The Effect of Ultrasonic Vibration Frequency on Double Pipe Heat Exchangers During the Cooling Process

Sudarmadji *, Bambang Sugiyono Agus Purwono, Santoso

Mechanical Engineering Department
State Polytechnic of Malang, Indonesia.
* Corresponding author E-mail: sudmaji@yahoo.co.id

Abstract - We investigate the effect of ultrasonic vibrations on heat transfer of 1000 mm long double pipe heat exchangers in parallel flow configuration during experimental cooling processes. The PVC inner diameter of the heat exchanger utilizes a 4 mm brass, 0.75 mm thickness, and a 32.5 mm for the outer diameter and 2.75 mm thickness. The ultrasound is applied and controlled in the range of 20, 30 and 40 kHz frequencies and power of 35 W. Both radiator-coolant and the Aquades cleaning fluid flow in the inner tube, while the cold fluid (tap water) flows in the outer tube. By investigating the overall heat transfer coefficient with and without the influence of ultrasound vibrations, this study has found that the faster the fluid flow rate the higher the overall heat transfer coefficient. The higher overall heat transfer coefficient enhancement was about 44% and 31% with ultrasonic vibration for radiator-coolant and Aquades fluids respectively at a frequency of 20 kHz.

Keywords - heat transfer, ultrasonic vibration, aquades, radiator-coolant, double pipe heat exchanger

I. INTRODUCTION

Challenges in the heat transfer processes technology is a relevant issue in industrial applications like foods, transportation, chemical, oil or gas. Because of this, many researchers and engineers seek to improve heat transfer rates with various methods. Two exiting of enhancement techniques are passive and active methods. Extended surface technologies such as fins and microchannels are within the passive category, but still have limitations. Another method with the potential to improve heat transfer is vibration with ultrasonic frequency. Ultrasound refers to ultrasonic waves whose frequency is above the upper limits of the human hearing range (~ 20 kHz). It is common to distinguish low frequencies or power ultrasounds (20 kHz – 1 MHz) and high-frequency ultrasound (> 1 MHz).

When ultrasonic waves pass through a liquid medium, it can induce the occurrence of a phenomenon known as acoustic cavitation. This term is used to describe the creation of tiny and transient cavitation bubbles with a diameter of less than 100 μm [1]. These cavitation bubbles exist for an extremely short (transient supercritical) time, then are violently collapsed during the compressional phase, so that they emit shock waves [2, 3] with high temperatures (up to 5000K) and pressures (up 90 to 1000 atm) [4, 5, 6]. This microscopic process acts with sufficient energy on the dirty surfaces, and penetrate nearly every corner and crevice which conventional cleaning methods cannot reach [7]. Essentially, the main benefits of the ultrasonic cleaning method include better efficiency, shortened cleaning time, safety, easy installation, simple operation, and reduced labour costs, despite the slightly higher electrical power consumption.

Recently, the passive methods of ultrasonic vibrations have been widely used in welding, cleaning and drying applications and in recent years there has been an interest in the implementation of ultrasonic for heat transfer enhancement. The undeniable advantage of using ultrasound is providing dual improvements in a single system, both for heat transfer enhancements and cleaning possibilities of heat exchangers [8].

The experimental study was conducted by Bergles [9] to determine the effects of high-intensity ultrasonic vibrations on heat transfer to water flowing in annuli. The inner tube of an annulus was electrically heated and ultrasonic emitters were mounted on the outer tube to supply vibration energy to the fluid in a direction normal to the heated surface. The heat transfer was improved by the presence of vibrations dependent on the flow conditions and the extent of cavitations in the annular gap

Legay et al [10] designed, built and studied a double pipe heat exchanger. The largest one is a tube coupled to an ultrasound transmitter placed at its center which makes the whole pipe vibrate at 35 kHz. The measurement of the mass flow rate of the inlet side allows for calculating the overall heat transfer coefficient for parallel and counter flow configuration. The experimental results showed that an enhancement of about 150 % obtained in a laminar regime of the flow in the external tube. In the eexperimental work of Gondrexon et al [11] a shell and tube configuration for a fluid-to-fluid heat exchanger was built and studied with the same test rig as that used in the preceding section. The heat exchanger used the same external tube a shell and an internal tube with two passes (U-shaped tube). The ratio between the overall heat transfer coefficient with ultrasound and the one without ultrasound was found ranging from 1.2 up to 2.6 depending on the liquid flow rate in the shell side.

