J Ther Eng, Vol. 7, No. 7, pp. 1731–1742, November 2021

Journal of Thermal Engineering
Web page info: https://jten.yildiz.edu.tr
DOI: 10.18186/thermal.1025962

Research Article

Positive impact of vibration on heat transfer in twisted tape inserted heat exchanger

Shanmukh Sudhir ARASAVELLI[1,2*], Ramakrishna KONIJETI[1], Govinda Rao BUDDA[2]

[1]Department of Mechanical Engineering, Koneru Lakshmaiah Education Foundation, Guntur, India
[2]Department of Mechanical Engineering, Gayatri Vidya Parishad College of Engineering (Autonomous), Visakhapatnam, India

ARTICLE INFO

Article history
Received: 18 January 2021
Accepted: 17 April 2021

Keywords:
Heat exchanger, Counter flow, Heat transfer enhancement, Nusselt number, Vibration, Twisted tape insert

ABSTRACT

This paper describes experimental investigations on convective heat transfer in counter flow double pipe heat exchanger under transverse vibration for single-phase flow with twisted tape insert in the inner tube. Experiments were conducted on twisted tape inserted counter flow double pipe heat exchanger under vibration for twist ratio from 7 to 17, amplitude from 23 to 69 mm, frequency from 20 to 100 Hz and Reynolds number (Re) changing from 10710 to 21420. A maximum gain of 91% in Nusselt number (Nu) was obtained at 40 Hz frequency and 69 mm amplitude for twist ratio of 7 and Re of 10710. The maximum value of performance evaluation criteria with compound enhancement technique on double pipe heat exchanger reached 1.38 in turbulent flow conditions. Empirical correlations for Nu were developed and predicted values were found to be within ± 9% of experimental values for both frequency ranges.

Cite this article as: Shanmukh S A, Ramakrishna K, Govinda R B. Positive impact of vibration on heat transfer in twisted tape inserted heat exchanger. J Ther Eng 2021;7(7):1731–1742.

INTRODUCTION

Heat exchangers are systems used to transfer heat between two or more fluids. They are widely used in industrial and domestic applications where heat transfer is involved. Double pipe heat exchangers are unique in operating temperature range, overall size and maintenance ease compared to other heat exchangers. They are particularly suitable for different processes in wastewater treatment and food processing units. Heat transfer intensification of double pipe heat exchangers can result in considerable energy and material savings. Though different enhancement techniques exist to improve heat transfer, these techniques unfortunately increase pressure drop inducing higher pumping cost. Therefore, optimization is essential between enhanced heat transfer and higher pumping cost in any enhancement technique utilized on double pipe heat exchangers.

***Corresponding author.**
*E-mail address: arasavellipublications@gmail.com

This paper was recommended for publication in revised form by Editor Ali Celen

Published by Yıldız Technical University Press, İstanbul, Turkey

Surface Vibration

Omidi et al. [1] revealed considerable research on different enhancement techniques applied to double pipe heat exchangers. Suitable active techniques that require external power to double pipe heat exchangers are surface vibration, flow vibration, rotating pipes etc. Sheikholeslami et al. [2] explained benefits in applying active techniques to heat exchangers. Active techniques increase formation of convection currents in fluid regions of heat exchanger compared to popular passive techniques. Atashi et al. [3] experimented on heat transfer of vibrated vertical cylinder in a water vessel at different frequencies and heat fluxes. Strong influence of vibration on heat transfer was found at 25 Hz frequency and 30 kW/m^2 heat flux.

Lemlich and Hwu [4] imposed vibrations at resonant frequencies to improve heat transfer between working fluids in double pipe heat exchanger significantly. Nu increased in both laminar and turbulent fluid flow conditions. Klaczak [5] exposed heat exchanger to vibrations at non-resonating frequencies and showed decrease in heat transfer between steam and water. Heat transfer improved by a maximum of 5% compared to plain heat exchanger under laminar conditions.

Gondrexon et al. [6] conducted experiments on heat exchanger by using 35 kHz piezoelectric vibrator to show positive effect on convective heat transfer. Overall heat transfer coefficient with vibration increased in the range of 123% to 257% for different hydrodynamic configurations. Legay et al. [7] developed data acquisition system for vibrating double pipe heat exchanger to find accurate inlet and outlet temperatures for both fluids at regular intervals. Effect of 35 kHz vibrator on thermal resistance was more on the annulus side compared to tube side due to the hindrance in vibration transmission. Legay et al. [8] experimentally compared the performance of two different tubular heat exchangers at vibration frequency of 35 kHz and found that enhancement ratio for shell and tube heat exchanger is slightly higher.

Gondrexon et al. [9] illustrated interesting results of heat transfer intensification with fouling reduction by applying 35 kHz vibrations on double pipe heat exchanger. Energy balance method compared results of heat transfer with and without vibration in a heat exchanger. Arasavelli et al. [10] demonstrated the effect of transverse vibration on heat transfer in a tubular heat exchanger experimentally. 33% maximum increase in Nusselt number is noticed at specific frequency, amplitude and vibrator position. In another work [11], they concluded that Nusselt number improved maximum of 44% for heat exchanger with different configuration at a vibrator position of 0.25. Sarma et al. [12] determined variation in fouling thickness with respect to time for double pipe heat exchangers and compared with corresponding data available in the existing literature.

Twisted Tape Inserts

Twisted tape inserts provide heat transfer enhancement in tube heat exchangers with less penalty on pumping power compared to other available passive techniques. Liu and Sakr [13] reviewed experimental and numerical works done by various researchers and provided different categories of twisted tapes namely multiple twisted tapes, twisted tape with fins, twisted tapes with cuts etc. In another review paper, Varun et al. [14] described the effective method of changing twisted tape geometries to improve heat transfer in heat exchanger systems. A few studies have been made on the use of twisted tape inserts in heat exchanger systems of food processing units. Kumar et al. [15] summarized experimental and numerical studies on twisted tape inserts in heat exchanger tubes. Swirl fluid motion due to twisted tape caused increase in heat transfer and friction factor of heat exchanger tubes.

Gupte and Date [16] experimentally determined the Nu for air flowing through annulus with radius ratios of 0.41 and 0.61 in a twisted tape inserted heat exchanger. At lowest Re of 25000, maximum heat transfer coefficient is obtained at lowest twist ratio of 2.65 and lowest radius ratios of 0.41. Sivashanmugam and Sundaram [17] studied experimentally the heat transfer rates of heat exchanger with inserts at twist ratios ranging from 15.64 to 4.14. Percentage gain in heat transfer reduced exponentially with raise in Re for all twist ratios. Man et al. [18] performed experiments to estimate heat transfer in a pipe heat exchanger using rotated tapes at turbulent conditions. Full length rotated tapes had better heat transfer compared to typical tapes with maximum performance evaluation criteria of 1.42 at Re of 3700.

