energies

MDPI

Article

The Effect of the Welding Technology on the Thermal Performance of Welded Finned Tubes Used in Heat Exchangers

Janusz Adamiec [1,*] and Michał Urbańczyk [2]

[1] Faculty of Materials Engineering, Silesian University of Technology, Krasińskiego 8, 40-019 Katowice, Poland
[2] Łukasiewicz Resarch Network—Institute of Welding, Błogosławionego Czesława 16-18, 44-100 Gliwice, Poland
* Correspondence: janusz.adamiec@polsl.pl

Abstract: Due to the use of welded finned tubes in heat exchangers, gas blocks are characterized by very good electric energy production performance, and their reliability can reach 98%. Finned tubes used in heat exchangers are usually welded. Such tubes should be characterised by the following properties: high thermal performance, good resistance to high-temperature corrosion in a flue gas atmosphere, and appropriate joint strength and hardness. The most popular technology for welding finned tubes is MAG. MAG-welded joints are characterised by considerable spattering, weld discontinuities (up to 60%), and non-axial fin alignment. Such irregularities result in a considerably reduced heat flux due to the heat transfer resistance occurring in the welded joint. It has been shown that with weld discontinuities of 20%, the thermal performance of welded finned tubes reduces considerably. This paper proposes the possibility of welding finned tubes with a laser. The thermal properties of laser-welded finned tubes were compared with those of MAG-welded tubes. It was found that the thermal performance of welded finned tubes was three times higher than that of plain tubes. However, the thermal performance was not found to be affected by the welding technology. The correct heat flow at the level of 95% occurs in the tube/fin joint even with joint penetration of 0.01 mm, however, the absence of metallic continuity in a joint results in a drastically reduced thermal performance (by 50%) and the overheating of fins, which affects their durability.

Keywords: finned tubes; heat exchanger; heat flow of finned tube; finned tubes welding; thermal performance of heat exchanger

Citation: Adamiec, J.; Urbańczyk, M. The Effect of the Welding Technology on the Thermal Performance of Welded Finned Tubes Used in Heat Exchangers. *Energies* **2023**, *16*, 1320. https://doi.org/10.3390/en16031320

Academic Editor: Artur Blaszczuk

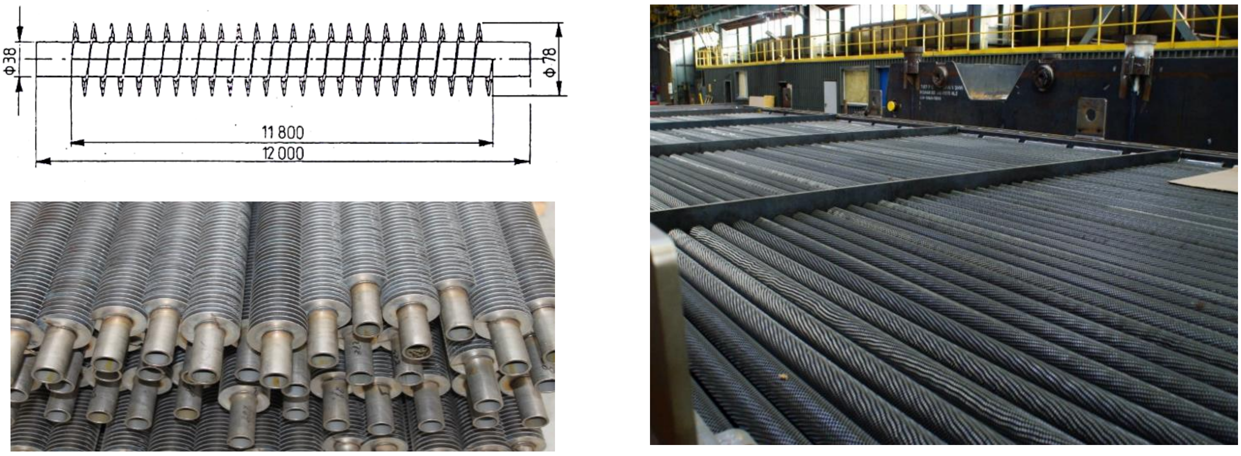
Received: 9 November 2022
Revised: 6 January 2023
Accepted: 23 January 2023
Published: 26 January 2023

1. Introduction

In modern gas boilers, such as water heaters, evaporators, and steam superheaters, welded finned tubes are used to increase the heat exchange efficiency (Figure 1) [1]. Due to the use of welded finned tubes in heat exchangers, gas blocks are characterized by very good electric energy production efficiency, and their reliability can reach 98% [2]. Welded finned tubes are usually applied where the heat transfer coefficients on the two sides of a barrier have significantly different values (e.g., flue gas and steam). The presence of fins on heat exchanger tubes increases the heat exchange surface even up to 30 times in comparison to non-finned tubes, leading to the heat exchange flux increasing by nearly 300% [1,3].

The basic finned tube manufacture technologies include wrapping a fin strip directly onto the tube, mechanical bending of the wound strip [4], mechanical working [5–9], high-frequency welding [10–12], and electric arc welding, most frequently using the MAG method [13]. Recently, there have been attempts at manufacturing laser-welded finned tubes [14,15].

Tubes with a wound or bent fin strip are not used in the energy industry due to their separable structure, which does not provide sufficient heat exchange conditions. Additionally, at time passes, the joint quality decreases due to the loss of bonding as a result of different thermal expansion coefficients of the materials and the vibrations involved in the boiler's operation [16].



(**a**) (**b**)

Figure 1. Finned tubes with incised fins manufactured by Energoinstal SA, Poland (**a**) and a heat exchanger made of finned tubes–evaporator, Hattorf boiler (**b**).