Another experimental work has been carried out by Yao et al.[12] on an internal U-shaped tube heat exchanger with hot water flowing in the inner tube. Ultrasound emitted at a frequency of 21 kHz, and enhancement of the heat transfer coefficient is observed in the presence of ultrasound smaller than that found in [3[.

Very few papers have investigated the effects of ultrasounic frequency on double pipe heat transfer for the cooling process. Therefore, this experimental study was initiated to investigate the influence of ultrasounic vibration on the overall heat transfer coefficient of the cooling processes.

II. EXPERIMENTAL DATA ANALYSIS

The double pipe heat exchanger used in this study is the parallel flow configuration. The heat and the cold heat transfer fluid rate are calculated as follows:

$$Q_h = \dot{m}_h Cp_h (Th_{in} - Th_{out}) \qquad (1)$$

$$Q_c = \dot{m}_c Cp_c (Tc_{in} - Tcc_{out}) \qquad (2)$$

Where $\dot{m}_h$, Cp_h, $Th_{in}$and Th_{out} are flow rates, specific heat, temperature inlet and temperature outlet of hot fluids, respectively, and subcript h , c indicates the hot and cold fluid.

In the ideal process, the heat released by the hot fluid should be equal to the heat absorbed by the cold fluid. However, this was never achieved due to many factors such as heat leaks by convection and experimental errors. These differences between fluid are seen as heat looses by environment and calculated by equation (3).

$$Q_{env} = Q_h - Q_c \qquad (3)$$

The overall heat transfer coefficient in this study is calculated by the Log Mean Temperature Difference (LMTD) method as an equation (4)

$$Q_h = UA\Delta_{LMTD} \qquad (4)$$

Where U is the overall heat transfer coefficient, A is the surface area and $\Delta_{LMTD}$is the log mean temperature calculated by equation (5)

$$\Delta_{LMTD} = \frac{\Delta T_1 - \Delta T_2}{\ln\left(\frac{\Delta T_1}{\Delta T_2}\right)} \qquad (5)$$

For parallel flow configuration: $\Delta T_1 = Th_{in} - Tc_{in}$ and $\Delta T_2 = Th_{out} - Tc_{out}$

A. Experimental Apparatus

The experimental system used in this study is shown in Figure 1. The test section are double pipe heat exchangers using a parallel-flow configuration (1). The inner pipe is made from brass in1000 mm long, 4.0 mm in inner diameter, and 5.5 mm in outer diameter, while the outer pipe was made from a PVC pipe with a diameter of 27.5 mm and a thickness of 2.5 mm. It consisted of two closed loops, loop of hot and cold fluid. The temperature of the hot fluids in the inlet of the heat exchanger maintained at 60°C, 70°C and 80°C using an electrical heater (9). A PID controller (10) was installed to keep the temperature constant, and valves (6) to control fluids flow through the DAKOTA ACRYLIC rotameter type 6B4100-01B flow meter (7). The hot fluids for this experiment are radiator-coolant fluid and aquades.

To maintain the inlet temperature of the outer tube constant, a cooler tank with thermostat was installed (4).The outer of double pipe heat exchanger was thermally isolated using Aeroflex tube 33.5 mm diameter and 10 mm thickness. Two K-type thermocouples (8) were inserted into the flow at the entrance and exit of the test sections to measure the bulk temperatures of the hot fluids, and two K-type thermocouples (8) measured the flow at the entrance and exit of the cold water flows in the annular temperatures. During the experiments, all temperatures were recorded by the TC-08 PICO TECHNOLOGY UK thermocouple data acquisition module.

