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# Thermal Performance Enhancement in Flat Plate Solar Collector Solar Water Heater: A Review

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Received: 8 May 2020; Accepted: 23 June 2020; Published: 29 June 2020

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**Abstract:** Various studies to improve the thermal performance of flat plate solar collector (FPSC) solar water heater have been conducted, and more are currently in progress. This study aims to review existing methods on thermal performance enhancement for FPSC and discuss on heat-transfer enhancement using vibration and its potential application for FPSC. Ten methods for improving thermal performance are identified, which include applications of nanofluids, absorber coatings, phase change materials (PCM), thermal performance enhancers, FPSC design modifications, polymer materials, heat loss reduction, mini and micro channel and heat-transfer enhancement using vibration. An examination of heat-transfer enhancement using vibration in low frequency ranges for an evacuated-tube solar collector (ETSC) solar water heater system showed that it can potentially achieve heat-transfer enhancement of up to 78%. Nevertheless, there is still a lack of research on the applications of heat-transfer enhancement using vibration on FPSC to date.

**Keywords:** flat-plate collector; solar water heater; heat-transfer enhancement using vibration; thermal performance; infrasound

## 1. Introduction

Demand for renewable energy such as solar energy has grown steadily due to increasing trend in global energy consumption and depletion of fossil-fuel sources [1–3]. One of the most well-known and common applications of solar energy is the solar water heater (SWH) system, due to its viability and economics advantages. The solar water heating system has two main components, namely storage tanks and solar collectors. Solar collectors are mainly classified into flat plate solar collectors (FPSC), photovoltaic thermal hybrids (HPV/T), evacuated-tube solar collectors (ETSC) and compound parabolic solar collectors (CPSC). They can be further categorized into tracking and non-tracking collectors [4]. Despite having many other new solar collector systems, the favored method in harvesting sunlight as heating sources for heated fluid for household applications is either using low-temperature solar thermal technology or photovoltaic (PV) technology [5–8]. Solar PV is considered a much better technique in generating electricity directly from sunlight to run electric heaters [7]. However, the electrical efficiency of the system decreases rapidly as the PV module temperature increases [5]. From a general perspective, solar thermal technology where solar insolation is converted into heat and transmitted via a transfer medium appears to be a more convenient method to produce heated fluid for domestic use [3,9]. SWH has been widely applied in countries such as Australia [10], Pakistan [7], Rwanda, South Africa [11], Canada and China [12]. In Australia, SWH has not gained much popularity in recent years, despite having the right amount of solar radiation, due to the cost and reliability issues [13]. In low-solar-energy regions such as Malaysia—where solar irradiance has average potential of 4–4.9 $KWh/m^2/day$ (compared to the other parts of the world with average of 6–6.9 KWh/m$^2$/day [5,14]—the preferred technology is a low-temperature solar thermal energy conversion method, such as the FPSC system [15]. FPSC, which is best for low and medium heating applications, can absorb both beam and diffused component of the solar insolation. Conversely, compared to concentrating solar collectors, the FPSC has relatively low efficiency [4].

Pioneer research work on SWH has been carried out by Horace De Saussure in 1760 [6]. Since then many researches have been carried out and resulted in significant contributions towards improving current SWH performance, which utilizes an FPSC or ETSC to harness energy from sun and heat the fluid to a temperature less than 80 °C (domestic use) [16]. Considering both collectors, the ETSC has better efficiency compared to the FPSC due to its design [17], which reduces solar heat loss from radiation. However, the FPSC is more favorable because of its simplicity, low maintenance requirement and more cost-effective [18]. SWHs are available in passive and active techniques, where uniquely passive systems (thermosyphon) make use of the rise of enthalpy in the fluid while active systems (forced circulation) rely on the pump [18].

The FPSC as shown in Figure 1, consists of several significant parts that can influence its thermal performance. These include a glass cover, casing, absorber plate, riser tube and insulation material [4,19–21]. From the top, the glass covers the riser tube and traps heat inside the collector. The riser tube acts as a heat exchanger while the absorber plate increases the heat-transfer area of the system. The side and bottom parts are insulated using insulation material to prevent heat loss to surrounding from conduction and radiation, thus increases the efficiency of the FPSC. The common problem that reduces the FPSC performance over time is the effect of dust settlement which requires regular cleaning to maintain its performance [22]. Hawwash et al. [23] stated another common reliability issue in FPSC is overheating due to stagnation temperature. Overheating will cause material degradation which may lead to leaking and disruption of system operation, hence reducing FPSC reliability.

