Influence of Far Infrared TiO$_2$ and Multi-Walled Carbon Nanotubes Coatings on the Performance of a Hot Water Heater

Tun-Ping Teng $^{1,*}$, Shang-Pang Yu $^2$, Yeou-Feng Lue $^1$, Qi-Lin Xie $^3$, Hsiang-Kai Hsieh $^3$ and Chia-Cing Huang $^3$

1 Undergraduate Program of Vehicle and Energy Engineering, National Taiwan Normal University, No. 162, Sec. 1, He-ping E. Road, Da-an District, Taipei 10610, Taiwan; yfntue@ntnu.edu.tw
2 College of Mechanical & Electrical Engineering, National Taiwan University of Technology, No. 1, Sec. 3, Zhongxiao E. Rd., Taipei 10608, Taiwan; ysp010221@gmail.com
3 Department of Industrial Education, National Taiwan Normal University, No. 162, Sec. 1, He-ping E. Road, Da-an District, Taipei 10610, Taiwan; e7438666@gmail.com (Q.-L.X.); hsiangkai@0570104x@gmail.com (H.-K.H.); hcc0820@gmail.com (C.-C.H.)

* Correspondence: tube5711@ntnu.edu.tw; Tel.: +886-2-774-933-58; Fax: +886-2-239-294-49

Abstract: This study selects titanium dioxide (TiO$_2$) and multi-walled carbon nanotubes (MWCNTs) as far-infrared materials (FIRMs), and further adds water-based acrylic coatings to prepare far-infrared coatings (FIRCs). FIRCs are uniformly coated on #304 stainless steel sheets to make the test samples, which are then installed between the shell and insulation material of the hot water heater to measure the influences of various FIRCs on the performance of the hot water heater. The research results show no significant difference in the heating rate or heat insulation performance of the hot water heater with or without FIRCs coating. However, the uniformity of the water temperatures of the test samples is significantly improved with FIRCs. Considering that the uniformity of water temperature will inhibit the heating rate and heat insulation performance of the hot water heater, TiO$_2$-FIRC should provide better performance improvement when applied to the hot water heater in this study. The application of TiO$_2$-FIRC to large-scale hot water heaters with a high aspect ratio will effectively improve the quality of hot water supply in the future.

Keywords: far-infrared coatings; heat insulation performance; multi-walled carbon nanotubes; titanium dioxide; uniformity of water temperature

1. Introduction

In recent years, far-infrared rays have attracted considerable attention from the public. Various application fields have different wavelength ranges for the classification of infrared rays. Among them, the wavelength range of far-infrared rays (FIRs) as defined in the medical field is 5.6–1000 µm [1]. As the energy of far-infrared rays can promote blood circulation [2–4], cell repair [5], tissue regeneration [3,6], intestinal function [7], diminish inflammation [8], and inhibit cancer [9], it is often used in medical, health, and beauty fields [10]. However, the action mechanisms of FIR on humans are still little known [10]. In addition, FIR is commonly used to promote industrial and civil applications, such as heating, cooling, and combustion. According to their material characteristics, far infrared materials (FIRMs) can resonate at different temperatures and wavelengths, and promote the disturbance of the working fluid or collision with surrounding objects, thereby enhancing energy transfer.

Generally, metal oxides, carbon-based materials, and rare earth elements have high FIR emissivity ($\varepsilon$) and are often selected as candidate materials for FIRs. The $\varepsilon$ is the ratio of the emitted energy of the substance to the emitted energy of the black body [11]. These FIRMs can produce resonance effects at different temperatures and wavelengths, as based on their infrared radiation characteristics and according to the Wien displacement law, to promote the working fluid (such as: water, refrigerant, air, fuel, etc.) to produce more severe
disturbances of the working fluid itself and collisions with external objects (the tube wall of the heat exchanger or the heater), thereby enhancing energy transfer. The most common application examples of FIR in industry are heating/cooling (heat treatment, boiler, heat exchange, heat preservation, etc.) [12–20], internal combustion engines (gasoline and diesel engines) [21–23], and other equipment. In order to achieve the purpose of improving system efficiency, the resonance of FIR promotes uniform temperature distribution, thermal convection, working fluid disturbance, thermal radiation, and fuel atomization. In addition, it can reduce fuel consumption and emissions in the field of combustion [14,16,21–23].

