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Experimental Investigation of Heat Transfer Enhancement in a Double Pipe Heat Exchanger Using Compound Technique of Transverse Vibration and Inclination Angle

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ABSTRACT

Numerous tests are recently conducted to assess vibration's role in accelerating the heat transfer rate in various heat exchangers. In this work, the enhancement of heat transfer by the effect of transfer vibration and inclination angles on the surface of a double pipe heat exchanger experimentally has been investigated. A data acquisition system is applied to record the data of temperatures, flow rates, and frequencies over the tests. A compound technique was adopted, including the application of a set of inclination angles of (0°, 10°, 20°, and 30°) under the effect of frequency of vibration ranging from sub-resonance to over-resonance frequencies. The results showed that the overall heat transfer coefficient enhances by applying the compound technique at all the working fluid's temperatures and flow rate ranges. The maximum increase in overall heat transfer coefficient occurs at an angle of 30° and the resonance frequency. Moreover, the effectiveness of the double pipe heat exchanger gradually expanded when temperature, inclination angles, and vibration amplitude rosed. But the effectiveness value declined as the hot working flow rate increased considerably. Finally, the enhancement factor demonstrated that the combined strategy (vibration frequencies and inclination angles) had been the most effective technique in improving and enhancing heat transfer and was superior to the other ways. Additionally, the extremes improvement in overall heat transfer coefficient, effectiveness, and enhancement factor are 183.4, 191, and 164.4 %. The improvement was situated at the resonance frequency with a 30° inclination angle.

Keywords: Double pipe heat exchanger, Inclination angle, Resonance frequency, Enhancement factor, Effectiveness.

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دراسة عملية لتعزيز انتقال الحرارة لمبادل حراري مزدوج الانبوب باستخدام التقنية المركبة من الاهتزاز العرضي وزاوية الميلان

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الخلاصة

تم إجراء العديد من الاختبارات مؤخرًا لتقييم دور الاهتزازات في تسريع معدل انتقال الحرارة في المبادلات الحرارية المختلفة. في هذه الدراسة ، تمت اجراء دراسة عملية لتعزيز انتقال الحرارة باستخدام الاهتزازات العرضية وزوايا الميل على سطح مبادل حراري مزدوج الأنابيب. تم استخدام منظومة رقمية للحصول على بيانات درجات الحرارة ، ومعدلات التدفق ، وترددات الاهتزاز خلال اجراء الاختبارات العملية . تم اعتماد التقنية المركبة والذي يتضمن تطبيق مجموعة من زوايا الميل بقيمة (0 ° ، 10 ° ، 20°، 30 °) وتحت تأثير الاهتزازات العرضية ضمن (ترددات منخفضة ,ترددات الرنين والترددات العالية). أظهرت النتائج ، بشكل عام ، أن معامل انتقال الحرارة الكلي يُعزز من خلال تطبيق التقنية المركبة في جميع درجات الحرارة ومعدلات التدفق للماء. تحدث الزيادة القصوى في معامل انتقال الحرارة الكلي بزاوية 30 درجة وعند تردد الرنين. علاوة على ذلك ، فإن فعالية المبادل الحراري للأنابيب المزدوجة تزداد تدريجياً ، عندما تنخفض درجة الحرارة وزوايا الميل وسعة الاهتزاز ولكن قيمة الفعالية تنخفض ، عند زيادة معدل تدفق الماء الساخن بشكل كبير. أخيرًا ، أظهر معامل التعزيز أن استراتيجية التقنية المركبة (ترددات الاهتزاز وزوايا الميل) كانت أكثر التقنيات فاعلية في تحسين وتعزيز انتقال الحرارة ، وكانت متفوقة على الطرق الأخرى. بالإضافة إلى ذلك ، كان افضل قيم للتحسين بالنسبة لمعامل انتقال الحرارة الكلي ومعامل فعالية انتقال الحرارة ومعامل التعزيز بقيمة 183.4 ،191 ، و 164.4 % على التوالي وكان يقع عند تردد الرنين بزاوية ميل 30 درجة.

الكلمات الرئيسية: مبادل حراري مزدوج، زاوية الميلان، تردد الرنين، معامل التعزيز ، فاعلية

1. INTRODUCTION

The heat exchanger is a system for managing heat and is vital to numerous industries. Typically, heat exchangers effectively transfer heat from one medium to another, with the transferring media including gas, steam, vapors, and various other liquids **(Addepalli et al., 2015)**. The tubular heat exchanger is utilized for larger fluid systems than the plate type, and they are both available in plate and tubular configurations. Several crucial factors, including corrosion resistance, thermal conductivity, material strength, and cost, are considered when choosing materials for heat exchangers. Heat exchangers efficiently transfer heat between two fluids with or without separating a solid wall. Evaporation, condensation, or a phase shift alone could transfer heat between two fluids. When a temperature difference occurs, energy is transferred in heat, which can either be sensible heat or latent heat in thermal energy storage, which utilizes the latent heat of phase-change materials.

