Research Article

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Study of ultrasonic influence on heat transfer and resistance performance of round tube with twisted belt

https://doi.org/10.1515/phys-2023-0183
received October 23, 2023; accepted January 05, 2024

Abstract: In this study, ultrasonic technology is combined with twisted belts to explore the comprehensive performance, and this study also investigated the effect of different Reynolds numbers, ultrasonic frequencies, and number of transducers on the performance of circular and twisted band tubes. It was found that ultrasonic waves applied on the tube plate enhanced the heat transfer performance of the heat exchanger tubes, reduced the flow resistance, and improved the overall performance, and the lower the ultrasonic frequency, the better the heat transfer and resistance reduction ability, and at the experimental condition frequency of 21 kHz, the maximum increase of Nu is 19.06%. With the increase of Reynolds number, the better the ultrasonic enhancement heat transfer performance, but the worse the resistance reduction performance. For different heat exchanger tube structures, the synergistic enhanced heat transfer effect of ultrasonic waves with the twisted belt is better than round tubes, and the synergistic drag reduction effect with the round tube is better than the twisted tape round tube. When the installed ultrasonic transducers are two, the heat transfer performance of the heat exchanger tube is the best, and the maximum increase in the value of Nu was 28.06%.

Keywords: ultrasonic wave, torsion band, enhanced heat transfer, flow resistance

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1 Introduction

In industrial production, heat exchanger, a kind of equipment to exchange heat between hot and cold fluids, has been widely used in engineering fields such as petroleum, chemical, energy, and other fields as well as high-tech fields such as aviation, electronics, nuclear energy, and so on [1]. In the production process, the performance of the heat exchanger is very important. Heat transfer capacity and flow resistance are the main criteria to judge the performance of the heat exchanger. Production processes with high-energy utilization and efficiency generally correspond to heat exchangers with high heat transfer capacity and low flow resistance. So improving heat transfer capacity and reducing flow resistance are now in the design of heat exchangers to focus on the issue of research.

Scholars around the world have achieved fruitful results in the study of enhanced heat transfer. It is known that nowadays the heat transfer enhancement technology is divided into active reinforced heat transfer technology and passive reinforced heat transfer, in which the active heat transfer enhancement includes: 1) mechanical agitation [2]; 2) surface vibration [3]; and 3) electromagnetic field [4–7], and the passive reinforced heat transfer includes: 1) reinforced tube technology [8]; 2) surface treatment technology; 3) internal plug-in technology [9]; and 4) nanofluidic technology [10]. Although passive reinforcement technology is more widely used, it is necessary to develop new reinforcement heat transfer technology and conduct further research because it usually causes a large increase in frictional resistance while enhancing heat transfer. Among them, ultrasonic wave has been widely used in the field of heat exchanger anti-scaling and descaling due to their environmental protection and reliable advantages, and it has been found to have the ability to strengthen heat transfer in the further research of scholars. Therefore, ultrasonic technology as an emerging active strengthening technology shows its great potential in engineering applications.

As early as 1917, Rayleigh [11] first proposed the ideal spherical cavitation bubble model and cavitation theory, which has an important significance for the later study of ultrasonic cavitation effect. It also became the theoretical basis for scholars to study the enhanced heat transfer by ultrasonic waves. Tam *et al.* [12] conducted experiments on the effect of ultrasonic waves on the heat transfer coefficient of the laminar flow zone in the tube, and the test showed that ultrasonic waves enhanced the heat transfer coefficient of the laminar flow to a large extent. Viriyananon *et al.* [13] studied heat transfer capacity of the heat exchanger with different frequencies of ultrasonic waves. The ultrasonic waves of 25, 33, and 40 kHz were chosen to test the narrow rectangular pipe. It was concluded that the heat transfer performance of the narrow rectangular pipe was best enhanced when the ultrasonic frequency was 25 kHz. Luo *et al.* [14] experimentally studied the effect of ultrasonic waves on the pressure drop inside the pipe, and it was found that the pressure drop inside the pipe was reduced under the action of ultrasonic waves, and with the increase of ultrasonic frequency, the drag reduction effect of ultrasonic waves was enhanced.

Thungthong *et al.* [15] investigated the effect of the ultrasonic transducer mounting method on the enhancement of heat transfer in the experiment, and the results showed that a higher heat transfer coefficient can be obtained when the ultrasonic transducer is mounted on the upper part of the heat exchanger. Du [16] studied the change of heat transfer performance of staggered heat exchanger tubes under the action of ultrasonic waves of different frequencies and sound intensities, and the results showed that the heat transfer performance of the tubes under the action of ultrasonic waves changes, and the larger the ultrasonic frequency and the lower the amplitude of the sound pressure, the worse the ultrasonic enhancement of heat transfer, and the coefficient of friction increases first and then decreases. Azimy *et al.* [17] investigated the effect of mounting ultrasonic transducers on the heat exchanger wall on increasing the heat transfer coefficient of distilled water. Ultrasonic transducers with powers of 35 and 50 W were installed on the heat exchanger wall to generate ultrasonic waves. The results showed that the heat transfer coefficient can be improved by using ultrasonic transducers.

Treegosol *et al.* [18] experimentally investigated the effect of 28 kHz ultrasonic waves on the heat transfer characteristics and friction losses of turbulent water flow in a circular tube at surface temperatures such as 45°C. The results showed that ultrasonic waves have a positive effect on the heat transfer and pressure losses of the flow in the tube. The maximum thermal efficiency value under the action of ultrasound is 5.43 when the number of transducers is 1. Lin *et al.* [19] loaded ultrasonic waves on the wall surface of the immersed heat exchanger and experimentally investigated the influence of different ultrasonic amplitudes to strengthen the heat transfer effect, and the results showed that with the increase of ultrasonic amplitude, the surface convective heat transfer coefficient increased, and when the ultrasonic amplitude was 35 μm, the maximum increase of heat transfer coefficient was 26.71%. Yang *et al.* [20] investigated the changes in boiling heat transfer on smooth and porous surfaces in the presence of ultrasound. It was shown that the addition of ultrasound enhanced the heat transfer capacity and the heat transfer coefficients of smooth and porous surfaces increased by 23.7 and 30.9%, respectively. Zhang *et al.* [21] experimentally investigated the effect of 2.8 MHz high-frequency ultrasound on the flow and heat transfer performance of different types of microchannels. The results show that ultrasound disturbs the wall velocity boundary layer, improves the heat transfer between the fluid and the wall, and enhances the heat transfer capacity of the heat exchanger.