Yadav [19] investigated the heat transfer behaviour in a U bend concentric pipe heat exchanger with twisted tape insert of half-length. Their results showed considerable increase in heat transfer with half-length insert in a heat exchanger. Mohanty et al. [20] conducted numerical analysis on different configurations of heat exchanger by employing different inserts with different twist ratios using Fluent 14.0 in CFD package. Middle turn twisted tape insert has 21% to 29% higher heat exchanger effectiveness compared to other types of twisted tape inserts. Piriyarungrod et al. [21] used both experimental and numerical methods to study thermal performance of flowing air in a heat exchanger tube with multiple-twisted tape inserts at six different twist ratios in different quantities. Maximum heat transfer is achieved by using highest number of tapes i.e. 6 with 2.5 twist ratio. Corresponding friction factor is evaluated and performance factor found to be 1.2. Aliabadi and Feizabadi [22] examined performance index of twisted tubes in twisted tape inserted tubular heat exchangers numerically. Heat transfer coefficient for twisted tube with twisted tape insert increased by 216% compared to straight tube. Using pressure drop calculations, highest performance index of 3.21 is obtained at Re of 1800.

Bhakta and Singh [23] placed perforated twisted tape in absorber tube of solar water heater to enhance its heat transfer. They changed flow rate from 0.0326 to 0.0667 kg/s and tape porosity from 0.747 to 4.667% to analyse performance of water heater. At flow rate of 0.0667 kg/s and porosity of 4.667%, Nusselt number is found to be approximately 45% higher than that of plain absorber tube. Afsharpanah et al. [24] numerically studied the effect of single, normal dual, perforated dual, V-cut dual, S- cut dual and centre cleared dual twisted tapes in absorber tube of solar trough collectors. Simulations are conducted in the Reynolds number range of 10,000 to 20,000. The authors found that Nusselt number with v-cut dual tapes is approximately 20% more than that of plain tube at Reynolds number of 10,000.

From the literature, surface vibration is recognized as an effective active technique to enhance heat transfer in heat exchanger. Few studies in existing literature showed improvement in convective coefficient by imposing transverse vibrations on heat exchangers at single frequencies [6-9]. They located transverse vibrator at the middle of the heat exchangers. Certain number of studies investigated the influence of longitudinal vibrations on convective heat transfer in heat exchangers over a span of frequencies. They conducted their works by positioning vibrator at one side of the heat exchanger. Whereas, other researchers explored passive technique of twisted tape insert to increase heat transfer in tubular heat exchangers. Despite various works done on surface vibration and twisted tape inserts separately, there is a lack of investigation on the combined effect of surface vibration and twisted tape insert on heat transfer in double pipe heat exchanger. The objective of the present study is to conduct experiments and explore the compound impact of twisted tape insert with vibration on Double Tube Heat Exchanger with Counter Flow (DTHECF) under turbulent flow conditions. Positive impact of compound technique is estimated through performance evaluation criteria. Correlations are also developed to estimate Nusselt number for two different frequency ranges from the experimental data.

EXPERIMENTAL SETUP

The structure of the experimental setup used in this study is shown in Figure 1. DTHECF experimental system consists of twisted tape inserted heat exchanger, electrodynamic vibrator, hot water system, cold water system and measuring devices. Twisted tape inserted heat exchanger consists of inner pipe with inserts, outer pipe and insulation. The inner pipe was made of copper with 2 mm thickness, 19 mm outer diameter and 2000 mm length while the outer pipe was made of Chlorinated Poly Vinyl Chloride (CPVC) with 3 mm thickness, 35 mm outer diameter and 1750 mm length. Asbestos rope with thickness of 5 mm insulated the outer pipe to minimize heat transfer losses from the heat exchanger.

Twisted tapes used in experiment are aluminium tapes that are twisted in one direction with 2 mm thickness (t), 14 mm width (w) and 2000 mm length (l). As shown in Figure 2, twisted tapes with three different pitches (p) of 100, 170 and 240 mm equals to three Twist Ratio's (TR = p/w) of 7, 12 and 17 approximately. These twisted tapes are inserted into inner pipe of the heat exchanger to enhance heat transfer with a little penalty on pressure drop.

Figure 1. Structure of the experimental system.

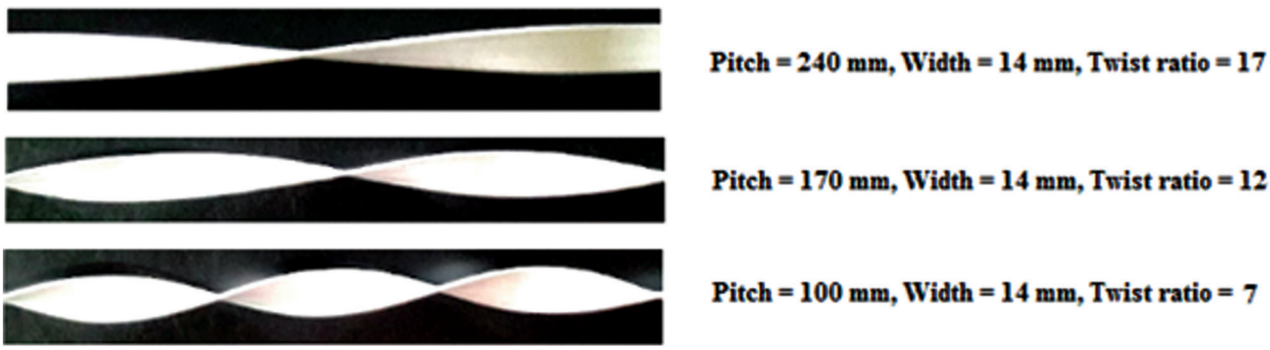

Figure 2. Twisted tape inserts in heat exchanger.

Electrodynamic vibrator with amplifier is positioned at the centre of DTHECF. Present heat exchanger had 8, 40, 107, 186 and 288 Hz as first five resonating frequencies respectively [25]. 8 Hz as a first frequency had modest impact on heat transfer since heat exchanger components absorb majority of forced vibration from vibrator. Frequencies from third to fifth crossed 100 Hz, which are far away from the present vibrating capacity. Using second resonating frequency, experiments are executed by imposing vibration on a twisted tape inserted DTHECF. In vibration analyser, maximum amplitude of DTHECF with twisted tape inserts was found to be 69 mm at 40 Hz resonating frequency. Therefore, Nu in twisted tape inserted heat exchanger are examined in 23 to 69 mm amplitude range and 20 to 100 Hz frequency range.

Figure 3 show the simplified arrangement of hot water system and cold water system for twisted tape inserted DTHECF. Hot water system consists of a hot water tank with heater and stirrer, a hot water pump, a hot water rotameter, a piping system, and a tube with twisted tape insert. Hot water at heat exchanger inlet is maintained at 40^{0}C using thermostat. Convection currents are strengthened inside the tank by stirring hot water at variable speeds. Hot water is pumped into the inner tube at five different flow rates ranging from 5 to 10 LPM.

Similarly, cold water system consists of a cold-water tank, a cold-water pump, a cold-water rotameter, a piping system, and annulus side in heat exchanger. Cold water from another tank is pumped into annulus side. Cold-water inlet temperature was set at 28^{0}C and its flow rate is fixed to 8 LPM using rotameter. Thermo-physical properties for working fluids flowing in twisted tape inserted DTHECF are given in Table 1 [26].