Shell and tube heat exchangers are most frequently employed in industrial cooling systems, water power plants, nuclear power plants, lubrication oil coolers, and petrochemical and oil industries **(Ghayad et al., 2015; Fathi and Mussa, 2021).** Numerous earlier attempts have been made to improve the heat transfer of double-pipe heat exchangers. Enhancing techniques effectively lower the thermal resistance in a typical heat exchanger by encouraging a better convective heat transfer coefficient with or without surface area increases. Enhancement methods can often be divided into three categories: passive techniques, active techniques, and compound techniques. These techniques typically include changing the flow channel's surface or geometry, inserting a substance or an extra device allowing for the desired flow alteration, and the ensuing increase in the heat transfer rate **(Sarafraz et al., 2016; Hamzah and Nima, 2019).**

Many researchers have identified vibration as one of the active strategies for improving heat transfer. Incorporating vibration in heat exchangers increases the heat transfer rate and turbulence intensity in boundary layers. In addition, vibrations promote fluid mixing, which raises the heat transfer coefficient. Up to a 20-fold increase in heat transfer coefficient compared to stationery tubes, depending on oscillation amplitude-to-tube diameter ratios and vibration Reynolds numbers **(Rohsenow et al., 1998).** Examples of typical applications for active heat transfer enhancement techniques include the employment of an external force to accelerate heat transfer, such as reciprocal plungers, surface vibration, and electromagnetic fields **(Zhang et al., 2012).** Since the late 1930s, much research has focused on creating sufficiently strong surface vibrations or oscillations to promote heat or mass transmission, especially in the free convection mode**.** In the active approaches, electromagnetic fields are also used by an outside force along with surface or flow vibration to speed up heat transfer. Active processes that need external power include fluid vibration, surface vibration, injection, suction, and electric or acoustic fields. One of the best active strategies for accelerating heat transfer rates is surface vibration **(Hosseinian et al., 2018; Mohammed, 2020)**.

Increasing the efficiency of heat exchangers has received more attention from researchers. Various heat transfer enhancement methods are discussed and explored to reduce the heat exchanger size and increase performance. These techniques can generally be divided into three major categories: active, passive, and compound, depending on whether they require external power. The literature reviews in the present work are devoted only to introducing and discussing the active and compound methods. The first way in the active methodology is flow-induced vibration, discussed by **(Cheng et al., 2009).** They have produced a vibration inflow by changing the center of curvature of the coils that carry the flowing fluids and using the theory of changing the natural frequency of each alternate coil. Beyond an increase in heat transfer coefficient, the main advantage of flow-induced vibration is a reduction in the fouling factor, a problem caused by scale buildup at heat exchanger walls that prevents heat exchange with the influx of vibration. The second type is ultrasonic wave-induced vibration, which produces a phenomenon known as acoustic streaming when ultrasonic vibrations pass through a liquid **(Slama et al., 2019).** The advantages of ultrasonic vibrations for increasing the effectiveness of fluid-to-fluid heat exchangers have been comprehensively discussed by **(Legay et al., 2012).** They assert that acoustic waves homogenize the sub-flow velocity vectors in pipes, reducing the fluid's surface tension at the borders, which increases thermal resistance and result in a notable performance boost.

Thirdly, surface vibration causes an increase in the boundary layer turbulence by speeding up the heat transfer rate using a double pipe heat exchanger with surface vibration **(Hosseinian et al., 2018)** conducted research and presented some intriguing findings. As vibration intensity rises, the heat transmission rate increases, reaching a maximum increase of 97%. In some related work, Lin and others **(Lin et al., 2008)** found that vibrating sidewalls in rectangular horizontally heated walls increased heat transfer. In an

experimental study of surface vibration on tube bundles, **(Lee et al., 2004; Michaelides et al., 1986)** found that the vibration causes the average heat transfer coefficient of the tube bundles to increase dramatically when fluid mixing increases. The improvement of heat transfer in a water-water rectangular channel heat exchanger is also examined. According to their research results, increasing of vibration intensities can somewhat improve heat transmission qualities. Compound techniques increase heat transmission by combining active and passive methods. **(Zhang et al., 2015)** investigated the effects of mechanical vibration on forced convection heat transfer for Silicon dioxide (SiO_2-water nanofluids). Their results show that a 182 % increase in the heat transfer coefficient is achieved. One of the hardest issues limiting the usage of nanofluids in business is the aggregation of nanoparticles and it is predicted that the presence of vibration in nanofluids will lessen nanoparticle agglomeration.
The literature review concludes that applying the compound technique to heat exchangers to raise the heat transfer rate is a relatively new technique that lacks investigation and needs more research to explore their effects on the performance of double pipe exchangers. Thus, the mutual effect of surface vibration and inclination at counter-flow conditions has been studied extensively for a double-pipe heat exchanger in the present work. The effect of various vibration frequencies and inclination angles on overall heat transfer coefficient, effectiveness, and enhancement factor is carried out experimentally.

2. MATHEMATICAL APPROACH

The present section introduces the essential mathematical relationships and formulas to determine the different parameters that reflect the double-pipe heat exchanger performance. Also, the following assumptions are adopted to carry out the mathematical formulations:
1. The working fluid was treated as an incompressible flow.
2. The heat transferred by radiation was considered negligible, being two.
3. The cold-water temperature and flow rate are considered to be constant.
4. The transverse vibration is applied to the perpendicular direction of the heat exchanger plane.

2.1 Experimental Estimation of the Overall Heat Transfer Coefficient

The experimental estimation of the overall heat transfer coefficient mainly depends on the temperature measurement of the hot and cold-water temperatures and flow rates. The heat transfer rate between the hot-water Q_h and the cold-water Q_c can be found by the following relations **(Cheng et al., 2009)**.

$$Q_h = \dot{m}_h \times C_{ph}(T_{h\,in} - T_{h\,out}) \quad (1)$$

$$Q_C = \dot{m}_c \times C_{pc}(T_{c\,out} - T_{c\,in}) \quad (2)$$

where
C_{pc} and C_{ph}: specific heats of the cold and hot water.
$T_{h\,in}$, $T_{h\,out}$: inlet and outlet temperatures of the hot water.
$T_{c\,in}$, $T_{c\,out}$: inlet and outlet temperatures of the cold water.
And the mass flowrates of the cold and hot water ($\dot{m}_c$, $\dot{m}_h$) are given by:

$$\dot{m}_h = \dot{V}_h \times \frac{\rho_h}{3600000} \quad (3)$$

$$\dot{m}_c = \dot{V}_c \times \frac{\rho_c}{3600000} \tag{4}$$

where

$\dot{V}_h, \dot{V}_c$ are the volume flow rates of the hot and cold water.

