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Heat Transfer and Velocity Measurement of Laminar Pipe Flow Induced by Ultrasound Released along Mainstream Direction

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***Abstract* -** In this paper, heat transfer characteristics of laminar pipe flow using low frequency ultrasound released along the mainstream direction were investigated experimentally. The test section was a square duct with an inner cross-sectional area of 60 mm^2 and a length of 1500 mm. The Reynolds number ranged between 400 and 1,600. A heater with a power of 400 W was installed at the bottom wall to heat the water at 23 °C. Thermocouples were used to measure the wall temperature at a distance of 0.16-0.58 m with an interval of 0.07 m. The ultrasonic transducer with a frequency of 28-80 kHz was set at the entrance to release the waves in a streamwise direction. In addition, the flow behaviour of the water flow induced by ultrasound was illustrated by Particle Image Velocimetry (PIV). The results showed that the heat transfer enhancement factor (*HTEF*) was increased when the heating wall was close to the ultrasonic transducer position. In particular, acoustic streaming was found to convect the heat transfer by swerving from the entrance to the heating wall. The maximum *HTEF* of 163.04% was achieved using 28 kHz ultrasonic waves at Reynold number of 400. These results would clearly demonstrate the potential of ultrasonic waves to improve heat transfer in a thermal system in the future.

***Keywords*:** Ultrasound, Heat transfer, Velocity, Laminar flow, Internal flow

1. Introduction

Nowadays, heat transfer enhancement techniques have gained substantial attention for the industrial sector. Many researchers are finding solutions to enhance the heat transfer of heat exchangers, aiding the operation of thermal systems. The active heat transfer enhancement technique is one of the popular techniques that requires external power. Ultrasound is one of the active techniques that provide a good return in economic consideration and environmentally friendly processes. It has been well known that the ultrasound is helpfully used to improve the heat exchanger and becomes more interesting in the last decade [1]. Ultrasonic waves also have the capability to decrease the pressure drop across the system when compared with the other enhancement techniques. The major phenomena of augmented heat transfer under ultrasound are acoustic cavitation and acoustic streaming, which strongly disturb the flow domain. These two phenomena were found under the influence of low-frequency ultrasound, having a frequency range of 20-100 kHz [1]. When an ultrasonic transducer vibrates the local fluid bulk continuously, the vibration energy is transferred to the fluid, and the fluid current is driven by the gradient of momentum flux, known as acoustic streaming [2]. Meanwhile, acoustic cavitation is the phenomenon that arises from the propagation of ultrasonic waves in a liquid. It is the formation, growth, oscillations, and powerful collapse of gas bubbles in a liquid, occurring when the local pressure of the gas bubbles is decreased below the vapor pressure during the rarefaction period of the sound wave [1]. Many researchers take the advantage of these phenomena from ultrasonic waves to gain heat transfer in the water flows because they can reduce the thickness of the thermal boundary layer, reducing thermal resistance and aiding heat transfer enhancement. Many studies have confirmed the effect of ultrasound on heat transfer in internal convection, and they all came to the same conclusion: low-frequency ultrasound promotes heat transfer by 4.76-44.4% [3-6]. Nevertheless, those studies investigated the effect on heat transfer enhancement from ultrasound released perpendicular to the mainstream flow. Thus, in this paper, the thermal characteristics of pipe flow disturbed by 28-80 kHz ultrasound propagating along the main flow direction were investigated experimentally. The Reynolds number was set at 400 and 1,600, and the bottom surface of the test section had a heat flux of 9.8 kW/m^2. The temperature signals were detected at the dimensionless distance, x/D_h of 2.58-9.35 from the ultrasonic source. Furthermore, the velocity field of water flow induced by ultrasound was investigated by the particle image velocimetry (PIV) system to clarify the physics behind the change in heat transfer.