B. Ultrasonic Power Transmitted into the Fluid

Before starting the heat transfer experimentations, it is necessary to estimate the power of the ultrasonic frequency that's to be delivered into the fluids. It is assumed that all of the mechanical energy of the waves will dissipate into the fluid. The calculations for ultrasonic power to the fluid flow is determined by equation (6)

$$P_{us} = \dot{m}\, Cp\Delta T \qquad (6)$$

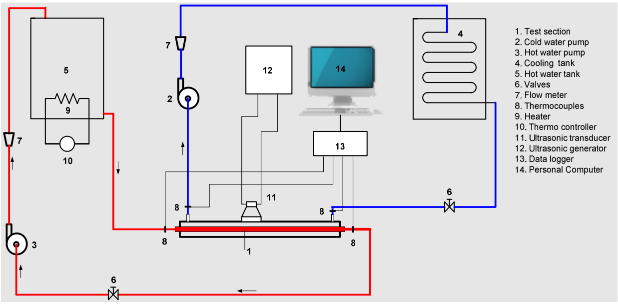

Figure 1. Experimental apparatus

Where P_{us} is the ultrasonic power dissipated into the fluid, $\dot{m}$is the mass flow rate, *Cp* is the specific heat of the fluids, and Δ*T* is the temperature differences between the inlet and the outlet, respectively. Figure 2 shows the graph of the inlet and oultlet temperature of fluid. The ultrasonic generator switch on at the 125th second up to 225th second. Temperature different beetwen inlet and outlet by 2.4°C (32.4°C–30°C) without ultrasonic and 5.8°C with ultrasonic vibration, respectively. And figure 3 shows the ultrasonic vibration was increased the temperature outlet of the fluid flow at approximately 3.8°C, and it can be seen that, in the presence of ultrasonic vibrations of 30 kHz in frequency increasing the outlet temperature of the fluids from 32°C to 35.8 °C.

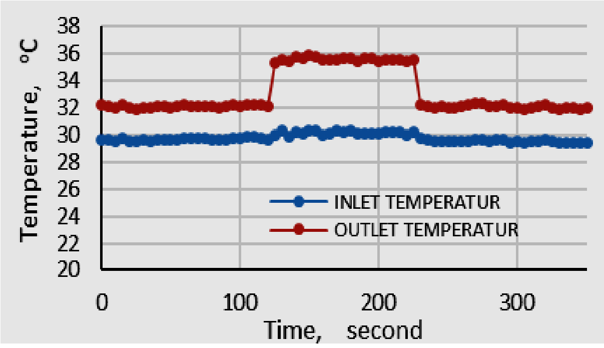

Figure 2. Effect ultrasonic vibration on inlet and outlet fluid temperature at 30 kHz.

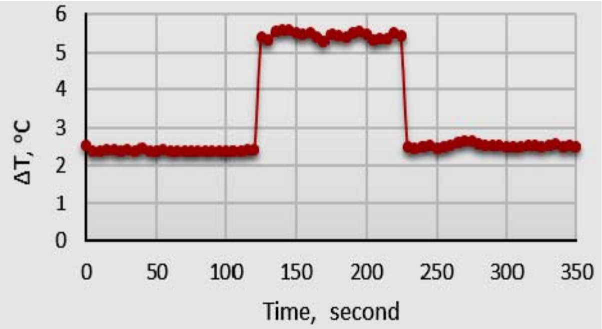

Figure 3. The temperature difference between the inlet and outlet of fluid flow by ultrasonic vibration at 30 kHz

III. EXPERIMENTAL RESULTS AND DISCUSSION

Table I shows an example of energy balance obtained without ultrasonic vibration, for hot fluid (aquades and radiator- coolant) at flows rates of 0.5, 1.0, 1.5, 2 and 2.5 litres per minute (LPM) and cold fluid (tap water) flow rate at a constan of 1 LPM in parallel flow configuration.

