Numerical study of performance augmentation of a vertical coil and shell heat exchanger using high frequency ultrasonic waves

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Abstract
This research focuses on the performance augmentation of a coil and shell heat exchanger using high frequency ultrasonic waves by the commercial computational fluid dynamics program FLUENT. The model was validated both heat transfer and ultrasound propagation with the results from other researchers. Then, the simulation of the flow and heat transfer enhancement in the heat exchanger under 1.7 MHz ultrasound. Four ultrasonic transducers were installed at the corners of the shell at the middle height of the coil. The ultrasound from transducers was emitted to induce the vortex flow in the shell with the angle of 0, 15, and 30 degrees with the horizontal line. The results show that the high frequency ultrasound is applicable for heat transfer enhancement of a shell and coil heat exchanger. Therefore, the obtained results can be used to innovate an ultrasonic coil and shell heat exchanger in the future.

Keywords: Ultrasound, Heat exchanger, Heat transfer, Vertically coil.

1. Introduction
A coil and shell heat exchanger are important equipment, used in many thermal applications such as chillers, oil cooling, SDHW systems, power plant cooling systems, etc. This heat exchanger type provides high thermal efficiency, low installation space, and low maintenance cost [1-4]. However, performance augmentation is still needed for the reduction of operating cost. Following the advancement of numerical simulation, this heat exchanger has been studied numerically and experimentally [2-8]. In an attempt to augment the heat exchanger performance, the heat transfer enhancement techniques such as the use of twisted tape [9], extended area [10], turbulent spot [11-14], baffle [15], water jet [16], etc. are typically employed. The use of ultrasound is one of those techniques, giving high performance to enhance the heat transfer [17-18]. Besides, ultrasonic waves, having high frequency or above 1 MHz can initiate the streaming by momentum gradient [8]. They should significantly increase heat transfer of thermal systems. Thus, this research study’s the heat transfer augmentation of a coil and shell heat exchanger using 1.7 MHz ultrasonic waves by the commercial computational fluid dynamics program
FLUENT. The continuity, momentum, and energy equations are mutually utilized and they are as follows:

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \]  
\[ \frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot (\rho \mathbf{v} \mathbf{v}) = -\nabla p + \mu \nabla^2 \mathbf{v} + \mathbf{F} \]  
\[ \rho c_p (\mathbf{v} \cdot \nabla T) = k \nabla^2 T + S \]

In this study, 4 ultrasonic transducers were installed in the heat exchanger and the waves were released in 3 directions. The results, including pumping power factor, heat transfer performance factor, and thermal performance factor will be presented to evaluate the performance of the heat exchanger.

2. Numerical validation

2.1 Heat transfer validation

The heat transfer of numerical models was validated by comparing the results from the simulation of water flow in a vertical coil and shell heat exchanger and the experiment of [2]. The fluid model was created in accordance with their test section. The water flow rate and temperature inlet were 0.05 kg/s and 20˚C, respectively, while the outlet pressure was 0 Pa. In the simulation, coil surface was set to have a constant heat flux of 23.16 kW/m². The Reynolds number in shell-side [8] was calculated as follows:

\[ Re = \frac{\rho U D_{eq}}{\mu} \]  

where \( \rho \) is density, \( \mu \) is dynamic viscosity, \( U \) is inlet velocity. The \( D_{eq} \) is equivalent diameter [8], calculated as follows:

\[ D_{eq} = \frac{4 V_{sh} \pi d L}{\pi d} \]

where \( V_{sh} \) is fluid volume in shell-side, \( d \) is coiled tube diameter, and \( L \) is coiled tube diameter length.

For the simulation, the standard k-epsilon model was used and the element number of 2147164, 1,380,417, 913,022, 739,016, 398,540, 126,247, 90,485 and 66,575 were employed for the mesh sensitivity and validation process as depicted in Figure 1.