Finned tubes used in heat exchangers are usually welded. Such tubes should be characterised by the following properties: high thermal performance, good resistance to high-temperature corrosion in a flue gas atmosphere, and appropriate joint strength and hardness, as required by technical regulations, especially the requirements for quality level B according to ISO 5817 (for arc welding) and ISO 13919 (for laser welding) [17].

Significant structural factors determining the properties of welded finned tubes include weld continuity, weld shape, and weld microstructure. These factors determine the thermal performance of the pipe and thus the performance of the entire heat exchanger.

The most popular technology for welding finned tubes is MAG [18–20]. The structure and properties of welded finned tubes with fillet or butt welds beneath the fins are well-described in the literature [14,15,17]. The manufacture of finned tubes with fillet welds is characterized by low efficiency (welding rate of up to 2.5 m/min) and the welded joint can be affected by weld discontinuities (up to 20%) and irregularities in the geometry of the fillet welds [17]. The lack of full penetration and the non-symmetric weld increase the welded joint's susceptibility to crevice corrosion. MAG-welded joints located beneath the fins, in turn, are characterised by considerable spattering, weld discontinuities (up to 60%), and non-axial fin alignment. Such irregularities result in a considerably reduced heat flux due to the heat transfer resistance occurring in the welded joint. In work [21], it was shown that with weld discontinuities of 20%, the thermal performance of welded finned tubes reduced considerably.

At present, lasers are not used for welding thick-walled boiler components for the power industry due to the limited beam power, difficulties with precise joint preparation, the possibility of hardening both in the narrow HAZ and in the weld, and the hot cracking susceptibility of such welds [20,22]. However, the advantages of disc and fiber lasers, in particular the stability of the welding process, higher joint preparation tolerance, high welding energy concentration, and considerably increased welding efficiency, have prompted attempts at the laser welding of finned tubes. The results of those attempts indicate that the quality of the welded joints depends on the welding parameters, in particular the welding rate and the beam power [23].

Issues related to laser-welded finned tubes have not been extensively investigated and described in the literature. For this reason, research was undertaken to determine the influence of laser welding parameters on the structure and properties of finned tubes used in heat recovery boilers.

In this paper, the thermal performance of a finned pipe is defined as the ratio of the heat flux through a finned pipe to the heat flux through a smooth pipe, i.e., without a rib.

The effect of the degree of remelting of the ribbed pipe joint on the thermal performance of the entire pipe was also determined. The results of these studies are particularly relevant to design engineers who plan to use modern laser-welded finned tubes in heat exchangers. The research was carried out on a test stand developed at Energoinstal S.A., Poland.

2. Testing Methodology

The complex finned pipe model was simplified to a flat baffle, allowing the steady-state heat flow flux to be defined. In a stationary state, a heat flux ($\dot{Q}$) passing through a finned barrier (W) is defined by surfaces A_1 (the surface on the water or steam side) and A_2 (the surface on the flue gas side); thickness δ; and heat flow conditions T_1, α_1, T_2, and α_2 (Figure 2).

$$\dot{Q} = \dot{Q}_W = \dot{Q}_2 = Q_1 = A_1\alpha_1(T_1 - T_{W1}) = A_{WM}\frac{\lambda_W}{\delta_W}(T_{W1} - T_{W2}) = A_{20}\alpha_2(T_{W2} - T_2) + A_{2\dot{Z}}\alpha_2\left(T_{\dot{Z}M} - T_2\right), \quad (1)$$

where: $\dot{Q}$–heat flux, $\dot{Q}_1$—heat flux flowing from medium 1 to the surface of barrier W, $\dot{Q}_W$—heat flux conducted through barrier W, $\dot{Q}_2$—heat flux penetrating the surface of barrier W from medium 2, A_1—barrier surface on the side of medium 1, m^2, A_{WM}—average (integral) barrier surface, m^2, A_{20}—surface between the ribs, m^2, A_{2z}—side fin surface, m^2, α_1—coefficient of heat transfer from medium 1 to the barrier surface, W/(m^2 · °C), α_2—coefficient of heat transfer from the barrier surface to medium 2, W/(m^2 · °C), T_1—temperature of medium 1, °C, T_{W1}—barrier temperature on the side of medium 1, °C, T_{W2}—barrier temperature on the side of medium 2, °C, T_2—temperature of medium 2, °C, $T_{\dot{Z}M}$—average fin temperature, °C, λ_W—coefficient of heat transfer through barrier W, and δ_W—thickness of barrier W.