ρ_h, ρ_c are the densities of the hot and cold water.

The convective heat transfer coefficient h_i can be evaluated from the expression presented by **(Murshed and Lopes, 2017):**

$$h_i = 1429(1 + 0.0146\, T_{avg,h}) \frac{{v_h}^{0.8}}{{D_{i,h}}^{0.2}} \tag{5}$$

where

v_h is the velocity of hot water inside the inner pipe.

$D_{i,h}$ is the inner tube characteristic diameter of the hot water.

$T_{h\,avg}$ is the average temperature of hot water.

The Nusselt number (Nuh) can be expressed as follows:

$$Nu_h = \frac{h_i \times D_i}{K_h} \tag{6}$$

where

K_h is the thermal conductivity of the hot-occupied water.

$D_{i,h}$ is the inner tube characteristic diameter of hot occupied water.

The inner and outer overall heat transfer coefficients are employed for the heat exchanger as follows:

$$U_{i,exp} = \frac{Q_{avg}}{A_{siip} \times LMTD} \tag{7}$$

$$U_{o,exp} = \frac{Q_{avg}}{A_{soip} \times LMTD} \tag{8}$$

where

A_{siip}, A_{soip} are inner and outer surface areas of the inner pipe.

Whereas Q_{avg} is the average heat transfer capacity and LMTD is the logarithmic mean temperature difference for counter-current flow and are calculated by:

$$Q_{avg} = \frac{Q_h + Q_c}{2} \tag{9}$$

$$LMTD = \frac{(T_{h\,in} - T_{c\,out}) - (T_{h\,out} - T_{c\,in})}{\ln\left\{\frac{(T_{h\,in} - T_{c\,out})}{(T_{h\,out} - T_{c\,in})}\right\}} \tag{10}$$

The effectiveness of the heat exchanger is calculated by using the following expression:

$$\varepsilon = \frac{actual\ heat\ transfer}{maximum\ heat\ transfer} = \frac{Q_{avg}}{Q_{max}} \tag{11}$$

where Q_{max} represents the maximum heat transfer, and it is given by **(Khalil et al., 2019)**:

$$Q_{max} = \dot{m}_h \times C_{p\,min}(T_{h\,in} - T_{c\,in}) \tag{12}$$

where $C_{p\,min}$ is the minimum value of the specific heat for hot and cold water.

2.2 Theoretical Prediction of the Overall Heat Transfer Coefficient

The theoretical prediction of the overall heat transfer coefficient, including the determination of the Reynolds numbers for hot water and cold-water side at inner and outer pipe surfaces and may be calculated by:

$$Re_h = \frac{\rho_h \times v_h \times D_h}{\mu_h} \quad (13)$$
$$Re_c = \frac{\rho_c \times v_c \times D_c}{\mu_c} \quad (14)$$

where
D_h, D_c is characteristic diameters of the occupied hot and cold water.
v_h, v_c is the velocities of the hot and cold water.
μ_h, μ_c is dynamic viscosities of the hot and cold water.
ρ_h, ρ_c is the densities of the hot and cold water.
It is important to note that the characteristics of water, including thermal conductivity, density, specific heat, and dynamic viscosity, are all measured at the average water temperature (k, ρ, Cp, μ). The Nusselt number of the hot-water and cold-water sides are given by the Dittus-Boelter equation for heating and cooling liquids **(Kreith et al., 2011):**

$$Nu_h = 0.023 \times (Re_h)^{0.8} \times (Pr_h)^{0.3} \quad (15)$$

$$Nu_c = 0.023 \times (Re_c)^{0.8} \times (Pr_c)^{0.4} \quad (16)$$

where
Pr_h and Pr_c are Prandtl numbers for hot and cold fluid based on average hot and cold water. In this work, heat is transferred from hot water to the tube wall by convection, through the tube wall by conduction, and from the tube wall to cold water again by convection. Thus, the second method adopted to calculate the overall heat transfer coefficients at the inner and outer surfaces is given by **(Cheng et al., 2009; Holman, 2010; Rajput, 2007):**

$$U_{i\,theo} = \frac{1}{\left\{\frac{1}{h_h}\right\}+\left\{\frac{(r_{oip}-r_{iip})A_{siip}}{k_{ip} * A_{sm}}\right\}+\left\{\frac{A_{siip}}{A_{soip} * h_c}\right\}} \quad (17)$$

$$U_{o\,theo} = \frac{1}{\left\{\frac{1}{h_o}\right\}+\left\{\frac{(r_{oip}-r_{iip})A_{soip}}{k_{ip} * A_{sm}}\right\}+\left\{\frac{A_{soip}}{A_{siip} * h_h}\right\}} \quad (18)$$

where h_c and h_h represent the convection heat transfer coefficients of the cold and hot water and are given by:

$$h_h = \frac{Nu_h \times K_h}{D_h} \quad (19)$$
$$h_c = \frac{Nu_c \times K_c}{D_c} \quad (20)$$

Also, k_{ip} represent the thermal conductivity of the inner pipe and A_{sm} represent the logarithmic mean area difference and it is given by:

$$A_{sm} = \frac{(A_{soip})-(A_{siip})}{ln\left(\frac{A_{soip}}{A_{siip}}\right)} \quad (21)$$

2.3 Practical Prediction of Enhancement Factor

In the present work, to better understand how the application of the compound technique (inclination angle and transverse vibration) on the performance of the double pipe heat exchanger, a definition of an enhancement factor can be introduced, such that **(Hosseinian et al., 2018)**:

$$E_f = \frac{U_{i\,E}}{U_i} \tag{22}$$

$U_{i\,E}$ represents the inner overall heat transfer coefficient calculated at various effects of the temperatures and flow rates of the hot water under the application of the mutual transverse vibration and inclination angle. The U_i represents the inner overall heat transfer coefficient calculated at different temperatures and flow rates of the hot water under conditions of zero inclination angle and without vibration.