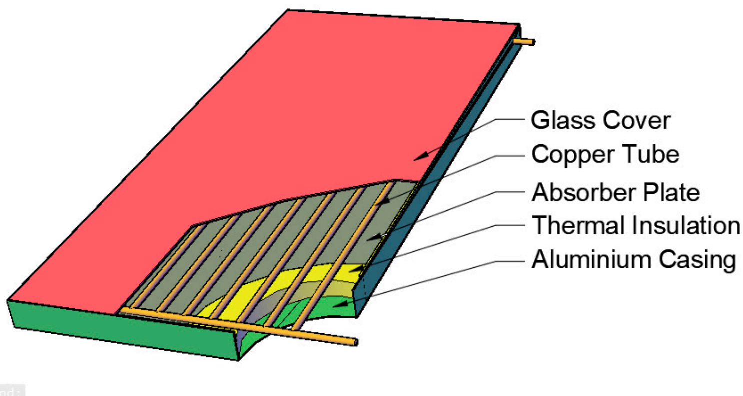


**Figure 1.** The structure of a flat plate collector.

To further enhance the FPSC's water heater performance and efficiency, various experimental studies have been conducted by many researchers, particularly on thermal performance improvement. Recent study indicates that the application of low-frequency vibration enhances the heat exchange hence increases the thermal efficiency of SWH. This study aims to review past and current methods for enhancing FSPC thermal performance. The study also discusses on heat-transfer enhancement method using vibration and potential research and application of such method for improving FPSC thermal performance.

## 2. Thermal Performance Enhancement Methods for FPSC

Most of thermal performance enhancement studies have been conducted by modifying FPSC components or by adding enhancement devices to the system. Suman et al. [22] discussed three methods of enhancement: (1) modification in surface geometry, (2) solar selective coatings and (3) using nanofluid. Pandey et al. [21] reviewed seven types of FPSC development which include; utilization of polymer material as absorber plate [24], modification of riser tube into a mini and microchannel, application of nanofluids [25,26], modification of absorber plate designs, employment of phase change materials, reduction of heat and usage of enhancement devices. Sakhaei and Valipour [4] discussed four methods, which include applications of turbulators, enhancement devices [27], heat loss reduction [28], phase change material (PCM) and nanofluids [29].

In 2019, more studies were conducted on thermal performance enhancement mechanisms. The thermal efficiency achieved is within a range of 50% to 78%. Heat-transfer enhancement using vibration in SWH achieved thermal efficiency of up to 78%. However, this result achieved in an evacuated-tube solar collector (ETSC). The methods studied include applications of: (1) nanofluid, (2) absorber coatings, (3) insulation material, (4) PCM (5) thermal performance enhancer, (6) polymer, (7) modified FPSC design and (8) heat-transfer enhancement using vibration (ETSC). Most of the improvement are achieved by keeping the flow in the turbulence regime, improving the fluid mixing in the tube for better temperature uniformity, increasing the heat-transfer area and the heat capacity. Table 1 summarizes the methods used in FPSC thermal performance improvement studies.

**Table 1.** Summary of methods studied in FPSC thermal performance enhancement.

| Method | Description |
|---|---|
| Modifying FPSC Design | Changing the FPSC standard design |
| Absorber Coatings | Adding a coating to the glass cover to improve absorbance |
| polymer Material | Using polymer as FPSC material to reduce cost |
| Nanofluid | Adding nanoparticle to the working fluid to increase the heat-transfer area |
| Mini and Microchannel | Shrinking the heat exchanger tube to increase the heat-transfer area |
| phase change material (PCM) | Store excess energy to be used later |
| Heat Loss Reduction | Adding extra insulation to reduce heat loss |
| Enhancement devices | Adding devices to increase heat capacity, turbulences or promote fluid mixing |
| turbulators | Adding turbulator to increase and promote fluid mixing |

### 2.1. *Current Research on FPSC Thermal Performance Improvement*

#### 2.1.1. Modification of FPSC Design

Several researchers had modified the design of FPSCs for enhanced performance. Tadahmun et al. [30] redesigned the collector into an integrated solar water heater with a corrugated absorber surface, which also acts as a storage tank instead of using a copper tube for domestic use. By doing this, a bigger storage tank with minimal space achieved. The authors reported that the daily thermal efficiency values of the solar collector were 59%, 65% and 67% when the mass flow rate values were 0.005 kg/s, 0.0091 kg/s and 0.013 kg/s, respectively and it can supply 140 L of hot water at 42 °C in the early morning. However, this setup encountered significant thermal losses during night–time due to direct exposure to ambient temperature; thus, the author recommended to add insulation to the collector. Another design was developed by Visa et al. [31], whom came out with a new triangle flat plate solar thermal collector design for facades integration. They claimed the design had better heat-transfer area compared to conventional collectors. From the indoor testing conducted, the thermal efficiencies up to 55% achieved under both irradiance value of 800 and 900 $W/m^2$, which was very promising considering the small overall dimensions of the collector (prototype). Since it was a new prototype, the real efficiency and reliability were not proven.

