate. A flat plate was fabricated from 3 mm aluminium plate and it was covered by a thin PVC sheet to dampen the heat from a plate heater. The heater was utilized to generate the heat flux of 1,040 W/m² to the water flow. Between the heater and 3 mm plate, a 10 mm aluminium plate was inserted for the better heat distribution. Underneath the heater, a thermal insulator was installed to block the heat flux in the downward direction and then a steel plate was mounted to strengthen the flat plate installation. Above a PVC sheet, 7 type-K thin leaf thermocouples, having an uncertainty of 0.75% were well glued at the center of section width and at the distance of 0.47 - 1.07 m from the plate leading edge with an increment of 0.1 m. A new boundary layer was created at the plate leading edge by the aid of the bleeding channel.

In this research, the mainstream velocity was set at 0.127 m/s, corresponding to the local Reynolds number between 60,000 and 150,000 at the test area. This velocity was measured with a Nixon Streamflow velocity meter type 403 having an uncertainty of 0.35%. Also, the water temperature was maintained at 24 °C. An ultrasonic transducer was attached on a 1 mm stainless steel plate above the test surface at the streamwise distance of 0.47 m or \( Re_x = 65,181 \). It could release 40, 80, and 120 kHz ultrasound in the downward direction with the power of 60 W. With these setups, the heat transfer capability of water laminar flow over a heating plate, induced by ultrasound could be characterized.

\[ h_x = \frac{h_x x}{k} \]  

(1)

\[ q = h_x (T_s - T_\infty) \]  

(2)

In this study, the local Nusselt number, \( Nu_x \), in the streamwise direction was determined as follows:

\( Nu_x = h_x / k \)

where

- \( h_x \) = local heat transfer coefficient (W/m²·K)
- \( x \) = streamwise distance from the plate leading edge (m)
- \( k \) = thermal conductivity (W/m·K)

From the experiment, the local heat transfer coefficient was evaluated as follows:

\[ q = h_x (T_s - T_\infty) \]

where

- \( q \) = heat flux (W/m²)
- \( T_s \) = surface temperature (K)
- \( T_\infty \) = free stream temperature (K)
3. Results and discussions

The experimental setup was verified by comparing the local Nusselt number, obtained from experiment and [16] during $Re_x = 65,181$ to 148,390 as depicted in Figure 2. The local Nusselt number from the experiment was obtained from Equations (1) and (2), while the value from [16] was evaluated as follows:

$$Nu_{x,uh} = \frac{Nu_x}{1 - (\frac{\xi}{x})^{3/4}}^{1/3}$$

(3)

where $\xi = \text{unheated starting length (m)}$

In this equation, the $Nu_x$ was calculated as follows [16]:

$$Nu_x = 0.453 Re_x^{0.5} Pr^{1/3}$$

(4)

where $Pr = \text{Prandtl number}$

![Figure 2. Comparison of local Nusselt numbers from experiment and [16]](image)

As shown in Figure 2, these results are consistent with data obtained in [16]. This study has been unable to demonstrate that the test setup is reliable. Figure 3 shows the surface temperature at the $Re_x$ of 65,181, 79,049, 92,917, 106,785, 120,653, 134,522, and 148,390 under the condition with and without the interference of 40, 80, and 120 kHz ultrasound. It shows that the surface temperature gains with the increasing streamwise distance. When the ultrasound released from the transducer, the surface temperature under the 40 and 120 kHz waves increased at the location of $Re_x = 65,181$. The waves decreased the surface temperature when $Re_x$ was greater than 92,917. The 80 kHz ultrasound was found to have a slight effect on the distribution of surface temperature along the test surface. At each wave frequency, the maximum decrease in temperature was at the farthest position in the downstream direction.
In this research, the temperature ratio variable, $\theta$, induced by ultrasound was determined as follows:

$$\theta = \frac{(T_{w,x} - T_\infty)}{(T_{nw,x} - T_\infty)}$$  \hspace{1cm} (5)

where $T_{w,x}$ = local surface temperature under ultrasound (°C)

$T_{nw,x}$ = local surface temperature without ultrasound (°C)

$T_\infty$ = free stream temperature (°C)

From Figure 4 below we can see that the distribution of the $\theta$ represented the surface temperature of a heating plate under the 40 and 120 kHz. It also revealed that the ultrasound decreased in the streamwise direction. Further analysis showed that the heat transfer between water flow and the heating surface is enhanced by the ultrasonic waves. At the farthest position or the $Re_x$ of 148,390, the 40 and 120 kHz waves reduced the $\theta$ to 0.87 and 0.78, respectively. In the meantime, the $\theta$ induced by 80 kHz was around 1 over the entire test surface. It means that 80 kHz ultrasound has a small effect on heat transfer enhancement. The lowest $\theta$ under these waves was at 0.97.

Figure 5 provides the ratio between the local Nusselt number under the condition with and without ultrasound. At the location underneath the ultrasonic transducer, the Nusselt number was reduced.
approximately 4% by 40 and 120 kHz ultrasonic waves, while it gained about 3% by 80 kHz ultrasound. The Nusselt number increased up to 15 and 31% at the $Re_x$ of 148,390 by 40 and 120 kHz ultrasound, respectively. The results indicated that the 120 kHz ultrasonic waves are attributed to for the heat transfer enhancement over a flat plate.

![Graph showing Nusselt number ratio under 40, 80, and 120 kHz ultrasonic waves](image)

**Figure 5.** Nusselt number ratio under 40, 80, and 120 kHz ultrasonic waves

4. Conclusion
The present study was designed to determine the effect of ultrasound on heat transfer of laminar water flow over a heating flat plate when the waves have the frequency of 40, 80, and 120 kHz during the $Re_x$ of 65,181 – 148,390. This study has found that generally the ultrasound, having frequencies of 40 and 120 kHz, provides the maximum Nusselt number up to 15% and 31%, respectively at the most downstream position of the test area. These results are likely to be related to the effect of acoustic cavitation and streaming. A possible explanation for this might be that the ultrasound frequency of 80 kHz, was found to have very low effect on heat transfer at the experimental condition. The present study raises the possibility that the distance and ultrasonic frequency must be well--considered to use the ultrasound to enhance the heat transfer of a flat plate.

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