

Research Paper

An active approach to heat transfer enhancement in indirect heaters of city gate stations: An experimental modeling

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ABSTRACT

A major problem with gas pressure reduction stations is the very low thermal efficiency of indirect water bath heaters (IWBHs) used to prevent gas hydration. In this study, an innovative active method based on the ultrasonication technology is investigated to improve heat transfer in IWBHs. Considering the sophisticated thermophysical phenomena involved in this problem and its complex governing equations, a laboratory-modeled ultrasonic heater is used to conduct the experiments. The results have been successfully validated using an empirical relationship. In order to evaluate the effect of ultrasonic vibrations, all the tests were done in two modes, namely without vibration and with vibrating at different ultrasonic power levels. The results show that the positive thermal impact of ultrasonic vibration on increasing the heat transfer rate is more evident at lower fluid flow rates and lower heater power levels. In the current experiments, the maximum value of ultrasonic heat transfer enhancement was evaluated as 166 % at a fluid flow rate of 0.5 LPM and a heater power of 200 W. Findings of this novel research can lead to the efficiency enhancement of existing gas pressure reduction stations and significant energy savings.

1. Introduction

Natural gas is one of the main sources of energy thanks to its unique features, such as low pollution, wide availability in nature, adequate heating value, and easy transfer. Despite the possible risks, the natural gas has been welcomed by many countries in the world [1]. Considering the increasing demand for gas resources, providing solutions to reduce gas consumption has been one of the main concerns of researchers in this field.

The City gate station (CGS) is a critical component where significant gas wastage occurs. In CGS, high-pressure gas from transmission lines undergoes controlled depressurization to a specific level (250 psi). However, this process poses risks, particularly during colder seasons. The Joule-Thomson effect explains that reducing the gas pressure through the choke valve leads to a substantial decrease in temperature. If the passing gas reaches temperatures below the threshold for gas hydrate formation, it can freeze and potentially block transmission lines or damage station facilities. To address this issue, preheating of the gas is

performed prior to pressure reduction in CGSs. Line heaters, which function as indirect water bath heat exchangers (IWBH), utilize water as a safe medium for transferring heat from fire tubes to serpentine coil pipes containing the flowing gas [2,3]. A portion of the passing gas is burned to generate the energy required for this process. However, an inherent problem arises at this stage due to low thermal efficiency (below 40 %) caused by reliance on natural convection mechanisms for indirect heat transfer [4].

This study focuses on enhancing heat transfer through ultrasonic vibration (UV), which has been recognized as an advanced active method for improving heat transfer since the 1960 s. Previous research by Larson [5] and other scholars [6] has reported a significant increase in heat transfer rate (HTR) when UV is present, both in forced convection and natural convection scenarios. Niemczewski's investigation [7] into cavitation intensity during industrial cleaning processes revealed that air content and fluid temperature have a notable impact, with tap water exhibiting maximum cavitation intensity at temperatures below 20°C. Mont et al. [8] conducted experiments using a test device

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comprising a reactor, a cooling coil, and an ultrasonic transducer placed at the bottom of the reactor to study the effects of UV. Their findings demonstrated that the heat transfer enhancement (HTE) depends on wave frequency, heater power level, and flow rate. HTE could be defined as the ratio of the heat transfer rate in the presence of ultrasound divided by its value in silent conditions. Notably, exposure to ultrasonic fields led to a remarkable 100 % increase in the convective coefficient within the coil. Furthermore, they explored how flow velocity influenced the HTE at a frequency of 1.6 MHz and observed its noteworthy effect on the heat transfer coefficients inside the coil.

Yao et al. [9] focused on the HTE of a shell-and-tube HE by UV. Two parameters of flow rate and inlet water temperature are investigated. They reported that increasing the water flow in the pipe and decreasing the ultrasonic power led to the reduction of the HTR. Acoustic cavitation was introduced as the main cause of turbulency in the fluid flow. The HTE of a shell-and-tube HE under low-frequency UV was examined by Gondrexon et al. [10]. Experimental tests showed that UV could increase the HTR in both shell and tube sections of HE. A vibrating double-tube HE has been tested by Legay et al. [11]. They reported that UV decreases the convective thermal resistance and leads to HTE of the thermal system. A comparison between ultrasonic vibrating double-pipe and shell-and-tube HEs was also accomplished by Legay et al. [12]. The results confirmed that the shell-and-tube HE performed relatively better. Tam et al. [13] applied UV onto a horizontal tube with laminar water flow. Both entrance and fully developed regions' heat transfer coefficients were studied. They claimed that the ultrasonic thermal effect is more highlighted in the entrance region. In this study, HTE ranges from 1.3 % to 23.7 %. Nomura et al. [14] investigated the impact of UV on a water vessel and showed that ultrasonic waves and pressure distribution could affect heat transfer. Amiri Delouei et al. [15] directed a laboratory test to assess the UV impact on HTE and pressure drop of an internal turbulent flow. The test section was considered to be a straight vibrating tube that was immersed in a two-phase fluid. It was reported that there is no considerable change in HTE and pressure drop in their turbulent flows compared to a laminar flow regime [15]. Bulliard-Sauret et al. [16,17] conducted studies on the increase of forced convection under UV with frequencies of 25 kHz and 2 MHz. They stated that the HTE at high frequency (2 MHz) decreased with increasing Reynolds number because of poor acoustic streaming. They explained that acoustic streaming and acoustic cavitation are the main causes of ultrasonic HTE at high and low frequencies, respectively. In this study, unlike most previous work, an increase in the thermal effect of UV with a frequency of 25 kHz has been reported at higher Reynolds numbers [16]. Furthermore, Poncet et al. [18] continued the Bulliard-Sauret et al. [16] experiments. They investigated the effect of the simultaneous application of low-frequency (25 kHz) and high-frequency (2 MHz) ultrasound on forced heat transfer. Also, UV is applied in two conditions perpendicular to the direction of the current and parallel to the direction of the current. The results show that the use of UV with dual-frequency has a synergetic effect, and the HTE can be better than the sum of the increase due to the independent application of single-frequency vibrations. They report that in the optimal case, the local HTE factor could increase up to 366 %. Setareh et al. [19] studied the convection improvement in a double-tube HE under the effect of UV both numerically and experimentally. UV is applied to the inner tube of heat. The results displayed a growth in the outlet cold water temperature and a reduction in the outlet hot water temperature by increasing the ultrasonic power level. Numerical simulation showed that cross-stream flows resulting from the propagation of UV into the cold fluid have the main role in HTE. Setareh et al. [20] continued their investigation by testing an annulus under constant thermal boundary conditions. In this experiment, the heat transfer between distilled water flowing in the inner pipe and saturated vapor flowing in the outer pipe is investigated in the presence of UV with a frequency of 25.7 kHz. They reported an HTE equal to 87 % and 25 % in the Reynolds numbers of 32 and 674 for ultrasonic power of 100 W, respectively. Recently, Azimy et al. [21] studied the impact of UV on the