Twisted belt is a common type of internal inserts, which can enhance heat transfer by inducing the secondary flow. Scholars have explored various types of twisted bands and various enhanced heat transfer techniques compounded with twisted bands. Yang *et al.* [22] experimentally investigated the effect of inserting twisted bands of different widths and twist ratios into the shell and tube heat exchanger on the enhancement of the heat exchanger and found that the heat transfer coefficients of the heat exchanger increased with the decrease of twist ratio of twisted bands and with the increase of twisted band widths. Zhang *et al.* [23] presented a novel structure of inserting three and four strands of twisted bands into the heat exchanger tube, and numerical simulations were carried out to study it, and the results showed that the Nusselt number increased when using both three and four strands of twisted bands, and the comprehensive performance evaluation factor after reinforcement ranged from 1.64 to 2.46. Yu *et al.* [24] investigated the effect of twisted bands with different structures on heat transfer and flow resistance of twisted tubes and found that hollow twisted bands have the best overall performance when synergized with twisted tubes.

Zheng *et al.* [25] numerically simulated the effect of nanofluids and pitted twisted bands on the heat transfer performance and flow resistance of circular tubes, and the results showed that both the pitted side and protruding side achieved a greater enhancement of the heat transfer, and that the pitted side of heat transfer [26]. In the present study, the variation of heat transfer capacity of heat exchanger with inserted twisted belt and external helical twisted belt was investigated using water as the working fluid, and the practical results showed that the Nussle number of the pipe with inserted twisted belt and helical twisted belt was increased by 219 and 315%, respectively, compared to that of the normal pipe heat exchanger.

Soltani *et al.* [27] placed bent twisted tape inserts of different configurations into the inner tubes of a double tube heat exchanger for an experimental study to analyze the Nu values, friction coefficients, and thermal performance factors. The results showed that all the inserts significantly increased the Nu and friction factor compared to the plain pipe, and the maximum thermal performance factor of the fluted louvered twisted tape heat exchanger was 1.24 when Re = 5,300. Altun *et al.* [28] studied the variation of heat transfer, pressure drop, and overall coefficient of performance of twisted trapezoidal twisted tape element heat exchanger under turbulent conditions. The experimental results show that twisted trapezoidal twisted tape element enhances the heat transfer of the heat exchanger and increases the pressure drop, the rate of which varies with the height of the threads. Boonsong *et al.* [29] experimentally investigated the effect of serrated twisted belt inserts on the coefficient of friction, heat transfer coefficient, *etc.*, and the experimental results showed that the serrated twisted belt improved the heat transfer efficiency, and when the serrated angle of the serrated twisted belt was 70°, it had the best aerodynamic thermal performance index, with a value of 1.33.

From the research status mentioned earlier, fewer scholars have studied the performance of ultrasonic technology and cyclone insert technology to strengthen heat transfer. Therefore, this article designs a kind of enhanced heat transfer test device that installs the ultrasonic transducer on the tube plate, combines the ultrasonic wave with the twisted belt insert, investigates the influence of acoustic ultrasonic frequency on the heat transfer performance, flow resistance, and overall performance of the round tube and the twisted belt round tube through the experimental study, and investigates the influence of applying different ultrasonic wave quantities on the heat transfer performance, flow resistance, and overall performance of the round tube and the twisted belt round tube under the condition of determining the frequency. The effects of applying different ultrasonic wave quantities on the heat transfer performance, flow resistance, and overall performance of round tubes and twisted band tubes are also investigated under determined frequency conditions.

2 Experimental content

2.1 Test main parameters range

1) Reynolds number range: 5,000–18,000 (corresponding to the flow velocity range: 0.20–0.68 m/s).
2) Ultrasonic frequency: 21, 25, and 28 kHz.
3) Number of ultrasonic transducers: 1, 2, 3.

2.2 Experimental device

The enhanced heat transfer performance test setup for ultrasonic action on the tube plate in this test setup consists of a test section, an electric heating system, an ultrasonic system, a water system, and a data acquisition system. As shown in Figure 1, the ultrasonic system consists of an

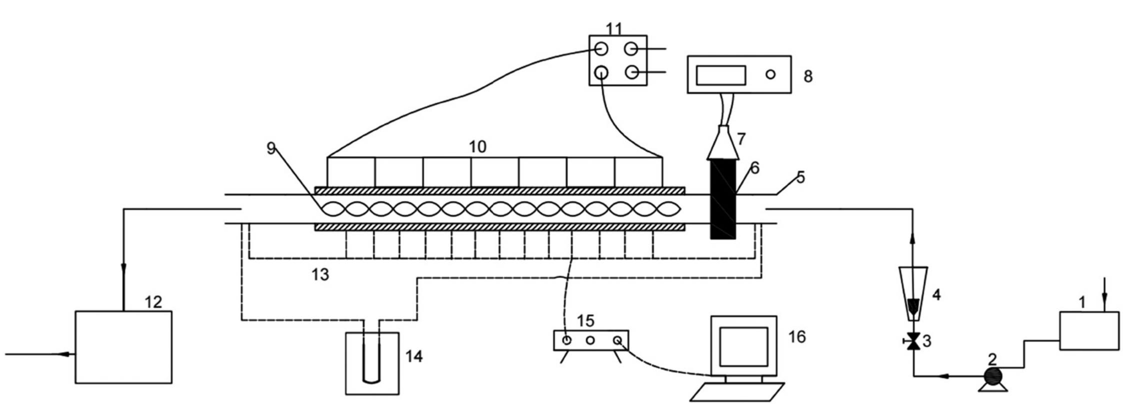

Figure 1: Schematic diagram of experiment system. 1 is a cold water tank; 2 is a solenoid pump; 3 is a ball valve; 4 is a rotor flowmeter; 5 is a 304 stainless steel tube; 6 is a tube plate; 7 is an ultrasonic transducer; 8 is an ultrasonic generator; 9 is a twisted band inside the plug-in; 10 is a heating jacket; 11 is a regulator; 12 is a hot water tank; 13 is a thermocouple; 14 is a U-type differential pressure gauge; 15 is an Agilent Data Acquisition Instrument; and 16 is the industrial control computer.