3. EXPERIMENTAL SETUP

The current experimental test rig is designed and implemented to explore the effect of compound techniques (transverse vibration and inclination angles) on the performance of a double-pipe heat exchanger and their accompanying parameters related to the evaluation process of the heat exchanger performance. The experimental setup is schematically represented in **Fig. 1**. At the same time; the overall view is presented in **Fig. 2.** The experimental test rig consists of three parts: the double pipe heat exchanger unit, the temperature and flow rates data acquisition system, and the vibration exciter apparatus. The double pipe heat exchanger is made of copper material and has a dimension of (8 mm inner pipe diameter, 15 mm outer diameter, 2 mm inner and outer pipe thickness, and an overall length of 1.596 m). The inner tube carries the hotter flow, while the outer shell confines the cooler flow. A 28-liter hot water tank is used to hold the heated hot fluid. A heater with a 2000 Watt power range controls the hot water temperature, and a pump under control allows for various hot fluid flow rates during the experimentation time. During all experimental test runs, cold water is pumped at a constant flow rate and temperature from a controlled temperature tank with a 100-liter capacity to maintain a constant temperature. The heat exchanger is supplied with a digital flowmeter to monitor and regulate the flow rate of hot water inside the heat exchanger. The hot and cold water flow rates are measured using a turbine flow meter. The fluids in a twin pipe heat exchanger may commonly be adjusted to counter the current flow type.

The data acquisition system monitors hot and cold fluids' inlet and output temperatures. The temperature sensor, data logger, and software comprise the bulk of the data-collecting system. The temperature measurement represents the major method used in the current study to determine how well the heat exchanger works. Thus, the temperature measurement system must exhibit quick response times and precise temperature readings. A thermocouple of type K consisting of Chromel and Alumel wires was employed. The thermocouple has the broadest operating temperature range of 0 °C to 1000 °C.

A vibration exciter is used to generate sinusoidal side wall transverse vibration for the firmly fixed base of the double pipe heat exchanger. The type of vibration exciter is a mechanical actuated one and provides a wide range of frequencies and amplitudes with a payload of 50 kg weight **(Lafta et al., 2018)**. At the same time, the shaker table has a tilting mechanism to set the required inclination angles. The excitation motor is equipped with various frequencies digitally controlled up to (60 ± 0.01) Hz. Consequently, a portable vibration meter was used to measure the vibration’s amplitude. Also, a frequency-amplitude test was conducted to determine the system’s total natural frequency **(Murad et al., 2019).**

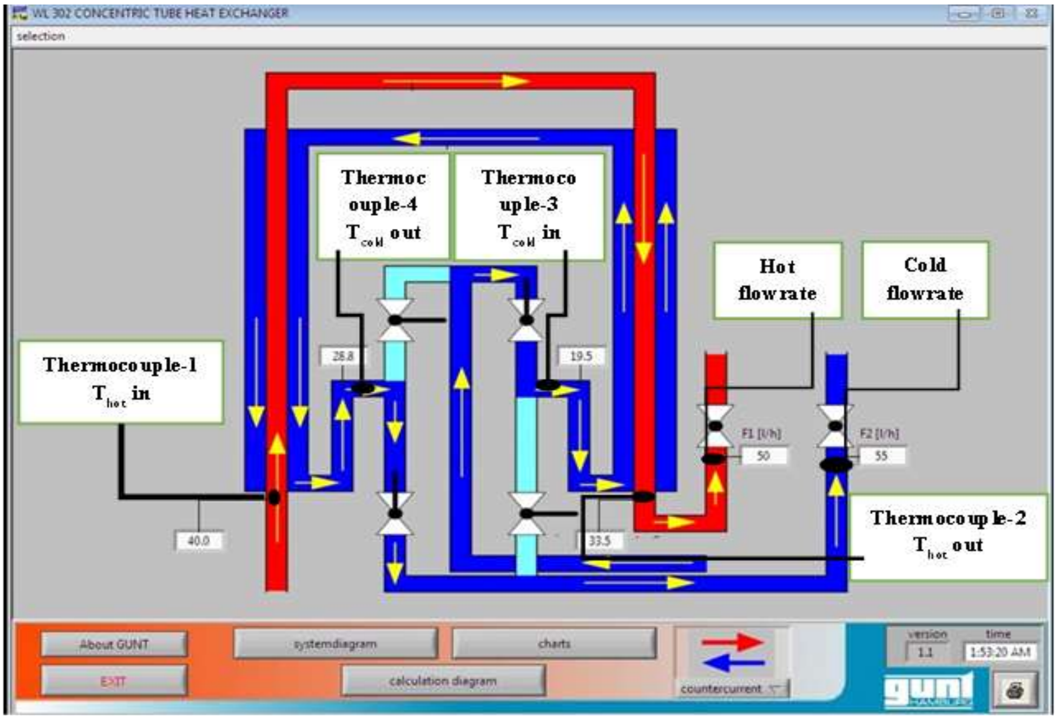

Figure 1. Schematic diagram of the test rig (temperature in ^{o}C and flow rate in lit/ hr).