2. Experimental Setup

The experimental setup was designed in order to investigate heat transfer enhancement and flow characteristics induced by ultrasound, as illustrated in Fig. 1(a). The test section has an inner cross-sectional area of 60 mm^2 and a length of 1500 mm. The top and side walls of the test section were fabricated from a 10 mm acrylic plate to provide a clear vision for the PIV visualization. A heater, which had a length and width of 0.95 and 0.045 m, was used to heat the water flow from the bottom wall with a heat flux of 9.8 kW/m^2. The heat gain of the water flow in the system was removed by a cooling coil in a settling tank, so the inlet temperature can be controlled at 23 °C with a deviation of 0.1 °C throughout the experiment. An ultrasonic transducer with a frequency of 28-80 kHz was mounted at the entrance of the test section. The thermal information was measured by thermocouples that were glued on the test surface at a distance of 0.16-0.58 m with an interval of 0.07 m from the ultrasonic transducer position. These thermocouples had an uncertainty of 0.2 °C. The thermocouple was also used to measure the inlet and outlet temperatures at the upstream and downstream of the test section, respectively. The flow rate measured by the SIKA VTY 20 turbine flow sensor, having an uncertainty of ±1%. The test section, settling tank, and pipelines were insulated with a high thermal resistance insulator to minimize heat loss to the environment. The PIV measurement was utilized to investigate an acoustic streaming in the flow induced by ultrasound, as shown in Fig 1(b). A black PVC sheet was attached to the sidewall of the test section as a background. A 7 W laser beam was released in a downward direction and sheeted by a Powell prism with a spreading angle of 60 degrees at the middle of the test section. Polyamid seeding particles with a mean diameter of 20 μm and a density of 1.03 g/cm^3 were suspended as tracer particles in a bulk fluid at a concentration of 0.00008% by weight. The high-speed camera was used to capture the Regions of Interest (ROI) of 60×66 mm of water flow under the waves, corresponding a size of 510×560 pixels. PIVlab software was used for image processing to obtain the velocity field with the lowest bias and root-mean-square (RMS) error of the displacement estimates [7]. In this research, the average velocity fields were calculated from 1,000-1,500 instantaneous velocity fields with a time step of 4-12 ms, depending on the Reynold number conditions. The PIV measurement aims to access the velocity data of the flow field quantitatively and qualitatively at the position of x/D_h of 2.58, 4.83, 7.09, and 9.35. With this setup, the obtained results from the thermal information and the PIV measurement will aid the understanding and explain the characteristics of heat transfer enhancement by the ultrasound released along the mainstream direction.

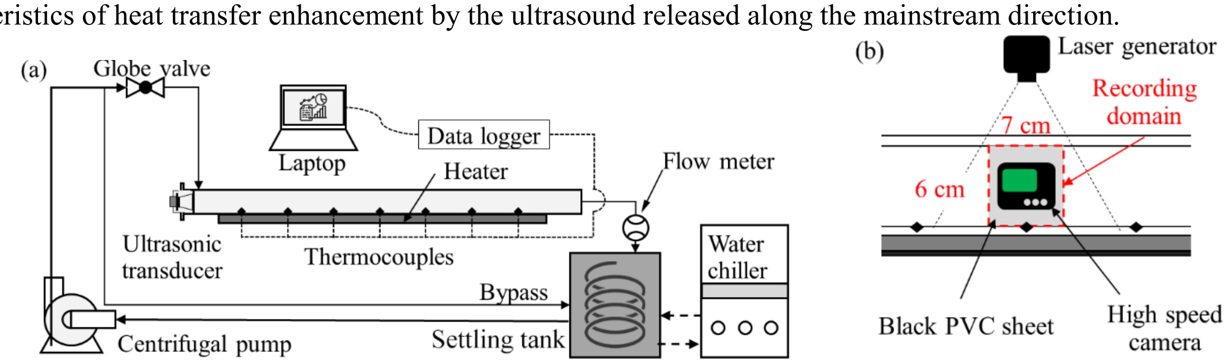

Fig. 1: Schematic diagram of (a) experimental setup and (b) PIV measurement.

3. Experimental analysis

In this study, the local convective coefficient can be calculated as follows:

$$h_x = \dot{q}/(T_i - T_o) \quad (1)$$

where $\dot{q}$ is the heating power [W/m^2] and T_i and T_o are the inlet and outlet temperatures [°C], respectively. The local Nusselt number can be evaluated as follows:

$$Nu_x = \frac{h_x D_h}{k} \tag{2}$$

where D_h is the hydraulic diameter [m] and k is the thermal conductivity[W/m.k]. The Reynolds number of an internal flow is given by:

$$Re = \frac{\rho U D_h}{\mu} \tag{3}$$

where U is the mean velocity of the mainstream flow [m/s], ρ is the density of the water [kg/m^3], and μ is the viscosity of the water [Pa.s]. The heat transfer enhancement in this research was presented as heat transfer enhancement factor, which can be calculated from:

$$HTEF = \left(\frac{Nu_w - Nu_0}{Nu_0}\right) \times 100 \tag{4}$$

Also, the Nusselt number ratio can be calculated from:

$$\overline{Nu_w/Nu_0} = \frac{\sum_{i=1}^{n} Nu_w/Nu_0}{n} \tag{5}$$

4. Results and Discussion

The average velocity in a square channel was validated to determine the reliability of the experimental setup using the PIV technique and was compared with the velocity calculation from Eq. (3). Fig. 2 shows an example of the average velocity field at Re = 2,000 without ultrasonic waves. In the figure, the mainstream direction is from left to right and the heightwise distance was non-dimensional in term of H/D_h. The mean velocity from PIV measurement is 0.007, 0.014, 0.022, 0.027, and 0.034 m/s, having the maximum errors of only 9.86% when compared with the velocity from the Reynold number formula.