TABLE I. ENERGY BALANCES OF THE HEAT EXCHANGER WITHOUT ULTRASONIC VIBRATIONAT IN INLET TEMPERATURE OF 60°C

Flow rate Hot fluid	Flow rate Cold fluid	Q_h	Q_c	Q_{env}
LPM	**LPM**	**Watt**	**Watt**	**Watt**
Aquades fluids				
0.5	1	409	250	159
1	1	660	349	311
1.5	1	781	464	317
2	1	910	448	462
2.5	1	920	508	412
Radiator-coolant fluids				
0.5	1	374	233	140
1	1	582	380	202
1.5	1	651	506	145
2	1	713	588	125
2.5	1	793	652	141

A. *The Effect of Inlet Temperature on the Overall Heat Transfer Coefficient*

Figure 4 shows the effect of the inlet temperature on the overall heat transfer coefficient for both aquades and radiator-coolant fluids. For fluid inlet temperature of 80°C the highest overall heat transfer coefficient for both fluids. While for the 60°C inlet temperature the differences value of the overall heat transfer coefficient. For a aquades fluid, the temperature difference in the range of the overall heat transfer coefficient is very narrow, but for radiator-coolant fluid its very wide. For example for aquades and radiator coolant fluids for inlet temperature of 80°C the overall heat transfer coefficient is almost the same about 3075 W/m^2 °C, while for the inlet temperature of 60 °C the overall heat transfer coefficient for aquades 2975 W/m^2 °C and for coolant radiator 2674 W/m^2°C, respectively. The reason is that these two fluids have different thermal properties.

TABLE II. ENERGY BALANCES OF THE HEAT EXCHANGER WITH ULTRASONIC VIBRATION AT 20 KHZ FREQUENCY

Flow rate Hot fluid	Flow rate Cold fluid	$Q_{US.h}$	$Q_{US.c}$	P_{US}	$Q_{US.env}$
LPM	**LPM**	**Watt**	**Watt**	**Watt**	**Watt**
Aquades fluids					
0.5	1	483	398	35	120
1	1	750	502	35	282
1.5	1	915	548	35	402
2	1	1022	560	35	496
2.5	1	1026	586	35	474
Radiator-coolant fluids					
0.5	1	469	349	35	154
1	1	714	518	35	231
1.5	1	821	607	35	249
2	1	894	680	35	249
2.5	1	973	741	35	266

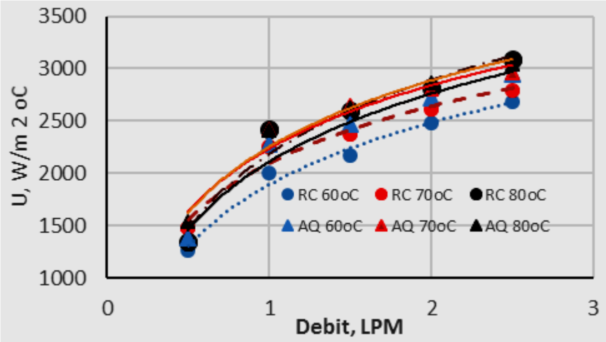

Figure 4. The overall heat transfer coefficient versus fluid flow rate aquades and coolant radiator at various inlet temperatures of 60°C, 70°C and 80°C without aultrasonic vibrations

B. *Effects of Ultrasonic Vibrations on the Overall Heat Transfer Coefficient*

Figure 5 shows the overall heat transfer coefficient *U* describes the improvement of heat transfer processes using equation (4) for the aquades fluid (AQ) at 20 kHz, 30 kHz and 40 kHz in frequencies and temperature inlet of 80ºC by 3377 W/m^2 ºC, 3162 W/m^2 ºC and 3354 W/m^2 ºC, respectively. The higher overall heat transfer coefficient was at a frequency of 20 kHz and at a flow rate of 2.5 LPM.