This study selected titanium dioxide (TiO$_2$) and multi-walled carbon nanotubes (MWCNTs) as FIRMs, which were further added to water-based acrylic coatings to prepare far-infrared coatings (FIRCs). The FIRCs were uniformly coated on #304 stainless steel sheets to make the test samples, which were then installed between the shell and insulation material of the hot water heater, for measuring and analyzing the water temperature, heating rate, and uniformity of water temperature to evaluate the influences of various FIRCs on the performance of the hot water heater.

2. Related Theories and Sample Preparation

2.1. Wien’s Displacement Law

FIRs are electromagnetic waves that can be absorbed by various objects in the same wavelength range to produce a resonance effect, which activates the molecules of the surrounding fluid and promotes disturbance. Generally, manufacturers of FIRMs and FIR equipment use Wien’s displacement law to explain the resonance relationship between the applicable temperature and wavelength of FIRMs. Wien’s displacement law states that the wavelength at the peak of the radiation curve of a black body is inversely proportional to the absolute temperature of the black body, and its mathematical representation is as follows [24]:

$$\lambda_{\text{max}} = \frac{b}{T}$$

where $T$ is the temperature (K) of the black body, $b$ is Wien’s displacement constant ($\approx 2897 \, \text{µm} \cdot \text{K}$) [25], and $\lambda_{\text{max}}$ is the wavelength (µm) of the maximum radiation energy of the black body; in other words, the maximum radiant energy can be obtained below this wavelength ($\lambda_{\text{max}}$). The $\varepsilon$ is the ratio of the radiation energy of a substance to the black body. The higher the $\varepsilon$ of the material, the closer the radiation energy of the material to the black body; in other words, according to Wein’s displacement law, the FIRCs on the outside of working fluid have higher $\varepsilon$ at the working temperature corresponding to the wavelength, which means that FIRCs have higher FIR radiation energy at this working temperature to promote the disturbance of the working fluid, and thus, improve the energy transfer of the working fluid itself and the working fluid to outside.

2.2. Preparation of FIRCs

This study used TiO$_2$ (TG-P25, Tokyo, Degussa, Japan) and MWCNTs (OD: 20–30 nm; Cheap Tubes, Grafton, VT, USA) as FIRMs, and the transmission electron microscope (TEM; H-7100, Hitachi, Saitama, Japan) image of these FIRMs are shown in Figure 1. The particle size of TiO$_2$ and the outer diameter of MWCNTs are about 30 nm and are in compliance with the specifications marked by the manufacturer. First, this study added 10 wt % FIRMs to the water and used an electromagnetic stirrer (PC420D with 600 rpm, Corning, Corning, NY, USA), an ultrasonic cleaner (5510R-DTH, Branson, St. Louis, MO, USA), and a high-speed homogenizer (YOM300D Yotec, Taiwan) with 3000 rpm to stir and disperse the FIRMs for 30 min by each dispersion equipment. Finally, the well-dispersed FIRM aqueous suspension was added to water-based acrylic paint (Asahipen, Osaka, Japan) at a ratio of 1:4 ($w/w$) to form FIRCs with a FIRMs concentration of approximately 2.5 wt %. Then, this study used the above dispersion equipment to alternately disperse FIRCs three times (each equipment is executed for 30 min each time), in order to uniformly disperse the FIRMs in FIRC and maintain superior suspension performance. At this time, the preparation procedure of FIRCs is completed.
Two FIRCs were evenly coated on the surface (single side) of #304 stainless steel sheets ($W \times L \times T: 160 \times 370 \times 0.18 \text{ mm}$, weight: $80.02 \pm 0.15 \text{ g}$) by the brushing method. After each coating was completed, it was heated and dried ($50^\circ \text{C}$) by a heating oven and weighed with an electronic balance (GX-6100, A&D, Tokyo, Japan; accuracy of $\pm 0.1 \text{ g}$, resolution of $\pm 0.01 \text{ g}$), and if the weight was insufficient, it was coated again. In order to compare the difference between samples with and without coatings, and coatings with and without FIRMs, the test samples also included uncoated stainless steel plates (Blank) and stainless steel plates coated with 25% water-based acrylic paint (Base). The coating weights of all coated samples (Base, TiO$_2$-FIRC, MWCNTs-FIRC) were controlled within $2.25 \pm 0.03 \text{ g}$. Figure 2 shows three coated test samples, where the coating weights of the Base, MWCNTs-FIRC, and TiO$_2$-FIRC are 2.28, 2.24 and 2.23 g, respectively.
Figure 3 shows the emissivity ($\varepsilon$) of the coated test samples with Base, TiO$_2$-FIRC, and MWCNTs-FIRC at the sample temperatures of 40 and 80 °C. The emissivity of the samples were measured at different wavelengths using an FT-IR spectrometer (VERTEX 70, Bruker, Ettlingen, Germany). According to Wein’s displacement law, the wavelength of the maximum radiation energy corresponding to 25–65 °C (approximate temperature range of hot water heater) is 9.72–8.57 µm. The average $\varepsilon$ of the Base, TiO$_2$-FIRC, and MWCNTs-FIRC at wavelengths of 9.72–8.57 µm under the average sample temperature were 0.82, 0.97, and 0.94, respectively.