Two rotameters, whose accuracy is within 2%, were used to estimate volumetric flow rate of working fluids. Two inlet temperatures, two outlet temperatures and two tank temperatures for hot and cold-water were measured by using six K-type thermocouples with accuracy of 0.1^{0}C. Six J-type thermocouples were placed with intermediate distance of 0.25 m on outer surface of the inner pipe to measure wall temperatures with accuracy of 0.1^{0}C. Six K-type and six J-type calibrated thermocouples were connected to two digital temperature indicators separately. Data of temperatures and flow rates were recorded in steady-state conditions. Table 2 gives specifications, accuracy and quantity of experimental instruments.

Initially, twisted tape with a twist ratio is inserted into the inner tube of the heat exchanger. Hot water from hot water tank was pumped and measured through rotameter. At the beginning, its flow rate is adjusted and allowed to

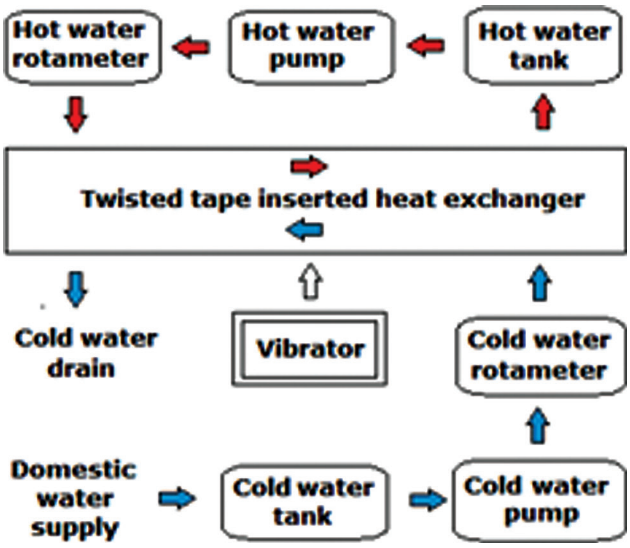

Figure 3. Simplified diagram of the fluid systems.

Table 2. Specifications of experimental instruments

S. No	Device	Specifications	Accuracy	Quantity
1	Tank	125 L, Stainless steel	–	02
2	Heater	2000 W, 30^{0}C to 110^{0}C	0.1^{0}C	01
3	Stirrer	1400 RPM	–	01
4	Pump	0.5 HP	–	02
5	Rotameter	0 to 10 LPM	2%	02
6	J–Type Thermocouple	0 – 100^{0}C	0.1^{0}C	06
7	K–Type Thermocouple	0 – 100^{0}C	0.1^{0}C	06
8	Temperature Indicator	6 Channels	0.1^{0}C	02
9	Vibrator	2 to 1250 Hz	–	01

Table 1. Thermo-physical properties for hot and cold water

S. No	Fluids	Inlet temperature [^{0}C]	Density (kg/m^3)	Dynamic viscosity [kg/m s]	Specific heat [J/kg K]	Thermal conductivity [W/m K]	Prandtl number
1	Hot water	40	991.80	0.00064	4174	0.633	4.28
2	Cold water	28	995.57	0.00083	4177	0.616	5.66

pass through twisted tape inserted inner tube. Its temperature is controlled by using rheostat and then recycled. Cold water is continuously drawn from another tank at a specific flow rate by using another rotameter and its temperature is maintained by using another rheostat. It flows through annulus side and then discharges. Transverse vibrator is placed below the twisted tape inserted DTHECF and then connected to amplifier for controlling vibrations. Now, heat exchanger is vibrated by fine tuning frequency and amplitude in the amplifier. After reaching steady state conditions, temperatures at twelve locations were noted from two temperature indicators. Using same procedure, experiments were conducted on twisted tape inserted DTHECF under vibrations in transverse direction at frequencies from 20 to 100 Hz with interval of 20 Hz, amplitudes from 23 to 69 mm with interval of 23 mm and at twist ratios from 7 to 17 with interval of 5 in the Re range of turbulent conditions.

Uncertainty represents the range of confidence level on heat transfer parameters, which are calculated from experimental data. Initially, uncertainties of independent parameters were evaluated and listed in Table 3. Uncertainties of experimental parameters were estimated from uncertainties of independent parameters by using Eq. (1) [27] and results were summarized in Table 4.

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

Table 3 Uncertainties of independent parameters

S. No	Parameter	Uncertainty (%)
1	Inner diameter for inner pipe (d_{in})	±0.33
2	Outer diameter for inner pipe (d_{out})	±0.26
3	Outer pipe inner diameter (D_{in})	±0.17
4	Heat exchanger length (L)	±0.02
5	Thermal conductivity of water ($k_{b,h}$)	±0.1
6	Thermal conductivity of copper (k_w)	±0.1
7	Specific heat of water (C_p)	±0.1
8	Dynamic viscosity of water (μ)	±0.1
9	Density of water (þ)	±0.1
10	Prandtl number (Pr)	±0.1

Table 4 Uncertainties of experimental parameters

S. No	Parameter	Uncertainty (%)
1	Overall heat transfer coefficient (U_i)	±1.61
2	Heat transfer coefficient for annulus side (h_a)	±0.91
3	Heat transfer coefficient for tube side (h_b)	±1.88
4	Nusselt number (Nu)	±1.90
5	Reynolds number (Re)	±0.35

DATA REDUCTION

Nusselt Number

Nu with and without vibration based on inner pipe diameter is determined by, [28]

$$Nu_v = (h_t d_{in})/k_{b,h} \; Nu = (h_t d_{in})/k_{b,h} \tag{2}$$

Tube side heat transfer coefficient has been evaluated by

$$h_t = 1/[\frac{1}{U_t} - \frac{d_{in} \ln\left(\frac{d_{out}}{d_{in}}\right)}{2k_w} - \frac{d_{in}}{d_{out} h_a}] \tag{3}$$

Overall heat transfer coefficient is estimated by

$$U_t = Q_{avg} / (A_{in} \Delta T_{lm}) \tag{4}$$

Where $\Delta T_{lm} = [(T_{h,i} - T_{c,o}) - (T_{h,o} - T_{c,i})] / \ln\left(\frac{T_{h,i} - T_{c,o}}{T_{h,o} - T_{c,i}}\right)$

and $A_{in} = \pi d_{in} L$

Annulus side heat transfer coefficient is calculated by

$$h_a = Q_c / [A_{in} (T_{w,o} - T_{b,c})] \tag{5}$$

Where $T_{w,o} = \frac{\sum T_{w,i}}{6}$ and $T_{b,c} = (T_{c,o} + T_{c,i})/2$

Heat transfer rate is given by following equation

$$Q_{avg} = (Q_c + Q_h)/2 \tag{6}$$

Rate of heat transfer for hot water can be evaluated by following equation

$$Q_h = (mC_p)_h (\Delta T)_h \tag{7}$$

Where $(\Delta T)_h = T_{h,i} - T_{h,o}$

Rate of heat transfer for hot water can be evaluated by following equation

$$Q_c = (mC_p)_c (\Delta T)_c \tag{8}$$

Where $(\Delta T)_c = T_{c,o} - T_{c,i}$

Pressure Drop

Formula for the calculation of friction factor with and without vibration is as follows [28]

$$f_v = \frac{\Delta P}{(\rho_{b,h} u^2/2)(L/d_{in})},\ f = \frac{\Delta P}{(\rho_{b,h} u^2/2)(L/d_{in})} \quad (9)$$

Where $\Delta P = (\rho_m - \rho_{b,h}) g (\Delta h)$

Influence estimated of vibration on pressure drop characteristics for DTHECF with twisted tape insert are not analysed since pressure-sensing devices were not included in the current experiments [8]. Nevertheless, pressure drops are from Nu in following sequence [26].