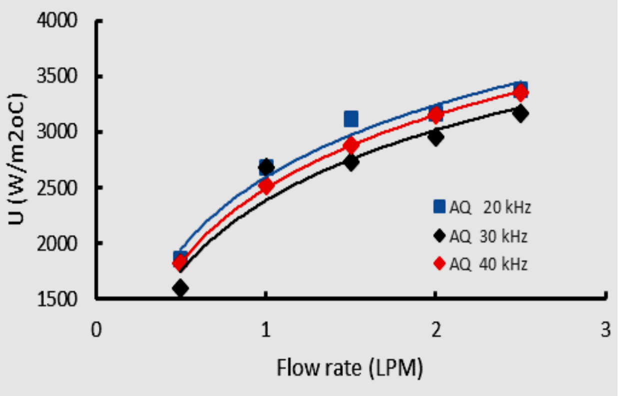

Figure 5. Overall heat transfer coefficient versus aquades flow rates by ultrasonic vibrations at 20, 30 and 40 kHz frequencies

Figure 6 shows the overall heat transfer coefficient (U) the radiator coolant (RC) for a different frequency, i.e, 20 kHz, 30 kHz and 40 kHz. From the figure, it can be seen that the higher overall heat transfer coefficient at 20 kHz frequencies compared to the 40 kHz frequency of 3804 W/m^2 ºC and 3545 W/m^2 ºC at a 2.5 fluid flow rate. The reason may be due to the thinner thermal boundary layer which easier to occur by the low frequency. Therefore, more heat could be transferred through the boundary layer from the radiator-coolant fluid to the wall tube. For the low flow rate, the overall heat transfer coefficient value is slighly smaller. The overall heat transfer coefficient is 1500 W/m^2 ºC at 40 kHz frequency on 0.5 LPM flow rate.

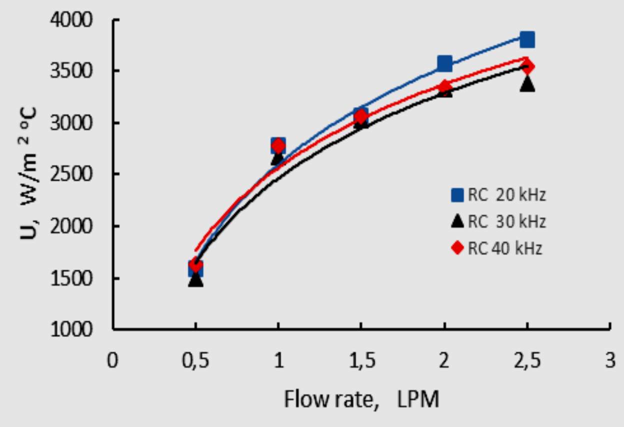

Figure 6. Overall heat transfer coefficient versus radiator-coolant fluid flow rate by ultrasonic vibration at 20, 30 and 40 kHz in frequency

Figure 7 shows the overall heat transfer coefficient (*U*) for both aquades and radiator-coolant with and without ultrasonic vibrations. As can be seen, the overall heat transfer coefficient of a double pipe heat exchanger was improved by increasing the flow rate. The higher overall heat transfer coefficient is the radiator-coolant fluids with ultrasonic vibration. For example, at the flow rate 2.5 LPM, the overall heat transfer coefficient of the radiator-coolat with and without ultrasonic vibration at 20 kHz frequency of 3804 $W/m^2 °C$ and 3189 $W/m^2 °C$, respectively, increasing heat transfer aproximately by 20%. The increase of heat transfer caused by the presence of ultrasonic in both fluids is 44% for radiator-coolant and 31% for Aquades at flow rate 0.5 LPM with 20 kHz in frequency. Very good agreement to the Table. 2 that energy balance presences ultrasonic vibration at 0.5 LPM which the lower energy loses absorbed by the environment is 120 W for aquades and 154 W for radiator-cooler, respectively. The lower ultrasonic vibration the higher overall heat transfer coefficient, as the result the total thermal resistance decrease.