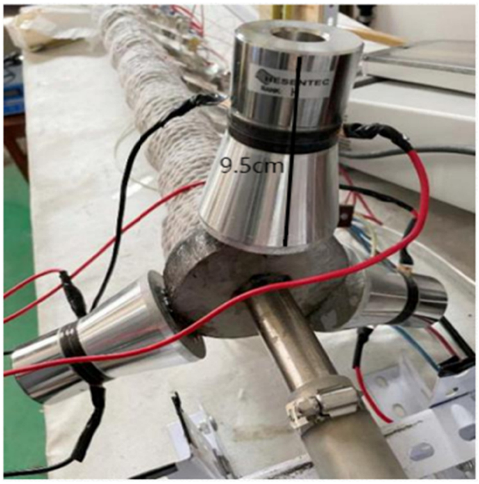

Figure 2: Installation drawing of ultrasonic transducer.

ultrasonic generator and piezoelectric ultrasonic transducer. Selection of different ultrasonic frequencies and number of ultrasonic transducers for the test.

The ultrasonic frequency is selected as 21, 25, and 28 Hz; the number of ultrasonic transducers is selected as 1, 2, and 3; and the ultrasonic transducer is installed as shown in Figure 2.

The test section consists of stainless steel round tube, tube plate, high temperature-resistant ceramic fiber tape, and twisted tape round tube inserted during the twisted tape. The heating section length is 1,200 mm, and the heating section upstream and downstream each left a non-heating stable flow section. The tube plate is welded at the entrance of the round tube, and the whole test section is fully wrapped with high temperature-resistant ceramic fiber tape to achieve the insulation effect and minimize the heat loss of the test process. When the test is conducted in the round tube with twisted belt, the twisted belt is inserted into the tube, and the twisted belt is made of resin material by 3D printing. Figure 3 shows a physical diagram of the insert within the twisted tape used for the test.

The dimensions of the twisted band are as follows: D_t = 12 mm, t_t = 2 mm, P_t = 100 mm, and L_t = 1,200 mm. Figure 4 shows a model diagram of the insert within the twisted band used for the test.

3 Data processing method

3.1 Calculation of Nusselt number

After the heat balance calculation verification, the steady-state convection heat exchange in the test can be assumed

Figure 3: The twisted tape used in the experiment.

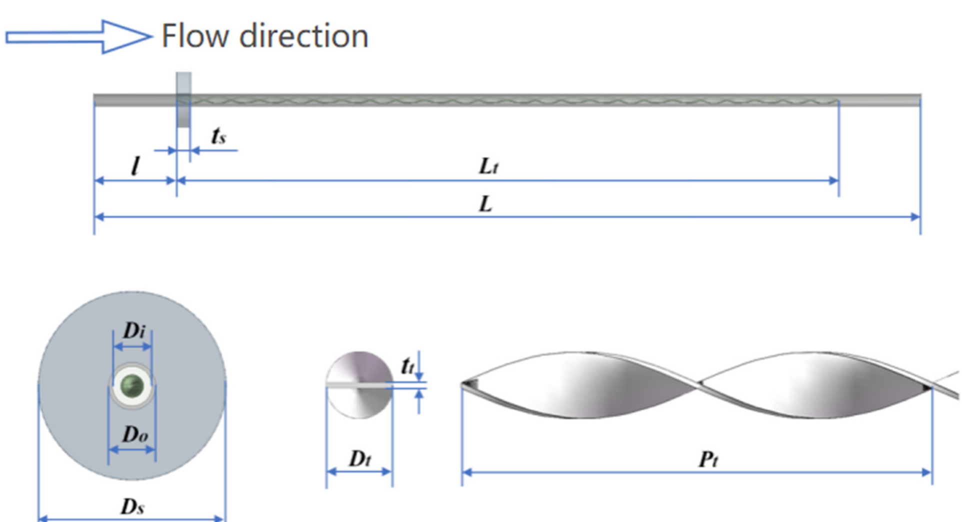

Figure 4: Test segment model.

to be equal to the heat absorbed by the water in the pipe, and the heat balance is expressed as follows:

$$Q_f = Q_{conv}. \tag{3.1}$$

The heat Q_f absorbed by the water in the tube is expressed as follows:

$$Q_f = mc_p(T_{out} - T_{in}), \tag{3.2}$$

$$m = \rho v_{in} A_i, \tag{3.3}$$

where m is the mass flow rate, kg/s; c_p is fixed pressure than heat capacity, J/(kg K); ρ is the density of water, kg/m^3, v_{in} is the inlet flow velocity, m/s; and A_i is the cross-sectional area in the heat transfer tube, m^2.

The steady convection heat exchange Q_{conv} is expressed as follows:

$$Q_{conv} = hA\Delta T_b, \tag{3.4}$$

$$\Delta T_b = \frac{T_{out} - T_{in}}{\ln\left(\frac{T_w - T_{in}}{T_w - T_{out}}\right)}, \tag{3.5}$$

$$T_w = T_{w'} - \frac{Q_{conv}}{2\pi\lambda_{tube}L_t}\ln\left(\frac{D_o/2}{D_i/2}\right), \tag{3.6}$$

where h is the convection heat transfer coefficient, W m^2/K; A is the heat transfer area, m^2; ΔT_b is the log average temperature difference, K; T_w is the inner wall temperature of the heat exchange tube, K; $T_{w'}$ is the outer wall temperature of the heat transfer tube, K; λ_{tube} is the thermal conductivity of the heat transfer tube, W/(m K); D_o is the outer diameter of the round tube, m; and D_i is the inner diameter of the round tube, m.

Combining Eqs. (3.2) and (3.4) can get convection heat transfer coefficient h calculation formula:

$$H = \frac{mC_p(T_{out} - T_{in})}{A\,\Delta T_b}. \tag{3.7}$$

Nusselt number Nu is expressed as follows:

$$\mathrm{Nu} = \frac{hD_i}{\lambda}. \tag{3.8}$$

The Reynolds number Re is expressed as follows:

$$\mathrm{Re} = \frac{\rho D_i v_{in}}{\mu}. \tag{3.9}$$

3.2 Calculation of the friction coefficient

The friction coefficient f is a function of the pressure drop and can be expressed as follows:

$$f = \frac{D_i}{L}\left(\frac{2\Delta p}{\rho v_{in}^2}\right). \tag{3.10}$$

3.3 Calculation of the comprehensive performance evaluation factor

To comprehensively evaluate the ability of strengthening technology, both heat transfer and flow resistance should be considered simultaneously. Some researchers and scholars [30] have proposed the factor PEC to evaluate the overall performance with the following equation:

$$\mathrm{PEC} = \frac{\mathrm{Nu}/\mathrm{Nu}_0}{(f/f_0)^{1/3}}. \tag{3.11}$$

3.4 Experimental uncertainty analysis

The accuracies of K-type thermocouple, Pt100 RTD, rotor flow meter, and U-tube differential pressure meter used in this test were ±0.75%, ±0.1%, ±2.5%, and 5 Pa. The absolute errors of the test parameters are presented in Table 1. In the experimental process, taking into account the experimental errors caused by experimental chance, we utilized the reproducibility of the test and repeated each group of experiments more than six times to ensure that the experimental results were true and reliable. Using the calculation method of Kline and McClintock [31] to calculate the indirect measurement error, the maximum errors of the dimensionless parameters Re, Nu, and f can be obtained as 2.50, 2.62, and 3.20%, respectively, which indicates that the data measured in this test are accurate and reliable. The calculation formula is as follows:

Table 1: Absolute error of the measured parameters

Measured parameter	Instrument name	Absolute error
Heat exchanger diameter	Dial calipers	0.02 mm
Heat exchanger tube length	Tape rule	0.5 mm
Pressure	U-tube manometer	5 Pa
Heat exchanger wall temperature	Type K thermocouple	0.75%T
Fluid inlet and outlet temperature	PT100 RTDs	0.1%T
Fluxes	Rotor flow meter	2.5%Vs

$$\frac{\Delta \mathrm{Re}}{\mathrm{Re}} = \left[\left(\frac{\Delta D}{D}\right)^2 + \left(\frac{\Delta V}{V}\right)^2 + \left(\frac{\Delta \rho}{\rho}\right)^2 + \left(\frac{\Delta \mu}{\mu}\right)^2\right]^{0.5}, \tag{3.12}$$

$$\frac{\Delta \mathrm{Nu}}{\mathrm{Nu}} = \left[\left(\frac{\Delta D}{D}\right)^2 + \left(\frac{\Delta h}{h}\right)^2 + \left(\frac{\Delta K}{K}\right)^2\right]^{0.5}, \tag{3.13}$$

$$\frac{\Delta f}{f} = \left[\left(\frac{\Delta D}{D}\right)^2 + \left(\frac{\Delta \rho}{\rho}\right)^2 + \left(\frac{\Delta L}{L}\right)^2 + \left(\frac{\Delta V}{V}\right)^2 + \left(\frac{\Delta(\Delta P)}{\Delta P}\right)^2\right]^{0.5} \tag{3.14}$$

.

Included among these:

$$\frac{\Delta h}{h} = \left[\left(\frac{\Delta Q_{\mathrm{conv}}}{Q_{\mathrm{conv}}}\right)^2 + \left(\frac{\Delta A}{A}\right)^2 + \left(\frac{\Delta(\Delta T_{\mathrm{b}})}{\Delta T_{\mathrm{b}}}\right)^2\right]^{0.5}, \tag{3.15}$$

$$\frac{\Delta Q_{\mathrm{conv}}}{Q_{\mathrm{conv}}} = \left[\left(\frac{\Delta m}{m}\right)^2 + \left(\frac{\Delta C_{\mathrm{P}}}{C_{\mathrm{P}}}\right)^2 + \left(\frac{\Delta(\Delta T)}{\Delta T}\right)^2\right]^{0.5}. \tag{3.16}$$

4 Analysis of experimental results

4.1 Experimental validation without ultrasound action

In this section, the changes of Nu and f at different Reynolds numbers of twisted tape round tubes and round tubes in the absence of ultrasonic waves are tested, for the comparison of the subsequent tests with the addition of ultrasonic waves. Through this set of experimental results, the strengthening performance of ultrasonic wave is verified, which proves that the experiment is scientific and reasonable.

For the Nu test of round tube and twisted belt round tube, Gnielinski [32] and Sarma [33] formulas are selected for verification:

$$\mathrm{Nu} = \frac{(f/8)(\mathrm{Re} - 1{,}000)\mathrm{Pr}}{1 + 12.7\left(\frac{f}{8}\right)^{\frac{1}{2}}\left(\mathrm{Pr}^{\frac{2}{3}} - 1\right)}\left[1 + \left(\frac{d_{\mathrm{i}}}{L}\right)^{\frac{2}{3}}\right]\left(\frac{\mathrm{Pr}}{\mathrm{Pr_w}}\right)^{0.11}, \tag{4.1}$$

$$\mathrm{Nu} = 0.1012\mathrm{Re}^{2/3}\,\mathrm{Pr}^{1/3}\left(1 + \frac{D_{\mathrm{i}}}{P_{\mathrm{t}}}\right)^{2.065}. \tag{4.2}$$

As shown in Figure 5, the test results are generally in accordance with the empirical equations, and the Nusselt number deviations for both round tubes and twisted band round tubes are within the error range of less than 6%.

For the f test of round tube and twisted belt round tube, the Filonenko [34] and Naphon [35] formulas are selected, respectively, for verification:

$$f = (1.82\lg \mathrm{Re} - 1.64)^{-2}, \tag{4.3}$$

$$f = 3.517\,\mathrm{Re}^{-0.414}\left(1 + \frac{D_{\mathrm{i}}}{P_{\mathrm{t}}/2}\right)^{1.045}. \tag{4.4}$$

As shown in Figure 6, the test results are in good agreement with the empirical equations, and the deviation of f-value is less than 5% for round tubes and less than 6% for twisted band round tubes. According to Figures 5 and 6, it can be concluded that the experimental setup is reasonable for the test of twisted tape round tube and round tube.

