

An experimental investigation of heat transfer in a spiral-coil tube with pulsating turbulent water flow

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Abstract In this study, in order to increase the heat transfer rate in a spiral-coil tube by an active method, a rotating ball valve was mounted downstream/upstream of the spiral-coil tube and used as a pulse generator. Influence of pulsation on heat transfer in the spiral-coil tube was experimentally investigated. Cold water was used as a working fluid inside the spiral-coil that was immersed horizontally in a hot water reservoir tank. The Average temperature of the hot water bath was kept constant at 60 °C to establish a uniform temperature. All experiments for both pulsator locations (upstream and downstream pulsation) were performed at fixed pulsation amplitude. Reynolds number was ranged from 6220 to 16,300 while pulsation frequency was varied from 0 to 20 Hz. It can be clearly observed from heat transfer results that the overall average heat transfer coefficient was enhanced up to 26 % for pulsating flow compared to steady flow without pulsation at all pulsation frequencies. It is also clear that the relative overall average heat transfer coefficient is strongly affected by Reynolds number. Finally, it was obtained that the upstream pulsation heat transfer coefficient has better heat transfer results than the corresponding ones of downstream pulsation in the studied range of Reynolds number.

List of symbols

A Inside heat transfer area (m²)
C_p Specific heat capacity (J/kg K)

D_i Inner diameter of tube (m)
f Frequency (Hz)
K Thermal conductivity (W/m K)
L Length of tube (m)
 \dot{m} Mass flow rate (kg/s)
N Revolution per minute of the rotating valve spindle (rpm)
Pe Peclet number
Pr Prandtl number
Q Heat transfer rate (W)
r Inner radius of tube (m)
R Radius of spiral coil (m)
Re Reynolds number
T Temperature (K)
U Average overall heat transfer coefficient (W/m² K)
V Average velocity of mean flow (m/s)
Wo Womersly number

Greeks

α Thermal diffusivity (m²/s)
 μ Dynamic viscosity (kg/ms)
 ρ Density (kg/m³)
 ν Kinematic viscosity (m²/s)
 ω Angular pulsation frequency (1/s)
 ∞ Ambient medium

Superscript

– Average

Subscripts

a Average
i Inlet
m Mean
o Outlet
p Pulsated

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r Relative
s Steady

1 Introduction

Optimization of heat transfer equipment to achieve higher efficiency has been investigated by many researchers. There are many techniques to increase heat transfer rates which are classified into two general categories: passive techniques and active techniques. Using coiled tubes to increase turbulence near tube wall, lies in the passive category while using an external power source such as fluid pulsator lies in the active category [1, 2].

Studying of heat transfer and flow characteristics in coiled tubes has been conducted for many years. This is due to complexity of fluid dynamics and multiple applications of curved geometries in industry processes. Coiled tubes are used in variety of heat exchangers such as storage tanks, chemical reactors, agitated vessels and heat recovery systems. Helical- and spiral tube heat exchangers are used extensively in food processing, dairy, refrigeration and air conditioning. The generation of secondary flow due to centrifugal forces, cross-sectional mixing enhancement and heat-mass transfer coefficients improvement are reasons for using these techniques. Vashisth et al. [3] reviewed potential industrial applications of curved tubes for single and two-phase flow. Most studies on heat transfer and flow characteristics in the curved tubes were carried out within helical-coil tube whereas there are few researches for spiral-coil tube. Kubair and Kuloor [4] studied heat transfer to Newtonian fluids in the coiled pipes for laminar flow. The Experiments were based on two spirals that were enclosed in a steam chamber using glycerol solutions. They recommended a correlation for the Nusselt number as a function of Graetz number and the average radius of curvature. Naphon and Suwagrai [5] investigated effects of curvature ratios on heat transfer and flow developments in the horizontal spirally coiled tubes. Three spirally coiled tubes with different curvature ratios of 0.02, 0.04 and 0.05 were selected and the experiments were performed under constant wall temperature. They reported that average heat transfer coefficient increases with decreasing curvature ratio. To evaluate the heat transfer characteristics of conical spiral tube bundle, Ke et al. [6] carried out a study based on numerical simulation. They examined the effect of the structural parameters of the conical spiral tube such as cross section, cone angle and the helical pitch. Their results show that the cross section and the cone angle tube have a significant influence on the heat transfer coefficient.

Pulsation in fluid flow is another method of heat transfer enhancement despite the fact that effects of pulsating flow on heat transfer are still unpredictable. Widespread studies

have been allocated to pulsating flows and their associated heat transfer problems over the past decades [7–21]. Martinelli et al. [7] initiated the work on heat transfer characteristics of pulsating flow in 1943. They conducted the experiments on pulsating turbulent flow heat transfer in a vertical tube under uniform wall temperature boundary condition. The results showed that heat transfer reduced for pulsatile flow compared to steady flow at Reynolds numbers greater than 4500 and increased at Reynolds number less than 4500. West and Taylor [8] experimentally investigated the effect of pulsations on heat transfer in a horizontal tube. An increase of 60–70 % was observed in the heat transfer coefficient at pulsation frequency of 1.6 Hz. Havemann and Rao [9] performed an investigation on the heat transfer of pulsating turbulent flow in a horizontal pipe which is heated by steam. Reynolds number was ranged from 5000 to 35,000 while pulsation frequency was varied from 5 to 33 Hz. The heat transfer results showed that the effect of pulsation was negative below a certain frequency and positive above it. Lemlich [10] investigated the effect of pulsation on heat transfer in a double pipe heat exchanger. Pulsating flow was produced by steady flow pump with a solenoid valve. The overall heat transfer coefficient of pulsating flow at pulsation frequency 1.5 Hz was enhanced by 80 % over the steady flow at Reynolds number of 2000. An experimental investigation was carried by Mamayev et al. [11], where the air was passed through a vertical tube under constant wall heat flux condition. The maximum relative heat transfer coefficient was about 44 % at pulsation frequency of 12 Hz. Liao et al. [12] investigated an experimental study for the heat transfer in pulsating turbulent flow in a tube. Reynolds number was ranged from 3400 to 27,000 while pulsation frequencies were varied from 0.074 to 0.38 Hz. The heat transfer coefficient without flow reversal was reduced by about 20 %, while there was a 25 % increase in the heat transfer coefficient with flow reversal. Al-Haddad and Al-Binally [13] investigated the experimentally heat transfer coefficient of air flowing through a heated circular tube in pulsating flow. Their results indicated that the heat transfer coefficient was increased by pulsation at high Reynolds number. Genin et al. [14] reported the heat transfer characteristic of water flowing in a tube which was heated electrically in pulsating flow condition. In general, the effect of pulsating flow on the heat transfer coefficient was insignificant, in the range of investigated frequencies. Habib et al. [15] evaluated heat transfer characteristics of air in pulsating turbulent flow in a pipe. A rotating ball valve driven by a variable speed electric motor was used to generate flow pulsation while the pulsating mechanism was located downstream the tested pipe. They carried out their studies at a wide range of variables, Reynolds numbers of 8462–48,540 with the pulsation frequencies of 1–29.5 Hz. Their experimental results