Pressure drop can be obtained by

$$\Delta P = f(\rho_{b,h} u^2/2)(L/d_{in}) \quad (10)$$

Colburn analogyis expressed as

$$(St)(\Pr)^{2/3} = \frac{f}{8} \quad (11)$$

Stanton number is defined as

$$St = \frac{Nu}{(\mathrm{Re})(\Pr)} \quad (12)$$

Performance Evaluation Criteria

Vibration enhancement technique on twisted tape inserted DTHECF reduces its thermal resistance by creating turbulence. This results in higher maintenance cost from additional pumping power. Now, effectiveness of vibration enhancement technique was calculated by using Performance Evaluation Criteria (PEC) [29].

$$PEC = \frac{Nu_v / Nu}{(f_v / f)^{1/3}} \quad (13)$$

RESULTS AND DISCUSSION

Validation

To validate the accuracy of the experimental setup, experimental friction factors are evaluated using Eq. (9) at different Reynolds numbers when the twisted tape inserted heat exchanger is not exposed to vibrations. Values of experimental friction factors at different twist ratios are compared with the corresponding theoretical friction factors from existing correlation [30] as shown in Figure 4.

Manglik - Bergles correlation for friction factors:

$$f = \frac{0.0791}{\mathrm{Re}^{0.25}} \left(\frac{\pi}{\pi - (4\delta/d)} \right)^{1.75} \left(\frac{\pi + 2 - (2\delta/d)}{\pi - (4\delta/d)} \right)^{1.25} \left(1 + \frac{2.752}{y^{1.29}} \right) \quad (14)$$

Maximum deviations between experimental and theoretical friction factors from Manglik - Bergles correlation are 5.10 %, 8.01% and 8.94% for twist ratios of 7, 12 and 17 respectively. Thus, it may be concluded that values of experimental friction factors deviated less than 9% compared to theoretical friction factors for all twist ratios considered in this study.

Now, experimental Nu are evaluated using Eq. (2) at different Reynolds numbers when the heat exchanger with twisted tape inserts is not exposed to vibrations. Values of experimental Nu at different twist ratios are compared with corresponding theoretical Nu from existing correlation [30] for the same set of flow and temperature conditions as shown in Figure 5.

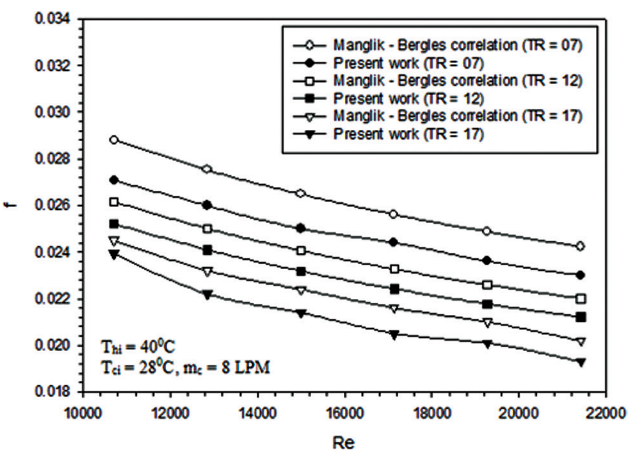

Figure 4. Experimental friction factors validation for DTHECF.

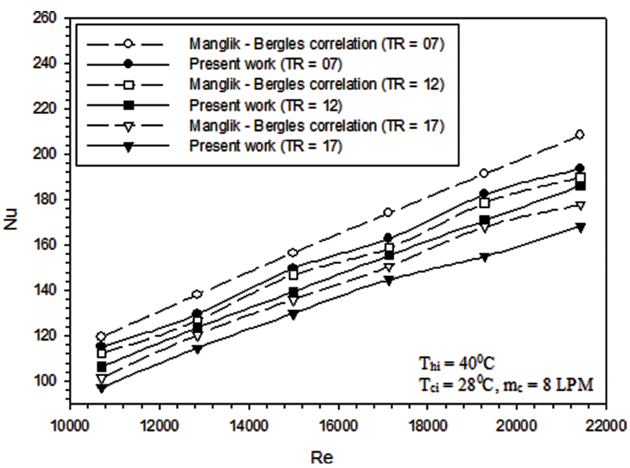

Figure 5. Experimental Nusselt number validation for DTHECF.

Manglik - Bergles correlation for Nusselt number:

$$Nu = 0.023\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4}\left(\frac{\pi}{\pi-(4\delta/d)}\right)^{0.8}\left(\frac{\pi+2-(2\delta/d)}{\pi-(4\delta/d)}\right)^{0.2}\left(\frac{\mu_b}{\mu_w}\right)^{0.30}\left(1+\frac{0.769}{y}\right)^{0.2} \quad (15)$$

Maximum deviations between experimental and theoretical Nu from Manglik - Bergles correlation are 7.29 %, 9.15 % and 9.53 % for twist ratios of 7, 12 and 17 respectively. Thus, it may be observed that values of experimental Nu deviated less than 10% compared to theoretical Nu for all twist ratios considered in this study.

Twist Ratio

Figure 6 shows variations of Log Mean Temperature Difference (LMTD) with three different twist tape inserts in DTHECF vibrating at 40 Hz frequency and 69 mm amplitude for six different Reynolds numbers. LMTD decreased gradually with decline in twist ratio and also with decline in Re of vibrating twisted tape inserted DTHECF. Decrease in LMTD is due to increase in swirl flow generated by twisted tape in tube side of vibrating heat exchanger. Twisted tape inserts in the inner tube of the heat exchanger creates geometrical modifications to the flow channel inside it. They also increase effective surface area and residence time of the flowing fluid. A repeated change in the axial direction of fluid flow at tube side induces turbulence. This turbulence helps for better mixing in single phase fluid and consequently enhances heat transfer within the heat exchanger [13]. Eq. (4) clearly suggests that lower LMTD gives higher heat transfer coefficient. For all Reynolds numbers, lowest LMTD is registered at twist ratio of 7 giving higher improvement in heat transfer. Lowest LMTD is achieved in transversely vibrating heat exchanger with lowest twist ratio at lowest Re.