3. Experimental Design and Procedures
3.1. Experiment Apparatus

Figure 4 shows the equipment diagram of the hot water heater performance experiments. A copper tube with two PVC tube caps was used to make the outer shell of the hot water heater. A 150 W electric heating tube with a programmable DC power supply (constant power mode; EV202, Consort, Belgium; accuracy of ±1.0 W) was installed on the fixed tube cap at the bottom to provide the heating capacities of 40 and 80 W (different heating rates). Two thermocouples (T-type, $\psi = 2$ mm, accuracy of ±0.75%) with stainless steel protective tubes of different lengths were installed on the removable tube cap to measure the water temperatures ($T_1$ and $T_2$) in the center and upper parts of the hot water heater, and a recorder (TRM-20, TOHO, Kanagawa, Japan; accuracy of ±0.1%) was used to measure and record temperatures with a sampling interval of 3 s.

The temperature difference between $T_1$ and $T_2$ is inversely proportional to the uniformity of the water temperature in the hot water heater. Therefore, the temperature difference between the $T_1$ and $T_2$ can be used to evaluate the uniformity of the water temperature of the hot water heater. Although installing multiple thermocouples to measure the temperature at multiple points can more accurately assess the uniformity of the water temperature, it is not easy to stably and accurately install multiple temperature sensors to measure temperature changes of multiple points because of the small internal space of the hot water heater. Furthermore, the distance between the measurement points between $T_1$ and $T_2$ is not large, and it can be expected that the temperature difference between $T_1$ and $T_2$ will not be large, resulting in little practical significance for installing multiple temperature measurement points. Therefore, this study only uses two measuring points to measure the water temperature.
The target temperature setting \( T_{\text{Tar}} \) of water for the temperature controller (TTM-i4N, TOHO, Japan; accuracy of \( \pm 0.3\% \)) was based on the measurement data of the thermocouple \( T_1 = T_w = T_{\text{Tar}} \) located in the center of the hot water heater as the control reference. The coating of the test sample was crimped toward the inside to cover the outer layer of the copper tube, then the test sample was tightly affixed to the outside with aluminum foil tape, and then, a PU foam tube with a thickness of 1.2 cm was placed to cover the outer layer of the test sample for insulation to improve the stability of the experiment.

### 3.2. Experimental Procedure and Calculation

This experiment used an electronic balance (GX-6100, A&D, Japan; accuracy of \( \pm 0.1 \) g, resolution of \( \pm 0.01 \) g) to weigh 480 g of pure water (keep the water temperature at 25 \( ^\circ \)C with an isothermal unit in advance), placed it in the hot water heater, and then, the upper tube cap was covered and heated with constant power (40 W and 80 W). The \( T_{\text{Tar}} \) was set to 43, 53, and 63 \( ^\circ \)C, respectively, and when the water temperature reached \( T_{\text{Tar}} \), the temperature controller and circuit control unit automatically powered off to stop heating. At this time, the recorder continued to record temperature changes until the end of the test time (the total experiment time was 90 min). The temperature and humidity of the experimental environment were controlled by a temperature/humidity control system at 25 \( ^\circ \)C \( \pm 0.5 \) \( ^\circ \)C and 60\% RH \( \pm 5\% \), respectively. Each experimental parameter (four test samples: Blank, Base, TiO\(_2\)-FIRC, MWCNTs-FIRC; three \( T_{\text{Tar}} \): 43, 53, and 63 \( ^\circ \)C; two heating powers: 40 W and 80 W, for a combination of 24 test parameters in total) were performed four times (96 tests were performed in total, and each experiment time was 90 min). Because the heating load used by the hot water heater in this study is only 480 g of pure water, the experimental results are easily affected by environmental conditions and operating errors. Therefore, it is necessary to control the experimental environmental conditions and repeatedly measure to reduce the deviation of the experiment.
The heating rate ($S_{tr}$, °C/sec) was calculated from the recorded data in each experiment, and this study took the time and water temperature ($T_1$) differences corresponding to 10% to 90% of the $T_{tr}$, where a high $S_{tr}$ meant that the hot water heater had high heating efficiency (a greater temperature rise at the same time). In addition, this study recorded the residual water temperature ($T_r$) within 10 min before the end of the experiment ($T_{la10}$ °C), where the higher $T_{la10}$ represents the better thermal insulation performance of the hot water heater. Furthermore, regarding the standard deviations ($STD_{Tw}$) of the temperature difference between the upper ($T_2$) and center ($T_1$) water temperatures during the experiment, the lower $STD_{Tw}$ means the water temperature between $T_2$ and $T_1$ is closer, and the water temperature is better distributed in the hot water heater. The $S_{tr}$, $T_{la10}$, and $STD_{Tw}$ were taken as the performance indicators to evaluate the influence of FIRC on the performance of the hot water heater. Finally, the calculation results of the four repeated experiments with the same experimental parameters were averaged to obtain the final experimental results.