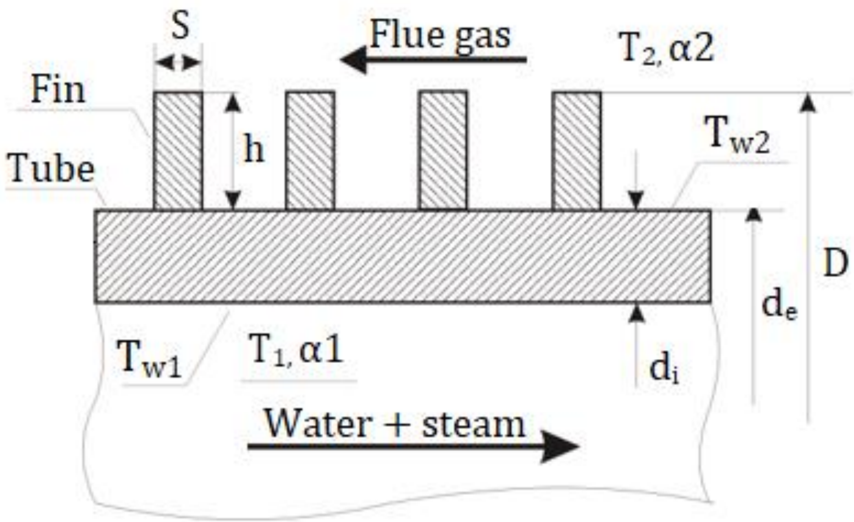


Figure 2. Diagram of heat exchange in a finned tube, where: T_1—temperature of medium 1 (water, steam), α_1—heat transfer coefficient in the medium-tube system, T_{W1}—barrier temperature on the side of medium 1, °C, T_2—temperature of medium 2 (flue gas), α_2—heat transfer coefficient in the flue gas–fin system, h—fin height, S—fin thickness, T_{W2}—barrier temperature on the side of medium 2, °C, d_e—external tube diameter, d_i—internal tube diameter, D—finned tube diameter, is defined by the following formula.

After applying the thermal performance for the fin:

$$\varepsilon_{\dot{Z}} = \frac{T_{\dot{Z}M} - T_2}{T_{W2} - T_2}, \quad (2)$$

one obtains:

$$\dot{Q}_2 = \alpha_2(T_{W2} - T_2) \cdot \left(A_{20} + A_{2\dot{Z}} \cdot \varepsilon_{\dot{Z}}\right) \tag{3}$$

Following a transformation, the Peclet equation is obtained [4]:

$$\dot{Q} = k \cdot A_1 \cdot (T_1 - T_2), \tag{4}$$

where the following formula:

$$\frac{1}{k} = \frac{1}{\alpha_1} + \frac{\delta_W \cdot A_1}{\lambda_W \cdot A_{WM}} + \frac{A_1}{\alpha_2 \cdot \left(A_{20} + A_{2\dot{Z}} \cdot \varepsilon_{\dot{Z}}\right)} \tag{5}$$

defines the heat transfer coefficient k for the finned barrier in relation to the barrier surface on the plain (non-finned) side [24,25]. However, the equation above does not take into consideration the contact resistance between the base tube and the fin (at the welded joint) and may only be applied to heat calculations, e.g., rolled finned tubes produced by a deepening or thinning method.

In the case of welded tubes, the contact resistance must be taken into consideration, i.e., the resistance offered to heat transfer by the welded joint (RS) [25–27]. Thus, the heat flux on the finned side can be described by the following formula:

$$\dot{Q}_2 = A_{20} \cdot \alpha_2(T_{W2} - T_2) + \dot{Q}_{22}, \tag{6}$$

where

$$\dot{Q}_{22} = A_S \cdot \frac{1}{R_S}(T_{W2} - T_S) \tag{7}$$

and

$$\dot{Q}_{22} = A_{2\dot{Z}} \cdot \alpha_2 \cdot \varepsilon_{\dot{Z}}(T_S - T_2) \tag{8}$$

By transforming the equations above, one obtains:

$$A_S \cdot \frac{1}{R_S}(T_{W2} - T_S) = A_{2\dot{Z}} \cdot \alpha_2 \cdot \varepsilon_{\dot{Z}}(T_S - T_2), \tag{9}$$

and

$$(T_{W2} - T_S) = \frac{\dot{Q}_{22}}{A_S \cdot \frac{1}{R_S}}, \tag{10}$$

and

$$(T_S - T_2) = \frac{\dot{Q}_{22}}{A_{2\dot{Z}} \cdot \alpha_2 \cdot \varepsilon_{\dot{Z}}} \tag{11}$$

After summing up the temperature drops, one obtains:

$$(T_{W2} - T_2) = \dot{Q}_{22} \cdot \frac{\left(A_S \cdot \frac{1}{R_S}\right) + \left(A_{2\dot{Z}} \cdot \alpha_2 \cdot \varepsilon_{\dot{Z}}\right)}{\left(A_S \cdot \frac{1}{R_S}\right) \cdot \left(A_{2\dot{Z}} \cdot \alpha_2 \cdot \varepsilon_{\dot{Z}}\right)}, \tag{12}$$

and

$$(T_{W2} - T_2) = \dot{Q}_{22} \cdot \frac{\left[1 + \left(\frac{A_{2\dot{Z}} \cdot \alpha_2 \cdot \varepsilon_{\dot{Z}}}{A_S \cdot \frac{1}{R_S}}\right)\right]}{A_{2\dot{Z}} \cdot \alpha_2 \cdot \varepsilon_{\dot{Z}}}, \tag{13}$$

and

$$(T_{W2} - T_2) = \dot{Q}_{22} \cdot \frac{\left[1 + \frac{R_S \cdot A_{2\dot{Z}} \cdot \alpha_2 \cdot \varepsilon_{\dot{Z}}}{A_S}\right]}{A_{2\dot{Z}} \cdot \alpha_2 \cdot \varepsilon_{\dot{Z}}} \tag{14}$$

The heat flux on the finned side is described by the following equations:

$$\dot{Q}_2 = A_{20} \cdot \alpha_2 \cdot (T_{W2} - T_2) + \frac{A_{2\dot{Z}} \cdot \alpha_2 \cdot \varepsilon_{\dot{Z}}}{\left[1 + \frac{R_S \cdot A_{2\dot{Z}} \cdot \alpha_2 \cdot \varepsilon_{\dot{Z}}}{A_S}\right]} \cdot (T_{W2} - T_2) \quad (15)$$

and

$$\dot{Q}_2 = \left\{ A_{20} \cdot \alpha_2 + \frac{A_{2\dot{Z}} \cdot \alpha_2 \cdot \varepsilon_{\dot{Z}}}{\left[1 + \frac{R_S \cdot A_{2\dot{Z}} \cdot \alpha_2 \cdot \varepsilon_{\dot{Z}}}{A_S}\right]} \right\} \cdot (T_{W2} - T_2) \quad (16)$$