All the measurement instruments are calibrated to evaluate their performance and accuracy measurement. Also, the uncertainty uranalysis was carried out to determine the percentage error of readings. The statistical analysis shows that the thermocouples temperature measurement has an accuracy of ± 0.42 ^{o}C, and the flowmeters are to be ± 1 lit/hr. While for the vibration meter used in the present experimental work is an unused new one, and it is provided with a calibration manufacturer certificate that explains the displacement accuracy within ± 0.001 mm and the frequency controller it is accuracy reading within ± 0.01 Hz

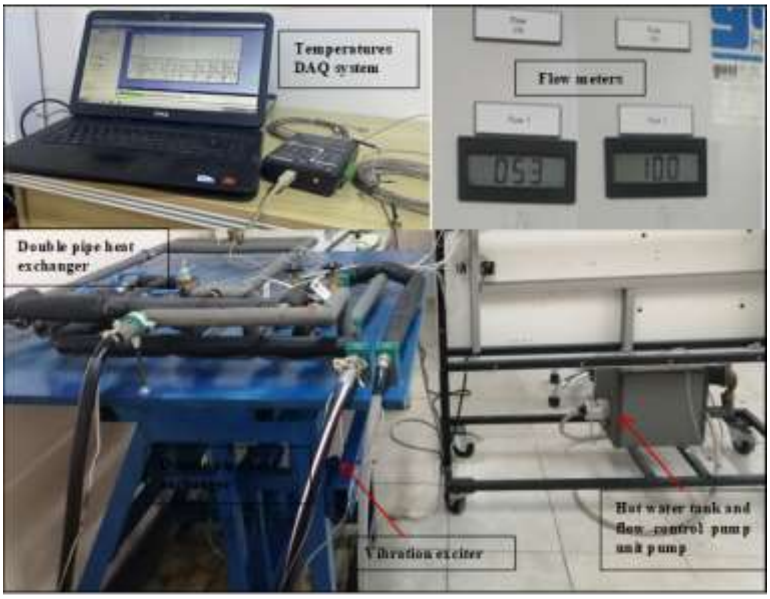

Figure 2. Overall view of the test rig

4. RESULTS AND DISCUSSION

4.1 Validation of Experimental Setup

Firstly, the experimental setup must be validated for the results to be trustworthy. Thus a validation test of the experimental is presented and shown graphically in **Fig. 3**. For validation purposes. The experimental results included the calculation of the inner overall heat transfer coefficient (Ui) at conditions of $\dot{V}_h$ = 100 lit/hr, inclination angle 30°, at a vibration frequency of (6.89 Hz), and amplitude of (3.993mm), cold water flowrate and temperature are constant at a value of (50 lit/hr and 20 °C), and the theoretical overall heat transfer coefficient calculated from Eqs. (17, 18) for temperatures of (40, 55, and 70) °C. The results show that the experimental method has good dependability compared with the theoretical one, with a minimum difference of 1.26 % and a maximum difference of 7 %.

4.2 Effect of Compound Technique on Heat Exchanger Performance

The effect of compound techniques (transverse vibration and inclination angle) on the overall heat transfer coefficient, enhancement factor, and effectiveness is reported. A combination of parameters is studied, namely: vibration frequencies (sub-resonance 3.89 Hz, resonance 6.89 Hz, and over-resonance 9.89 Hz), inclination angles of (0, 10, 20, 30°) for a range of hot water temperatures of (40, 55, 70)°C and flow rates of (50, 75, 100) lit/hr, which experienced a range of Reynolds number of (4000 to 12000). The effect of the vibration frequency on the overall heat transfer coefficient at different inclination angles, temperatures, and flow rates is shown in **Figs. 4 (a) to (i),** respectively.

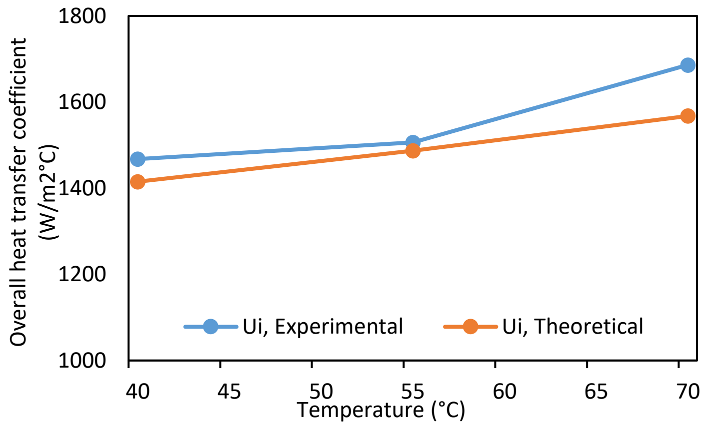

Figure 3. Experimental and theoretical overall heat transfer coefficient results

In general, the results show that a sudden increase in the temperature of a hot fluid under any scenario was the primary cause of the increase in the total heat transfer coefficient significantly. Since the temperature is more conducive to heat transfer, thermal characteristics also rise, increasing the heat transfer coefficient. For all runs, the maximum values of the overall heat transfer coefficient are attained at the resonance frequency of 9.89 Hz because the maximum vibration energy is experienced at the natural frequency, providing maximum shaking energy and improving heat transmission.