When Re is increased, Nu is also found to be increasing for vibrating heat exchanger with and without inserts in Figure 7. Vibrational Nu with twisted tape inserts performed better than vibrational Nu without inserts for all Reynolds numbers. At all Reynolds numbers, vibrational Nu with twist ratio of 7 is higher than other twist ratios of 12 and 17 due to their respective LMTDs. Figure 6 indicated that lower LMTD in heat exchanger had greater heat transfer enhancement. Highest Nu is achieved for vibrating DTHECF with twist ratio of 7 at top most value of Re. Vibrational Nu at bottom most value of Re for twist ratios of 17, 12 and 7 enhanced maximum by 52%, 72% and 91% respectively compared to vibrational Nu without insert in DTHECF vibrating at 40 Hz frequency and 69 mm amplitude.

Amplitude

Figure 8 presents the experimental results for different amplitudes and different Reynolds numbers in terms of Nu. For all three amplitudes of vibrating DTHECF with insert, Nu improved with rise in Re. Nu without vibration in twisted tape inserted DTHECF also followed similar trend of augmentation. For smallest twist ratio, vibrational Nu at all three amplitudes are higher than Nu without vibration. Twisted tape inserted DTHECF vibrating at 69 mm amplitude had higher vibrational Nu compared to other vibrational Nu at amplitudes of 46 and 23 mm. This is due to increase in the displacement of twisted tape inserted heat exchanger in transverse direction with increase in amplitude. Generally, conduction mode of heat transfer within

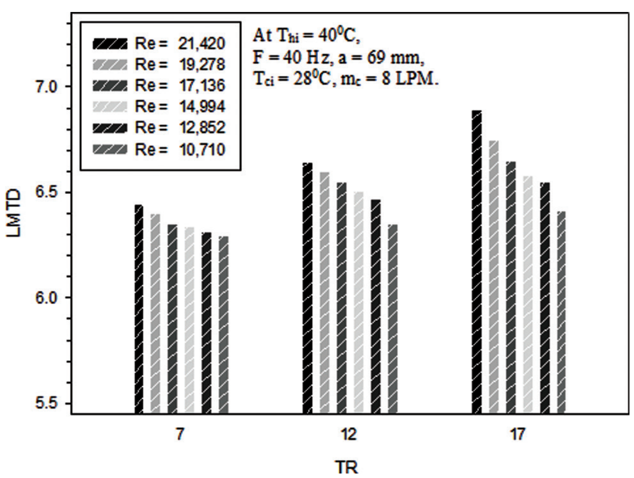

Figure 6. Variation of LMTD with twist ratio for different Reynolds numbers.

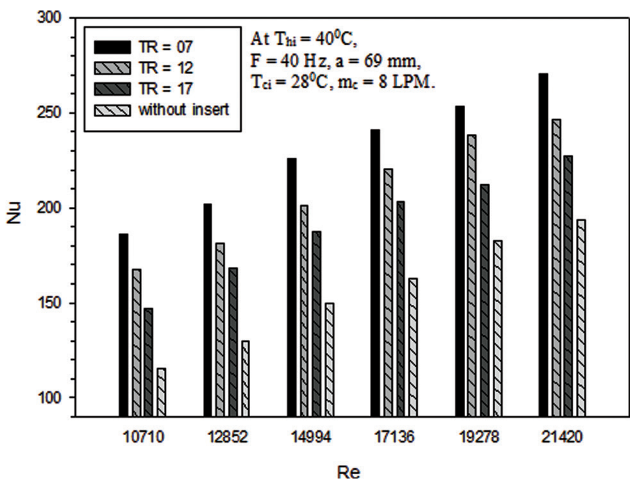

Figure 7. Variation of Nusselt number with Reynolds number for different twist ratios.

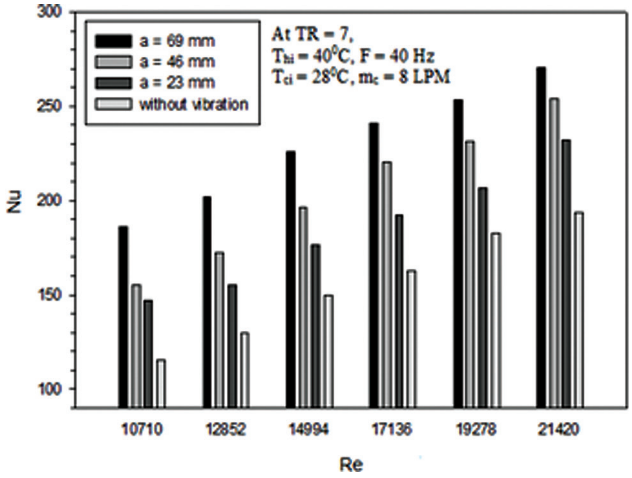

Figure 8. Influence of amplitude for different Reynolds numbers.

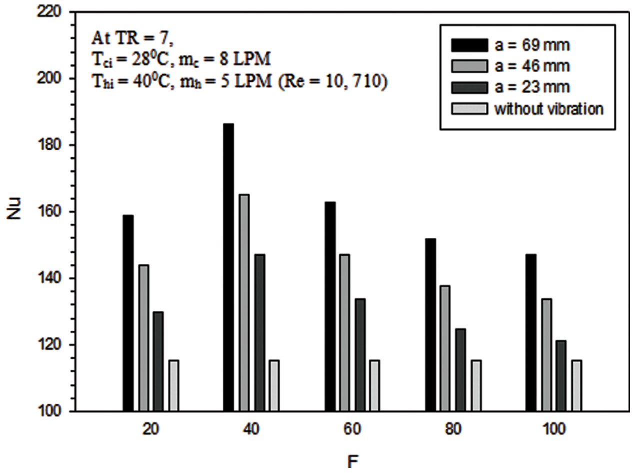

Figure 9. Variation of Nusselt number with frequency for different amplitudes.

fluid regions of heat exchanger in radial direction happens slowly. Now, transverse vibration creates radial mixing in the fluid regions. It also develops temperature profile in axial direction quickly reducing entrance length. This disturbance will intensify convective heat transfer in both axial and radial directions of fluid flow inside the heat exchanger. [1] For twist ratio of 7, highest Nu is reported for DTHECF with 69 mm vibration amplitude at highest Re. For highest Re, vibrational Nu at peaked frequency with increasing amplitudes increased approximately by 20%, 31% and 40% when compared to Nu in twisted tape inserted DTHECF.

Frequency

As displayed in figure 9, in the current analysis, Nu are examined at three different amplitudes of 23, 46 and 69 mm in the experimental frequency range and compared to Nu in DTHECF with twisted tape. It is apparent that Nu increases first and then decreases with increase in frequency. Nu rose up to specific frequency since it is second frequency of twisted tape inserted heat exchanger [4]. Second frequency for present heat exchanger found to be 40 Hz [25]. Twisted tape insert with vibration in heat exchanger will create swirl flow and triggers more turbulence breaking boundary layer. It minimizes thermal resistance and improves convective form of heat transfer between fluids and walls of heat exchanger.

Now, Nu in heat exchanger starts to decrease with further increase in frequency due to its non-resonating frequencies [5]. Vibration energy at these frequencies is not sufficient to create more turbulence, which allows formation of thin boundary layer in twisted tape inserted heat exchanger. Influence of vibration on convective coefficient will start to diminish slowly. This decreasing trend in Nusselt number will continue up to 100 Hz. It is also seen in figure 9 that Nu at all frequencies improves with an increase in amplitude.