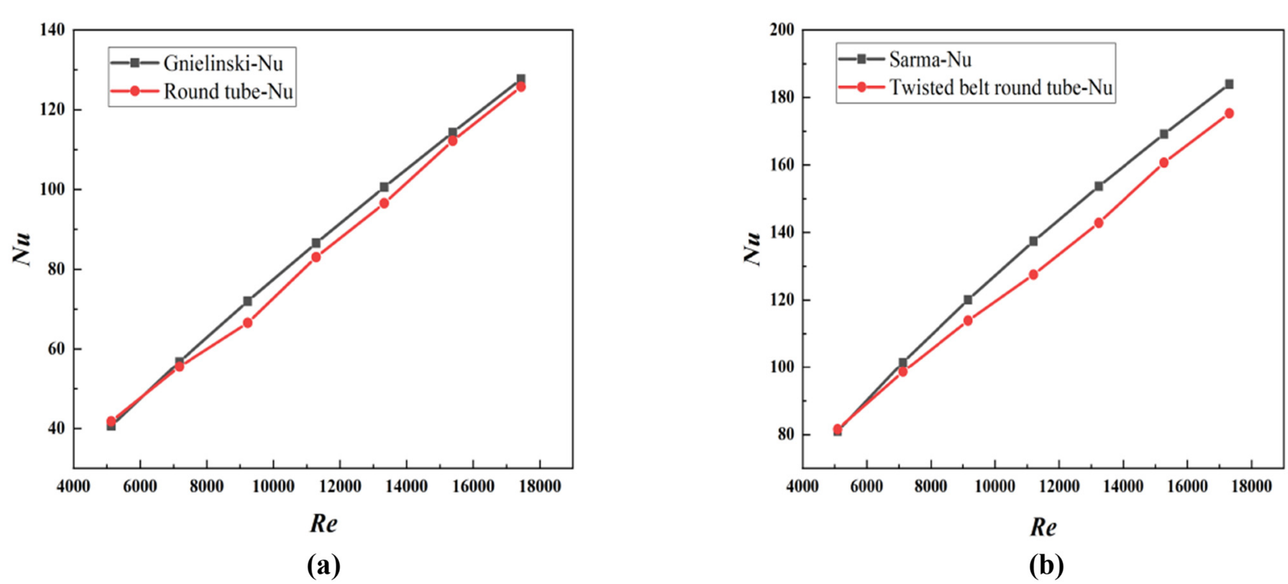

Figure 5: (a) Verification of round tube Nu without ultrasonic and (b) verification of twisted belt round tube Nu without ultrasonic.

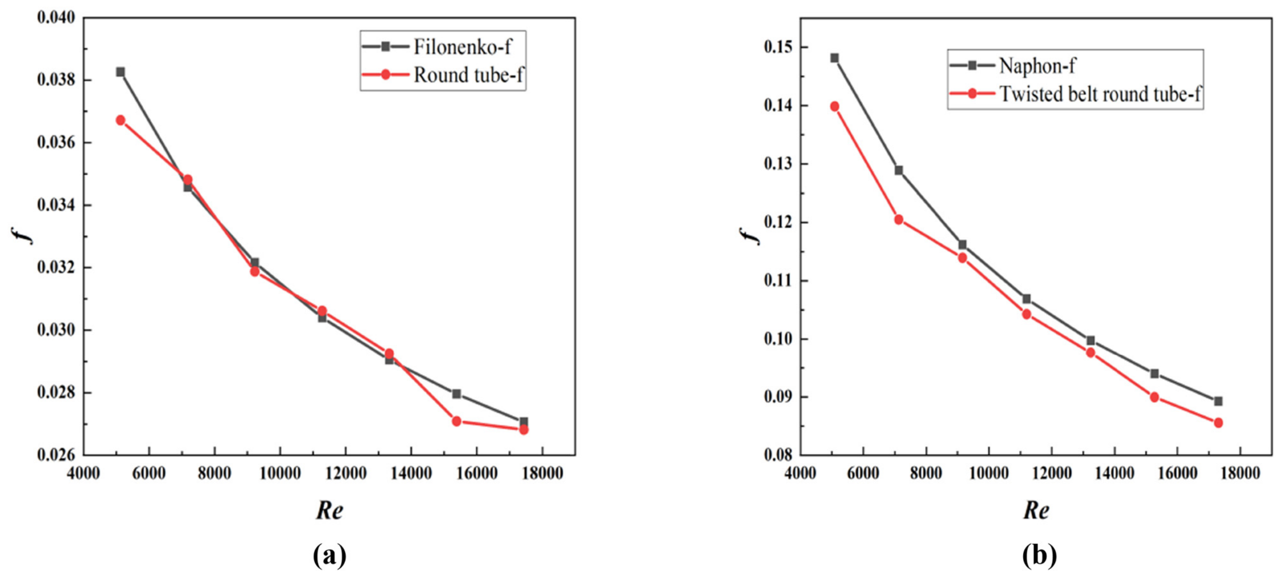

Figure 6: (a) Verification of round tube *f* without ultrasonic action and (b) verification of twisted band round tube *f* without ultrasonic action.

From Figures 5 and 6, it can be seen that after the insertion of the twisted tape in the round tube, Nu increased significantly, but also accompanied by a large increase in flow resistance, and in the test Re range, the maximum increase in Nu of the twisted tape round tube compared with the round tube is 95.33%, accompanied by an increase in the resistance coefficient of 280.67%. This is due to the insertion of the twisted belt after the fluid around the twisted belt to form a spiral flow, extending the flow path, strengthening the wall of the hot fluid and the center of the tube cold fluid mixing, the tube fluid flow rate increases and the formation of the wall of the tube scouring, thinning of the boundary layer, and strengthened convective heat transfer; the insertion of the twisted belt helps the core of the tube fluid to produce a strong perturbation, resulting in the flow blockage and resulting in the increase in the consumption of the pumping power, so the resistance is significantly increased.

4.2 Effect of ultrasonic frequency

For the influence of ultrasonic frequency on the performance of round tube and twisted round tube, the sound