After summing up the temperature drops from Equation (6) transformed to (17):

$$(T_1 - T_{W1}) = \frac{\dot{Q}_1}{A_1 \cdot \alpha_1}, \quad (17)$$

from Equation (7) transformed to (18):

$$(T_{W1} - T_{W2}) = \frac{\dot{Q}_W}{A_{WM} \cdot \frac{\lambda_W}{\delta_W}}, \quad (18)$$

and from Equation (13) transformed to (19):

$$(T_{W2} - T_2) = \frac{\dot{Q}_2}{A_{20} \cdot \alpha_2 + \frac{A_{2\dot{Z}} \cdot \alpha_2 \cdot \varepsilon_{\dot{Z}}}{\left[1 + \frac{R_S \cdot A_{2\dot{Z}} \cdot \alpha_2 \cdot \varepsilon_{\dot{Z}}}{A_S}\right]}}, \quad (19)$$

Equation (20) is obtained, which describes the heat transfer from medium 1 to medium 2 in the case of resistance at the fin/base tube joint (for welding):

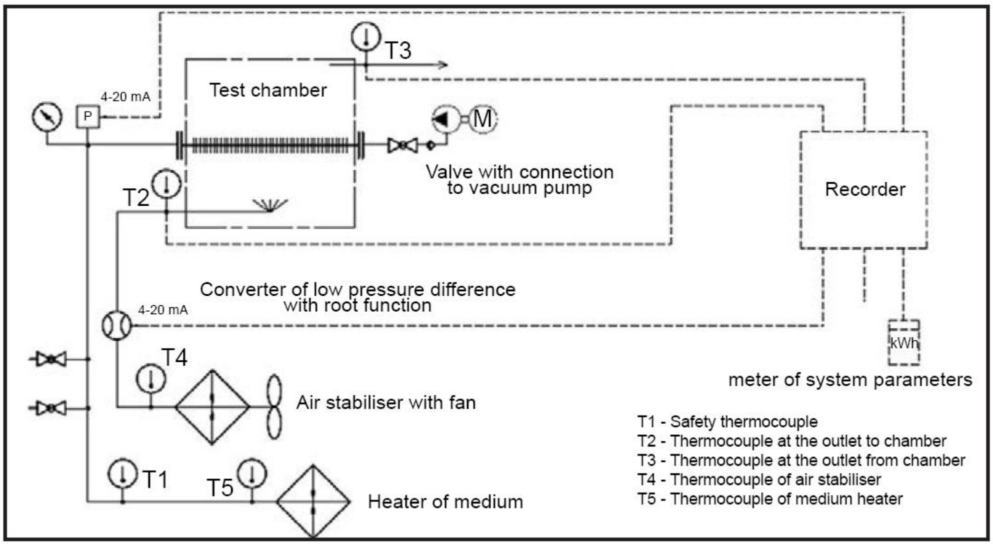
$$(T_1 - T_2) = \dot{Q} \cdot \left\{ \frac{1}{A_1 \cdot \alpha_1} + \frac{1}{A_{WM} \cdot \frac{\lambda_W}{\delta_W}} + \frac{1}{A_{20} \cdot \alpha_2 + \frac{A_{2\dot{Z}} \cdot \alpha_2 \cdot \varepsilon_{\dot{Z}}}{\left[1 + \frac{R_S \cdot A_{2\dot{Z}} \cdot \alpha_2 \cdot \varepsilon_{\dot{Z}}}{A_S}\right]}} \right\} \quad (20)$$

This is the Peclet Equation (4), where k is described by Equation (21):

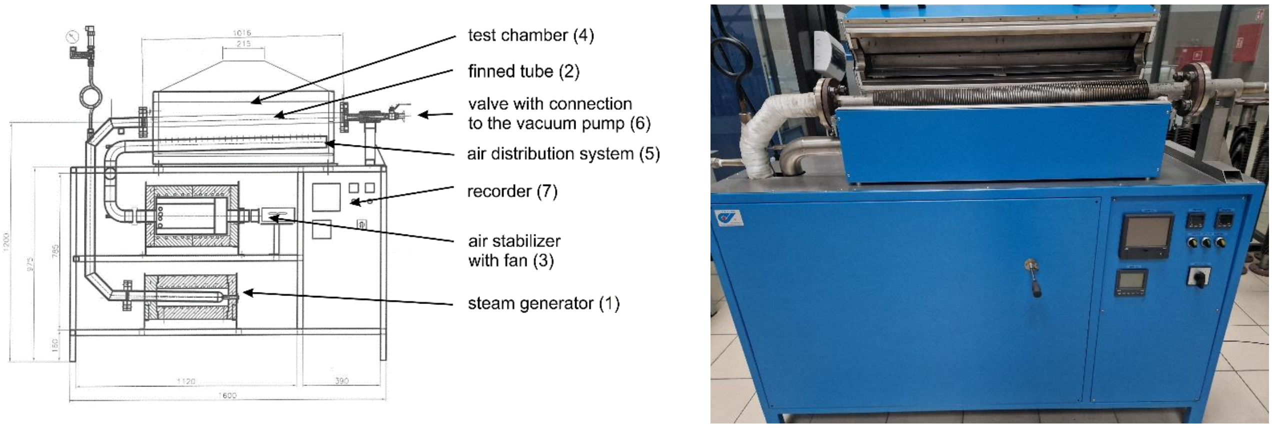
$$\frac{1}{k} = \frac{1}{A_1 \cdot \alpha_1} + \frac{1}{A_{WM} \cdot \frac{\lambda_W}{\delta_W}} + \frac{1}{A_{20} \cdot \alpha_2 + \frac{A_{2\dot{Z}} \cdot \alpha_2 \cdot \varepsilon_{\dot{Z}}}{\left[1 + \frac{R_S \cdot A_{2\dot{Z}} \cdot \alpha_2 \cdot \varepsilon_{\dot{Z}}}{A_S}\right]}} \quad (21)$$