#### 2.1.2. Absorber Coatings

Adding an absorber coating to the collector can improve the absorptance of the collector, thus increasing its efficiency. The selection of absorber coating depends on the usage and the cost of the collector. A high coating absorptance is the best to ensure high thermal performance. Researchers need to determine which are the best absorber coating or insulation material for the collector. Müller et al. [32]

conducted a test on three selected absorber coatings: black chrome; highly selective sputtered PVD coatings; and solar paints. The aims were to investigate the thermal performance and the stagnation behavior of FPSC with the coatings and compared them with the standard. The results showed all coatings featured absorptances above 90% and thermal emittances in the range of 5% to 90%. The evaluation was based on performance and reliability of the FPSC. The results also showed that absorber coating can enhance thermal performance and reduce the risk of collector overheating during stagnation period, i.e., summer. By selecting a coating that has higher emittance or lower absorptance at a higher temperature, it will reduce the maximum temperature of the collector and significantly prevent stagnation temperature [32]. As the temperature increases, the coating with lower absorptance will increase thermal resistance and slow down solar absorption, hence reducing the time to reach stagnation temperature. The best absorber among the four was solar paint as it resulted in the best performance which provided the highest auxiliary energy demand while extending the life of the collector by preventing a long stagnation period ($T_{abs} > 120$ °C). Maximum absorber temperatures of up to 175 °C, 165 °C, 145 °C and 135 °C and stagnation period of 178 h $a^{-1}$ to 118 h $a^{-1}$ 162 h $a^{-1}$ and 11 h $a^{-1}$ were reported for standard, black chrome, thermochromic and solar paint coatings, respectively.

### 2.1.3. Heat Loss Reduction

Thermal performance is very much affected by heat losses from various sections. The top part is exposed to the ambient, and hence, the heat lost from this surface is significant. Heat loss is mostly through convection and radiation. Due to wind, the influence of convection is more significant. Convective heat losses occur between the absorber plate and the glazing. The air cavity needs to be optimized to act as an insulating gap, promoting convective heat transfer to the collector while also minimizing losses when ambient temperatures drop [28]. Zhou et al. [20] studied the performance of flat plate solar collector with transparent insulation material (TIM) including the effects of the weather conditions on the FPSC's performance. The authors showed that TIM reduced the heat loss from the front. Under wind influence, the heat loss due to natural convection was reduced significantly. However, they highlighted that the transmittance of TIM should be higher than 80%, as the collector with a TIM lower than 80% had poor efficiency compared to conventional ones because higher transmittance means the coating would absorb more incident solar radiation. The authors concluded that the collector with TIM work best in a colder environment.

### 2.1.4. Nanofluid

In general, achieving higher heat-transfer rates is one of the main goals in industrial applications. Instead of using water as heat-transfer fluid (HTF), adding nanoparticles into the HTF may increase the overall conductivity of the working fluid. A closed-loop system is required for this operation to separate the HTF from the working fluid (tap water). Previous scholars' study different types and sizes of the nanoparticles, changing the nanoparticles concentrations and nanoparticle material [21]. Utilizing nanoparticles resulted in significant thermal performance improvement and it has the advantage of integrating it with other thermal performance enhancement methods. Different types of nanoparticle configuration give a different thermal performance. The selection of nanoparticles should consider utilization of materials that are environmentally friendly and with proper sizing to prevent blockage in the flow paths. Tong et al. [33] experimentally investigated the energy and exergy efficiency of a flat-plate solar collector using water, $Al_2O_3$ nanofluid and CuO nanofluid as working fluids. They found that when 20 nm—1.0 vol% $Al_2O_3$ and 40 nm—0.5 vol% CuO nanofluid were used, the flat-plate solar collector recorded efficiency improvement of 3.4% and 3.7%, respectively.

### 2.1.5. Polymer Material

Researchers not only focused on improving the thermal performance of FPSC, but they also focused on reducing its cost. Filipović et al. [34] suggested utilization of polymer material to reduce the overall cost of the collector. They also used wooden box as its base and polycarbonate plate as the absorber. However, they found that the collector suffered from a lower thermal performance, in which the efficiency decreased to 30% than the standard FPSC. Nonetheless, using polymer material and wood had resulted in significant decrease in FPSC cost.