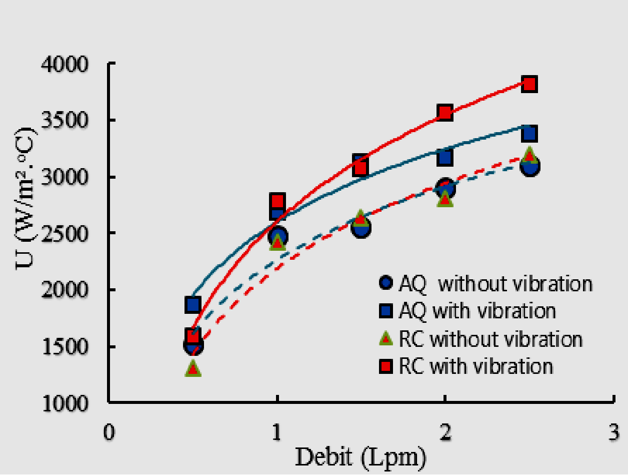

Figure 7. Comparison of the overall heat transfer coefficient for fluid Aquades and Radiator-coolant with and without ultrasonic vibration at of 20 kHz at 80ºC inlet temperature

C. *Effects of Ultrasonic Vibrations on Thermal Resistance*

The theoretical equation of overall heat transfer coefficient *U* on a double pipe heat exchanger can be written as the thermal resistance total [13], as in Eq. (7) as shown in Fig 7.

$$\frac{1}{UA} = R \qquad (7)$$

Figure 8 shows the results of the total thermal resistance of the heat exchanger with and without ultrasonic vibrations. As can be seen, the total thermal resistance (*R*) decreased while flow rate increases. Thermal resistance higher when not exposed to vibrations compare to those exposed by ultrasonic vibration. For example, at the flow rate of 0.5 LPM, the total thermal resistance with and without ultrasonic vibrations are 0.0616 $°C/W$, and 0.0427 $°C/W$, respectively. The thermal resistance decreased according to equation (13) with ultrasonic vibrations of about 23.6 % (from 0.0303 °C/W to 0.0231 °C/W) at the flow rate of 2.5 LPM.

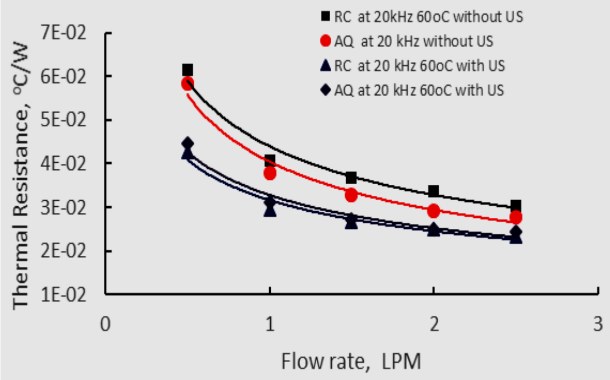

Figure 8. Thermal resistance for aquades and radiator-coolant with and without ultrasonic vibrations at 20 kHz frequency.

IV. CONCLUSIONS

An experimental investigation was conducted on the effects of ultrasonic vibration on the overall heat transfer coefficient of the aquades and radiator coolant fluids flowing in a double pipe heat exchanger. The impact of the fluid flow and ultrasonic vibration were an important aspect. From the above discussion the following conclusions are obtained:

1. The higher the fluid flow rate, the higher the overall heat transfer coefficient with and without ultrasonic vibration.
2. The overall heat transfer coeficient of the radiator-coolant fluid significantly gives higher than using the aquades fluid by 3490 W/m^2 °C and 3297 W/m^2 °C with ultrasonic vibration at 20 kHz.
3. The maximum percentage enhancement affected by ultrasonic vibration of the radiator-coolant fluids and aquades fluids is 44% and 31%, respectively.
4. Limitations: For practical applications, this method is undesirable because ultrasonic vibration is an active method for improving heat transfer, which requires energy supply, the energy supply of 35Watt is higher than the overall heat transfer coefficient enhancement.

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