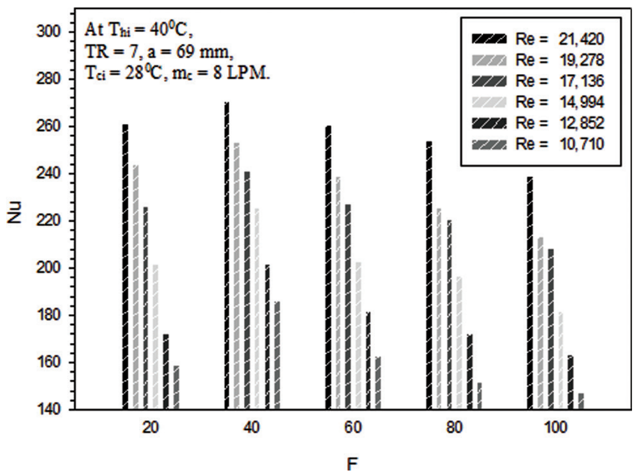

Figure 10. Influence of Reynolds number on Nusselt number at different frequencies.

At 40 Hz, Nu with amplitude of 69 mm was found to be higher than other amplitudes. For twist ratio of 7, vibrational Nu at all frequencies and amplitudes was also found to be more than Nu in twisted tape inserted DTHECF. Nu in comparison with Nu without vibration improved maximum by 28%, 35% and 62% for amplitudes of 23, 46 and 69 mm applied to twisted tape inserted DTHECF at lowest Re and second frequency in the figure 9.

Figure 10 illustrates Nu at different Reynolds numbers for 20 to 100 Hz frequencies and 69 mm amplitude of DTHECF with twisted tape insert. It is observed that increasing the Re, the Nu increased steadily for all frequencies of vibrating DTHECF. High Nu was observed at highest Re for all frequencies. Bar chart diagram showed that Nu peaked at 40 Hz frequency in experimental Re range of turbulent flow conditions. For Re, Nu at 10710 enhanced by 7%, 21%, 31%, 36% and 46% in correspondence with Nu at 12852, 14994, 17136, 19278 and 21420 respectively for twisted tape inserted DTHECF vibrating at 40 Hz and 69 mm.

Figure 11 indicates the dependence of Nu on vibration frequencies at different twist ratios of 7, 12 and 17 for Re of 10710. From the figure, it is clear that Nu spiked at second vibration frequency for experimental twist ratios in DTHECF vibrating at 69mm amplitude. Nu with twisted tapes inserts at all twist ratios is higher than without insert for all vibration frequencies ranging from 20 to 100 Hz. It is increasing with decrease in the twist ratio value for twisted tape inserted heat exchanger exposed to vibration. Nu displayed high at 40 Hz for lowest twist ratio of 7. At minimum Re, Nu with twist ratios of 17, 12 and 7 enhanced maximum by 52%, 72% and 91% compared to Nu without twisted tape insert. Finally, highest enhancement of 91% in Nu is attained for lowest Re in twisted tape inserted DTHECF vibrating at highest amplitude with a second experimental frequency.

Pressure Drop

Variations in pressure drop against vibration frequencies are plotted for twisted tape inserted DTHECF at three amplitudes in figure 12. For Re of 10710, pressure drop is high in a twisted tape inserted DTHECF when it is vibrating at 40 Hz frequency and 69 mm amplitude. Pressure drop for twisted tape inserted DTHECF with three different vibration amplitudes are higher than without vibration at all experimental frequencies and at Re of 10710.This sharp rise in pressure drop with frequency increase is due to swirl flow from twisted tape and additional turbulence up to second resonance of twisted tape inserted heat exchanger [4]. Present heat exchanger had second frequency of 40 Hz [25]. So, increasing trend of pressure drop with increase in vibration frequency continues up to 40 Hz. Pressure drop starts to fall with further frequency increase due to existence of swirl flow and decrease in additional turbulence inside the non-resonating heat exchanger [5]. After 40 Hz, pressure drop decreases up to highest frequency of 100 Hz in the experimental range.

As seen from figure, pressure drop raised with increment in amplitude for all Reynolds numbers. This increase in pressure drop is due to swirl flow and internal movement of fluid particles in fluid zones of twisted tape inserted heat exchanger. With further increase in amplitude, most of the fluid particles will continue to move within the layers. This will create additional frictional losses to existing pressure drop. For twisted tape inserted DTHECF, pressure drop increased by 29%, 36% and 64% for three amplitudes in increasing order when compared to pressure drop with no vibration.

Performance Evaluation Criteria

Performance of heat transfer with pressure drop is evaluated on Eq. (13) to study the feasibility of imposing transverse vibration on twisted tape inserted double pipe heat exchanger. Values of PEC for different Re at three twist ratios of 7, 12 and 17 are plotted in Figure 13. For a twist ratio, values of PEC are deteriorating gradually with increase in Re. Insert with twist ratio of 7 achieved the best performance on enhancement in heat transfer in present heat exchanger and its PEC ranged from 1.25 to 1.38. Performance of twisted tape insert with twist ratio of 12 is slightly inferior to that at twist ratio of 7 and its PEC ranged from 1.24 to 1.34. For the present work, PEC values are above 1, which is desirable. Advantage of improved heat transfer with extra pumping cost using twisted tape insert in vibrating DTHECF is feasible since its PEC is greater than one.

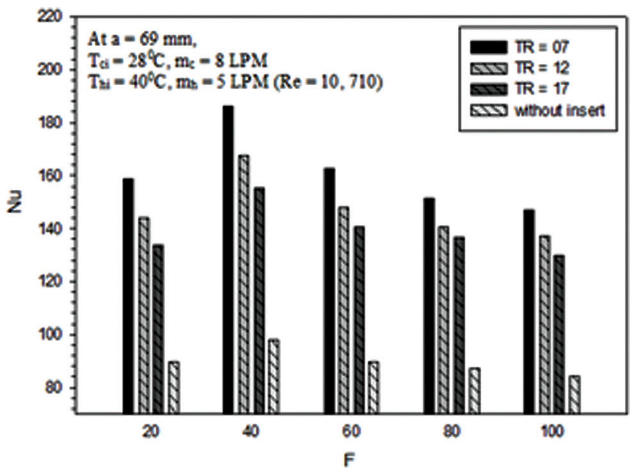

Figure 11. Change in Nusselt number due to frequency at different twist ratios.

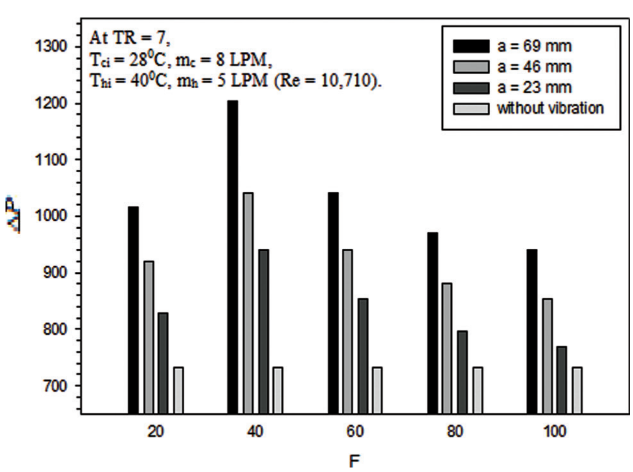

Figure 12. Variation of pressure drop with frequency for different amplitudes.