#### 2.1.6. Phase Change Material

Phase change material (PCM) integrated with solar collectors show promising features that can eliminate the need for storage units. The main advantages of these collectors involve large space capacity and isothermal behavior during melting. By making use of its high latent heat and heat capacity, Wang et al. [35] proposed dual PCM collector to solve the freezing and overheating problems of a collector. At high water temperature, the high melting PCM absorbs the heat and changes its state from solid to liquid through melting while storing the excess heat. At lower temperature, the low-melting PCM removes heat and solidifies while slowly prevents the collector from freezing. However, researchers found that FPSC thermal performance has slightly increased. Zhou et al. [36] proposed a PCM flat-plate solar collector system with antifreeze characteristics. The results showed that the conventional FPSC system would get frozen when the daily average temperature is less than 5 °C. The flat-plate collector with antifreeze system can work when the daily average temperature is in the range of 0–5 °C. However, 30% minimum thermal energy of the collector was required to be contained by PCM to prevent from freezing. They also reported that 15 mm thickness PCM module was a reasonable choice to achieve a high utilization rate of the PCM.

#### 2.1.7. Enhancement Devices

Enhancement devices are categorized as inserting static devices that act as a catalyst to increase the heat-transfer area of a collector, thus improving its thermal performance. These types of thermal enhancer are cheap and easy to employ; however, some of the devices are heavy and adding these means adding weight to the collector and making the system bulky. In addition, by inserting these devices, the collector will experience considerable pressure drop due to the restriction of the flow by the inserts and the possibilities of corrosion which may cause the insert to rust. Balaji et al. [19] performed research on heat-transfer enhancement using rod and tube. The authors stated that utilizing the rod (76% efficiency achieved) was better than using the tube (72% efficiency achieved) because of its higher heat capacity. However, this method caused blockage in the system and increased the pressure drop. In general, these thermal enhancer perform better at lower Reynold's numbers.

A porous material with high thermal conductivity and porosity is used in solar water systems to increase the rate of heat transfer by increasing the heat capacity or heat-transfer area. Kanimozhi et al. [37] used a porous medium with an agitator to improve the thermal efficiency of an FPSC. Pebble stone was used as a porous medium and an aluminum sheet metal as an agitator. The authors concluded that using a porous medium and agitator would increase the heat-transfer area, hence improving thermal efficiency, which resulted in 63.8% efficiency with a disadvantage of high pressure drop, whereas system without porous medium recorded 56.6% thermal efficiency.

Fan et al. [38] developed a new type of V-corrugated absorber with multichannel (VFPSCT) and compared it with sheet and tube flat plat collector (TFPSC). The result showed that the thermal efficiency of VFPSCT was 69.1%, whereas TFPSC achieved a maximum thermal efficiency of 58.6%. The authors also concluded that collector thermal efficiency increased with increasing mass flow rate, ambient temperature, wind speed and diffused solar irradiance. However, challenges with recording high pressure drop remains.

#### 2.1.8. Turbulators

Using discs, wire coils, twisted tapes and metal foams allows improving the heat transfer by reducing the thermal boundary layer thickness and increasing the turbulence and swirling flow by maintaining the turbulence in the fluid flow. Felipe et al. [39] performed a numerical study on collector using turbulators (longitudinal vortex generator) to enhance heat transfer in an FPSC using two configurations, rectangular-winglet and delta-winglet by keeping the flow in turbulence state. The results showed that the highest heat-transfer efficiency was achieved by utilizing rectangular-winglet vortex generator at angle of attack of 45° at 750 W/m$^2$; however, issues with high pressure drop remained.

### 2.1.9. Heat-Transfer Enhancement Using Vibration

Utilizing vibration to enhance heat transfer is a promising method to be employed in FPSC. Research showed that this method was able to achieve up to 78% thermal efficiency in an evacuated-tube solar collector (ETSC) solar water heater system by employing a low-frequency (infrasound acoustic range) vibration without sacrificing the internal pressure of the system. In addition, this method could be integrated with other performance enhancing methods such as applications of nanomaterial, heat loss reduction, insulation and absorber coatings to improve the overall thermal performance further. This method is further discussed in Sections 3 and 4. Table 2 summarizes recent improvement in FPSC and heat-transfer enhancement using vibration on ETSC.

**Table 2.** Recent studies (late 2019) in FPSC thermal performance enhancement and heat-transfer enhancement using vibration on ETSC.