3.3. Uncertainty and Data Analysis

The relative uncertainty analysis performed in this study involved calculation of the measurement deviations ($m$). The relative uncertainty ranges, as determined in the hot water heater performance experiments, included those of $S_{tr}$, $T_{la10}$, and $STD_{Tw}$, which reflect the deviations from the relevant temperature controller, temperature sensors, power supply, and data recorder. The maximum relative uncertainty ranges of $S_{tr}$, $T_{la10}$, and $STD_{Tw}$ were ±2.84%, ±1.11%, and ±1.34%, respectively. As the same experimental parameters were repeated four times, the relative uncertainty of the final experimental data should be further reduced. The maximum relative uncertainty ranges ($u_m$) in the hot water heater performance experiments did not include any deviations caused by using the sample weight and ambient conditions.

$$u_m = [(m_1)^2 + (m_2)^2 + (m_3)^2 + \ldots + (m_n)^2]^{1/2} \times 100\%$$ (2)

The experimental and calculation results are presented as a change ratio ($R$) to reveal differences between the experimental data of “Blank” ($ED_{Blank}$) and those of samples with coatings ($ED_{Coatings}$), where $R$ can be expressed as:

$$R = [(ED_{Coatings} - ED_{Blank})/ED_{Blank}] \times 100\%$$ (3)

4. Results and Discussion

Figures 5–7 show the average water temperature (from $T_1$) of the four repeated experiments for each test sample under different $T_{tr}$ and heating powers. It can be seen from these figures that there are slight differences between the test samples, and the maximum water temperature ($T_{max}$) under each experimental parameter is slightly higher than the $T_{tr}$. In this study, the temperature difference between $T_{max}$ and $T_{tr}$ is named $dT_{tr}$ (°C). This phenomenon is mainly caused by the continued heating of the water by the residual heat after the heater was turned off, and the residual heat of the heater after the power was turned off should be the same under the same heating power. In addition, the $dT_{tr}$ with heating power of 80 W had a higher residual heat than the 40 W after the power was turned off; therefore, it can be expected that the $dT_{tr}$ with heating power of 80 W was higher than that of the 40 W. The higher $dT_{tr}$ shows the higher heating capacity of the water by the residual heat of the heater that had better thermal insulation performance. However, the residual heat of the heater after the power was turned off should be the same under the same heating power. Therefore, the high $dT_{tr}$ may be caused by the poor natural convection of the water in the hot water heater, which caused the higher local temperature, and this issue can be determined by referring to the temperature difference between $T_2$ and $T_1$. Furthermore, whether the high $dT_{tr}$ comes from the better thermal insulation effect can be determined by referring to $T_{la10}$. Moreover, based on the $T_{tr}$, $S_{tr}$ will also affect the overshoot of $T_1$. According to the above analysis, it can be known that $dT_{tr}$
will simultaneously be affected by $S_{tr}$, $T_{Id10}$, and $STD_{dTw}$. Therefore, as these performance indicators also consider $dT_{Tar}$, this study only used $S_{tr}$, $T_{Id10}$, and $STD_{dTw}$ as performance indicators to evaluate the hot water heater performance.

Figure 5. The $T_1$ for test samples at $T_{Tar}$ of 43 °C.