showed about 50 % augmentation of mean Nusselt number at pulsation frequency between 13.9 and 29.5 Hz and Reynolds number of 15,000. The results also showed that mean Nusselt number reduced at Reynolds number more than 21,000 and this trend can be intensified by increasing the pulsation frequency. A numerical study was carried out by Wang and Zhang [16] on heat transfer in pulsating turbulent flow in a pipe with constant wall temperature. In the turbulence modeling, a low-Reynolds-number k - ϵ turbulent model was considered. According to their studies, it could be found that higher velocity at certain moments and the flow reversal during a period of the flow pulsation were the most important improvement mechanisms of the heat transfer. Effect of pulsation on the heat transfer coefficient of air in a pipe, was studied experimentally by Zohir et al. [17]. They evaluated the heat transfer characteristics under different conditions of Reynolds number, pulsation frequency, pulsator location and tube diameter for both laminar and turbulent pulsating pipe flows. They stated that the effect of pulsation on the heat transfer coefficient will improve the heat transfer if the pulsator valve becomes very closer to the entrance of the tested section. They obtained that the relative mean Nusselt number of downstream pulsation has better results than the upstream pulsation, at Reynolds number of 1366 and 1643. They also reported that, more improvement in heat transfer rate was obtained for a larger tube diameter at a Reynolds number range of 8000–12,000 with 1–10 Hz pulsation frequency. Elshafei et al. [18] investigated heat transfer characteristics of pulsating turbulent air flow in a pipe with constant wall heat flux. Their experimental results showed that the relative mean Nusselt number may be increased or decreased, depending on the pulsation frequency and Reynolds number. Considering the obtained data, the great Influence of pulsation on heat transfer in the entrance region relative to the fully developed region was established. An experiment on the prediction of heat transfer coefficient in pulsating flow in a concentric double-pipe heat exchanger was performed by Zohir [19]. The Various parameters such as pulsation frequency, Reynolds number, and inlet hot water temperature were investigated for both parallel and counter flows. The result showed maximum increase of about 20 % in Nusselt number for the parallel flow and nearly 90 % for counter one. Another experimental study was carried out by Li et al. [20] on heat transfer characteristics of pulsating laminar flow in rectangular grooved channels. They examined the effect of Reynolds number, pulsation frequency, depth and length of groove on the heat transfer characteristics. The results indicated that Nusselt number was enhanced by flow pulsation especially at higher Reynolds

numbers. Recently, Yu et al. [21] investigated numerically flow and heat transfer characteristics of pulsating laminar flow in a heated square cylinder. The results were evaluated at same Reynolds number which was maintained fixed at 100. Pulsation amplitude was varied from 0.2 to 0.8 while frequency of pulsation ranged from 0 to 20 Hz. In general, the effect of pulsation on the detailed kinematics of flow, drag coefficient and the heat transfer characteristics was investigated in details.

On the other hand, it can be effective to combine the heat transfer enhancement techniques if development of thermal systems is guaranteed. In the open literature, few papers have been reported the effect of pulsating flow on heat transfer for curved tubes [22–25]. Simon et al. [22] studied heat transfer characteristics of pulsating laminar flow in curved tubes, employing a perturbation analysis. They evaluated their studies for a wide range of excitation parameters and Prandtl numbers. They reported that augmentation of time averaged Nusselt number was obvious at high Prandtl numbers, high excitation relative amplitudes, and low excitation frequencies. Based on the other research, Rabadi et al. [23] studied effects of pulsatile flow upon heat transfer characteristics in curved tubes under axially uniform heat flux boundary conditions with peripherally uniform wall temperature. The conflicting results were reported compared with the above-stated perturbation analysis. Chung and Hyun [24] solved numerically the time dependent incompressible Navier–Stokes equations over a range of Reynolds number, pulsation amplitude and frequency. They studied the heat transfer and flow characteristics in a strongly curved pipe while the curvature ratio was considered small in the above-stated literature. They stated that the effect of pulsation on time and space-averaged Nusselt numbers was negative when the Womersley number was small while the change was insignificant at moderate and high Womersley number. Guo et al. [25] performed experiments on transient convective heat transfer in fully developed pulsating turbulent flow in a helically coiled tube. They reported that the pulsatile flow through helical coils can induce complicated secondary flows with flow reversals and is very difficult to analyze.

According to the aforementioned literature review, it can be found that there are few studies on heat transfer in pulsating flow in curved tubes despite their numerous applications in nature and engineering, especially in a spiral-coil tube. The present work aims to identify the effect of pulsatile flow upon the heat transfer characteristics in a spiral-coil tube. The influence of Reynolds number, pulsation frequency and pulsator location on the heat transfer characteristics are investigated experimentally.