heat transfer coefficient of a HE. The heat exchanger consists of a straight rectangular tube, and the ultrasonic transducer is located on the HE's wall. Due to the designed structure, UVs are transmitted directly to the water flow, and the authors claimed that this improves the efficiency of the vibrating HE. Also, recent research has been done on the effect of UV on improving heat transfer in fin-and-tube HEs used in automobiles [22,23] and CPU water cooling systems [24,25]. The results indicated the improvement of heat transfer in this type of HE due to the application of UV. Furthermore, recent research conducted by Hedeshi et al. [26] explored the impact of ultrasonic vibration on Heat Transfer Enhancement (HTE) in double-pipe heat exchangers utilizing nanofluid. The findings demonstrated a significant enhancement in heat transfer efficiency with increasing concentrations of nanofluid. Additionally, Esfandyari et al. [27] presented an optimization study focusing on this specific type of heat exchanger, considering the effects of ultrasonic vibrations and other parameters to improve its performance.

While UV technology has found widespread application in water tank cleaning, its potential to enhance heat transfer in IWBHs is yet to be adequately investigated. The current experimental study demonstrates the applicability and innovation of using ultrasonic vibrations as an active method for improving heat transfer in IWBHs.

Here the focus is on comparing two different cases: (1) no vibration during the preheating process (using CGS heaters), and (2) in presence of ultrasonication during the preheating process. Unlike passive methods, the addition of a vibrating system to the water tank does not require any modification to the existing heater design. Although previous research has examined the impact of ultrasonic waves on HTR in different types of heat exchangers with varying structures, these studies have produced disparate results even within similar thermal systems [21]. Consequently, further laboratory investigations are necessary to comprehensively understand the complex heat transfer mechanisms across different types of heat exchangers. Trying to address the insufficiency of information on possible thermal effects of ultrasonic vibrations in CGS heaters, this study represents the first attempt to fill in this research gap.

2. Experimentation

In this section, the fabrication of the required apparatus in the laboratory is presented. The current setup is dimensionally modeled based on a real CGS heater with a capacity of 2500 standard cubic meters per hour (SCMH) at a scale of 1:4. This particular heater is located in Bojnord city, North Khorasan Province, Iran. Fig. 1 shows the schematic illustration of the different equipment of the current setup. During the simulation of the experimental device, dimensional analysis should be employed to establish similarity.

Regarding the governing equations and also previous studies in this field, three dimensionless groups were Recognized: Reynolds number (Re), length-to-diameter ratio (L/D), and Euler Number ($\Delta P/\rho v^2$) [28,29]. In this regard, in addition to selecting an appropriate scale, efforts have been made to bring the Reynolds number of fluid flowing through the helical coil pipe closer to the range of real Reynolds numbers. Furthermore, the pressure in both laboratory and real samples is equal to atmospheric pressure. It is important to acknowledge that due to limitations in the laboratory and considerations for health, safety, and environmental (HSE) factors, only an incomplete similarity could be achieved in this study. However, even with this incomplete similarity, it was possible to predict the variation trends in thermal parameters under ultrasonic vibrations.

2.1. CGS heater dimensional modeling

The first step in the construction of the equipment required for the present setup is the dimensional modeling of the heater. The modeled heater consists of three main parts: (1) heater body, (2) serpentine coil pipe, and (3) heating system. The laboratory model is made on a scale of 1:4 compared to the real heater. Based on this, a tube (length = 375 mm

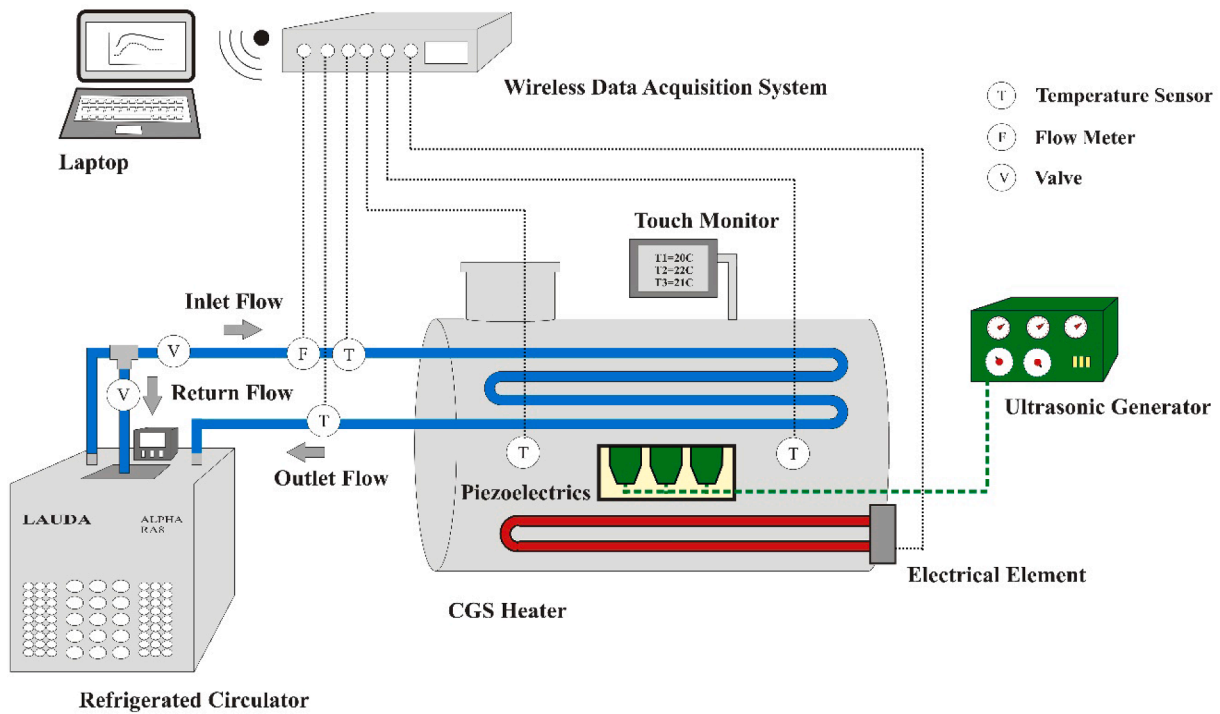


Fig. 1. Schematic of the IWBH and the laboratory equipment.

and diameter = 160 mm) was used to make the body of the laboratory model. Two flanges are attached to this circular tube to seal the water storage tank of the CGS heater. Six holes, along with the bushings welded to them, have been created around the CGS heater body to install five temperature sensors inside the tank and also to exit the cables related to the submerged piezo-electrics. Several copper tubes connected to the bushings of the main body have been used for the correct and stable placement of the temperature sensors inside the heater tank. Copper pipes with a diameter of 1/2 in. have been used to make the serpentine coil pipe.