Figure 6. The $T_1$ for test samples at $T_{Tar}$ of 53 °C.

Figure 7. The $T_1$ for test samples at $T_{Tar}$ of 63 °C.
As shown in Table 1, all experimental results are further aggregated into various performance indicators such as the heating rate ($S_{tr}$), the average water temperature ($T_1$) within 10 min before the end of the experiment ($T_{la10}$), the standard deviations ($STD_{dTw}$) of the temperature difference between the upper ($T_2$) and center ($T_1$) water temperatures during the experiment, and its change ratios to facilitate comparison. It can be seen from Table 1 that $S_{tr}$ and $T_{la10}$ do not have a certain trend; however, $STD_{dTw}$ presents all the experimental parameters, and shows that the uniform water temperatures of the samples coated with TiO$_2$-FIRC and MWCNTs-FIRC are better. Since the heating load used by the hot water heater in this study is only 480 g of pure water, it is expected that the experimental results of each test sample have little difference under the same experimental parameters. In order to comprehensively evaluate the performance of hot water heaters, the different heating powers are divided into two groups of 40 and 80 W, and the four samples are ranked 1 to 4 according to the sorted order of the performance indicators ($S_{tr}$, $T_{la10}$, and $STD_{dTw}$); the smaller the sorted cumulative number, the better the overall performance. When the accumulated numbers are the same, $STD_{dTw}$ is used to distinguish the difference. The order of the overall performance of the hot water heater at the heating power of 40 W is MWCNTs, TiO$_2$, Blank, and Blank; while the order is TiO$_2$, MWCNTs, Blank, and Blank for the heating power of 80 W. The results show that the sample with MWCNTs-FIRC has better performance at the low heating power (40 W); while the sample with TiO$_2$-FIRC has better performance at the high heating power (80 W).

Next, this study conducted a more in-depth discussion on the relationship between the three performance indicators of $S_{tr}$, $T_{la10}$, and $STD_{dTw}$. As shown in Figure 3, the $\epsilon$ of MWCNTs-FIRC is higher than TiO$_2$-FIRC only when the wavelength is greater than 9.43 (sample temperature of 80 °C for $\epsilon$ test) and 9.52 µm (test sample temperature of 40 °C for $\epsilon$ test) at the wavelength range of 9.72–8.57 µm. The temperatures calculated by the two wavelengths, as based on Wein’s displacement law, are 34.2 and 31.3 °C, respectively; in other words, most of the water temperatures of TiO$_2$-FIRC in the experiment had a higher

| $T_{Ian}$ (°C) | Item | 40 W | 80 W |
|----------------|------|------|------|
|                | Blank| Base | TiO$_2$| MWCNTs| Blank| Base | TiO$_2$| MWCNTs|
| 43             | $S_{tr}$ (°C/s) | 0.01491 | 0.01482 | 0.01453 | 0.01404 | 0.02829 | 0.02745 | 0.02775 | 0.02804 |
|                | $R_{Str}$ (%) | 0.00 | -0.60 | -2.60 | -5.84 | 0.00 | -2.96 | -1.89 | -0.87 |
|                | $T_{la10}$ (°C) | 36.69 | 36.70 | 36.92 | 36.93 | 35.80 | 35.52 | 35.97 | 36.06 |
|                | $R_{Tla10}$ (%) | 0.00 | 0.00 | 0.62 | 0.65 | 0.00 | -0.78 | 0.48 | 0.73 |
|                | $STD_{dTw}$ (%) | 0.43 | 0.48 | 0.41 | 0.42 | 0.68 | 0.74 | 0.62 | 0.66 |
|                | $R_{STD}_{dTw}$ (%) | 0.00 | 10.94 | -5.66 | -3.95 | 0.00 | 8.83 | -8.54 | -2.14 |
| 53             | $S_{tr}$ (°C/s) | 0.01327 | 0.01317 | 0.01312 | 0.01331 | 0.02652 | 0.02625 | 0.02654 | 0.02658 |
|                | $R_{Str}$ (%) | 0.00 | -0.78 | -1.14 | 0.32 | 0.00 | -1.02 | 0.06 | 0.22 |
|                | $T_{la10}$ (°C) | 45.08 | 45.06 | 45.03 | 45.34 | 42.15 | 42.11 | 42.43 | 42.20 |
|                | $R_{Tla10}$ (%) | 0.00 | -0.05 | -0.12 | 0.57 | 0.00 | -0.09 | 0.67 | 0.12 |
|                | $STD_{dTw}$ (%) | 0.74 | 0.71 | 0.61 | 0.64 | 0.92 | 0.85 | 0.84 | 0.83 |
|                | $R_{STD}_{dTw}$ (%) | 0.00 | -4.52 | -17.27 | -13.21 | 0.00 | -7.06 | -8.87 | -9.51 |
| 63             | $S_{tr}$ (°C/s) | 0.01209 | 0.01219 | 0.01215 | 0.01180 | 0.02584 | 0.02584 | 0.02621 | 0.02589 |
|                | $R_{Str}$ (%) | 0.00 | 0.81 | 0.54 | -2.40 | 0.00 | 0.02 | 1.43 | 0.19 |
|                | $T_{la10}$ (°C) | 56.22 | 55.79 | 55.68 | 56.29 | 49.40 | 49.25 | 49.44 | 49.16 |
|                | $R_{Tla10}$ (%) | 0.00 | -0.76 | -0.95 | 0.13 | 0.00 | -0.29 | 0.10 | -0.49 |
|                | $STD_{dTw}$ (%) | 0.85 | 0.83 | 0.79 | 0.81 | 1.07 | 1.05 | 0.95 | 0.97 |
|                | $R_{STD}_{dTw}$ (%) | 0.00 | -3.01 | -7.72 | -4.50 | 0.00 | -1.28 | -11.08 | -9.44 |