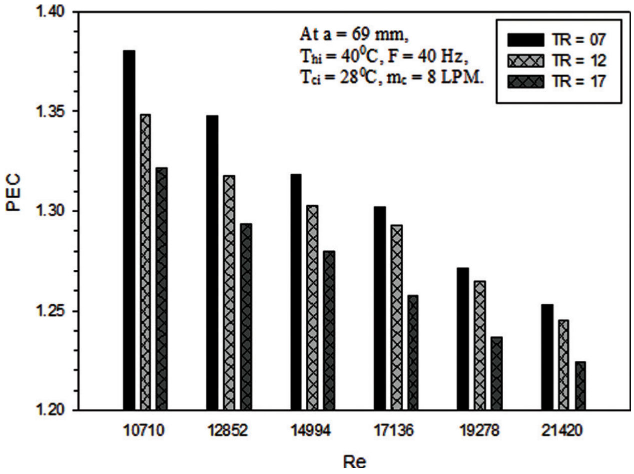

Figure 13. Variation of PEC with Reynolds number for different twist ratios.

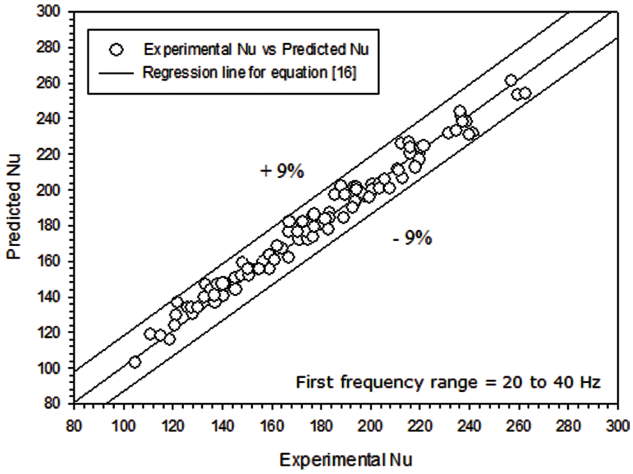

Figure 14. Comparison of Nusselt numbers for first frequency range.

Multi Linear Regression

Longitudinal vibration impact on transfer of thermal energy in a heat exchanger is examined experimentally and a correlation is formulated for enhancement in Nu at laminar flow conditions [5]. Present correlations are different from other existing correlations due to presence of twisted tape inserts in vibrating DTHECF. Empirical correlations of vibrational Nu with twisted tape inserts are established using multi linear variable regression from the present experimental data. Two correlations of vibrational Nu for two frequency ranges are as follows.

For 7 ≤ (p/w) ≤ 17 and 23 mm ≤ a ≤ 69 mm

$$Nu = 0.018(\mathrm{Re})^{0.8}(\mathrm{Pr})^{0.3}\left(\frac{d^2F}{v}\right)^{0.135}\left(\frac{p}{w}\right)^{-0.167}\left(\frac{a}{d}\right)^{0.180} \quad (16)$$

For 7 ≤ (p/w) ≤ 17 and 23 mm ≤ a ≤ 69 mm

$$Nu = 0.292(\mathrm{Re})^{0.8}(\mathrm{Pr})^{0.3}\left(\frac{d^2F}{v}\right)^{-0.162}\left(\frac{p}{w}\right)^{-0.141}\left(\frac{a}{d}\right)^{0.171} \quad (17)$$

Experimental values are compared with predicted values of Nu for two frequency ranges as shown in figures 14 and 15. The predicted values are closer to experimental values since deviations of vibrational Nu with inserts are within ±9% for both frequency ranges.

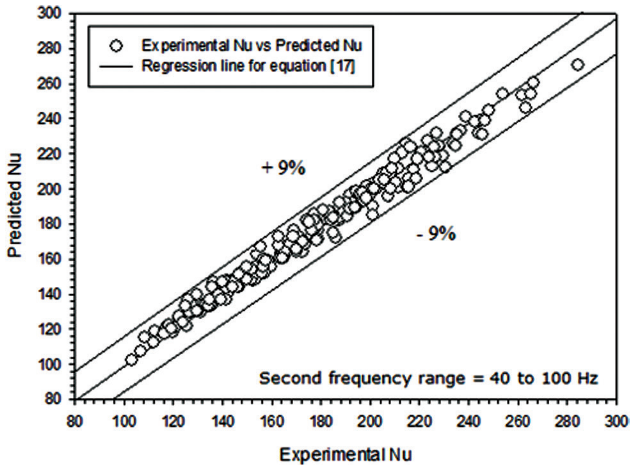

Figure 15. Differences in Nusselt numbers for second frequency range.

CONCLUSIONS

Experiments on heat transfer characteristics in twisted tape inserted DTHECF with transverse vibration for single-phase flow have been carried out in present analysis. Conclusions from the present work are

(1) Influence of vibration on twisted tape inserted heat exchanger is prominent at lowest Re in turbulent conditions. At lowest Re, vibrational Nu with twist ratio of 7 enhanced by 12% and 27% compared to other twist ratios of 12 and 17 respectively due to increment in swirl flow. Changes in flow direction created turbulence and better convection currents are formed for higher heat transfer enhancement.

(2) For 40 Hz with smallest twist ratio, Nu at amplitudes of 23, 46 and 69 mm are 28%, 35% and 62% respectively higher than the non-vibrating Nu. At highest amplitude, Nu improved remarkably

due to transverse displacement of present heat exchanger. Temperature distribution in both axial and radial directions is also promoted.

(3) Nu enhanced maximum of 91% for twisted tape inserted DTHECF vibrating at 40 Hz and 69 mm compared to vibrational Nu without insert. Additional turbulence increased with rise in frequency up to 40 Hz and then decreased with further increase in frequency up to 100 Hz.

(4) Heat transfer characteristics of twisted tape inserted DTHECF is enhanced by applying vibrations on it. At the same time, pressure drop also increased. Using vibration enhancement technique is feasible since its PEC is 1.38, which is greater than one. This metric implies that the increase in heat transfer rate more than compensates the undesirable penalty of pumping power.

(5) Empirical correlations for Nu were developed and deviations found to be within ± 9% for both frequency ranges. Using developed correlations, Nu can be estimated for a given twist ratio, frequency and amplitude in experimental range under turbulent conditions.