| Method | Author | Configuration | Thermal Efficiency Improved | Findings |
|---|---|---|---|---|
| Modifying FPSC design | Visa et al. [31] | Novel triangle FPSC | 55% | A good result achieved from a small overall dimension of the collector. Real efficiency and reliability are not yet proving. |
| | Tadahmun et al. [30] | Storage tank with corrugated absorber | 59% at 0.005 kg/s; 65% at 0.0091 kg/s; 67% at 0.013 kg/s | With an increasing flow rate, higher efficiency achieved. Setup encounters significant thermal losses during night–time due to direct exposure to ambient temperature. |
| Absorber coatings | Müller et al. [32] | 1—PVD<br>2—Black chrome<br>3—Thermochromic<br>4—Solar paint | n/a | Spectral selectivity of solar absorbers coatings can enhance thermal performance and reduce the risk of overheating or stagnation. |
| Heat loss reduction | Zhou et al. [20] | Transparent insulation material (TIM) | n/a | The operation of the collector with TIM at a small flow rate has more advantages than at a high flow rate. With TIM, cold operations (winter) has more advantages compare to without insulation. |
| Nanofluid | Thong et al. [33] | $Al_2O_3$<br>CuO | 56.9% efficiency<br>49.6% efficiency | Better efficiency achieved with higher concentration. |
| Polymer material | Filipović et al. [34] | Polymer solar collector | n/a | 30% lower efficiency compared to conventional |
| Phase change material | Wang et al. [35] | Dual-phase change material (PCM)<br>20% high purity graphite<br>80% natural grease | High temperature increased 19.6%; low temperature 24.1% increased. | Suitable for tackling freezing and overheating problems of a collector |
| Enhancement devices | Balaji et al. [19,40,41] | Rod and tube insert | 76% rod<br>72% tube | Rod is better than the tube because of its higher heat capacity; however, this method causes blockage in the system and increases the pressure drop. These thermal enhancer type performed better at lower Reynold's number (<200) |
| | Kanimozhi et al. [37] | Porous medium with agitator aluminum sheet metal (agitator) pebble stone (porous medium) | 63.8% | Higher heat-transfer area, however, immense pressure drops while adding more weight to the collector resulting in more robust support. |
| | Fan et al. [38] | V-corrugated absorber | 10.7% higher than non-V-corrugated absorber | Able to employ with other thermal enhancers such as nanofluid and turbulence creator. |
| Turbulators | Felipe et al. [39] | Vortex generator delta winglet rectangular winglet | n/a | Delta-winglet vortex generator achieved higher efficiency than a rectangular winglet. |
| Heat-transfer enhancement using vibration | Sahlani et al. [42] | Forced vibration on ETSC | 78% | Efficiency increased as frequency increased. |

## 3. Enhancement of Heat Transfer Using Vibration

The idea of improving heat transfer in SWH using vibration has been proven by researchers to be practical [43,44]. The application of vibration as a heat-transfer enhancement method such as in heat exchanger has been studied by many researchers [45,46]. This method is not just limited to heat-transfer enhancement in heat exchanger, but also applicable in processing melts [47], food drying [48] and melt treatment [49]. Authors such as Legay et al. [43] and Franco et al. [50] discussed the fundamental of heat-transfer enhancement using vibration.

Vibration can increase the convective heat transfer within a fluid medium. A different range of acoustic frequency refers to 'acoustic range' that can be applied to improve convective heat transfer by correctly applying the vibration range [51,52]. The acoustical energy is categorized into several range which are infrasound ($f < 20$ Hz), sounds (20 Hz $< f <$ 20 kHz), power ultrasounds (20 kHz $< f <$ 1 MHz) and low power ultrasounds ($f >$ 1 MHz) [43]. Low power ultrasound does not affect the medium of propagation and is suitable for nondestructive mechanism. Power ultrasound able to modify the medium (such as fluid) where it propagates to create two phenomena known as acoustic cavitation and acoustic streaming with powerful macroscopic effects for heat-transfer enhancement. Acoustic streaming induces fluid mixing at the thermal boundary layer [53]. Acoustic cavitation creates a violent alteration to the fluid and helps in the mixing of fluid flow, in particular, the thermal boundary layer, through the implosion of low-pressure vapor bubbles. The phenomena from power ultrasound is highly desirable for heat-transfer application. However, for SWH application, researchers utilized acoustic field within the infrasound range (low frequency), known as infrasound.

### *3.1. Heat-Transfer Enhancement Using Vibration at Infrasound Acoustic Range*

The main factors that are responsible for heat transfer in the infrasound acoustic range is the pressure amplitude given by the vibration. If the pressure amplitude is sufficiently large, it will improve the overall thermal performance [54]. Franco et al. [50] showed that periodic oscillation produces turbulent state that allows the acoustic energy to alter the system and improve the overall convective heat-transfer coefficient. The pulsating flow created from flow alteration disrupts the thermal boundary layer, promotes turbulent flow, hence further enhance the heat transfer [55]. Thus, the infrasound vibration could trigger or increase the turbulence rate within a liquid and improve heat transfer.