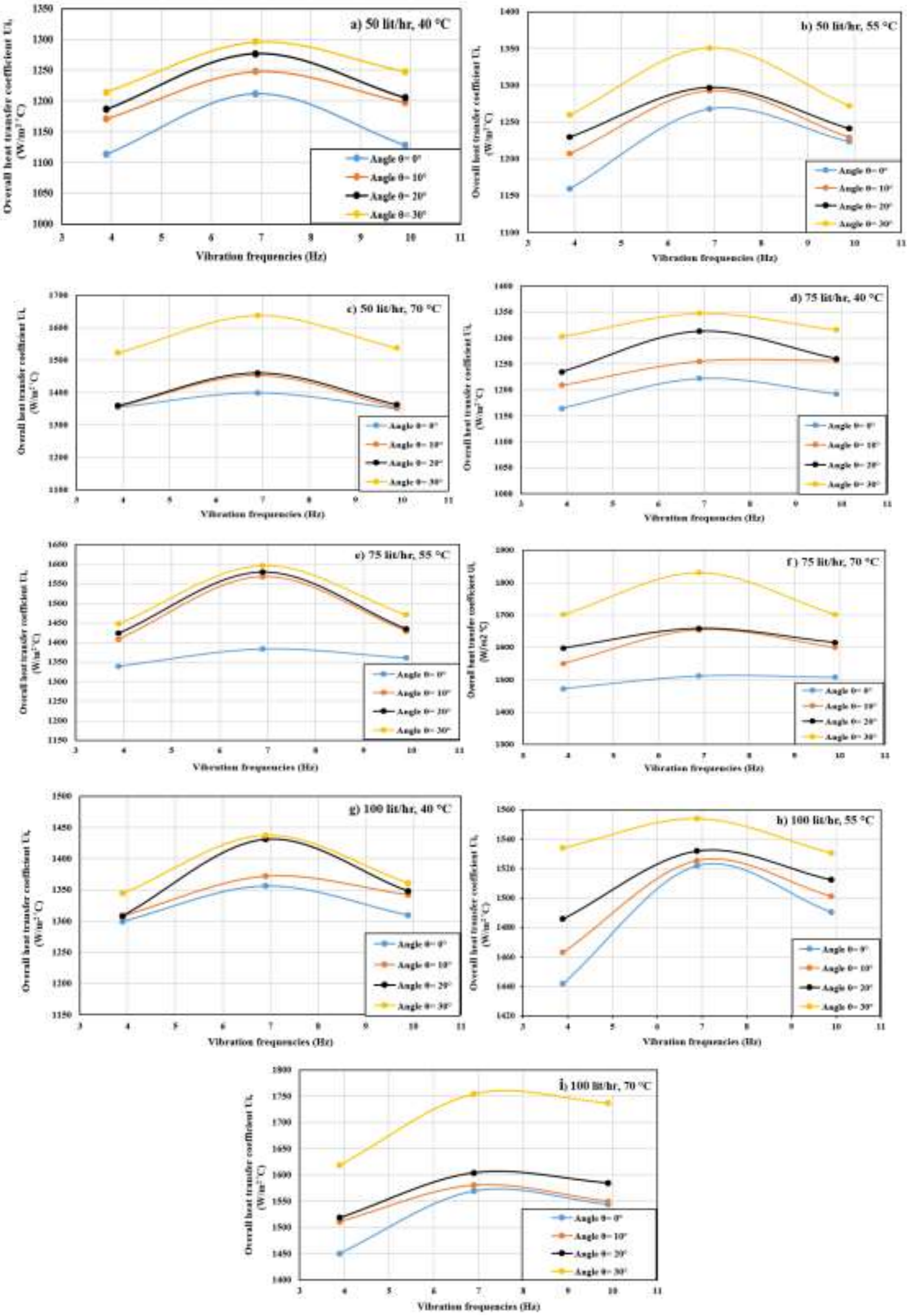

Figure 4. Variation of the Overall heat transfer coefficient with vibration frequencies at different inclination angles for a) 50 lit/hr, 40 °C, b) 50 li/hr, 55 °C, c) 50 lit/hr, 70 °C, d) 75 lit/hr, 40 °C, e)75 lit/hr, 55 °C, f)75 lit/hr, 70 °C, g)100 lit/hr, 40 °C, h)100 lit/hr, 55 °C, and i)100 lit/hr,70 °C.

Vibration may quickly lower the boundary layer and encourage the radial mixing of the fluid. Consequently, when angles of inclination increase, the overall heat increases valuably, especially at a higher temperature. And the increase is attributed to the fact that the components of buoyance force and gravitational force suddenly increase in the opposite direction of the fluid flow, which increases friction between the thermal boundary layer and the internal surface diameter of the inlet pipe. As a result, more heat is transferred to the wall diameter in that situation than from the fluid. Conversely, the results indicated that the amount of heat transfer moderately decreases as the volumetric hot working flow rate increases significantly under the influence of vibration. Additionally, as the hot working flowrate entered the turbulent regime (Re ≥ 10,000), the effect of vibration on the performance of the double pipe heat exchanger decreased in comparison to the laminar and transition regime, which is in good agreement with the assertion made by **(Setareh et al., 2019).**

The enhancement factor variation with the inclination angle for various vibration frequencies, different temperatures, and flow rates of the hot water is shown in **Figs. 5(a) to (i),** respectively.

The interlay experimental results of the enhancement factor demonstrated that the most significant improvement in heat transfer occurred at resonance frequency 6.89 Hz, the inclined angle of 30° for a flow rate of 75 lit/hr, and a temperature of 70 °C. The enhancement percentage value may exceed 183.4% compared with zero inclination angle and no vibration condition. Also, numerous researchers have demonstrated that an increase in frequency causes an increase in the enhancement factor because vibration increases fluid mixing and improves heat transmission **(Hosseinian et al., 2018).** Finally, the results demonstrated that the enhancement factor dramatically increased with increasing inclination angles from 0° to 30°, which attributes to the fact that with increasing the inclination angle, the component of inertia and gravitational forces opposite the direction of fluid flow increases, leading to higher heat transfer and soaring of enhancement factor.