The length of the serpentine coil inside immersed in water is about 1800 mm. The high thermal conductivity of copper pipes makes it possible to measure the thermal changes with more resolution. Fig. 2 shows the different parts of the IWBH equipped with ultrasonic piezo transducers. Water is used as the working fluid in the serpentine coil pipe. A high-precision refrigerated circulator is used to make fluid flow at a constant temperature and flow rate at the inlet of the modeled CGS

heater. The specifications of this circulator are shown in Table 1.

Unfortunately, the circulator pump works at a fixed speed. To adjust different flow rate values at the inlet of the serpentine coil, a three-way branch, including a way back to the tank at the water outlet from the circulator (Fig. 1), has been used. The flow rate of the water flowing into

Table 1
Specifications of the refrigerated circulator, Lauda Alpha RA8.

Minimum working temperature	-25 °C
Maximum working temperature	100 °C
Minimum ambient temperature	5 °C
Maximum ambient temperature	40 °C
Temperature stability	±0.05 K
Heater power	1.5 kW
Cooling output (at -25 to 20 °C)	0.03–0.225 kW
Power consumption	1.8 kW
Minimum bath volume	5 Liter

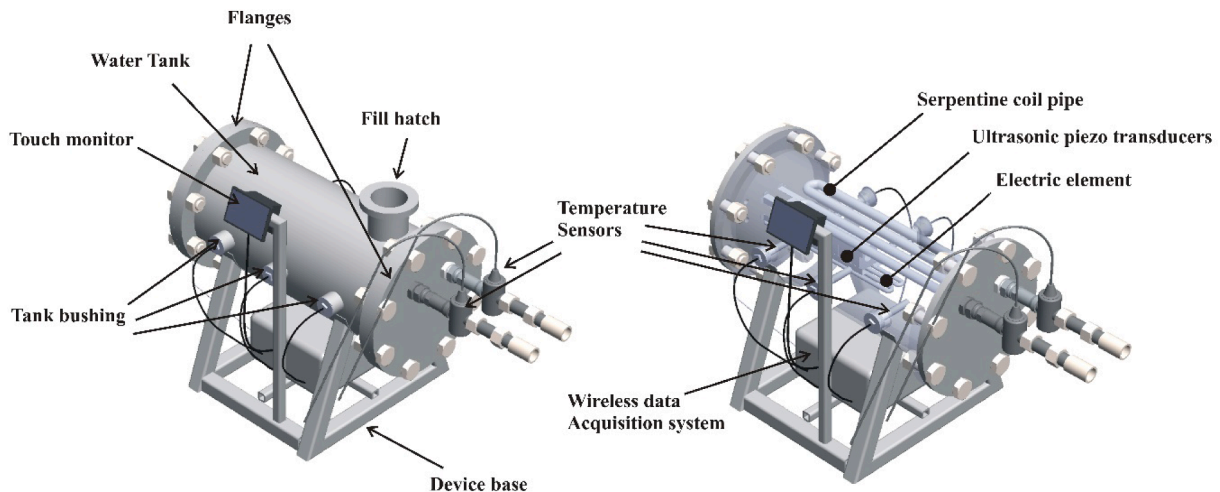


Fig. 2. The main body of the modeled heater equipped with ultrasonic piezo transducers.

the heater could be adjusted by manipulating a valve on the return path. In the laboratory model, an electric modulus operating a power of 2000 W was used to heat the water inside the tank. This offered several advantages, including better control and more accurate measurement of energy consumption compared to gas-fueled fire tubes. The prepared element is assembled on one of the flanges and can be controlled by a dimmer (Fig. 2). Using the specified software prepared for this purpose (section 2.3), it is possible to accurately adjust the heater power between 10 % and 100 % of nominal power.

2.2. Ultrasonic vibration system

The ultrasonic vibration generation system used in this work consisted of two main parts: (1) an ultrasonic generator and (2) immersed piezoelectric transducers. Three piezoelectric transducers with a frequency of 40 kHz and a power of 60 W were considered to stimulate the fluid inside the tank. The value of ultrasonic intensity is in the range of 4.1–8.2 kW/m² during the current tests. A sealed metal box is used to transmit the vibrations of the piezo components to the fluid inside the tank. This box is made of steel plates with a low thickness of 0.5 mm. The piezoelectric transducers are attached to the submersible box body by means of screws. This box is placed in the space between the electric element and the serpentine coil pipe (Fig. 2). The ultrasonic generator used has the ability to vibrate piezoelectric transducers with 50 % and 100 % of nominal power.

2.3. Control and data recording system

The control and data recording system consists of three main parts, including (1) accurate measurement equipment, (2) microcontrollers, and (3) display equipment and software. To determine the average temperature of the heater tank, a total of five temperature sensors were utilized. As mentioned earlier, these sensors were positioned within the tank using copper pipes connected to the bushings (refer to Fig. 2). The sensors were placed in two specific locations: at the center of the heater tank and at a distance of 45 mm from the flanges. Additionally, two similar sensors were installed at both ends of the serpentine coil pipe, maintaining a distance of 50 mm from one of the flanges (refer to Fig. 2). In addition, a temperature sensor is provided to measure the ambient temperature. Furthermore, a flow meter is installed at the inlet of the serpentine coil pipe. All sensors are calibrated before installation. A 2.3-inch full-color TFT touchscreen is installed on the heater to monitor and set the values of temperatures and flow rate of the setup directly.

In addition, it is possible to send information wirelessly to the computer system. The data can be received and stored as an Excel file. Table 2 shows the specification of the setup components in detail. It should be noted that due to limitations in laboratory simulations, especially safety considerations, it is not possible to achieve complete

Table 2
Specification of the setup components.