Most of the applications of enhancement devices have been focused mainly on disturbing the thermal boundary layer to alter the fluid flow and promote fluid mixing to take place. As an example, when a laminar flow in a pipe occurs and accompanied by radial heat transfer, the associated parabolic radial velocity profile leads to a wide radial temperature distribution as heat transfer controlled by slow conduction [51]. The region of the fluid in which these temperature gradients exist is the thermal boundary layer. With increasing distance from the leading edge, the effects of heat transfer penetrate farther into the stream and the thermal boundary layer grows. The thermal boundary layer between the inner core and outer core of the fluid prevents a uniform temperature distribution in the flow across the pipe. There is a considerable temperature difference between the inner core and outer core of the fluid. Thus, by altering the fluid flow and disrupt the boundary layer, the heat will be transferred uniformly across the fluid. In addition, having thermal resistance would theoretically help the thermal wave propagation. Lor et al. [56] illustrated that the thermal wave model propagated in a confined space. Some of the thermal pulse waves were reflected when in contact with thermal boundary layer due to the thermal resistance. The transmission–reflection-combination phenomena then occurred, and heat energy distributed uniformly in the confined space.

Research on infrasound vibration or 'low-frequency vibration' methods for heat-transfer enhancement has been reported in recent years using a numerical and experimental approach to understand the fundamental concept of fluid in the influence of vibration—the forced and passive technique used in this method. The main factors reported that should be considered are radiation intensity, inclination angle, the type of heat pipe, the type of working fluid, in addition to the ambient conditions [57]. The flow rate should be low to achieve the maximum impact using vibration on thermal performance [44].

Chandra et al. [58] had reviewed several thermal enhancement using vibration methods. The authors asserted that vibration may be able to reduce the resistance of thermal boundary layer very swiftly, and it could promote radial mixing of fluid because of the second velocity component on the flow system. The authors stated that nanofluid application under vibration conditions could increase heat transfer by 300% than the steady-state flow with no vibration, which was very promising. Having multiple methods for heat-transfer enhancement vibration and nanofluid heat-transfer enhancement was certainly better than a single method [59].

Even by using a passive method to induce low frequency vibration, a heat-transfer improvement could be achieved. Amandolese et al. [60] reviewed passive vibration method which uses fluid-induced flag vibration on three types of configuration (1) inverted, (2) standard and (3) flag behind the bluff able to enhance mixing and enhance heat transfer and these type of method are useful for mixing enhancement in the process industry. The induced vortices attributed to the interruption and redevelopment of thermal boundary layers force fluid mixing and enhance heat transfer. The vortex dynamics are strongly dependent on the flag's length-to-channel-width ratio to alter the fluid flow passively. Fluid-induced flag vibrations are promising solutions to mixing enhancement in process industries, which are of great significance, but lacks investigation to date [61].

Tian et al. [51] showed that a low-frequency vibration is much superior to the Kenics static mixer in terms of thermal performance. There was a much more uniform radial temperature profile achieved with the employment of transverse vibration at infrasound acoustic range. The temperature profile between the inner core and outer core of the fluid achieves a rapid temperature uniformity development throughout the tube with the transverse vibration. The vigorous swirling motion created from the transverse vibration improved thermal performance significantly without drastically increasing the pressure drop over the Kenics static mixer. The authors even introduced a unique method, transverse vibration with stepwise rotation which increased the thermal performance more than others. The use of vibration as the primary heat-transfer enhancer is a promising method.

Some authors reported the advantages and disadvantages of having heat-transfer enhancement using vibration in a fluid flow. Muhammad et al. [62] concluded that a forced vibration would have further benefits in reducing fouling in the pipe because of the energetic cleaning action that the fluid motion would create at the wall. However, the cyclic load can reduce the life of a structure and affect the reliability of the system. In passive vibration, to the authors best knowledge, researchers are yet to determine the fatigue responses of cyclically vibrating flags under a fluid load.

### *3.2. Current Research on Heat-Transfer Enhancement Due to Vibration at Various Acoustic Range*

#### 3.2.1. Power Ultrasound Acoustic Range (20 kHz < f < 1 MHz)

Amiri et al. [63] studied the effect of vibration with nanoparticle at an acoustic frequency of 28 kHz. The primary heat-transfer mechanisms included heating by acoustic energy dissipated, acoustic cavitation which results from formation, evolution, fluctuations and the great collapse of gas bubbles into the liquid medium. Ultrasonic vibration enhances fluid mixing and intensifies the convection heat transfer. Acoustic cavitation creates bubbles that implode and disturb the boundary layer and reduces thermal resistance. Increasing or decreasing cavitation intensity is related to the system condition such as temperature, pressure, boundary or even geometry and boundary conditions of the system. Cavitation is better at higher temperatures due to the reduction of liquid viscosity, and in adverse, the highest temperature reduces the dissolved gas in the liquid and raises the vapor pressure required which make it harder to form the cavitation bubbles. The effect of ultrasonic vibration is small in a turbulent flow. Up to 7.3% of heat convection enhancement is achieved in the influence of ultrasonic vibration.