Figure 1. a) Details of fluid model of [2] and b) results of heat transfer validation
Form the figure, the coefficient of determination, $R^2$ was determined from the comparison between numerical and experimental coil temperatures. It converged at 98.90% and the element number of 913,022. Thus, this model shows a very high reliability for heat transfer prediction in a coil and shell heat exchanger.

2.2 Ultrasound propagation validation

The numerical validation for ultrasound propagation was conducted as the experiment of [19]. For the numerical setup, the momentum energy was added to the cylindrical volume, having the length of the near field distance [8] as follows:

$$ N = \frac{d_s^2}{4\lambda} \quad (6) $$

where $N$ is Fresnel length or near field region length, $\lambda$ is acoustic wavelength, and $d_s$ is sound source diameter. The numerical validation for ultrasound propagation was conducted as the experiment of [19]. For the numerical setup following [8], the momentum energy was added to the force term in acoustic streaming equation as follows:

$$ \rho (v \nabla v) = -\nabla p + \mu \nabla^2 v + F \quad (7) $$

In the near field region, the acoustic force was added as 73.62 N/m$^3$ in the direction of ultrasonic waves. The heater surface was set as a constant heat flux of 6.9, 16.8, 34.1, and 55.5 kW/m$^2$, respectively. The water surface was set to be atmospheric condition or gauge pressure of 0 Pa. Other wall surfaces were constant temperature of 0°C. Also, the standard k-epsilon turbulence model was used in this work. The mesh sensitivity method was conducted at the element number of 1,503,744, 1,181,604, 734,713, 592,794, 377,757, 302,845, 271,793, and 122,556. It was found that the element number of 592,794 gave the convergence of surface temperature. At this mesh aspect, the validation process was done at the all-heat flux conditions and the results showed that the percentage error is below 6.57%, confirming the reliability of the numerical model of ultrasound propagation.

3. Numerical Method

This heat exchanger type, studied in this research was the model that was utilized in a commercial 1-ton water chiller of Ample Cool Co., Ltd. Its shell dimensions were width of 280 mm x length of 280 mm x height of 391 mm. The outlet was set near the bottom corner and the inlet was installed on the top wall. Both diameter sizes were 25 mm. The inlet was defined to have constant temperature of 25°C and volume flow rate of 10, 15, 20 and 25 L/min. Meanwhile, the temperature and gauge pressure at the outlet was 13°C and 0 Pa, respectively. The vertical coil was mounted at middle of the shell and it was lifted from the bottom wall about 23 mm. The coiled tube diameter, coil diameter, pitch, and coil height were 10 mm, 337.5 mm, 30 mm, and 225 mm, respectively as shown in Figure 3.
An ultrasonic source, having diameter of 25 mm, was installed at each corner of the shell on the middle height level of heat exchanger to emit the high frequency ultrasound in clockwise direction. The angles with respect to each horizontal line were 0, 15, and 30 degrees, respectively. The ultrasonic waves were set to have frequency and power of 1.7 MHz and 9.6 W, respectively. To generate the ultrasound propagation, the acoustic force was added as 73.62 N/m³ in the direction of ultrasonic waves in equation 7. The standard k-epsilon model was used as the turbulence model in this part. The spatial discretization of all convection terms was second order upwind except the gradient that was set as the least squares cell based. The calculation stopped when all scaled residuals were less than 10⁻⁵. For mesh sensitivity check, the element number of 12,053, 443, 9,529,035, 7,823,081, 5,634,562, 4,201,682, 2,224,615 and 1,322,985 were investigated. The results show that the mesh number of 5,634,562 was proper for the calculation as depicted in Figure 4 due to the convergence of temperature between inlet and outlet of the heat exchanger. Thus, this meshing method was employed through this research.