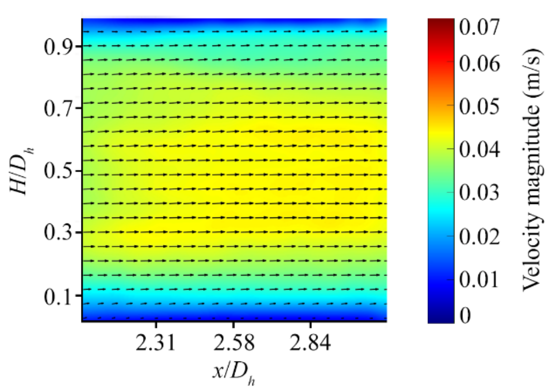

Fig. 2: Example of the average velocity fields at *Re* of 2,000.

The relationship between the heat transfer increment induced by 28-80 kHz ultrasound at *Re* of 400 and 1,600 was shown in Fig. 3(a) and (b), respectively. If the *HTEF* is above 0%, it indicates an increase in heat transfer due to the ultrasonic waves. On the other hand, a value below 0% shows the negative results of heat transfer. The results demonstrate that only the 28-40 kHz ultrasound increases the heat transfer, while the 80 kHz ultrasound has no substantial effect on heat transfer. In addition, the *HTEF* tends to decrease with the increase in the distance from the ultrasonic transducer position and applied frequency. In Fig. 3(a), ultrasonic waves with frequencies of 28, 33, and 40 kHz achieve the maximum *HTEF* of 163, 98.7, and 70.7%, respectively, at $x/D_h = 2.58$. When the *Re* increase up to 1,600, the *HTEF* decreases under 28-40 kHz waves, as shown in Fig. 3(b). Moreover, the *HTEF* didn't substantially increase and gave some negative results when the 80 kHz ultrasound was applied under both *Re* of 400 and 1,600. Nevertheless, the 80 kHz waves provided the maximum *HTEF* of 10.93% at $x/D_h = 2.58$ under $Re = 400$.

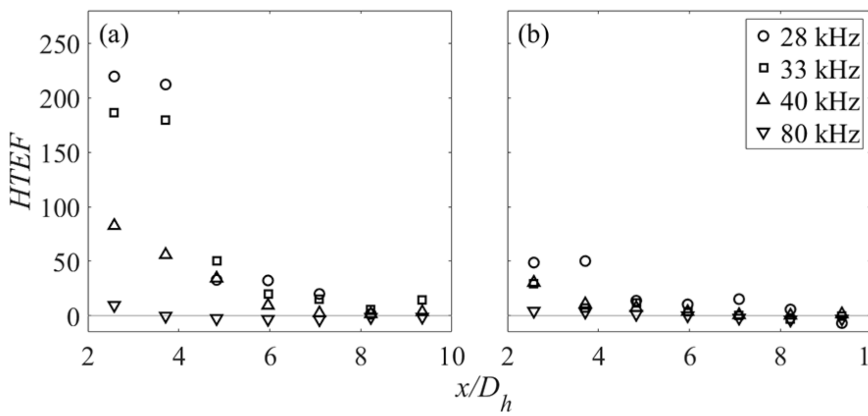

Fig. 3: Heat transfer enhancement factor induced by 28-80 kHz ultrasound at *Re* of (a) 400 and (b) 1,600.

The mean velocity field induced by ultrasonic waves at 28, 33, 40, and 80 kHz was used to explain the heat transfer characteristics at $Re = 400$, as shown in Fig. 4(a)-(d). The results show that acoustic streaming of 28 kHz ultrasound propagates from left to right and transports cooling water to the near-wall region, covering the heightwise range of $H/D_h = 0.1$ and later expanding to the distance of $H/D_h = 0.5$ at $x/D_h = 3.11$. Meanwhile, the acoustic streaming induced by 33 kHz ultrasound expands narrower and has a lower velocity magnitude, compared with the results obtained under 28 kHz ultrasonic waves. The acoustic streaming induced by 40 kHz ultrasonic waves has a different mechanism; the streaming occurs in the middle of the channel and provides a maximum velocity of 0.0106 m/s. Finally, the acoustic streaming from the 80 kHz transducer is intensely affected by the inlet flow. When the 80 kHz ultrasound irradiation while testing, many small bubbles which can seem with the naked eye induced by ultrasound are nucleated at the heating wall. These are obstacle to the acoustic streaming to convect more heat transfer from the heating surface. In addition, the results also show that the mean velocity is 0.0263, 0.0163, 0.0022 and 0.00423 m/s at the measuring point of $x/D_h = 2.58$ under the influence of 28, 33, 40 and 80 kHz ultrasound, respectively. This visualization demonstrates potential of the 28 kHz ultrasound that provides a better heat transfer than those yielded from the 33-40 kHz ultrasound.