Table 1. List of results of hot water heater performance tests for heating power of 40 and 80 W.
ε corresponding to this range of wavelengths (9.72~8.57 µm) than MWCNTs-FIRC. In theory, when TiO₂-FIRC is used in hot water heaters, the improved performance of the hot water heaters should be better than MWCNTs-FIRC, which is because the higher radiation energy of FIR can promote the disturbance of water during heating. However, the ranked results of the performance indicators show that the sample coated with MWCNTs-FIRC is better than the sample coated with TiO₂-FIRC under the heating power of 40 W. FIRCs with higher ε should be able to provide higher FIR radiation energy to disturb the water in the hot water heater and make the overall water temperature more uniform (lower STDₜ₁₄). Due to the disturbance of the FIR radiation energy (Sᵣ is only calculated by T₁ without considering T₂), the uniformity of T₂ and T₁ will suppress Sᵣ when the overall water temperature is more uniform; in the same way, the more uniform water temperatures at T₂ and T₁ will also make T₁₄₀ lower (T₁₄₀ calculated only by T₁ without considering T₂). The STDₜ₁₄ in Table 1 shows that the sample coated with TiO₂-FIRC has only one experimental parameter (T₉ₐ = 53 °C, heating power = 80 W), which is slightly higher (within 1%) than the sample coated with MWCNTs-FIRC. The above analysis shows that STDₜ₁₄ suppresses the two performance indicators of Sᵣ and T₁₄₀. Furthermore, it is well known that the thermal conductivity (k) of MWCNTs is much higher than that of TiO₂, which makes the k of MWCNTs-FIRC higher than that of TiO₂-FIRC. High k material is coated on the outside of hot water heater will be detrimental to the thermal insulation performance of the hot water heater. Therefore, in terms of all the experimental parameters in this study, the sample coated with TiO₂-FIRC should be better than the sample coated with MWCNTs-FIRC for improving the performance of the hot water heater in this study. This study suggests that the FIRCs with high ε and low k should be selected for the practical application of FIRC to hot water heaters, which should be better for improving the relevant performance of hot water heaters. However, FIRC with high ε and high k can be considered in the field of heat dissipation.

5. Conclusions

This study selected TiO₂ and MWCNT as FIRMs, which were added to water-based acrylic coatings to prepare FIRCs. In order to study the influence of FIRCs on the performance of the hot water heater, the two FIRCs were evenly coated on #304 stainless steel sheets and installed on the outer layer of the hot water heater to make test samples. According to the comprehensive performance indicators, such as Sᵣ, T₁₄₀, and STDₜ₁₄, MWCNTs-FIRC has better performance at the heating power of 40 W; while TiO₂-FIRC has better performance at the heating power of 80 W. Considering that the uniformity of water temperature will inhibit the Sᵣ and T₁₄₀ of a hot water heater, TiO₂-FIRC should have better performance improvement when applied to the hot water heater in this study. The actual use of FIRCs to improve the performance of hot water heaters should select the FIRCs with high ε and low k.