Bulliard-Sauret et al. [53] studied heat intensification with two different ultrasound frequencies. They investigated the effect of 25 kHz frequency on heat transfer and found that acoustic cavitation was the dominant. In contrast, when they increased the frequency to 2 MHz frequency, acoustic streaming was dominant. They reported that 2 MHz ultrasound frequency produced a strong convective effect, usually named acoustic stream1ing that induced turbulence enhancement and global mixing effect. Acoustic cavitation produced by 25 kHz ultrasound lead to an increase of turbulences both in bulk and within the boundary layer. When the mean velocity increases, the boundary layer effect decreases, thus leading to more efficient disruption of the boundary layer by bubble collapse and a reduction of the thermal resistance.

Lebon et al. [51] numerically model the acoustic streaming on the ultrasonic melt treatment of direct-chill (DC) casting. The authors show that low bubble volume fractions at low sonication power result in an upward centerline flow, which may be attractive in processing liquid metal in continuous processes. Ultrasound modifies the sump profile by depressing the slurry region along the axis of the billet and pushing the slurry sideways along the solidification front. This phenomenon contributes to the transport of floating grains towards the melt and increases the temperature gradient in the phase transition region.

### 3.2.2. Sound Acoustic Range (20 Hz < f < 20 kHz)

Rao et al. [64] experimentally investigated the natural convection on heat-transfer augmentation with vibration effect on the cylindrical surface within a vibrating frequency range between 100 Hz to 190 Hz. Better heat-transfer rate was seen when higher frequency or amplitude were utilized. The vibration effect on natural convection heat transfer increased heat-transfer coefficient up to 104%.

Santosh et al. [65] studied the convective heat-transfer coefficient of steady-state and unsteady-state (vibration) laminar flow of $Al_2O_3$–water-based nanofluid and of pure water at frequency 50 to 100 Hz. The result showed heat-transfer rate for nanofluid flow was greatly influenced by the amplitude and frequency. Vibration allows convection to present in the process allowing the fluid nearer to the core region of pipe gets exposed frequently to the wall due to cyclic motion and receives high heat from the wall which is not possible in steady-state flow. The heat-transfer enhancement reduced as the Reynold's number increased. The largest increase of about 540% was observed under the condition of vibrational flow with nanofluid compared to the one in a steady-state flow.

### 3.2.3. Infrasound Acoustic Range (f < 20 Hz)

Su et al. [66] studied the application of vortex-induced lateral vibration and heat-transfer characteristics of elastic supported single tubes with different cross-sectional shapes. The highest frequency achieved for vertical elliptical tube, circular tube and horizontal elliptical tube were approximately 13 Hz, 10 Hz and 5 Hz at maximum amplitude of 12.45 mm, 6.35 mm and 1.63 mm, respectively. The vortex-induced vibration frequency $f$ increased with the increasing flow velocity. The highest efficiency was achieved at the highest amplitude. As the flow velocity increases, the vibration frequency of the horizontal elliptical tube is always close to its natural frequency, and its vibrational amplitude is small. When the frequency is locked, the vibrational amplitude of the vertical elliptical tube is the largest. Compared with the heat-transfer effect of the static tube under the same working conditions, the maximum enhancement heat-transfer effect of the vortex-induced vibration of the vertical elliptical tube is 28.6%, whereas those of the circular tube and horizontal elliptical tube are 21.3% and 3.7%, respectively.

Sarhan et al. [67] experimental investigated the effect of vertical vibration on thermal performances of rectangular flat plate orientation angles (θ) (i.e., 30°, 45° and 60°) at the range of 0 to 16 Hz vibrating frequency and 1.5 mm to 7.5 mm amplitudes. The authors found that the increase in oscillation frequencies lead to an increase in the average heat-transfer coefficient. The maximum increase was obtained in the horizontal position and higher frequencies. Table 3 summarizes current research on heat-transfer enhancement using vibration.

**Table 3.** Current research on heat-transfer enhancement using vibration at various acoustic range.

| Acoustic Range | Author | Type | Vibration | Thermal Efficiency Improvement |
|---|---|---|---|---|
| Power ultrasound (20 kHz < f < 1 MHz) | Amiri et al. [63] | experimental | forced | increased by 7.3% |
| | Bulliard-Sauret et al. [53] | experiment | forced | n/a |
| | Lebon et al. [39] | numerical | forced | n/a |
| Sound (20 Hz < f < 20 kHz) | Sudhakara Rao et al. [64] | experimental | forced | n/a |
| | Santosh et al. [65] | numerical | forced | increased by 51% |
| Infrasound (f < 20 Hz) | Su et al. [66] | numerical | passive | increased by 28.6%. (vertical elliptical); 21.3% (circular tube); 3.7% (horizontal elliptical); |
| | Sarhan et al. [67] | experimental | forced | n/a |

## 4. Flat Plate Solar Water Heater Heat-Transfer Enhancement Using Vibration at Infrasound Acoustic Range

Methods for enhancing heat transfer using vibration are mainly in infrasound acoustic range and available in a forced and passive mechanism. Utilizing flow alteration from infrasound vibration has been proven effective in previous thermal enhancement study. A similar vibration mechanism can be applied in SWH to improve thermal performance. Such research, however, has not been performed for FPSC system.