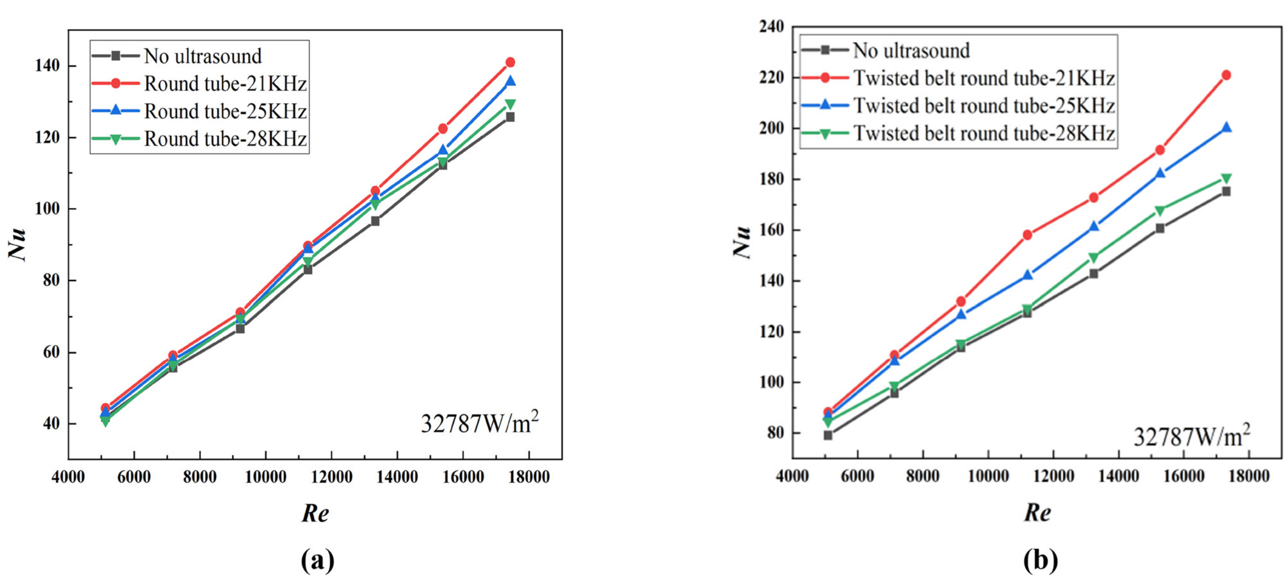

Figure 7: (a) Effect of ultrasonic frequency on tube Nu and (b) effect of ultrasonic frequency on twisted belt tube Nu.

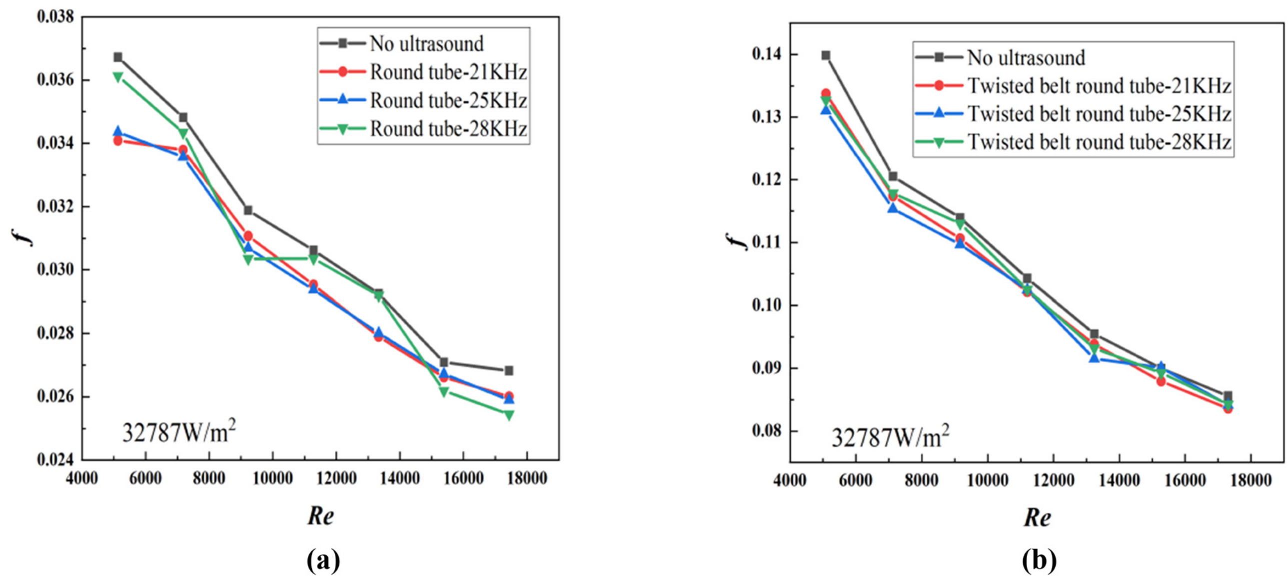

Figure 8: (a) Effect of ultrasonic frequency on round tube *f* and (b) effect of ultrasonic change frequency on twisted belt round tube *f*.

strength of 32,787 W/m^2 is selected for the test. During the test, the performance of the ultrasonic wave was applied with different frequencies, and the Nusselt number, friction coefficient, and comprehensive performance evaluation factor of 21, 25, and 28 kHz, respectively, were selected for the study.

As shown in Figure 7, the application of ultrasonic wave at different frequencies can increase the Nu of the round tube and the twisted round tube. This is because the ultrasonic vibration is transmitted to the heat exchanger tube through the tube plate, ultrasonic wave propagation process in the pipe, and the fluid inside the tube produces cavitation effect, acoustic flow effect, thermal effect and vibration effect, *i.e.*, the rupture of the cavitation bubble destroys the thermal boundary layer. The acoustic flow of the impact enhances the fluid turbulence and the mixing of the fluid near the wall surface, the movement of the plasmas and the friction produces the heat, and the