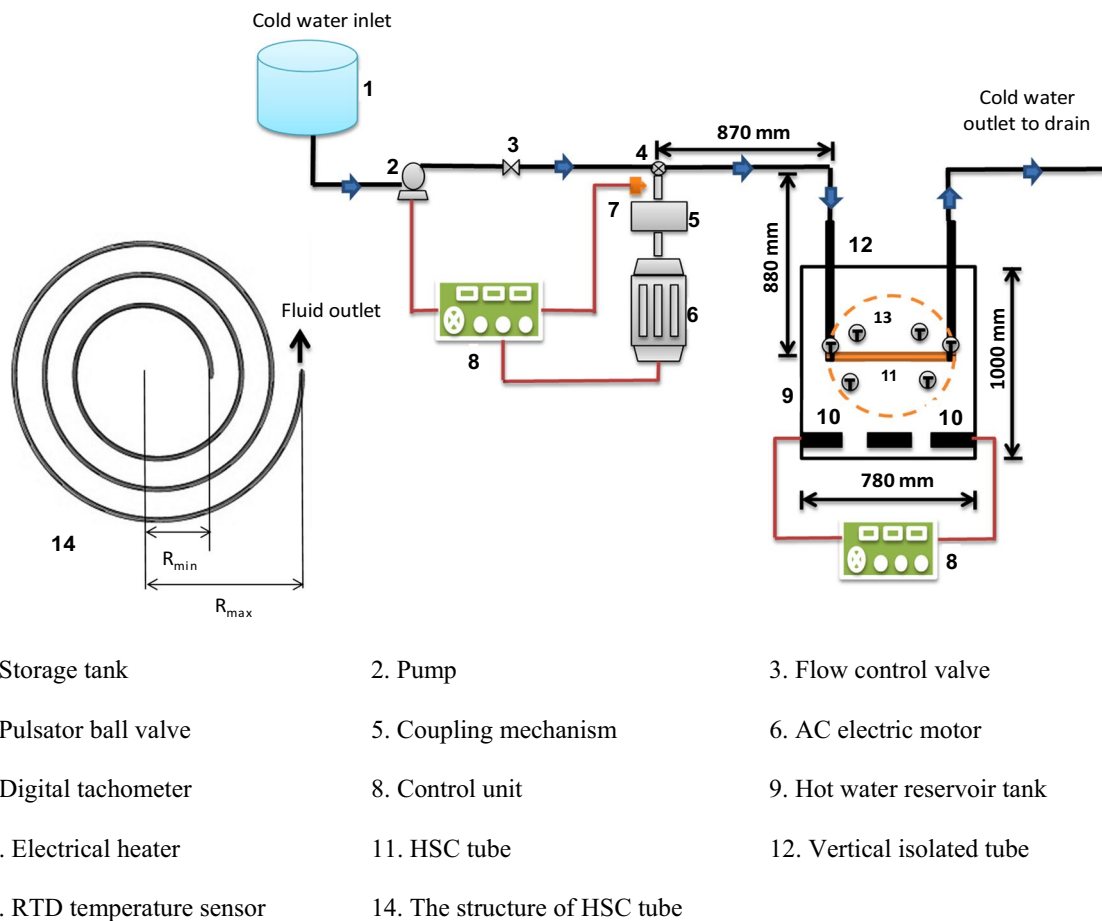


Fig. 1 Schematic diagram of the experimental setup

2 Experimental test rig setup and procedure

2.1 Experimental test rig setup

A schematic diagram of the experimental test rig setup was constructed to investigate the heat transfer in pulsating turbulent flow through a horizontal spiral-coil tube (HSC-tube), Fig. 1. The experimental setup is an open loop which includes a water supply unit, pulsating mechanism and test section.

2.1.1 Water supply unit

The water supply unit consists of a storage tank, pump and flow control valve. Cold water at 19 °C is pumped out of the storage tank by the peripheral electric pump (Lowara, Model PM16). The flow rate is controlled by the control valve. The flow rates are measured with calibrated standard beaker and stopwatch.

2.1.2 Pulsating mechanism

The pulsating mechanism includes an AC electric motor of 1 hp and 1500 rpm, a variable speed transmission and a rotating ball valve of 1/2 inch. A power inverter is employed to change direct current 12 V to alternating current 220 V and can produce the input power to the AC electric motor. A coupling mechanism is designated as the transmission between the output of the AC motor and the rotating ball valve. Flow pulsation is introduced by the ball valve that can be adjusted manually to rotate with different frequencies. A digital tachometer (Autonics, Model MP5W) is used for measuring the rotation speed of the electric motor.

2.1.3 Test section

The test section consists of a hot water reservoir tank, three electrical heaters and a spiral-coil tube. The cylindrical

Table 1 Dimensions of spiral-coil tube

Parameters	Dimensions
Inner diameter of tube (mm)	8.025
Outer diameter of tube (mm)	9.525
Innermost spiral-coil radius (mm)	100
Outermost spiral-coil radius (mm)	250
Length of spiral-coil tube (mm)	3450
Pitch of spiral-coil tube (mm)	50
Number of coil turns	3

reservoir tank is made of High-density polyethylene and is used as a hot water bath. The hot water reservoir tank is insulated by two layers of 15 mm-thick polyurethane and 5 mm-thick galvanized polyurethane to minimize heat loss through its wall and diminish input power of electrical heaters. Two 2.5 kW electrical heaters and an electrical heater of 4 kW are installed at the bottom of the reservoir tank. The electrical heater of 4 kW is equipped with a power controller (Autonics Power Controller Spc1-35) to maintain the ambient hot water temperature at a constant value. The entrance length for a laminar pulsating pipe flow to have fully developed flow can be calculated from [26]:

$$L/D_i = 0.049Re \quad (1)$$

For turbulent flow, based on experimental data, the entrance length is much shorter than the corresponding ones for laminar flow. The experiments are performed in the turbulent regime. A vertical isolated copper tube with 8.025 mm inner diameter and length of 880 mm is attached to the entrance of the HSC tube. This length is long enough to ensure a fully developed flow at the entrance of the HSC tube. The spiral-coil tube is fabricated by copper alloy, UNS C12200, and is horizontally immersed in the hot water. The HSC tube is also clamped by the reservoir tank wall to prevent vibration, induced by the flow pulsation. The dimensions of the spiral-coil tube are shown in Table 1. Four calibrated RTD temperature sensors are submerged in the hot water bath to measure the ambient temperature. In order to measure the temperature of the quiescent region accurately, the temperature sensors were placed in various locations of hot water bath. Two calibrated RTD temperature sensors are installed into the flow to measure bulk temperatures of working fluid at the inlet and outlet of the HSC tube. The RTD temperature sensors are connected to a rotary selector switch and a digital temperature indicator.