Author Contributions: Conceptualization, T.-P.T., S.-P.Y. and Y.-F.L.; designed the experiment, T.-P.T., S.-P.Y. and Y.-F.L.; carried out the measurements, T.-P.T., Q.-L.X., H.-K.H. and C.-C.H.; analyzed the measurements, T.-P.T., S.-P.Y. and Q.-L.X.; wrote and revised the paper, T.-P.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data available on request.

Acknowledgments: The authors would like to thank the Ministry of Science and Technology of China (Taiwan) for their financial support to this research under Contract no. MOST 106-2221-E-003-024-MY3.

Conflicts of Interest: The authors declare that they have no competing interests.
Nomenclature

\( \varepsilon \) emissivity (dimensionless)

\( \lambda_{\text{max}} \) Wavelength of the maximum radiation energy of the black body (\( \mu \text{m} \))

\( k \) Thermal conductivity (W/m-K)

\( T \) Temperature (K)

\( T_{\text{max}} \) Maximum water temperature (C)

\( T_{1} \) Center water temperature (C)

\( T_{2} \) Upper water temperature (C)

\( T_{w} \) Water temperature (C)

\( b \) Wien’s displacement constant (\( \approx 2897 \mu \text{m}-\text{K} \))

\( S_{\text{tr}} \) Heating rate (C/s)

\( T_{\text{Tar}} \) Target temperature setting (C)

\( T_{\text{avg}10} \) Average water temperature in the last 10 min (C)

\( \text{STD}_{\text{T}w} \) Standard deviations of the temperature difference between the upper and the center water temperature

\( m \) Measurement deviations (%)

\( \mu m \) Maximum relative uncertainty (%)

\( R \) Change ratio (%)

\( ED \) Experimental data

\( dT_{\text{Tar}} \) Temperature difference between the \( T_{\text{max}} \) and the \( T_{\text{Tar}} \) (C)

References

1. Dover, J.S.; Phillips, T.J.; Arndt, K.A. Cutaneous effects and therapeutic uses of heat with emphasis on infrared radiation. J. Am. Acad. Dermatol. 1989, 20, 278–286. [CrossRef]

2. Choi, S.J.; Cho, E.H.; Jo, H.M.; Min, C.; Ji, Y.S.; Park, M.Y.; Kim, J.K.; Hwang, S.D. Clinical utility of far-infrared therapy for improvement of vascular access blood flow and pain control in hemodialysis patients. Kidney Res. Clin. Pract. 2016, 35, 35–41. [CrossRef]

3. Ishimaru, K.; Nakajima, T.; Namiki, Y.; Ryotokuji, K. Influences of pinpoint plantar long-wavelength infrared light irradiation (stress-free therapy) on chorioretinal hemodynamics, atherosclerosis factors, and vascular endothelial growth factor. Integr. Med. Res. 2018, 7, 103–107. [CrossRef]

4. Io, H.; Nakata, J.; Aoyama, R.; Inoshita, H.; Nakano, T.; Ishizaka, H.; Fukui, M.; Tomino, Y.; Suzuki, Y. Far-infrared therapy for secondary vascular access spray of hemodialysis patients. Ren. Replace. Ther. 2019, 5, 31. [CrossRef]

5. Chen, T.Y.; Yang, Y.C.; Sha, Y.N.; Chou, J.R.; Liu, B.S. Far-infrared therapy promotes nerve repair following end-to-end neurorrhaphy in rat models of sciatic nerve injury. Evid. Based Complement. Altern. Med. 2015, 2015, 207245. [CrossRef]

6. Ou, S.M.; Hu, F.H.; Yang, W.C.; Lin, C.C. Far-infrared therapy as a novel treatment for encapsulating peritoneal sclerosis. Am. J. Gastroenterol. 2014, 109, 1957–1959. [CrossRef]

7. Khan, I.; Pathan, S.; Li, X.A.; Leong, W.K.; Liao, W.L.; Wong, V.; Hsiao, W.L.W. Far infrared radiation induces changes in gut microbiota and activates GPCRs in mice. J. Adv. Res. 2020, 22, 145–152. [CrossRef] [PubMed]

8. Kim, S.H.; Hwang, S.H.; Hong, S.K.; Seo, J.K.; Sung, H.S.; Park, S.W.; Shin, J.H. The clinical efficacy, safety and functionality of anion textile in the treatment of atopic dermatitis. Ann. Dermatol. 2012, 24, 438–443. [CrossRef] [PubMed]

9. Hamada, Y.; Teraoka, F.; Matsumoto, T.; Madachi, A.; Toki, F.; Uda, E.; Hase, R.; Takahashi, J.; Matsuura, N. Effects of far infrared ray on Hela cells and WI-38 cells. Int. Congr. Ser. 2003, 1255, 339–341. [CrossRef]

10. Cristiano, L. Use of infrared as a complementary treatment approach in medicine and aesthetic medicine. Asp. J. Biomed. Clin. Case Rep. 2019, 2, 77–81.