The thermal performance tests of laser-welded and MAG-welded finned tubes were performed on a dedicated test stand, whose diagram is shown in Figure 3. The thermal performance of a finned tube was defined as the ratio of the heat flux passing through a finned tube to the heat flux passing through a plain tube.

The dedicated test stand enables the performance of tests in both natural and forced heat convection. A two-phase thermosyphon was used as the heat exchanger, with the condensate flowing to the evaporator counter current to the steam flowing to the condenser. Water was used as the working fluid, enabling measurements at temperatures of 100–220 °C at pressures of 1–25 bar.



(**a**)



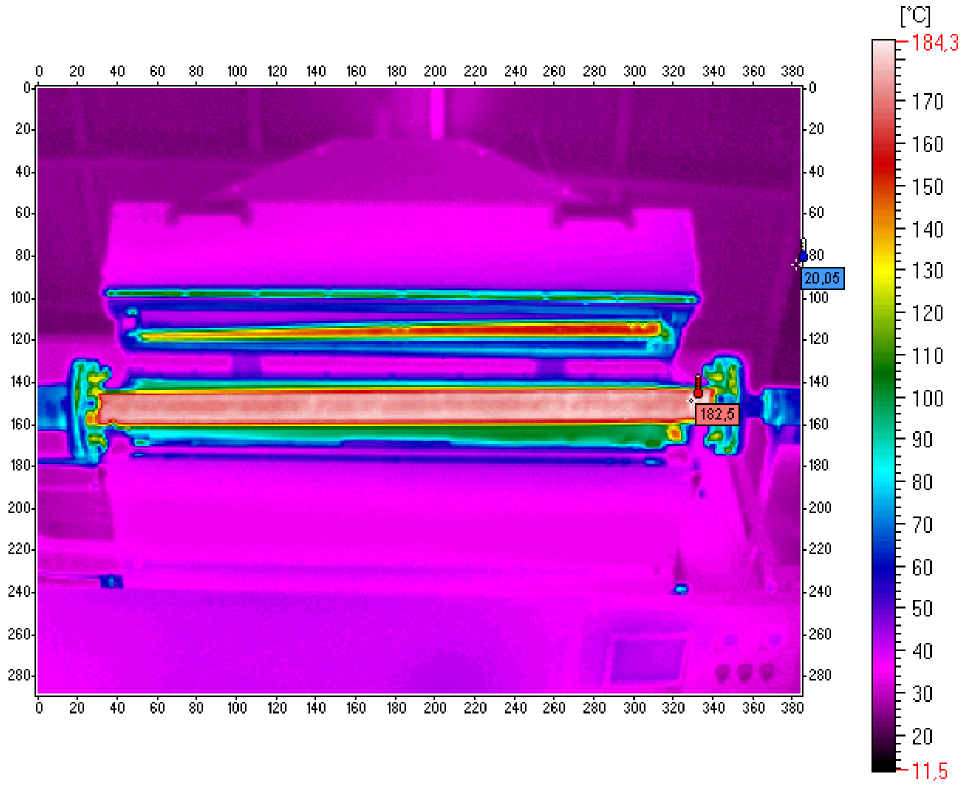
(**b**)

Figure 3. Diagram of the dedicated test stand for measuring the thermal performance of finned tubes: (**a**) conceptual design and (**b**) actual test stand built at Energoinstal SA, Poland.

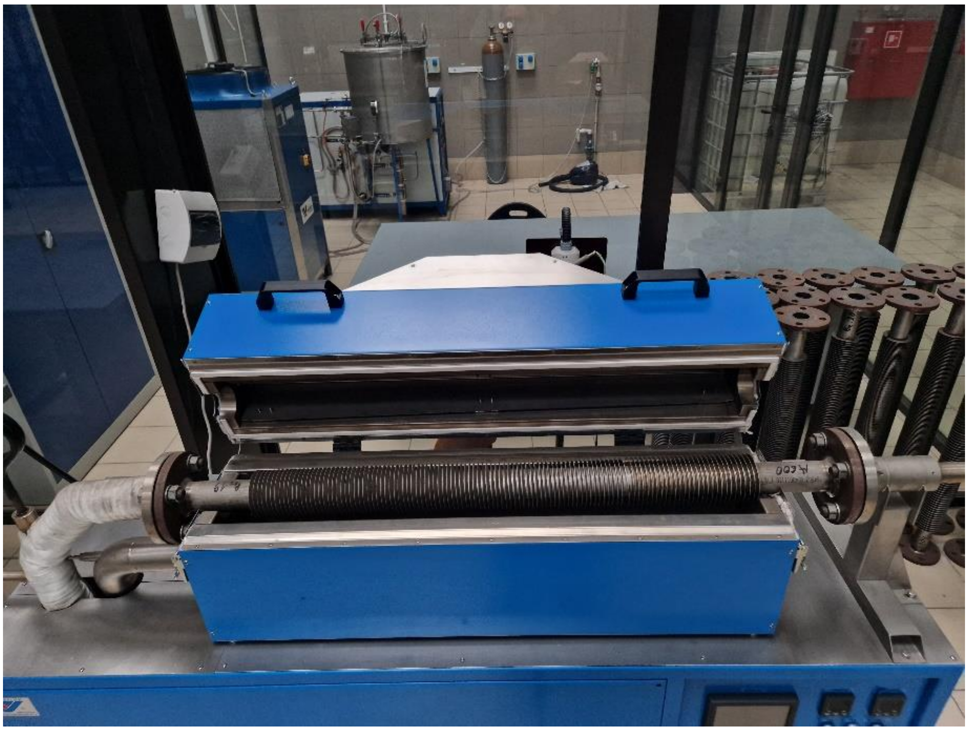
In order to confirm the uniform temperature distribution across the finned tubes, the temperature distribution was monitored during the experiment using a thermographic camera (Figure 4). On this basis, it was found that the designed and built test stand provided uniform temperature distribution across an entire tube and enabled the simulation of heat exchange in finned tubes.