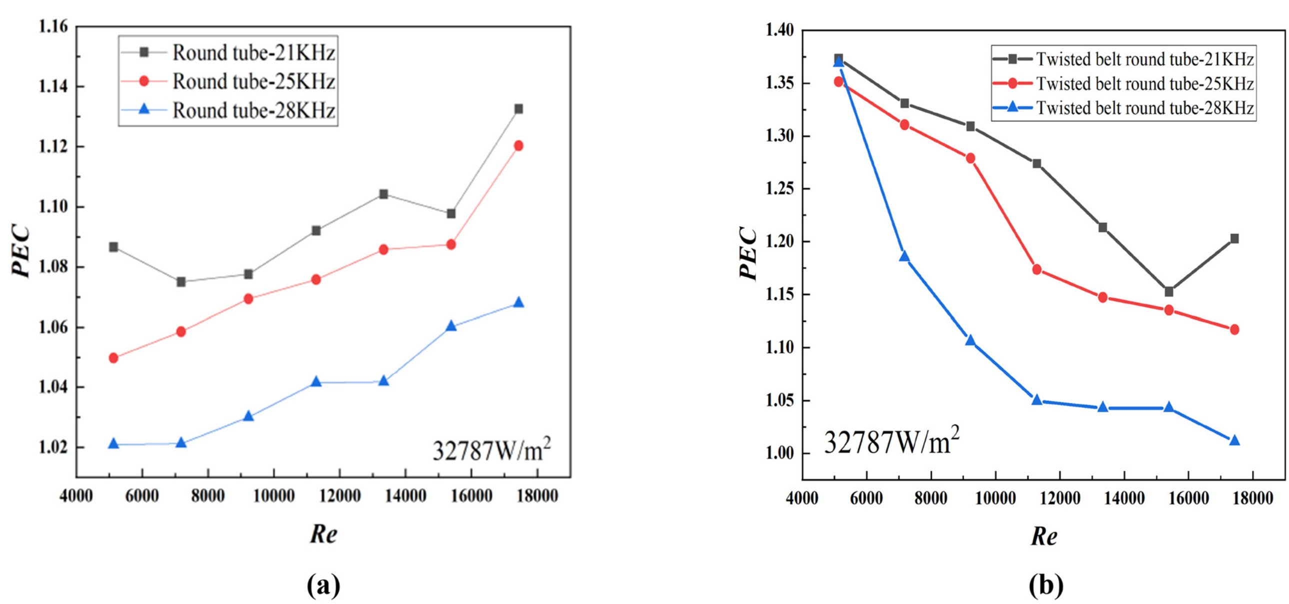

Figure 9: (a) Effect of ultrasonic changing frequency on PEC of round tube and (b) effect of ultrasonic changing frequency on PEC of twisted belt round tube.

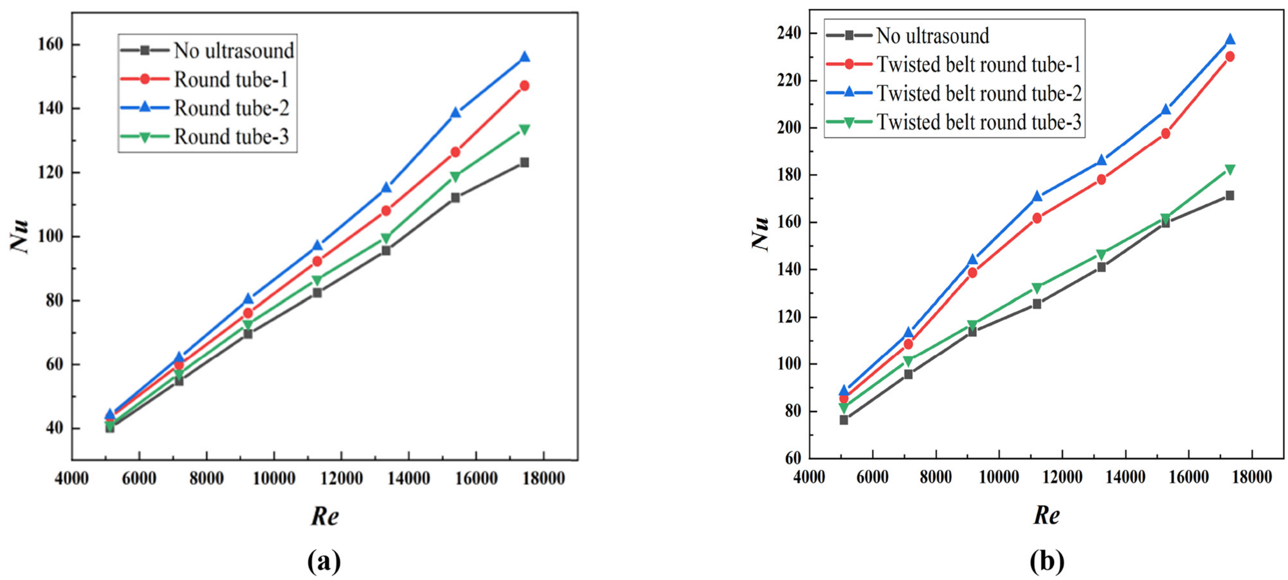

Figure 10: (a) Effect of ultrasonic number on round tube Nu and (b) effect of ultrasonic number on twisted belt round tube Nu.

vibration of the wall surface destroys the boundary layer and thus strengthens the heat transfer. Under the experimental conditions when the ultrasonic frequency is 21 kHz, the maximum increase in Nu is 19.06%; from Figure 8, the variation law of *f* of the heat exchanger tube is independent of whether it is a smooth tube or a round tube with twisted bands, and it decreases with the addition of ultrasonic waves. In Figure 9, we can conclude that the ultrasound of different frequencies can increase the PEC of the round tube, but not obviously, and the ultrasound of different frequencies decreases the PEC of the twisted belt round tube. Synthesizing Figures 7–9 can be analyzed to show that the twisted band circular tube has superior performance compared to the smooth tube.

Ultrasonic enhanced heat transfer capability decreases with the increase of ultrasonic frequency, because with the increase of ultrasonic frequency, the shorter the time required for the acoustic wave to complete a cycle, the cavitation bubble does not have enough time to complete the expansion, compression, and rupture of the process, resulting in a number of cavitation nuclei cannot be developed into cavitation bubbles or cavitation bubbles did not

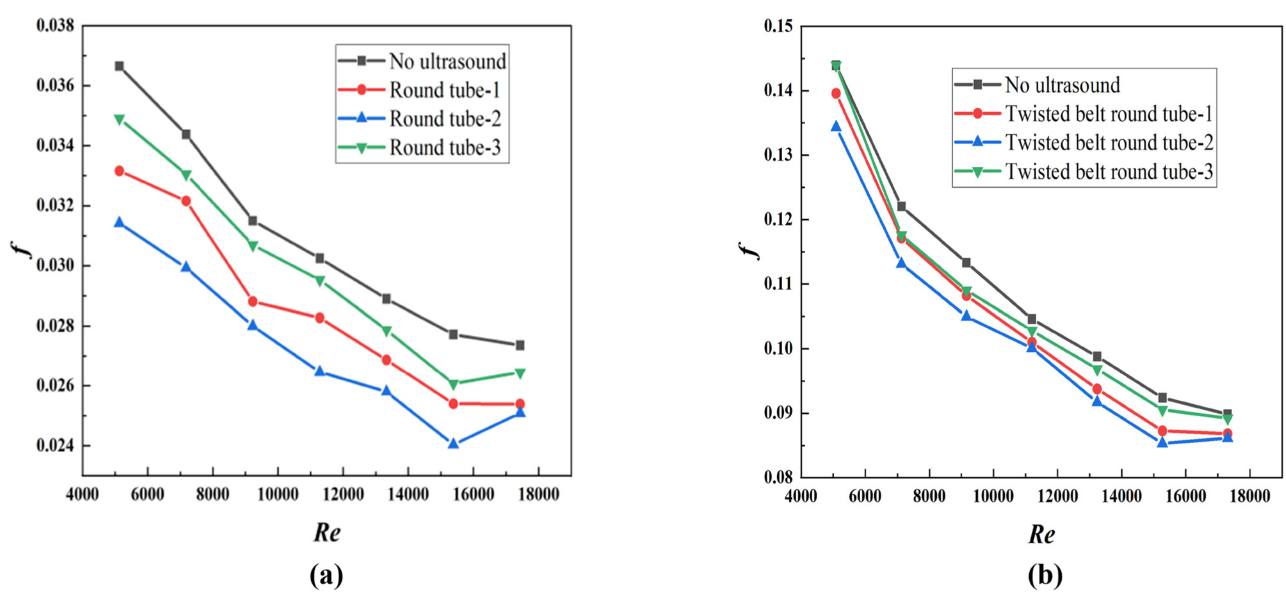

Figure 11: (a) Effect of ultrasonic number on round tube *f* and (b) effect of ultrasonic number on twisted belt round tube *f*.