The variation of the effectiveness of the double pipe heat exchanger with vibration frequencies for various inclination angles and at different temperatures and flow rates of the hot water is illustrated in **Figs. 6(a) to (i)**. At the same flow rates, the significant increase in temperatures from 40 to 70 °C increases effectiveness due to increasing the heat transfer coefficient, which is directly proportional to the temperature difference increase. In contrast, it was discovered that when the volumetric hot water flow rate increases considerably at the same temperature, heat exchanger effectiveness drops because the mass of flow increases. The heat transfer gradually increases at tiny temperature changes between intake and exit. However, when the mass flow rate increases beyond the transition Reynolds number, the maximum heat transfer immediately increases, and the actual heat transfer decreases considerably. In all cases and for different inclination angles, the results showed maximum efficacy at the resonance frequency of (6.89 Hz). This may be attributed to the fact that when the vibration frequency progressively increases toward the resonance one, the real heat transfer increases and the exchanger's effectiveness increases.

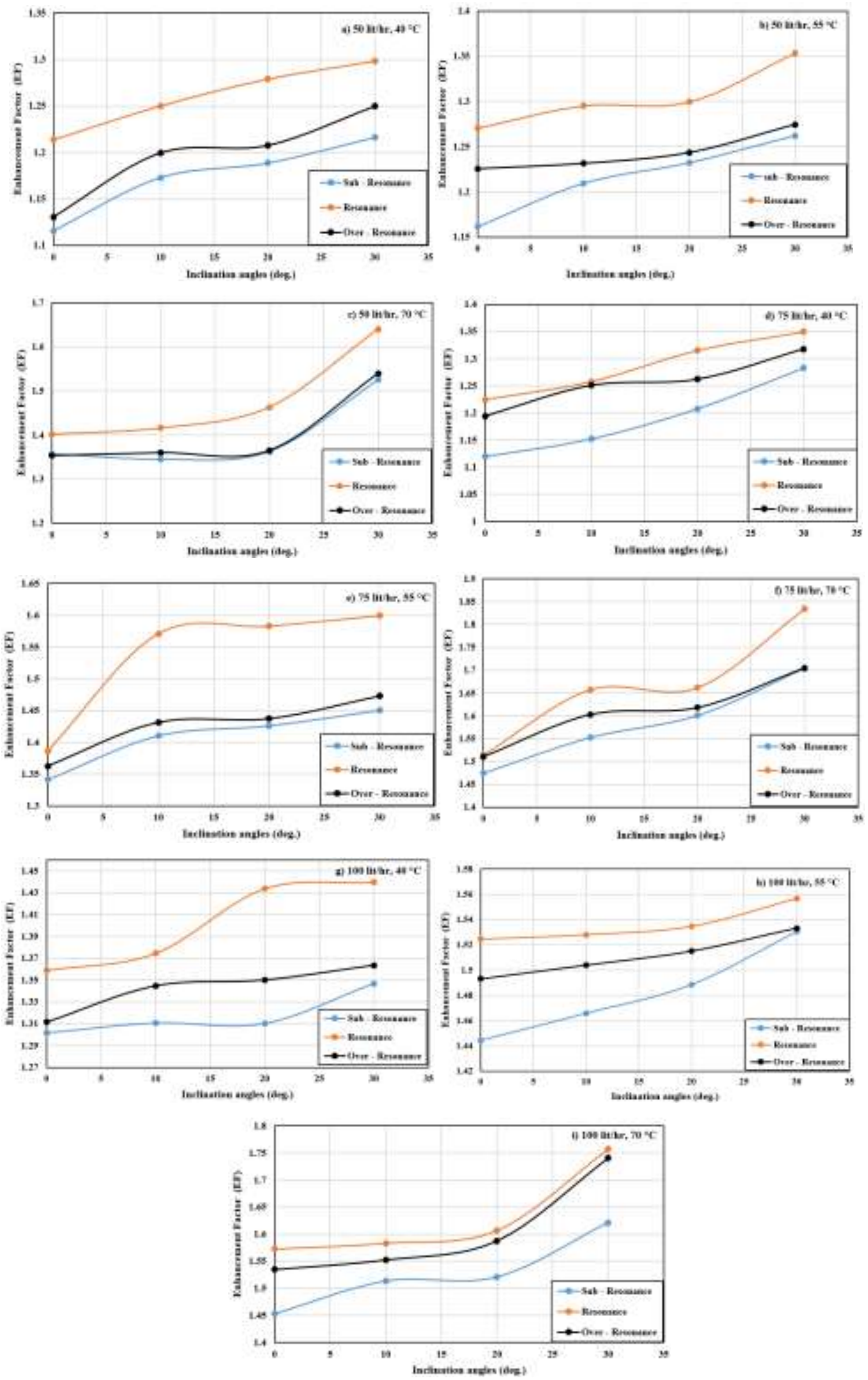

Figure 5. Variation of enhancement factor with inclination angles at different vibration frequencies, for a) 50 lit/hr, 40 °C, b) 50 li/hr, 55 °C, c) 50 lit/hr, 70 °C, d) 75 lit/hr, 40 °C, e) 75 lit/hr, 55 °C, f) 75 lit/hr, 70 °C, g) 100 lit/hr, 40 °C, h) 100 lit/hr, 55 °C, and i) 100 lit/hr, 70 °C.