The thermal performance tests were performed for finned tubes laser-welded with various beam power and welding rate parameters (designated as 1–5) and for finned tubes welded using the MAG method, with a butt weld beneath the fin and a fillet weld (designated as 6 and 7, respectively) (Table 1).

The test results were compared to a heat flux passing through a plain tube under the same conditions (temperature and pressure). The tests were performed for the temperatures of the medium inside the tube (steam) ranging from 100 °C to 170 °C.



(**a**)



(**b**)

Figure 4. Temperature distribution in a finned tube during the experiment: (**a**) even temperature distribution in the finned pipe and thermographic camera, and (**b**) the actual test stand built at Energoinstal SA, Poland.

Table 1. Technological parameters of the laser welding of finned tubes and MAG-welded methods tubes.

Joint No.	Power of Laser Beam/Welding Arc, kW	Welding Rate, m/min	Rotational Speed, rpm	Number of Fins Per 1 Running Meter of Pipe	Gas Flow Rate, dm^3/min	Comments
1	2.2	3.0	20	150	5	laser
2	3.2	5.2	50	150	5	laser
3	4.0	7.5	100	150	5	laser
4	6.0	15.0	150	150	5	laser
5	6.5	22.5	200	150	5	laser
6	2.2	4.5	40	150	14	MAG butt weld under the fin
7	3.6	1.8	15	150	14	MAG fillet weld

3. Results

Figure 5 shows the measurement results for the heat flux transferred in the tested tube section (800 mm) from steam to air under stabilized thermal conditions of the test stand. Figure 6 shows the measured value of the heat flux transferred by a finned tube from steam to air, reduced by the heat flux transferred by a plain tube under the same thermal conditions.

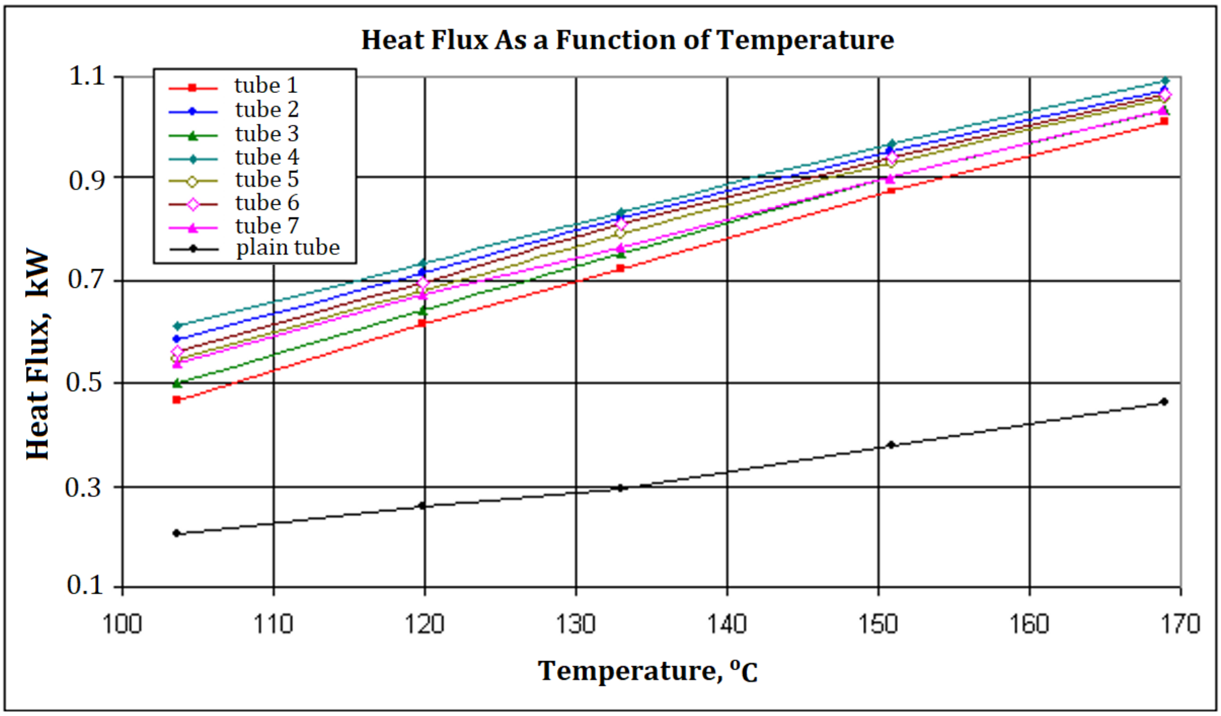


Figure 5. The measured heat fluxes transferred by the tested tubes from steam to air.