2.2 Experimental procedure

The heat transfer characteristics of pulsating turbulent water flow are evaluated using an experimental procedure. In order

to heat the quiescent water in reservoir tank, the electrical heaters are switched on and then the water temperature is controlled until the average temperature reaches 60 °C. Then, the electrical heaters of 2.5 kW are turned off while the water temperature is maintained at 60 °C by the electrical heater of 4 kW and the power controller during the experiment process. For all pulsation frequencies and different cold fluid flow rates, the temperatures at the inlet and outlet of cold fluid are recorded, after achieving the steady state. Experiments in both upstream and downstream pulsation are carried out while the pulsation amplitude is kept constant. The repeatability of measurements is observed in the repetitive runs. The investigated values of cold fluid flow rates are 2, 2.5, 3.333, 4.286 and 5.714 l/min. The values of revolution per minute of the rotating valve spindle used in this study are 12, 30, 75, 190, 375, 475 and 600 rpm.

2.3 Calculation methodology

The heat absorbed by the cold fluid is calculated by the following equation:

$$Q = \dot{m}C_p(T_{m,o} - T_{m,i}) \quad (2)$$

where $T_{m,o}$ and $T_{m,i}$ are the outlet and inlet mean bulk temperature, respectively.

The average total heat transfer coefficient is defined as:

$$\bar{U} = \frac{Q}{A\Delta T_{lm}} \quad (3)$$

where A is the inside heat transfer area of the spiral-coil tube, $(\pi D_i L)$ and ΔT_{lm} is the logarithmic mean temperature difference, which can be obtained from:

$$\Delta T_{lm} = \frac{(T_\infty - T_{m,i}) - (T_\infty - T_{m,o})}{\ln \frac{(T_\infty - T_{m,i})}{(T_\infty - T_{m,o})}} \quad (4)$$

The average temperature of hot water is kept constant at 60 °C and can be obtained from:

$$T_\infty = \frac{T_1 + T_2 + T_3 + T_4}{4} \quad (5)$$

where T_1 , T_2 , T_3 and T_4 are the temperatures measured of the four sensors that were submerged in the quiescent region.

Substituting (2) and (4) into (3) and after some simplifications, the overall average heat transfer coefficient is determined from the following equation [27]:

$$\bar{U} = \frac{\dot{m}C_p}{\pi D_i L} \ln \left(\frac{T_\infty - T_{m,i}}{T_\infty - T_{m,o}} \right) \quad (6)$$

The thermo-physical properties of water are evaluated at the mean bulk temperature for each test,

$$T_m = \frac{T_{m,i} + T_{m,o}}{2} \quad (7)$$

Table 2 Accuracy of measuring instruments

Parameter	Nomenclature	Accuracy	Maximum relative uncertainty (%)
Temperature	T	±0.1 °C	
Diameter of HSC tube	D	±0.00005 m	
Length of HSC tube	L	±0.0005 m	
Volume flow rate		±20 × 10 ⁻⁶ m ³	
Reynolds number	<i>Re</i>		±2.4
Average total heat transfer coefficient (upstream)	U		±2.8
Average total heat transfer coefficient (downstream)	U		±2.7

The flow is opened and closed twice for each revolution of the ball valve, so the frequency of pulsation can be calculated by the following equation:

$$f = \frac{N \times 2}{60} \quad (8)$$

where N is the revolution per minute of the rotating valve spindle.

On the other hand, the angular pulsation frequency is obtained from:

$$\omega = 2\pi f \quad (9)$$

The Reynolds and Womersly numbers are determined as follows:

$$Re = \frac{\rho \bar{V} D_i}{\mu} \quad (10)$$

$$Wo = \frac{D_i}{2} \sqrt{\frac{\omega}{\nu}} \quad (11)$$

where \bar{V} is the average velocity of the mean flow.

Relative average total heat transfer coefficient is defined as the ratio of the value of average total heat transfer coefficient for pulsated flow to the corresponding ones for steady flow at a same flow rate,

$$\bar{U}_r = \frac{\bar{U}_{pa}}{\bar{U}_{sa}} \quad (12)$$

In the field of determining the flow regime in pulsating flows, Hershey and Im [28] showed that transition from laminar to turbulent regime for pulsating flow of water in rigid tubes takes place at Reynolds number of about 1500 that it was less than 2300 for steady flow. Clamen and Minton [29] stated that the pulsating flow becomes turbulent when the mean flow Reynolds number approaches to the critical Reynolds number of the steady pipe flow. Recently, Trip et al. [30] investigated the transitional regime of a sinusoidal pulsatile flow in a pipe using particle image velocimetry. They

reported that pulsatile effects do not play any role in the transition regime, from laminar to turbulent flow. They also stated that for larger mean Reynolds numbers, the flow remains turbulent throughout the cycle. The critical Reynolds number for this study is calculated from the following correlation [31]:

$$Re_{cr} = 2100 \left[1 + 12 \left(\frac{r}{R_{ave}} \right)^{0.5} \right] \quad (13)$$

where $R_{ave} = \frac{R_{min} + R_{max}}{2}$ and r are the average radius of spiral coil and inner radius of the tube, respectively. In the present work, the transition occurs at the critical Reynolds number of about 5916.

3 Uncertainty analysis

The measurements are used for calculating the desired values of the experiments. The results dependent variable, R , is generally stated as a function of the independent variables V_i , $1 \leq i \leq n$, where n is the number of independent variables. The uncertainty equations for the above experiments are derived, based on the general equation for uncertainty by Kline and McClintock shown below [32]:

$$U_R = \left[\sum_{i=1}^n \left(\frac{\partial R}{\partial V_i} U_{V_i} \right)^2 \right]^{\frac{1}{2}} \quad (14)$$

where U_R and U_{V_i} are the uncertainties for the results and the independent variables, respectively. The accuracy of measuring instruments is given in Table 2. The maximum uncertainty of Reynolds number, upstream/downstream average total heat transfer coefficients are 2.4, 2.8 and 2.7 %, respectively.