This work investigated the effect of flow rate change and the angle of ultrasound propagation on heat transfer and pressure drop in a vertical coil and shell heat exchanger. In attempt to evaluate the performance of a heat exchanger, the pumping power factor, \( F \), the heat transfer performance factor, \( J \), and the thermal performance factor, \( TP \), were presented and the pumping power factor \([8]\) was determined as follows:

\[
F = f_s \times Re^3
\]
where $f$ is friction factor [8]. It was calculated as follows:

$$f = \frac{\Delta P (D_{eq} / l_s)}{(2/\rho U^2)}$$

(9)

where $\Delta P$ is pressure drop, $l_s$ is heat exchanger length.

The heat transfer performance factor [8] was determined as follows:

$$J = j \times Re$$

(10)

where $j$ is Colburn j-factor [8], evaluated as follows:

$$j = hPr^{2/3} \rho U c_p$$

(11)

where $h$ is heat transfer coefficient. $Pr$ is Prandtl number. $c_p$ is specific heat.

Finally, the thermal performance factor [8] was defined as follows:

$$TF = \left( \frac{J}{J_{ref}} \right) \left( \frac{f}{f_{ref}} \right)^{1/3}$$

(12)

where the subscript $ref$ means the condition without the interference of ultrasound.

4. Results and discussion

Figure 5 presents the $J$, the $F$ and the $TP$, depending on the $Re$ at $4.21 \times 10^5$, $3.37 \times 10^5$, $2.53 \times 10^5$, and $1.69 \times 10^5$. The results show that when the $Re$ was increased, the values of $J$ and $F$ gained too. In addition, Figure 5a shows that the application of ultrasound can enhance the heat transfer of exchanger. At the lowest $Re$, the $J$ was clearly increased by ultrasonic waves. The strength of this effect declined with the increase in $Re$. In the meantime, Figure 5b shows that the $F$ is slightly affected by the ultrasonic disturbance and the most effect from ultrasound is less than 3.5%. Figure 5c reveals the overview effect of ultrasound on the flow and heat transfer in the heat exchanger. In the figure, the maximum $TP$ of 1.1345 was yielded when ultrasound was emitted at angles of 0˚ and the lowest $Re$. It also decreased with the increase in the ultrasound propagation angle or the $Re$.

Figure 5. a) $J$, b) $F$, and c) $TP$ vs $Re$ under the effect of ultrasound propagation angle
Figure 6 shows the distribution of velocity vectors on the plane of middle height heat exchangers under conditions with and without ultrasound at the $Re$ of $1.65 \times 10^5$. Figure 6a shows that the water velocity on this plane is mostly below 0.05 m/s, while a relatively higher velocity region occurs at the lower left corner due to the inducement of inlet water. The velocity around the coil clearly increased when ultrasound was released into the heat exchanger as depicted in Figure 6b-d. The figures show that a large vortex has been created by ultrasound and different vortex behavior is obtained. At the propagation degree of 0˚, the vortex was formed at outer side of the coil and this gives the relatively highest performance as shown in Figure 6b. At the higher propagation angle of the waves, not only the size of vortex, but also the performance of heat exchanger is reducing as illustrated in Figure 6c-d. This clearly shows that the size of the induced vortex directly depends on the performance of the ultrasonic heat exchanger.

Figure 6. Distribution of velocity vectors on the plane of middle height of heat exchanger at the $Re$ of $1.65 \times 10^5$ under the condition a) without and with ultrasound at b) 0˚, c) 15˚, and d) 30˚
5. Conclusion
The performance of a vertical coil and shell heat exchanger under the ultrasound, was investigated at the flow rate effects of 10, 15, 20 and 25 L/min and ultrasound propagation angles of 0˚, 15˚, and 30˚. The results showed that the high frequency ultrasonic waves slightly affected the pumping power factor. Meanwhile, this ultrasound increased the thermal performance factor up to 13.45% at the relatively lowest Re and the angles of 0˚. At this angle, the vortex flow was initiated at the outer side of the coil. The higher angle gave the smaller size of induced vortex and also the performance of heat exchanger under the ultrasound.

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