	Type (Manufacturer)	Accuracy	Measuring/ operating range
Temperature Sensors	DS18B20 (Maxim Integrated Co.)	± 0.5 °C	−55 - +125 °C
Piezo Electrics	HS-8SH-3840 (Hesentec Ultrasonic Co.)	± 0.5 %	40 kHz
Ultrasonic Generator	Ultrasonic PCB Driver (Hesentec Ultrasonic Co.)	± 0.5 %	60 W
Flow Meter	NT5 (Nixon Flow MeterLTD Co.)	± 5 %	1.2–10 l/min
Electric Element	9000133–045 (Reliance)	± 0.5 %	2000 W
Refrigerated Circulator	Alpha RA8 (Lauda)	± 0.05 K	− 25 to + 100 °C

similarity between the experimental sample and the real-world sample.

2.4. Experimental procedure

To evaluate the HTE resulting from the ultrasonic vibrations, it is necessary to compare the heat transfer enhancement before and after applying these vibrations. The laboratory system ensures a constant temperature at the inlet of the pipe containing the test fluid. This is achieved using a precise circulator equipped with separate refrigerator and heater components, as described in section 2.1.

Once both temperature and inlet flow rate into the coil are set, sufficient time is allowed for steady-state operation. Data related to coil outlet temperature, as well as measurements from sensors embedded inside the reservoir and ambient temperature sensor, are recorded during this vibration-free state phase. Next, using developed software, half-power piezoelectric transducers (rated at 90 W) are activated. The system again reaches steady-state condition under ultrasonic vibrations while data specific to this vibration state at 90 W power level is recorded. The same procedure is repeated for full power mode (180 W). Taking advantage of different fluid flow rates that can be created within specified ranges of 0.5–3.0 LPM allows us to explore various conditions. After conducting experiments for specific flow rates under different ultrasonic powers and electric heater power levels, all setups are turned off so that reservoir temperature returns back to its initial state while maintaining constant environmental conditions.

Once all data points have been collected during these experiments, thorough investigations will be conducted on various parameters affecting heat transfer. It should be mentioned that each test was repeated three times to ensure the repeatability of the experiments.

2.5. Uncertainty analysis

The uncertainty test is of great importance in experimental studies owing to the measurement error related to each instrument. In the current experiments, the uncertainty analysis method proposed by Moffat [30] is utilized. The result ζ of the test can be assumed as a function of the independent variables ($\chi_1, \chi_2, \dots, \chi_n$) as follow:

$$\zeta = \zeta(\chi_1, \chi_2, \dots, \chi_n) \quad (1)$$

Moffat [30] introduced Eq. (2) to calculate the dependent variable (ζ) uncertainty.

$$\delta\zeta = \left[\left(\frac{\partial\zeta}{\partial\chi_1} \delta\chi_1 \right)^2 + \left(\frac{\partial\zeta}{\partial\chi_2} \delta\chi_2 \right)^2 + \dots + \left(\frac{\partial\zeta}{\partial\chi_n} \delta\chi_n \right)^2 \right] \quad (2)$$

in Eq. (2), $\delta\zeta$ is the dependent variable's uncertainty, and $\delta\chi_1, \delta\chi_2, \dots, \delta\chi_n$ are the independent variables' uncertainty related to function ζ . As it is described in section 2.1, information on the accuracy of the equipment is obtained from the suppliers. Table 3 presents the uncertainties for effective parameters in the current experiment.

3. Results and discussion

In this part, the results of experimental tests have been analyzed at different fluid flow rates, different heating power levels (HP) controlled by the electric element, and different ultrasonic power levels (UP). The results are validated by the available empirical correlation. These tests examine the influence of UVs on the heat transfer parameter, such as the

Table 3
Uncertainty of effective parameters.

Parameter	Uncertainty
Re	±4.9 %
Nu	±3.8 %
HTR	±3.2 %

outlet temperature, convection coefficient, and HTR.

In general, four main phenomena caused by the presence of UV in a fluid medium, include 1-heating, 2- acoustic cavitation, 3- acoustic streaming, and 4- nebulization [31]. Nebulization occurs only at high frequencies. Also, the first phenomenon is caused by the mechanical energy of the ultrasonic waves. The heating is noticeable at the very high powers of the ultrasonic source and is not dominant in the current study. Therefore, acoustic streaming and acoustic cavitation phenomena have been proposed as the main reasons for HTE in many previous studies [31].

When the local pressure of a liquid is reduced enough below its vapor pressure, gas bubbles are formed. These bubbles can oscillate, grow, and finally collapse powerfully. Acoustic cavitation is defined as the process of the formation, growth, fluctuations, and violent collapse of gas bubbles in a liquid [32,33]. Acoustic streaming was first introduced by Lighthill [34]. He claimed that acoustic energy dissipation causes momentum gradients and makes fluid currents in the solid-liquid interfaces. Acoustic streaming and acoustic cavitation lead to changes in the velocity and thermal boundary layers, thereby affecting the thermal resistance.

For the analysis of the experimental data, the nondimensional parameters of Reynolds number (Re) and Nusselt number (Nu) are defined as follows [35]:

$$Re = \frac{UD}{\nu} \quad (3)$$

$$Nu = \frac{hD}{k} \quad (4)$$

where U , ν , and h refer to the velocity, viscosity, and convection coefficient of the fluid, respectively. Also, k and D represent the conduction coefficient, and the circular serpentine coil pipe's diameter, respectively. Reynolds and Nusselt numbers are presented for the internal fluid flow of the serpentine coil pipe. The convection coefficient could be calculated by mean temperature or log mean temperature difference (LMTD) approaches [36]:

Mean temperature method

$$h = \frac{q}{A \left[\bar{T}_T - \left(\frac{\bar{T}_i + \bar{T}_o}{2} \right) \right]} \quad (5)$$

LMTD method

$$h = \frac{q}{A \left[\frac{\bar{T}_i - \bar{T}_o}{\ln \left(\frac{\bar{T}_T - \bar{T}_i}{\bar{T}_T - \bar{T}_o} \right)} \right]} \quad (6)$$

where, \bar{T}_i and \bar{T}_o refer to the serpentine coil pipe's inlet and outlet temperatures, respectively. \bar{T}_T is the temperature of the CGS heater's water tank. A indicates the surface area of the pipe. Also, the HTR could be calculated by the energy balance relation as follows:

$$q = \dot{m}c_p(\bar{T}_o - \bar{T}_i) \quad (7)$$

here, \dot{m} and c_p represent the mass flux and heat capacity at constant pressure, respectively.