4 Results and discussion

The most important aspects of this work are the extent of augmentation of heat transfer associated with the

Fig. 2 Average total heat transfer coefficient versus Reynolds number at different pulsation frequencies, upstream pulsation

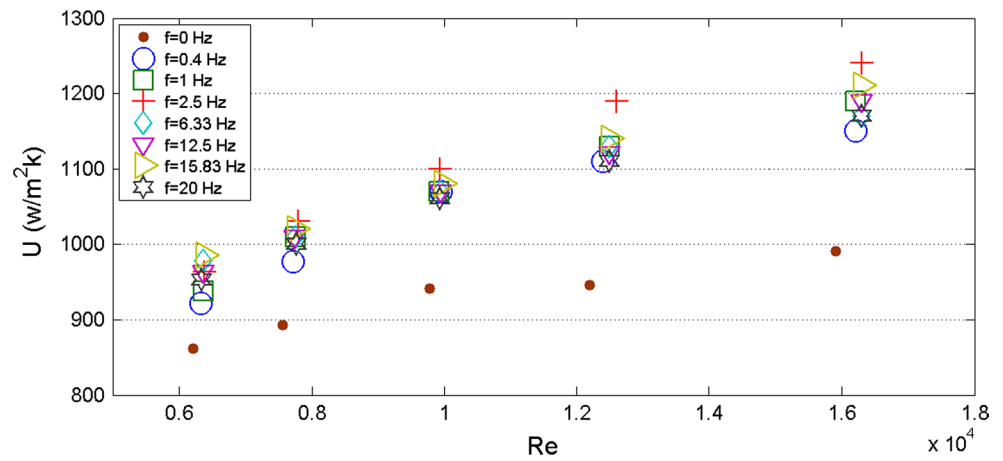


Fig. 3 Average total heat transfer coefficient versus Reynolds number at different pulsation frequencies, downstream pulsation

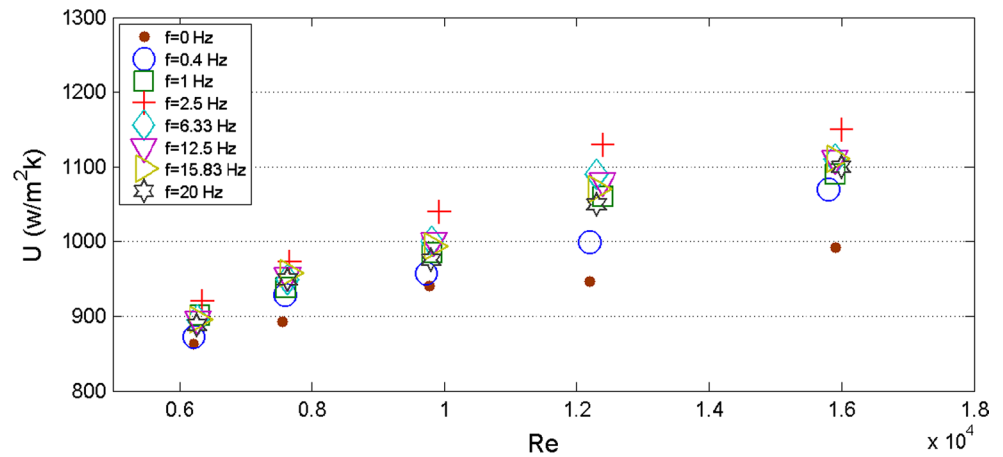
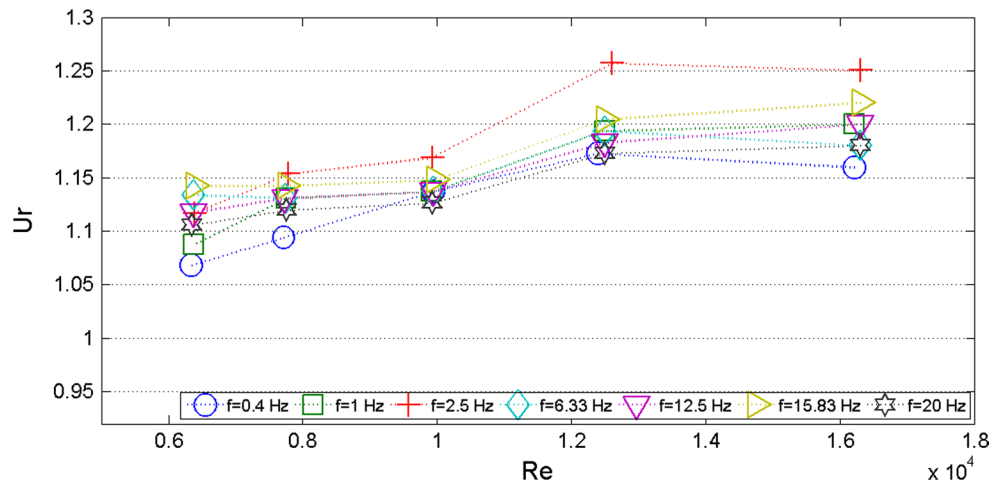


Fig. 4 Relative average total heat transfer coefficient versus Reynolds number, upstream pulsation



introduction of pulsation into the water flow. An experimental investigation is conducted to evaluate the effects of pulsation on heat transfer in a spiral-coil tube. Experiments are carried out over a range of 6220–16,300 for Reynolds number and of 0–20 Hz for the pulsation frequency. The results obtained from the experimental data are illustrated in Figs. 2, 3, 4, 5, 6, 7 and 8.