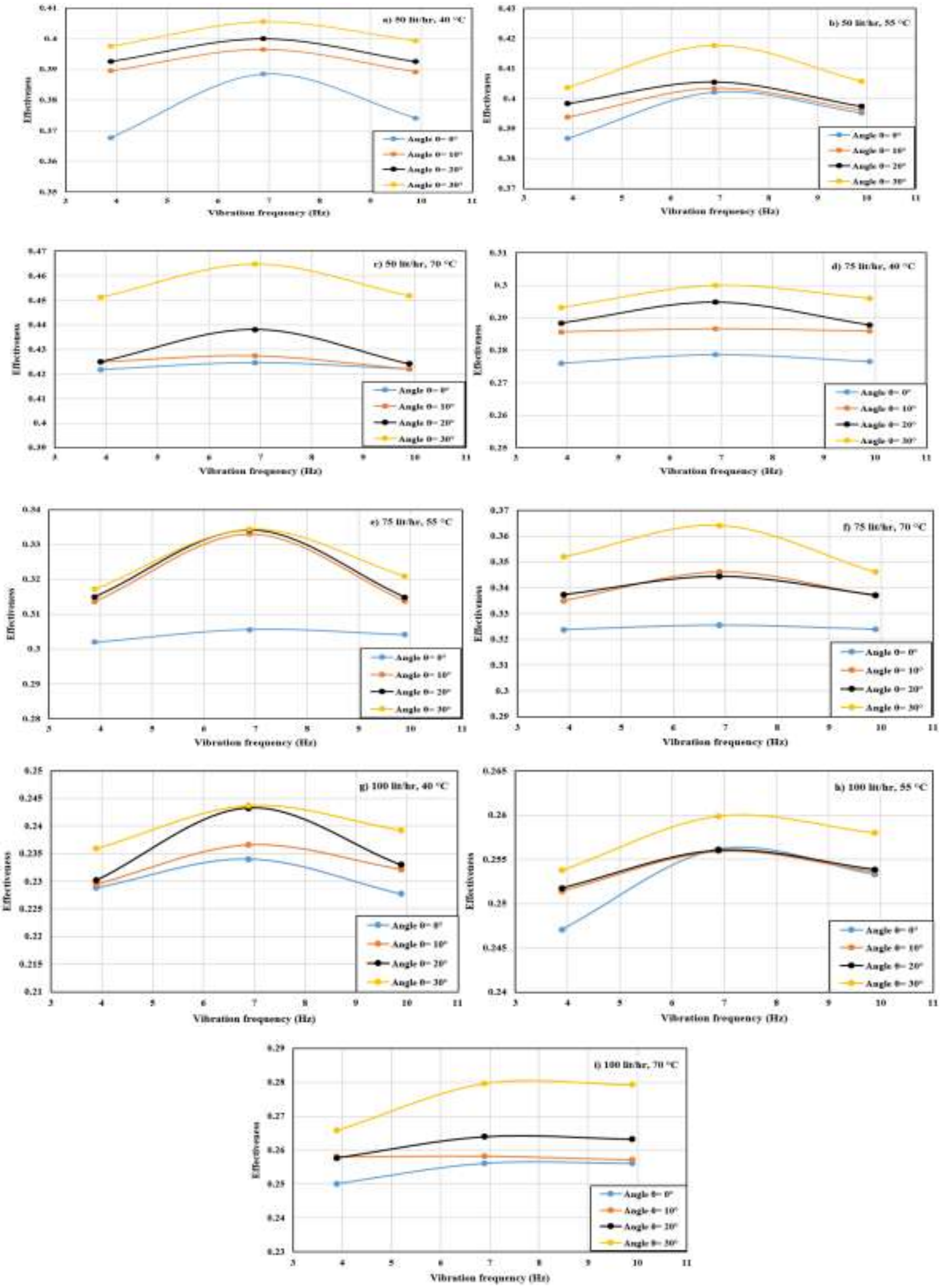

Figure 6. Variation of the effectiveness with vibration frequencies at different inclination angles, for a) 50 lit/hr, 40 °C, b) 50 li/hr, 55°C, c) 50 lit/hr, 70 °C, d) 75 lit/hr, 40 °C, e) 75 lit/hr, 55°C, f) 75 lit/hr, 70°C, g) 100 lit/hr, 40°C, h) 100 lit/hr, 55°C, and i) 100 lit/hr, 70°C.

Also, the effect of vibration frequency is maximized with the increase in the hot water temperature and at a low volumetric flow rate. It shows a maximum effectiveness value of 0.465 at a frequency of (6.89 Hz), an inclination angle of 30° at a hot water temperature of 70 °C, and a flow rate of 50 lit/hr. As well as the results emphasize the fact that at low temperatures and flowrate, the application of transverse vibration and inclination angles can improve the heat exchanger's effectiveness by more than 40 % compared with that at high temperatures and flow rates.

5. CONCLUSIONS

In the current work, the impact of vibration frequencies and inclination angles on the functionality of a double-pipe heat exchanger was studied experimentally, and the following inferences from these findings are possible:

1. The double pipe heat exchanger's heat transmission is improved by varying the inclination angles. The largest amount of heat transfer occurs at angles of 30° compared to other inclination angles.
2. Increasing heat transmission depends on the vibration amplitude and gets the maximum value at the resonance amplitude.
3. As the volumetric flow rates increase, the influence of vibration on heat transfer decreases.
4. A double-pipe heat exchanger becomes more efficient as temperatures rise, and further rises in efficacy occur with increasing the inclination angle and vibration frequency.
5. The overall heat transfer coefficient increases with increasing vibration frequency and inclination angles, and it has an extreme improvement of (183.4 %).
6. At angles of 30° under the vibration influence at the resonance frequency, the effectiveness of the heat exchanger had a maximum improvement of 191 %.
7. The enhancement factor indicates that applying the combined technique improves heat transfer, and it is exceeded (164 %).
8. The effectiveness of a double pipe heat exchanger increased with picked-up temperature and amplitude, but it went down with growth in hot working fluid flow rates.

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