NOMENCLATURE

A	heat transfer surface area (m^2)
a	amplitude (m/s^2)
C_p	specific heat (J/Kg K)
d	pipe diameter of inner pipe (m)
F	Frequency (Hz)
f	friction factor
g	Acceleration due to gravity (m/s^2)
h	heat transfer coefficient (W/m^2K)
Δh	Level difference in U tube manometer (m)
k	Thermal conductivity (W/mK)
L	heat exchanger length of test section (m)
m	mass flow rate (kg/s)
ΔP	Pressure drop (Pa)
Q	heat transfer rate (W)
T	temperature (K)
ΔT	temperature difference (K)
U	overall heat transfer coefficient (W/m^2K)
u	velocity (m/s)

Greek letters

μ	fluid dynamic viscosity (Ns/m^2)
ρ	fluid density (kg/m^3)

Subscripts

a	annulus side
avg	average
a,w	average wall
b,c	cold bulk mean
b,h	hot bulk mean
c	cold
cu	copper
h	hot
i	inlet
in	inner
m	mercury
o	outlet
out	outer
t	tube side
v	with vibration

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

REFERENCES

[1] Omidi M, Farhadi M, Jafari M. A comprehensive review on double pipe heat exchangers. Appl Therm Eng 2017;110:1075–1090. [CrossRef]

[2] Sheikholeslami M, Gorji-Bandpy M, Ganji DD. Review of heat transfer enhancement methods: Focus on passive methods using swirl flow devices. Renew Sustain Energy Rev 2015;49:444–469. [CrossRef]

[3] Atashi H, Alaei A, Kafshgari MH, Aeinehvand R, Rahimi SK. New pool boiling heat transfer in the presence of low-frequency vibrations into a vertical cylindrical heat source. Exp Heat Transf 2014;27:428–37. [CrossRef]

[4] Lemlich R, Hwu C -K. The effect of acoustic vibration on forced convective heat transfer. AIChE J 1961;7:102–6. [CrossRef]

[5] Klaczak A. Report from experiments on heat transfer by forced vibrations of exchangers. Heat Mass Transf Und Stoffuebertragung 1997;32:477–480. [CrossRef]

[6] Gondrexon N, Rousselet Y, Legay M, Boldo P, Le Person S, Bontemps A. Intensification of heat transfer process: Improvement of shell-and-tube heat exchanger performances by means of ultrasound. Chem Eng Process Process Intensif 2010;49:936–42. [CrossRef]

[7] Legay M, Simony B, Boldo P, Gondrexon N, Le Person S, Bontemps A. Improvement of heat transfer by means of ultrasound: Application to a double-tube heat exchanger. Ultrason Sonochem 2012;19:1194–200. [CrossRef]

[8] Legay M, Le Person S, Gondrexon N, Boldo P, Bontemps A. Performances of two heat exchangers assisted by ultrasound. Appl Therm Eng 2012;37:60–6. [CrossRef]

[9] Gondrexon N, Cheze L, Jin Y, Legay M, Tissot Q, Hengl N, et al. Intensification of heat and mass transfer by ultrasound: Application to heat exchangers and membrane separation processes. Ultrason Sonochem 2015;25:40–50. [CrossRef]

[10] Arasavelli SS, Konijeti R, Budda GR. Effect of vibrator position and frequency on heat transfer enhancement in counter flow concentric pipe heat exchanger. World J Eng 2020;17:751–760. [CrossRef]

[11] Arasavelli SS, Konijeti R, Budda GR. Influence of transverse vibrations on convective heat transfer in parallel flow tube-in-tube heat exchanger. Heat Transf 2020:1–22. [CrossRef]

[12] Sarma PK, Konijeti R, Subramanyam T, Prasad LSV, Korada VS, Srinivas V, et al. Fouling and its effect on the thermal performance of heat exchanger tubes. Int J Heat Technol 2017;35:509–519. [CrossRef]

[13] Liu S, Sakr M. A comprehensive review on passive heat transfer enhancements in pipe exchangers. Renew Sustain Energy Rev 2013;19:64–81. [CrossRef]

[14] Varun, Garg MO, Nautiyal H, Khurana S, Shukla MK. Heat transfer augmentation using twisted tape inserts: a review. Renew Sustain Energy Rev 2016;63:193–225. [CrossRef]

[15] Kumar B, Srivastava GP, Kumar M, Patil AK. A review of heat transfer and fluid flow mechanism in heat exchanger tube with inserts. Chem Eng Process Process Intensif 2018;123:126–137. [CrossRef]

[16] Gupte NS, Date AW. Friction and heat transfer characteristics of helical turbulent air flow in annuli. J Heat Transfer 1989;111:337–344. [CrossRef]

[17] Sivashanmugam P, Sundaram S. Improvement in performance of heat exchanger fitted with twisted tape. J Energy Eng 1999;125:35–41. [CrossRef]

[18] Man C, Lv X, Hu J, Sun P, Tang Y. Experimental study on effect of heat transfer enhancement for single-phase forced convective flow with twisted tape inserts. Int J Heat Mass Transf 2017;106:877–883. [CrossRef]

[19] Yadav AS. Effect of half length twisted-tape turbulators on heat transfer and pressure drop characteristics inside a double pipe u-bend heat. Jordan J Mech Ind Eng 2009;3:17–22.

[20] Mohanty RL, Bashyam S, Das D. Numerical analysis of double pipe heat exchanger using heat transfer augmentation techniques. Int J Plast Technol 2014;18:337–348. [CrossRef]

[21] Piriyarungrod N, Kumar M, Thianpong C, Pimsarn M, Chuwattanakul V, Eiamsa-ard S. Intensification of thermo- hydraulic performance in heat exchanger tube inserted with multiple twisted-tapes. Appl Therm Eng 2018;136:516–530. [CrossRef]

[22] Khoshvaght-Aliabadi M, Feizabadi A. Performance intensification of tubular heat exchangers using compound twisted-tape and twisted-tube. Chem Eng Process 2020;148:107799. [CrossRef]

[23] Bhakta AK, Singh SN. Thermo-hydraulic performance analysis of parabolic concentrating solar water heater. J Therm Eng 2020;6:802–815. [CrossRef]

[24] Afsharpanah F, Sheshpoli AZ, Pakzad K, Ajarostaghi SSM. Numerical investigation of non-uniform heat transfer enhancement in parabolic trough solar collectors using dual modified twisted-tape inserts. J Therm Eng 2021;7:133–47. [CrossRef]

[25] Young WC, Budynas RG. Roark's Formulas for Stress and Strain. 7th ed. New York: McGraw Hill; 2002.

[26] Holman JP. Heat Transfer. 10th ed. New York: McGraw Hill; 2010.

[27] Schultz RR, Cole R. Uncertainty analysis in boiling nucleation. AICHE Symp Ser 1979:189:32–38.

[28] Yaningsih I, Wijayanta AT, Miyazaki T, Koyama S. V-cut twisted tape insert effect on heat transfer enhancement of single phase turbulent flow heat exchanger. AIP Conf Proc 2018;1931:030038. [CrossRef]

[29] Maradiya C, Vadher J, Agarwal R. The heat transfer enhancement techniques and their Thermal Performance Factor. Beni-Suef Univ J Basic Appl Sci 2018;7:1–21. [CrossRef]

[30] Manglik RM, Bergles AE. Heat transfer and pressure drop correlations for twisted-tape inserts in isothermal tubes: Part II—transition and turbulent flows. J Heat Transfer 1993;115:890–896. [CrossRef]