3.1. Validation of the results

The investigation of heat transfer in IWBH, such as those in CGS stations, has a very small share compared to other types of heat exchangers. Most of the studies in this field have been done in Iran, and the results have not been validated. However, in a few similar studies [37], an experimental correlation known as the Dittus-Boelter equation [35,38] is utilized. This relation is applicable for both cooling and

heating of heat exchangers with circular tubes:

$$Nu = 0.023Re^{0.8}Pr^n, \begin{cases} n = 0.4 \text{ for heating} \\ n = 0.3 \text{ for cooling} \end{cases} \quad (8)$$

The comparison of the present results with the Dittus-Boelter equation [35,38] indicates the acceptable accuracy of the experimental measurements (Fig. 3).

3.2. Variation of outlet temperature

As discussed earlier in the introduction, employing UV leads to heat transfer improvement in heat exchangers. Acoustic streaming is a common phenomenon observed during the propagation of ultrasonic waves in a fluid [39]. As for acoustic streaming, one can refer to Eckart and Rayleigh streaming's as two of the foremost streaming patterns [40,41]. As for the former, since there is acoustic pressure attenuation in the bulk of fluid, it is a large-scale flow. However, viscous forces in the acoustic boundary layer would lead to Rayleigh's. This type of streaming can be categorized into inner and outer streaming. Actually, the latter owing to the small thickness of the boundary layer is more noticeable. Zarembo [42] pointed out that distinguishing these types of streaming is relatively stiff, and he stated that all types of streaming could happen simultaneously. Also, it is stated that various types of acoustic streaming can show common dependence on the various parameters, especially the sound intensity, so it would make it difficult to distinguish the dominant one. It is noteworthy to add that, in inner circulated flows via a pump, the increase in heat transfer because of acoustic streaming is slight, and the most significant share is related to bubble formation [11]. The UV can stimulate both the inner and outer zone of the serpentine coil pipe. The vibrations can mix fluid adjacent to the solid wall and would boost the convective heat transfer [39].

Fig. 4 shows the outlet temperature from the serpentine coil pipe in terms of the fluid flow rate inside this coil. Furthermore, the variation percentage of the difference in inlet and outlet temperatures (TVP%) is presented in these figures. TVP% is defined as follows:

$$TVP\% = \frac{\Delta \dot{T}_{Up} - \Delta \dot{T}_0}{\Delta \dot{T}_0} \times 100 \quad (9)$$

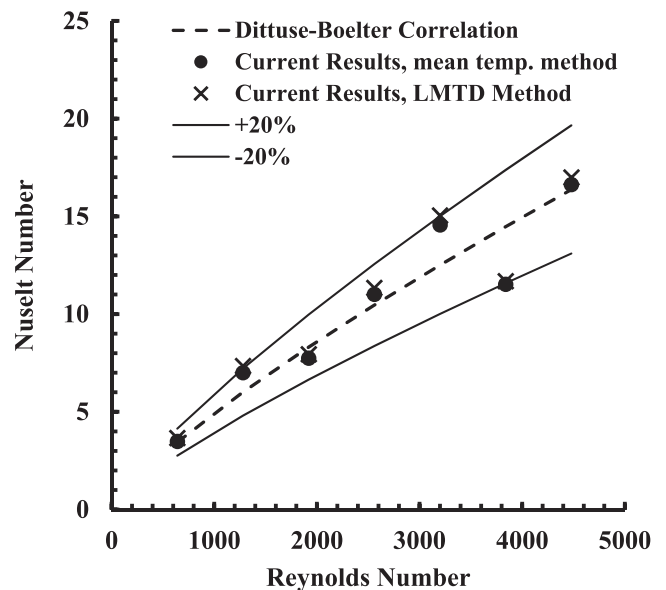


Fig. 3. Nusselt number values derived from our experimental results and those predicted by the Dittus-Boelter empirical correlation [38]. The laboratory findings from the current study are found to be consistent with the empirical correlation.