A "proof of concept" research conducted by Cioc et al. [57] has proven that the thermal performance of a solar collector can be improved using vibration at the infrasound acoustic range ((f < 20 Hz)). They experimentally investigated the effect of flow tube vibrations on the heat-transfer efficiency for a solar water heating collector using a vibration transducer (forced vibration) at five frequency values: 0; 9; 9.5; 10; 10.5; 11; 12 Hz, using a simple setup with no-flow system. Their experiment showed that the fluid under the influence of vibrations was heated faster compared to non-vibrating system. The result shows that the time for heat transfer is shorter when the vibrating frequency is near to the resonance. This was because the transducer 'wiper' achieved the highest amplitude at resonance thus achieving highest Reynold's number at that exact vibrating frequency. Under the vibrating condition, the highest temperature achieved was enhanced up to 1.15% compare to those in non-vibrated condition. Higher vibrating frequency, however required more power. The authors showed that using the variation of time constant against vibration amplitude could reveal the optimum balance between energy consumption and heat transfer.

Sahlani et al. [42] experimentally studied the effect of vibration on the thermal performance of evacuated tube collector solar water heater (ETSC) at 2 to 10 Hz frequency ranges. The authors used mechanical excitation to force vibration on the ETSC. The vibration caused uniform temperature distribution by destabilizing the thermal boundary layer of the fluid in the riser tube. At higher frequency, thermal performance was greatly enhanced and thermal efficiency of up to 78% was achieved.

The heat-transfer enhancement due to the vibration at infrasound acoustic range is a promising technique for the FPSC application. Previous research has shown increased in thermal efficiency at vibrating frequency below 20 Hz in force and passive methods and could reduce fouling layer in the pipe with slight pressure drop. However, the application in the FPSC system has not been largely explored and it would be interesting avenues for future research. In addition—and as discussed in Section 3—reliability of SWH under vibration needs to be investigated to determine the impact of such vibration on the lifetime and performance of SWH system.

## 5. Conclusions

This study reviews recent research on FPSC thermal performance enhancement methods and discusses studies on heat-transfer enhancement using vibration and its potential for FPSC application. From these reviews, these conclusions are drawn:

- Ten methods for enhancing thermal performance enhancement were identified: applications of nanofluid, absorber coatings, heat loss reduction, PCM, thermal performance enhancer, FPSC design modification, turbulators, mini and micro channel and polymer material;
- Heat-transfer enhancement using vibration creates a pressure amplitude that promotes flow alteration and fluid mixing, which enables triggering or increasing the turbulence rate within a liquid and improve heat transfer;
- Heat-transfer enhancement using vibration method on ETSC indicates a potential improvement in heat-transfer efficiency up to 78%; However, there is no such study done on FPSC;
- Vibration can potentially affect the reliability of FPSC; nevertheless, there is still a lack of research in this area.

Based on the above findings, future research on FPSC thermal performance enhancement should focus on two main areas; (i) application of heat-transfer enhancement using vibration particularly at infrasound acoustic range (f < 20 Hz), (ii) reliability study on FPSC SWH system subjected to vibration.

**Author Contributions:** Conceptualization, N.I.S.A. and H.H.; investigation, T.H. and N.I.S.A.; resources, T.H. and M.S.N.; supervision, H.H. and M.S.N.; validation, M.S.N.; writing-original draft preparation, N.I.S.A.; writing-review and editing, H.H. and M.S.N.; funding acquisition, H.H. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by Yayasan Universiti Teknologi PETRONAS (YUTP), Grant Number 015LC0-108.

**Acknowledgments:** The authors wish to acknowledge the support of Universiti Teknologi PETRONAS for providing some of the resources to support this research.

**Conflicts of Interest:** The authors declare no conflicts of interest.

## Abbreviations

| | |
|---|---|
| CPSC | compound parabolic collector |
| ETSC | evacuated-tube solar water heater |
| FPSC | flat plate solar collector solar water heater |
| HPV/T | photovoltaic thermal hybrid |
| HTF | heat-transfer fluid |
| PCM | phase change material |
| PVD | physical vapor deposition |
| PV | photovoltaic |
| SWH | solar water heater |
| TIM | transparent insulation material |

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