Figure 7 shows the heat fluxes transferred by the finned tubes compared to a plain tube, whereas Figure 8 shows the heat fluxes passing through the laser-welded finned tubes compared to the MAG-welded finned tube with a fillet weld.

The analysis of the heat fluxes measured under the test conditions indicates that the use of fins to expand the heat exchange surface area increased the heat flux by three times, i.e., in the test conditions at 100 °C, from approx. 0.2 kW for a plain tube to approx. 0.6 kW for finned tubes. Additionally, at 170 °C, the heat flux increased more than twofold (from 0.5 kW for the plain tube to over 1 kW for the finned tubes) (Figure 5). The comparison of the heat fluxes transferred by the laser-welded and MAG-welded finned tubes did not reveal any significant differences. The heat fluxes transferred by the finned tubes, reduced by the heat flux passing through the plain tube, fell within the range of 0.3 kW to 0.4 kW at 100 °C and from 0.57 kW to 0.6 kW at 170 °C (Figure 6).

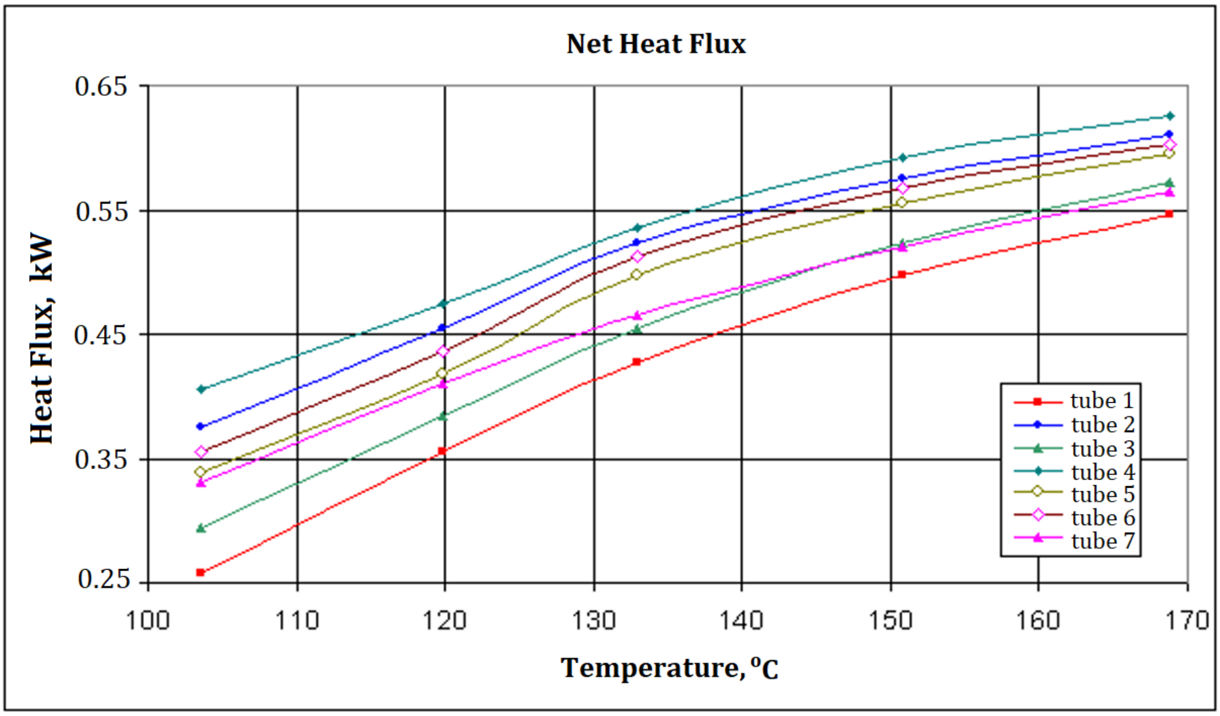


Figure 6. The "net" heat fluxes, i.e., the heat fluxes transferred by the tested tubes to air, reduced by the heat flux transferred by the plain tube.