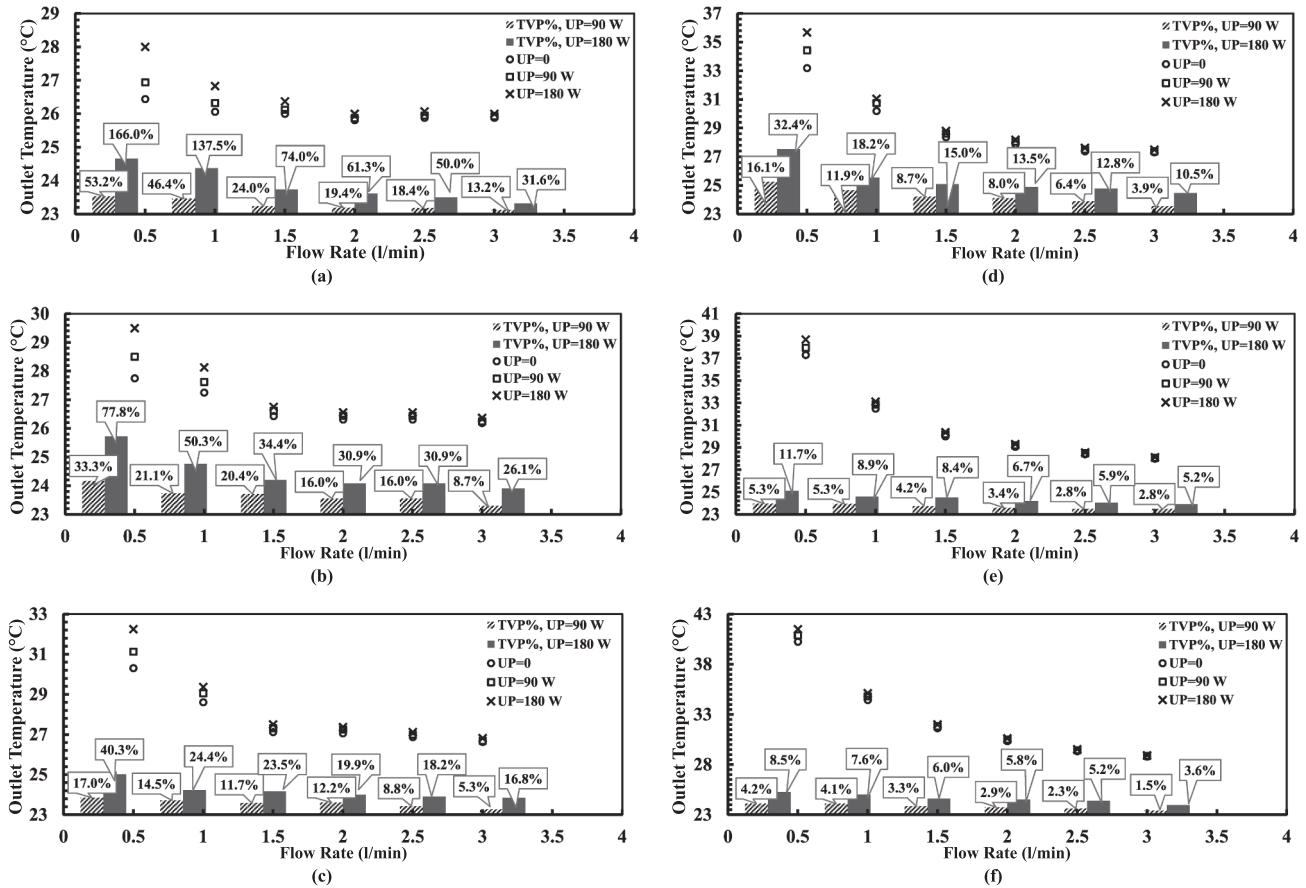


Fig. 4. Outlet temperature of serpentine coil pipe versus flow rate in different electric heat power levels of (a) 200 W, (b) 400 W, (c) 600 W, (d) 800 W, (e) 1000 W, and (f) 1200 W. The experiments are done at $T_i = 25.5^\circ\text{C}$. The results show that the increasing heating power level and fluid flow rate have negative effects on the ultrasonic heat transfer improvement.

where $\Delta\dot{T}_0$, and $\Delta\dot{T}_{UP}$ refer to temperature differences in the absence and presence of the ultrasonic vibration, respectively. Fig. 5a-5f are presented for different heating power levels of 200, 400, 600, 800, 1000, and 1200 W, respectively. In each of these figures (at constant heating power level), the outlet temperature variation is investigated in three states of (1) no vibration ($UP = 0$), (2) vibration with $UP = 90$ W, and (3) $UP = 180$ W.

Regarding these figures, the effect of the UV on the outlet temperature variation generally reduces with the increase of the fluid flow rate in all values of the ultrasonic power levels. Furthermore, the thermal effect of UV is more noticeable in lower heater power levels. In other words, the effect of UV decreases by increasing the heating power level.

Based on the available information, we can deduce that at lower flow rates, which are associated with lower Reynolds numbers, the impact of acoustic cavitation and boundary layer mixing within the serpentine coil pipe is expected to be more pronounced. This inference suggests that as fluid flow slows down, the phenomena of acoustic cavitation and boundary layer mixing become increasingly influential. At these reduced flow rates, it is likely that the formation and collapse of gas bubbles induced by acoustic cavitation will have a more significant effect on heat transfer processes within the serpentine coil pipe. The violent collapse of these bubbles generates localized pressure fluctuations and intense energy dissipation, leading to enhanced mixing between different fluid layers. Consequently, this increased mixing promotes efficient heat exchange between the flowing medium and the surrounding surfaces. It is worth mentioning that the observed trend of change in the outlet temperature concerning the flow rate bears similarity to the corresponding trend in the study conducted by

Dhanalakshmi et al. [43] for the heat transfer in furnace tubes in the presence of an ultrasonic field.

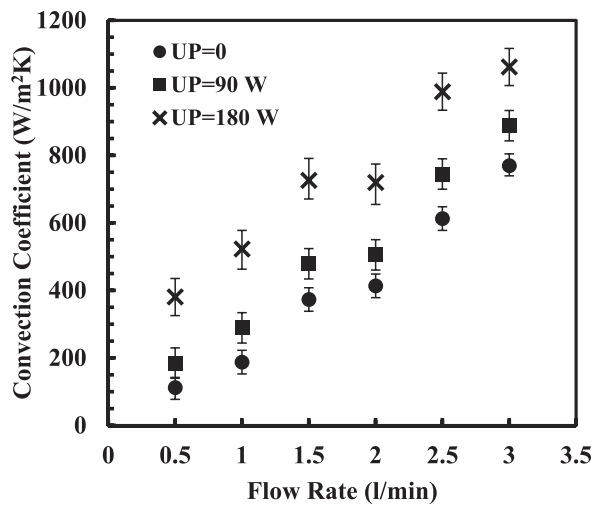
3.3. Variation of convection coefficient

Fig. 5 shows the variations of convective coefficient in three cases of $UP = 0, 90$, and 180 W. In this section, the convection coefficient variation percentage (CVP%) is defined as follows:

$$CVP\% = \frac{h_{UP} - h_0}{h_0} \times 100 \quad (10)$$

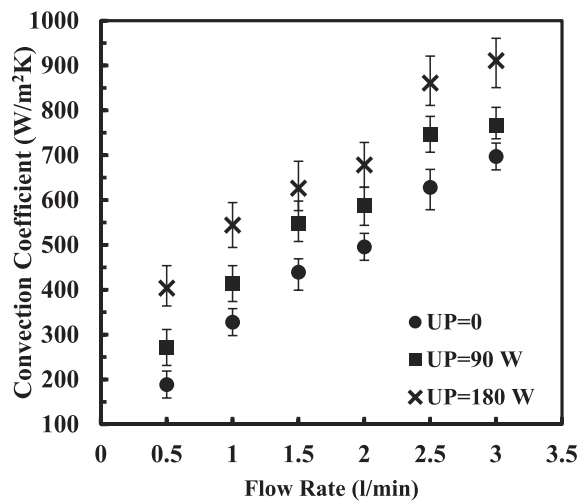
where h_0 , and h_{UP} refer to the convection coefficient in the absence and presence of the UV, respectively. CVP% for the heater power levels of 200, 400, 600, 800, 1000, and 1200 W are also shown in Fig. 6a to 6f, respectively. As it is clear from these figures, with the increase of the flow rate, the value of the convective coefficient increases, but the effect of the presence of UV will decrease for all the values of the ultrasonic power levels. Similar to the trend seen in Fig. 4, the effect of UV in the higher heater power levels is less noticeable. As previously mentioned, the observed trend can be attributed to two main factors: an augmentation in acoustic cavitation and enhanced boundary layer mixing within the serpentine coil pipe.