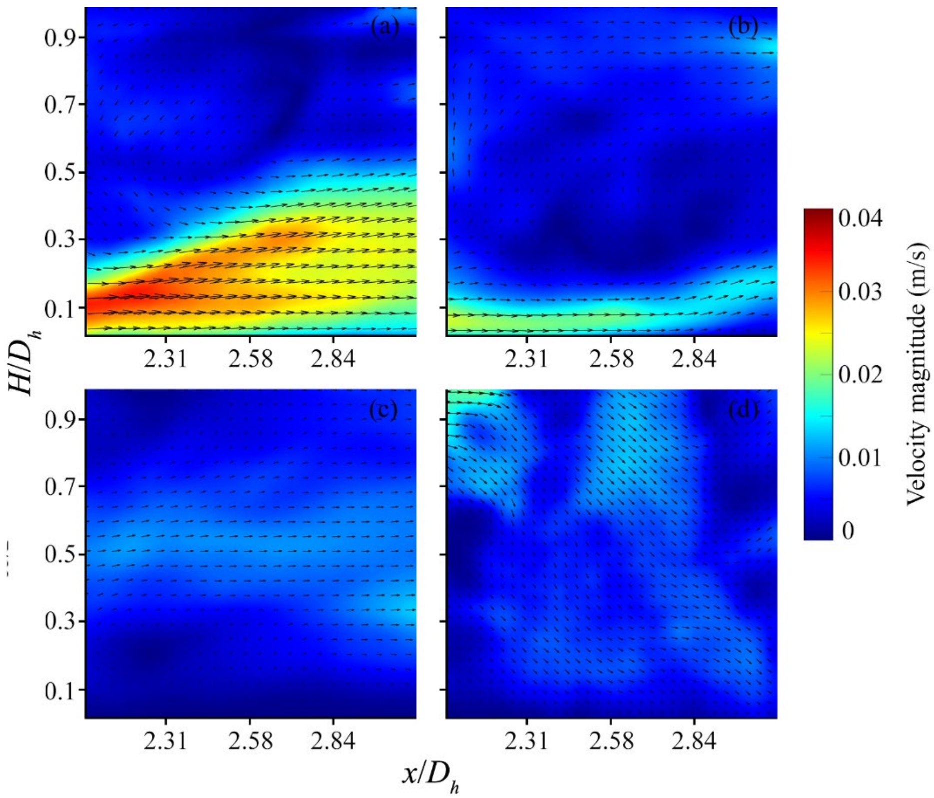

Fig. 4: Mean velocity field induced by (a) 28, (b) 33, (c) 40 and (d) 80 kHz ultrasonic waves at *Re* of 400.

This paper also demonstrates the overview results of heat transfer enhancement by ultrasound are presented as the *Nu* ratio, which can be calculated by Eq. (5). This parameter implies the capability to gain the heat transfer by average the *Nu* though the channel flow. The *Nu* ratio above 1 indicates an increase in heat transfer, while the value below 1 means the worse heat transfer. The results indicate that the *Nu* ratio was heavily depended on the values of *Re* and ultrasonic frequencies. The results show that the *Nu* ratio of 1.753, 1.694, 1.285, and 1.012 under *Re* = 400, whereas with *Re* increasing up to 1600, the *Nu* ratio decreased to 1.22, 1.09, 1.107, and 1.032 was achieved by 28, 33, 40, and 80 kHz ultrasonic waves, respectively.

5. Conclusion

Heat transfer and characteristics of laminar pipe flow using 28-80 kHz ultrasound released along the mainstream direction were investigated in this research. The Re was set at 400 and 1,600, and the one-sided heating surface was set with a constant heat flux of 9.8 kW/m2. The main mechanism for promoting the heat transfer using ultrasonic waves is an acoustic streaming, which was detected by the PIV technique. The heat transfer enhancement along the distance in the square channel by ultrasound depends on both Re and ultrasonic frequencies. The results showed that the heat transfer enhancement factor decreased with the increase in the distance from the ultrasonic transducer position, and the acoustic streaming was weakened when the ultrasonic waves irradiated at a relatively high Re. The streaming induced by 28-40 kHz waves appeared like a beam meanwhile the streaming induced by the 80 kHz ultrasound occurred like not homogeneous. In addition, the maximum heat transfer enhancement factor of 163.04% was achieved using 28 kHz ultrasonic waves at Re of 400. The results also showed that the Nu ratio was heavily depended on the values of Re and ultrasonic frequencies, having the maximum value of 1.753 was achieved by 28 kHz ultrasonic waves.

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