4.1 The influence of pulsator location on heat transfer

Figures 2 and 3 depict the behavior of the average total heat transfer coefficient with respect to Reynolds number at different pulsation frequencies for both locations of a pulsator ball valve. In the case of the upstream pulsation, Fig. 2, it is apparent that the average total heat transfer coefficient

Fig. 5 Relative average total heat transfer coefficient versus Reynolds number, downstream pulsation

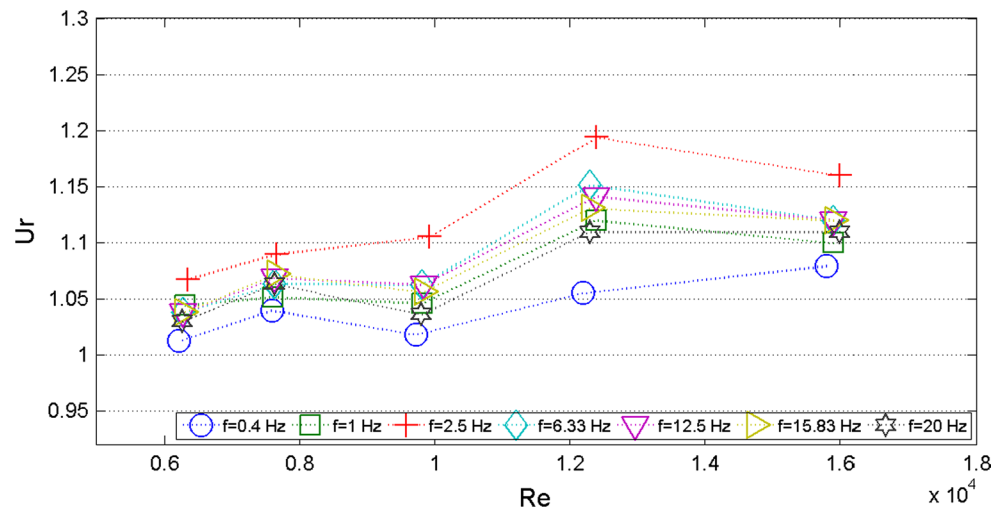


Fig. 6 Relative average total heat transfer coefficient versus Womersly number, upstream pulsation

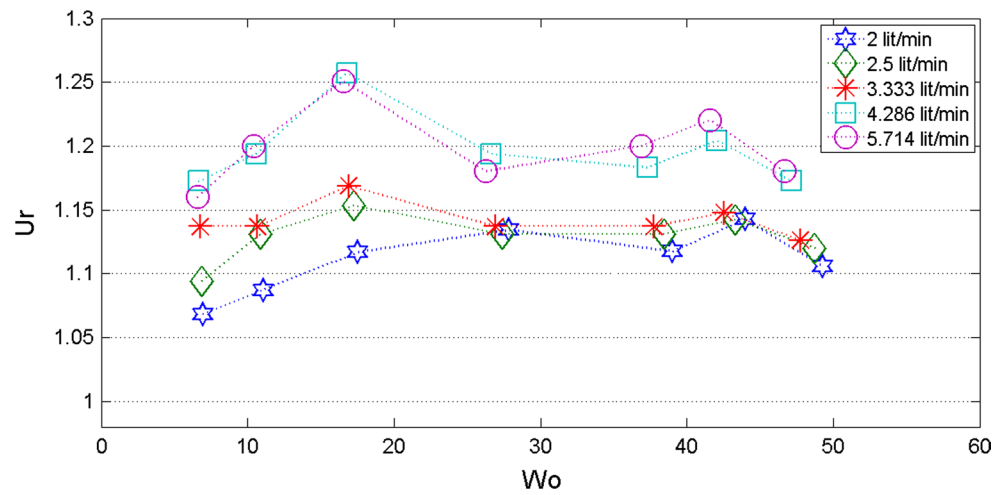
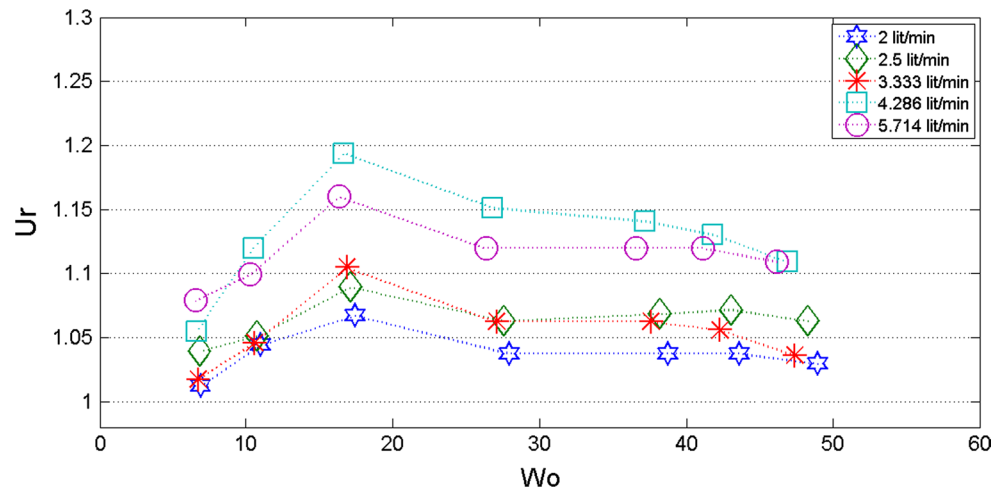


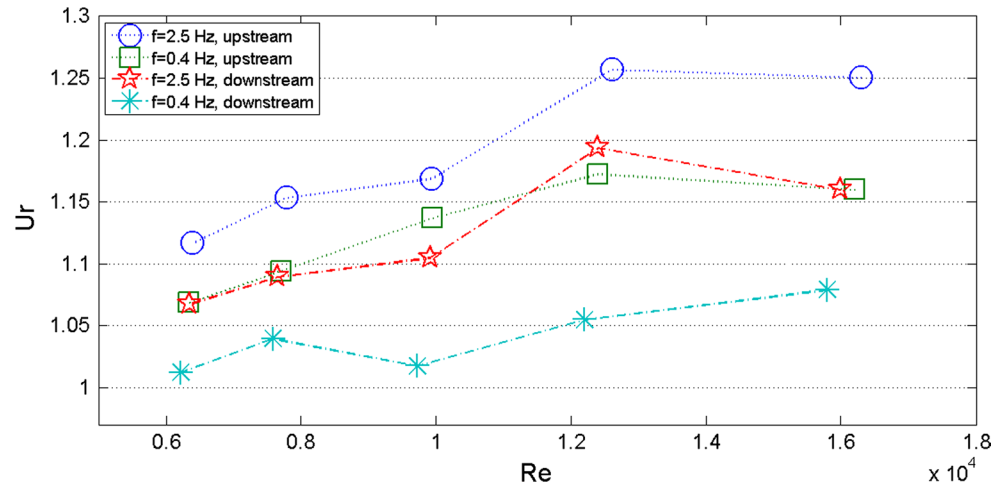
Fig. 7 Relative average total heat transfer coefficient versus Womersly number, downstream pulsation



increases with increasing Reynolds number for different pulsation frequencies. Based on the trend revealed in Fig. 2, it can be observed that the effect of pulsating flow on the heat transfer coefficient is more significant at high values

of Reynolds number. A similar behavior in the variation of average total heat transfer coefficient versus Reynolds number for the downstream pulsation can be seen in Fig. 3. It is clear from Fig. 3 that the average total heat transfer