It is evident that as the ultrasonic power level escalates from 90 to 180 W, the intensity of these phenomena - acoustic cavitation and boundary layer mixing - also intensifies correspondingly. As a result, this leads to a notable enhancement in the overall heat transfer rate (HTR). This finding highlights the significant impact of ultrasonic power levels on improving heat transfer rate within this experimental setup. It is



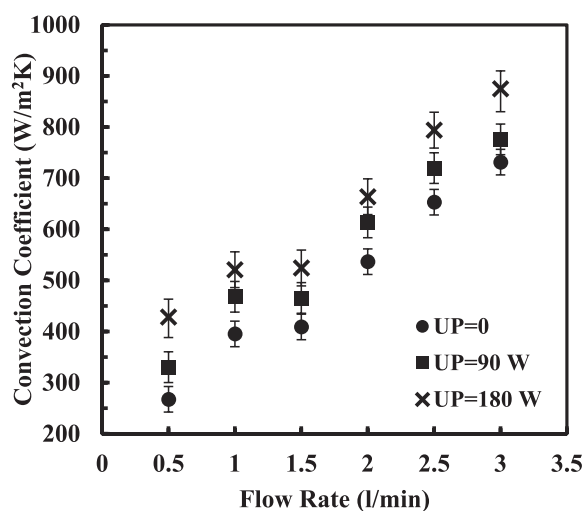
(a)

Flow rate (l/min)	CVP%, UP=90W	CVP%, UP=180W
0.5	64.5%	238.5%
1.0	54.1%	178.8%
1.5	28.4%	94.6%
2.0	22.2%	73.1%
2.5	21.5%	61.3%
3.0	15.4%	37.9%



(b)

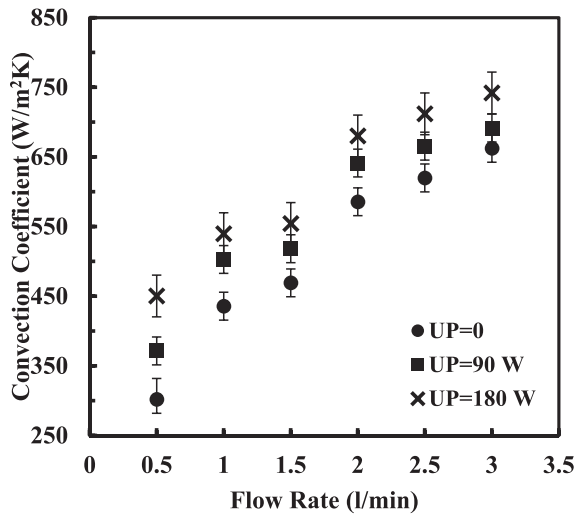
Flow rate (l/min)	CVP%, UP=90W	CVP%, UP=180W
0.5	43.7%	113.9%
1.0	26.2%	66.1%
1.5	24.7%	42.7%
2.0	18.9%	36.9%
2.5	18.8%	36.8%
3.0	9.9%	30.6%



(c)

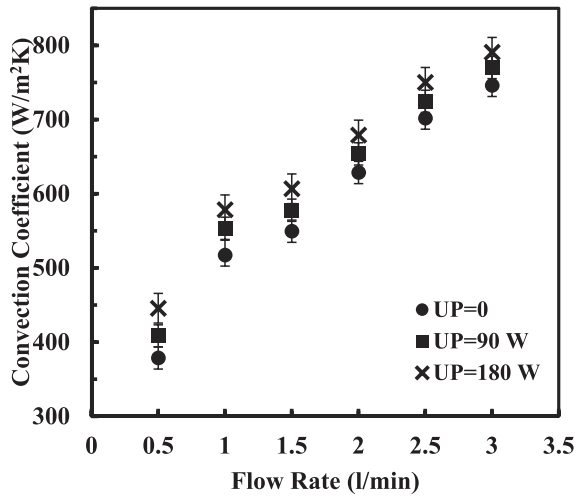
Flow rate (l/min)	CVP%, UP=90W	CVP%, UP=180W
0.5	23.5%	60.2%
1.0	18.4%	31.7%
1.5	13.8%	28.2%
2.0	14.3%	23.7%
2.5	10.2%	21.6%
3.0	6.1%	19.6%

Fig. 5. Convection coefficient versus flow rate in different heat power levels of (a) 200 W, (b) 400 W, (c) 600 W, (d) 800 W, (e) 1000 W, and (f) 1200 W. The results show that the increasing ultrasonic power level has a positive effect on the convective coefficient. Also, the convective coefficient reduces by increasing the fluid flow rate and heating power level.



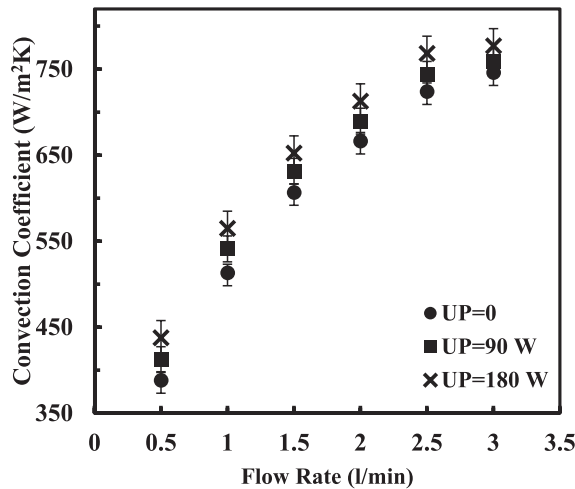
Flow rate (l/min)	CVP%, UP=90W	CVP%, UP=180W
0.5	23.0%	49.1%
1.0	15.4%	23.9%
1.5	10.4%	18.2%
2.0	9.5%	16.1%
2.5	7.4%	14.8%
3.0	4.4%	11.9%

(d)



Flow rate (l/min)	CVP%, UP=90W	CVP%, UP=180W
0.5	7.8%	17.7%
1.0	6.9%	11.8%
1.5	5.2%	10.4%
2.0	3.9%	8.1%
2.5	3.2%	6.9%
3.0	3.2%	5.9%

(e)



Flow rate (l/min)	CVP%, UP=90W	CVP%, UP=180W
0.5	6.2%	12.7%
1.0	5.4%	10.0%
1.5	4.1%	7.5%
2.0	3.5%	6.9%
2.5	2.7%	6.1%
3.0	1.7%	4.2%

(f)

Fig. 5. (continued).