11. Wikipedia. Emissivity. 2020. Available online: https://en.wikipedia.org/wiki/Emissivity (accessed on 6 December 2020).

12. Heynderickx, G.J.; Nozawa, M. High-emissivity coatings on reactor tubes and furnace walls in steam cracking furnaces. Chem. Eng. Sci. 2004, 59, 5657–5662. [CrossRef]

13. Zhu, D.; Ding, Y.; Wang, L.; Liang, G.; Wang, Y. Effect of rare earth composite ceramic materials on oil combustion of oil-burning boiler. J. Rare Earths 2006, 24, 244–247.

14. Li, F.; Liang, J.; Meng, J.; Ding, Y.; Liang, G.; Xue, G.; Liu, L. Effect of tourmaline/resin composite materials on the combustion of diesel oil for oil-burning boiler. J. Chin. Ceram. Soc. 2007, 35, 517–521.

15. Zhu, D.; Liang, J.; Liang, G.; Ding, Y.; Xue, G.; Liu, L. Effects on combustion of liquefied petroleum gas of porous ceramic doped with rare earth elements. J. Rare Earths 2007, 25, 212–215.

16. Liang, J.; Zhu, D.; Meng, J.; Wang, L.; Li, F.; Liu, Z.; Ding, Y.; Liu, L.; Liang, G. Performance and application of far infrared rays emitted from rare earth mineral composite materials. J. Nanosci. Nanotechnol. 2008, 8, 1203–1210. [CrossRef]

17. Lan, H.L. Research Some Questions of High Temperature Infrared Radiant Coating during the Application. Master’s Thesis, Wuhan University of Technology, Wuhan, China, 2012.
18. Chen, T.Y.; Cho, H.P.; Jwo, C.S.; Hung, M.H.; Lee, W.S. Analyzing how the ZrO2 far infrared material affects the performance of smooth tube heat exchangers. *J. Nanomater.* 2015, 2015, 124632.

19. Maznoy, A.; Kirdyashkin, A.; Pichugin, N.; Zambalov, S.; Petrov, D. Development of a new infrared heater based on an annular cylindrical radiant burner for direct heating applications. *Energy* 2020, 204, 117965. [CrossRef]

20. Qiu, K.; Elhassan, A.; Tian, T.; Yin, X.; Yu, J.; Li, Z.; Ding, B. Highly flexible, efficient, and sandwich-structured infrared radiation heating fabric. *ACS Appl. Mater. Interfaces* 2020, 12, 11016–11025. [CrossRef] [PubMed]

21. Xue, G.; Wu, X.M.; Liang, J.S.; Ding, Y.; Liu, L.H. Effect of mineral composite materials with far infrared radiation on diesel oil combustion. *Adv. Mater. Res.* 2008, 58, 47–53. [CrossRef]

22. Wey, A.C.T. Infrared-Emitting Ceramics for Fuel Activation. U.S. Patent US20110186010 A1, 4 August 2011.

23. Qin, X.L.; Yang, R.; Wang, Y.F.; Luo, L.; Qiao, S.F. Study of the effect of negative ions on energy efficiency of diesel engines. *For. Mach. Wood. Equip.* 2013, 41, 29–30. Available online: [http://en.cnki.com.cn/Article_en/CJFDTOTAL-LJMG201303007.htm](http://en.cnki.com.cn/Article_en/CJFDTOTAL-LJMG201303007.htm) (accessed on 7 July 2020).

24. Das, R. Wavelength- and frequency-dependent formulations of Wien’s displacement law. *J. Chem. Edu.* 2015, 92, 1130–1134. [CrossRef]

25. NIST. CODATA Value: Wien wavelength displacement law constant. In *The NIST Reference on Constants, Units, and Uncertainty*; U.S. National Institute of Standards and Technology: Gaithersburg, MA, USA, 2011.