Fig. 8 Comparison between upstream and downstream pulsation at $f = 0.4$ and 2.5 Hz



coefficient increases with increasing Reynolds number for both pulsating and steady flows, however, the effect of pulsation flow on the heat transfer is less for low Reynolds numbers. In order to evaluate the effects of pulsation on the heat transfer, the relative average total heat transfer coefficient is calculated as explained earlier. These enhancements in the heat transfer are related to the increased level of turbulence, to the introduction of forced convection in the boundary layer. Pulsations of sufficient frequency can improve heat transfer in such a way that increase the longitudinal flow for a part of the cycle which, in turn, decreases the film thickness in the tube.

Figures 4 and 5 illustrate the variation of relative average total heat transfer coefficient versus Reynolds number for both upstream and downstream pulsation, respectively. In the upstream pulsation, Fig. 4, the increase in the relative average total heat transfer coefficient is about 6–17 % for a range of $6330 \leq Re \leq 9970$, in the range of investigated frequencies. For larger mean Reynolds numbers, higher relative average total heat transfer coefficient is obtained about 16–26 % for all frequencies as indicated in Fig. 4. There is a slight increase in the relative average total heat transfer coefficient, about 1–11 %, over a range of 6220–9920 for Reynolds number in the downstream pulsation as can be seen from Fig. 5. According to this figure, the relative average total heat transfer coefficient is improved by about 6–19 % for larger mean Reynolds numbers. The highest and lowest effects of the pulsating flow on the heat transfer is reflected in the pulsation frequency of 2.5 and 0.4 Hz, respectively.

4.2 The influence of Womersly number on heat transfer

Figures 6 and 7 represent the variation of relative average total heat transfer coefficient versus Womersly number and different cold fluid flow rates for both upstream and downstream pulsations, respectively. As shown in the figures,

beneficial effects of pulsation on the heat transfer can be enhanced or reduced, depending on Womersly number at the same flow rate. Figures 6 and 7 also show that, at the same flow rate, there is a constant variation in the relative average total heat transfer coefficient with increasing Womersly number for high frequencies.

4.3 The influence of Reynolds number on heat transfer

The improvements in the heat transfer rates with pulsation are due to the higher pulse intensity imparted to the flow through the whole spiral tube. The effect of pulsation on the fluid results in a pressure gradient being created in the radial direction, thus affecting the boundary layer development. The increased rate of heat transfer in such flows is a consequence of the renewing and reducing the boundary layer thickness and increased resultant velocity leading to enhance the heat transfer. Figure 8 compares breakdown of the relative average total heat transfer coefficient over a range of 6220–16,300 for Reynolds number and pulsation frequencies of 0.4 and 2.5 Hz for both upstream and downstream pulsations. Based on the trend revealed in Figs. 2, 3, 4, 5, 6, 7 and 8, it can be noted that the greater augmentation of heat transfer is recorded when the pulsator is located upstream of the flow. A reason for this result may be due to the higher pulse intensity for the upstream pulsation compared to the downstream pulsation. Similar conclusion is reported in the existing literature [33].

The heat transfer coefficients of pulsating flows are affected by several parameters such as inlet fluid temperature, boundary condition, Reynolds number, Prandtl number, type of pulsator, location of pulsator, pulsation frequency, pulsation amplitude, length to diameter ratio and secondary flow. The pulsating flow can enhance heat transfer by reducing thermal boundary layer thickness due to higher turbulence intensity. Having higher velocity gradient at the tube wall, producing higher velocity at some

moments, pressure gradient reversal during a period, producing forced circulation in the fluid and promoting the formation of eddies are the most important mechanisms of the heat transfer enhancement [8, 10, 14, 16, 33]. Based on the interaction between the flow pulsation and secondary flow, it can be noted that increasing the intensity of the secondary flow at some moments of the cycle, radial and longitudinal mixing enhancement and the occurrence of secondary flow reversal play more important roles on the heat transfer improvement. Furthermore, it is reflected that temperature and velocity gradients are intensified near the outer wall at some moments with Reynolds number increase. Hence, the effect of pulsation flow on the heat transfer is more significant at high Reynolds numbers [23–25, 34]. The axial velocity gradients near the wall, specially the outer wall, are intensified by increasing Womersly number. It helps to decrease the thermal resistance, resulting to a decrease in the thermal boundary layer thickness. On the other hand, both the axial and secondary flows are weakened when Womersly number increases [24]. This implies the weakening of the convective terms in the energy equation. Based on the stated trends, the beneficial effects of pulsation on heat transfer can be enhanced or reduced, depending on the Womersly number range. According to the consumed pumping power due to both pulsation and coiled tubes, using pulsation enhances the heat transfer rate because of creating turbulences in the flow but it requires more pumping power. However, the heat transfer enhancement is achieved at the cost of pumping power required for the flow. This increase in the pumping power is much higher when coiled pipes are used which must be considered to optimize between the gained heat and the penalty of pressure drop.

5 Conclusions

Pulsation generators can be used to augment heat transfer rates. The pulsated flow enhances the heat transfer rates mainly due to increasing of turbulence levels in the boundary layer. The effects of Reynolds number, pulsation frequency and locations of a pulsator ball valve are investigated. According to the obtained heat transfer results, the following results can be concluded:

1. The average overall heat transfer coefficient increases for the pulsatile flow compared with the steady flow. The effect of pulsation on heat transfer becomes more significantly at higher Reynolds numbers.
2. The beneficial effects of pulsation on heat transfer can be enhanced or reduced, depending on the Womersly number range, pulsation frequency, pulsation amplitude, pulsator location and Reynolds number.