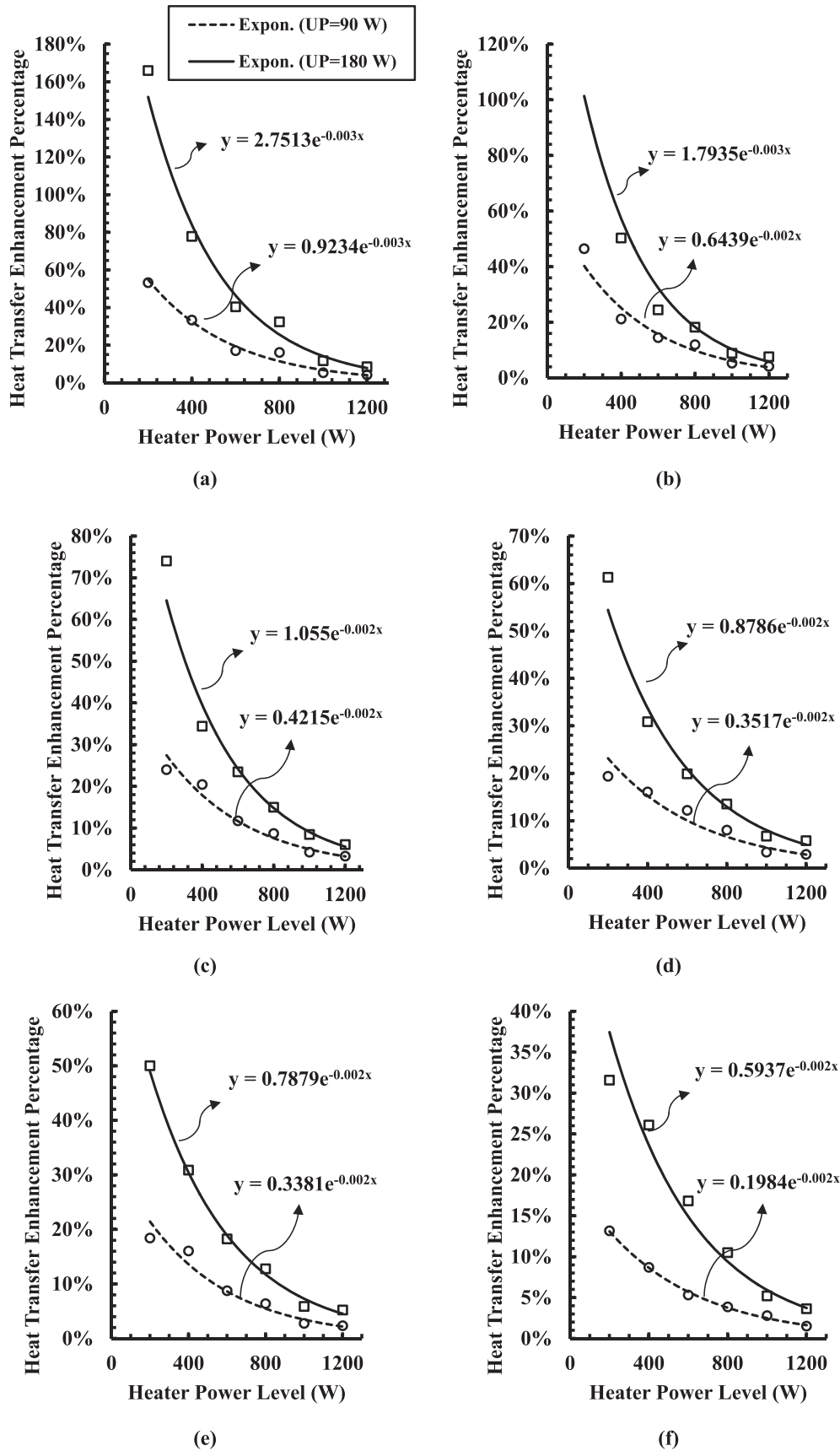


Fig. 6. Heat transfer enhancement percentage versus heater power level in different flow rates of (a) 0.5 LPM, (b) 1.0 LPM, (c) 1.5 LPM, (d) 2.0 LPM, (e) 2.5 LPM, and (f) 3.0 LPM. The equations related to the variation trend are presented for different ultrasonic power levels and flow rates. The results show that the thermal effects of UV are highlighted at lower values of heater power level and higher values of ultrasonic power level.

worth noting that the observed trend of change in the heat transfer rate against the flow rate bears resemblance to the corresponding trend in the studies conducted by Legay et al. [11], Gondrexon et al. [44], and Setareh et al. [19], who investigated HTE in ultrasonic-assisted double-pipe heat exchangers.

3.4. Heat transfer enhancement

Fig. 6 shows the heat transfer enhancement percentage compared to heater power levels for different fluid flow rates. In each of these figures (at constant fluid flow rate), variation of the heat transfer enhancement percentage due to ultrasonic vibrations in three states $UP = 0$, $UP = 90$ W, and $UP = 180$ W have been studied. Similar to the trend seen in the previous sections, the effect of applying UV is more evident in the lower powers of the heater. However, with the increase of heater power level, especially in higher fluid flow rates, the effect of UV will be reduced.

The equations related to the changes in heat transfer enhancement percentage in relation to heater power level are also shown in the graphs of Fig. 6, which confirms the downward trend of this parameter with increasing heater power. In the present experiment, as it is clear from these figures, the maximum effect of UV on the HTR of the CGS heater is at a flow rate of 0.5 LPM and a heater power of 200 W.

4. Conclusions

This research explores the impact of ultrasonic vibration on the heat transfer enhancement of CGS heaters through experimental investigation. A laboratory model based on a real CGS heater with a capacity of 2500 SCMH was developed at a scale of 1:4. The experimental results were validated using an existing empirical relationship. Until now, the impact of ultrasonic vibration on the heat transfer enhancement of CGS heaters has not been adequately investigated. This study delves into the influence of various parameters, such as ultrasonic power level, fluid flow rate in the serpentine coil pipe, and electric heater power level on the heat transfer enhancement of the CGS heater. The findings indicate that applying ultrasonic vibration, particularly at higher ultrasonic power levels, improves the thermal efficiency of the CGS heater. Conversely, lower power levels for electric heaters and lower fluid flow rates inside the serpentine coil pipe emphasize the effect of UV even more. Notably, when conducting these experiments with a fluid flow rate of 0.5 LPM and a heater power level of 200 W, the ultrasonication imposed substantial positive impacts on the convective heat transfer coefficient and heat transfer rate of the modeled CGS heater, increasing them by 238.5 % and 166 %, respectively. Considering the anti-fouling and anti-accumulation properties of ultrasonic waves, investigating the heat transfer enhancement of an ultrasonic-assisted indirect heat exchangers that utilizes a nanofluid in its reservoir can be valuable as an extension of the current research.

5. Availability of data and materials

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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