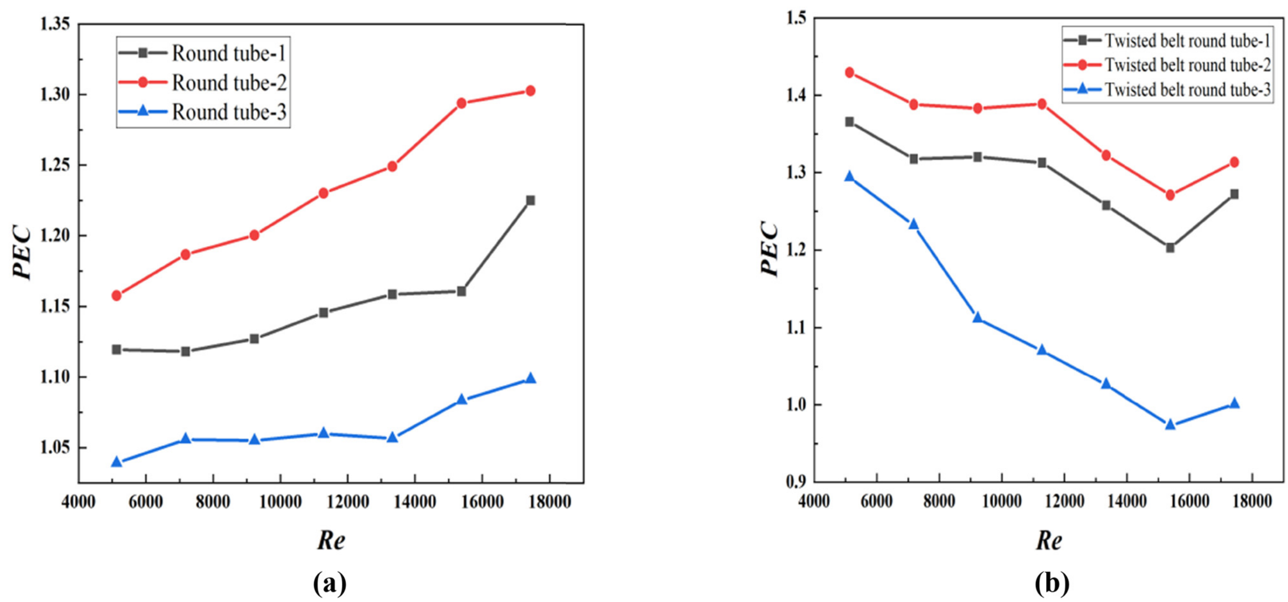

Figure 12: (a) Effect of number of ultrasound on PEC of round tube and (b) effect of number of ultrasound on PEC of twisted belt round tube.

occur in rupture, that is, with the increase of ultrasonic frequency, the more difficult to occur in the cavitation, the cavitation effect becomes weaker, resulting in the enhancement of the performance of the heat transfer with the increase of ultrasonic frequency and the diminution of the heat transfer.

4.3 Influence of the number of ultrasonic transducers

During the test, ultrasonic waves with frequency of 21 kHz and sound strength of 98,361 W/m^2 were selected to study the influence of different ultrasonic transducers on the performance of round tubes and twisted tubes. In the experiment, the number of ultrasonic transducers was 1, 2, and 3.

Figure 10 shows that applying ultrasonic waves increases the Nu of both round and bonded round tubes. When the number of ultrasonic heat exchanger is two, the Nu number is maximum, and the ultrasonic waves enhance the heat transfer performance best. Through Figure 11, it can be learned that applying different ultrasonic heat exchangers to either round or bonded round tubes reduces their friction coefficients, and the best drag reduction is achieved when two ultrasonic heat exchangers are applied. At the number of ultrasonic transducers of 1, 2, and 3, the average values of PEC for ultrasonic round tubes were 1.15, 1.23, and 1.06, respectively, and those for ultrasonic twisted-band round tubes were 1.29, 1.36, and 1.10, respectively, and the values of PEC for both round tubes and twisted-band round tubes were maximal at the time of applying two columns of ultrasonic waves (Figure 12).

5 Conclusion

In the test, we selected different ultrasonic frequencies and the number of different ultrasonic transducers as the test variables for the test, and draw the following conclusions:

1) The effect of ultrasonic frequency: ultrasonic enhancement of heat transfer capacity and comprehensive performance with the reduction of ultrasonic frequency and increase, under the experimental conditions, the Nusselt number of both round tubes and twisted-banded round tubes had the following pattern: 21 kHz > 25 kHz > 28 kHz > no ultrasound, and the maximum increase of Nu was 19.06% when the ultrasound frequency was 21 kHz.
2) Influence of the number of ultrasonic transducers: for this test setup, the order of enhanced heat transfer, drag reduction, and overall performance with the number of ultrasonic transducers are as follows: 2 > 1 > 3, *i.e.*, the heat exchanger tube has the best heat transfer performance and the best resistance reduction performance when the ultrasonic transducers are 2, the largest increase in its Nu was 28.06%.
3) The effect of ultrasonic waves on round tube and twisted tape round tube: the Nu coefficient and friction coefficient of the twisted band circular tube will

increase under the action of ultrasonic waves; in the range of test Re, the Nu of the twisted belt round tube increased by up to 95.33% compared to the round tube, and the *f*-value increased by up to 280.67%. It can be concluded that the twisted band circular tube has better heat transfer performance than the smooth tube.

Funding information The authors state no funding involved.

Author contributions: All authors have accepted responsibility for the entire content of this manuscript and approved its submission.

Conflict of interest: The authors state no conflict of interest.

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