3. Higher values of the heat transfer rates are observed in the upstream pulsation compared to the downstream pulsation. The maximum enhancement in the relative average overall heat transfer coefficients are about 26 and 19 % for the upstream and downstream pulsation, respectively.
4. Using pulsation into the plain or coiled pipes enhances the heat transfer rate because of creating turbulences in the flow but pulsation requires more pumping power.

References

1. Bergles AE (1988) Some perspectives on enhanced heat transfer—second-generation heat transfer technology. *J Heat Transfer* 110:1082–1096
2. Bergles AE (1998) Techniques to enhance heat transfer. In: Rohsenow WM, Hartnett JP, Cho YI (eds) *Handbook of heat transfer*. McGraw-Hill, New York, pp 11.1–11.76
3. Vashisth S, Kumar V, Nigam KD (2008) A review on the potential applications of curved geometries in process industry. *Ind Eng Chem Res* 47:3291–3337
4. Kubair V, Kuloor N (1966) Heat transfer to Newtonian fluids in coiled pipes in laminar flow. *Int J Heat Mass Transf* 9:63–75
5. Naphon P, Suwagrai J (2007) Effect of curvature ratios on the heat transfer and flow developments in the horizontal spirally coiled tubes. *Int J Heat Mass Transf* 50:444–451
6. Ke Y, Pei-Qi G, Yan-Cai S, Hai-Tao M (2011) Numerical simulation on heat transfer characteristic of conical spiral tube bundle. *Appl Therm Eng* 31:284–292
7. Martinelli R, Boelter LMK, Weinberg E, Yakahi S (1943) Heat transfer to a fluid flowing periodically at low frequencies in a vertical tube. *Trans ASME* 65:789–798
8. West F, Taylor A (1952) The effect of pulsations on heat transfer-turbulent flow of water inside tubes. *Chem Eng Prog* 48:39–43
9. Havemann HA, Rao NN (1954) Heat transfer in pulsating flow. *Nature* 7:4418
10. Lemlich R (1961) Vibration and pulsation boost heat transfer. *Chem Eng* 68:171–176
11. Mamayev V, Nosov V, Syromyatnikov N (1976) Investigation of heat transfer in pulsed flow of air in pipes. *Heat Transf Sov Res* 8:111–116
12. Liao N, Wang C, Hong J (1985) An investigation of heat transfer in pulsating turbulent pipe flow. In: *fundamentals of forced and mixed convection*. The 23rd national heat transfer conference, Denver, Co USA, pp 4–7
13. Al-Haddad AA, Al-Binally N (1989) Prediction of heat transfer coefficient in pulsating flow. *Int J Heat Fluid Flow* 10:131–133
14. Genin L, Koval A, Manchkha S, Sviridov V (1992) Hydrodynamics and heat transfer with pulsating fluid flow in tubes. *Therm Eng* 39:251–255
15. Habib M, Attya A, Said S, Eid A, Aly A (2004) Heat transfer characteristics and Nusselt number correlation of turbulent pulsating pipe air flows. *Heat Mass Transf* 40:307–318
16. Wang X, Zhang N (2005) Numerical analysis of heat transfer in pulsating turbulent flow in a pipe. *Int J Heat Mass Transf* 48:3957–3970
17. Zohir A, Habib M, Attya A, Eid A (2006) An experimental investigation of heat transfer to pulsating pipe air flow with different amplitudes. *Heat Mass Transf* 42:625–635
18. Elshafei EA, Safwat Mohamed M, Mansour H, Sakr M (2008) Experimental study of heat transfer in pulsating turbulent flow in a pipe. *Int J Heat Fluid Flow* 29:1029–1038

19. Zohir A (2011) The influence of pulsation on heat transfer in a heat exchanger for parallel and counter water flows. *N Y Sci J* 4(6):61–71
20. Li Y, Jin DX, Jing YQ, Yang BC (2013) An experiment investigation of heat transfer enhancement by pulsating laminar flow in rectangular grooved channels. *Adv Mater Res* 732:74–77
21. Yu J-Y, Lin W, Zheng X-T (2014) Effect on the flow and heat transfer characteristics for sinusoidal pulsating laminar flow in a heated square cylinder. *Heat Mass Transf* 50(6):849–864
22. Simon H, Chang M, Chow J (1977) Heat transfer in curved tubes with pulsatile, fully developed, laminar flows. *J Heat Transf* 99:590–595
23. Rabadi N, Chow J, Simon H (1982) Heat transfer in curved tubes with pulsating flow. *Int J Heat Mass Transf* 25:195–203
24. Chung JH, Hyun JM (1994) Heat transfer from a fully-developed pulsating flow in a curved pipe. *Int J Heat Mass Transf* 37:43–52
25. Guo L, Chen X, Feng Z, Bai B (1998) Transient convective heat transfer in a helical coiled tube with pulsatile fully developed turbulent flow. *Int J Heat Mass Transf* 41:2867–2875
26. Özdiñç Çarpınliođlu M, Yaşar Gündođdu M (2001) A critical review on pulsatile pipe flow studies directing towards future research topics. *Flow Meas Instrum* 12:163–174
27. Incropera FP, Lavine AS, DeWitt DP (2011) *Fundamentals of heat and mass transfer*. Wiley, New York
28. Hershey D, Im CS (1968) Critical Reynolds number for sinusoidal flow of water in rigid tubes. *AIChE J* 14:807–809
29. Clamen M, Minton P (1977) An experimental investigation of flow in an oscillating pipe. *J Fluid Mech* 81:421–431
30. Trip R, Kuik D, Westerweel J, Poelma C (2012) An experimental study of transitional pulsatile pipe flow. *Phys Fluids* (1994-present) 24:014103
31. Srinivasan P, Nandapurkar S, Holland F (1970) Friction factors for coils. *Trans Inst Chem Eng* 48:T156–T161
32. Kline SJ, McClintock F (1953) Describing uncertainties in single-sample experiments. *Mech Eng* 75:3–8
33. Karamercan OE, Gainer JL (1979) The effect of pulsations on heat transfer. *Ind Eng Chem Fundam* 18:11–15
34. Timité B, Castelain C, Peerhossaini H (2010) Pulsatile viscous flow in a curved pipe: effects of pulsation on the development of secondary flow. *Int J Heat Fluid Flow* 31:879–896