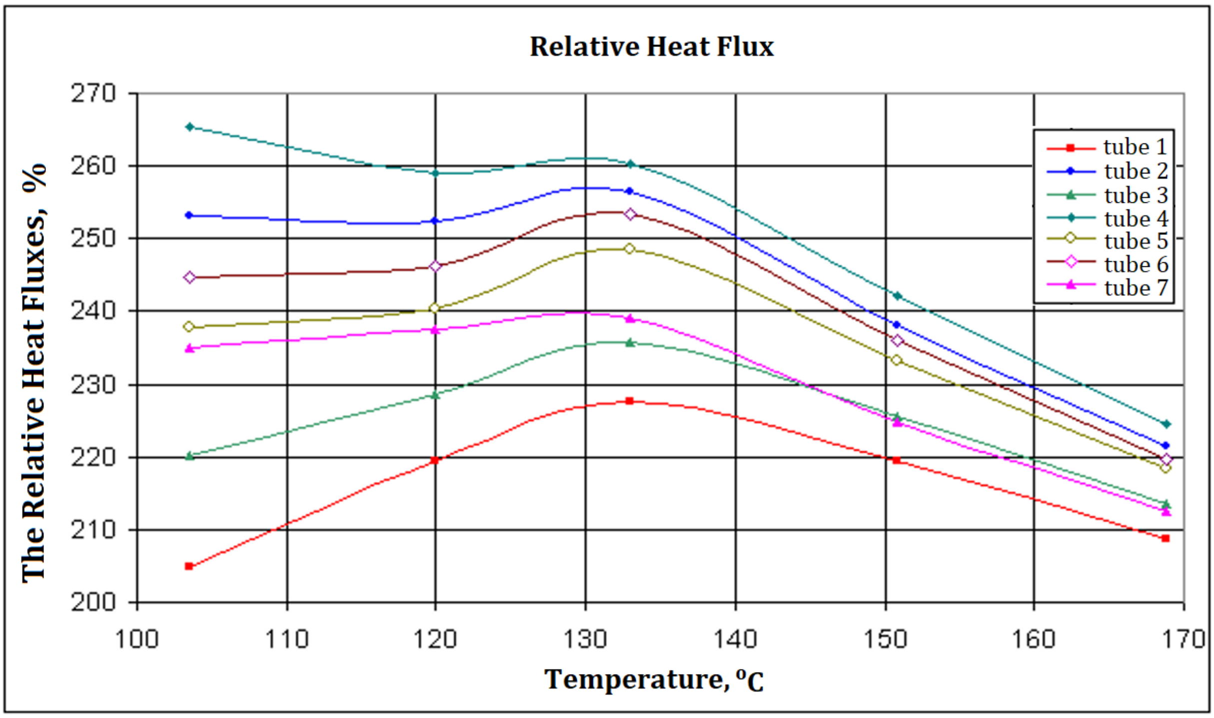


Figure 7. The relative heat fluxes transferred by the tested tubes to the air, compared to the plain tube.

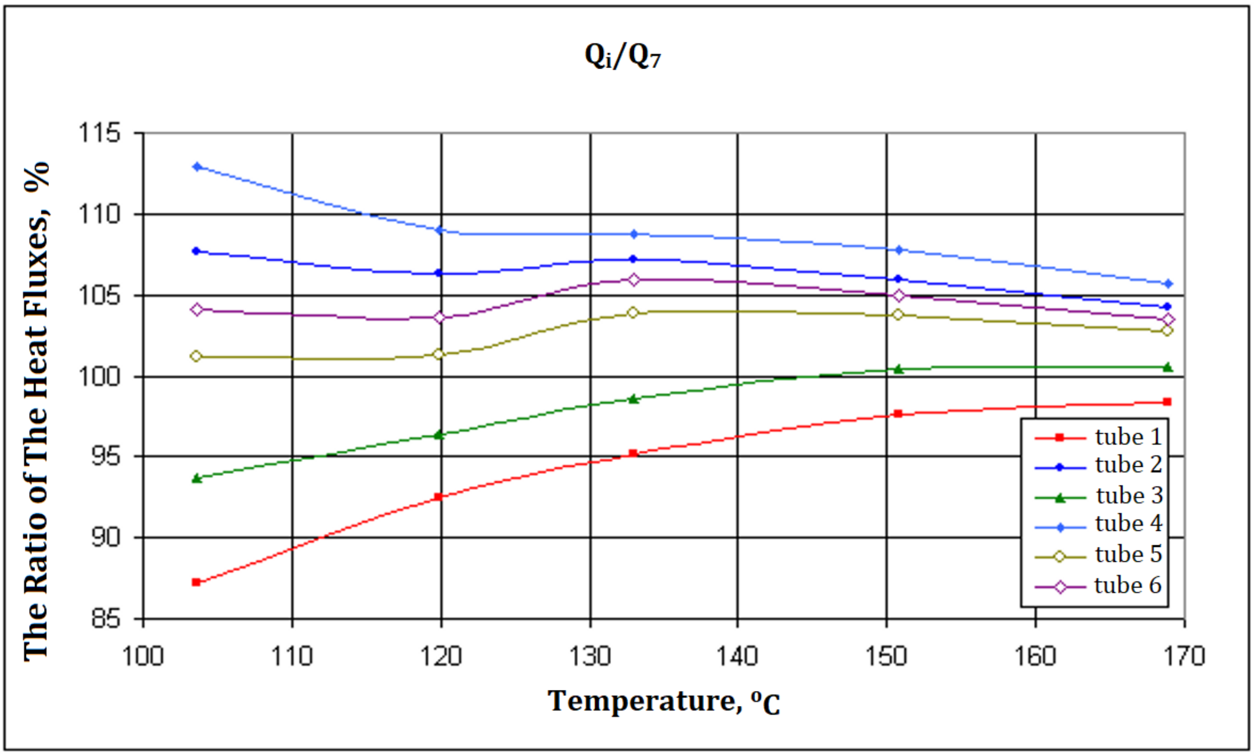


Figure 8. The ratio of the heat flux passing through the tested tubes to air (Qi) to the heat flux passing through (Q_7) the MAG-welded tube with a filler weld.

The comparison between the relative heat fluxes transferred by the finned tubes and the plain tube indicates that at 100 °C, the difference amounts to 60%, and as the temperature rises, the difference decreases to less than 20% at 170 °C (Figure 7). Such changes in the relative heat fluxes transferred by the finned tubes confirm information contained in the literature, to the effect that any type of welded joint provides correct heat exchange. The analysis of the heat fluxes transferred by the laser-welded finned tubes compared to the heat flux transferred by the MAG-welded tubes did not reveal any significant differences in thermal performance either (Figure 8). This indicates that laser-welded finned tubes are characterised by the same thermal performance as MAG-welded finned tubes.

The tests were complemented by an analysis of the temperature distribution field during heat transfer in the laser-welded and MAG-welded tubes. A test stand equipped with a forced heat convection system and a thermographic camera was built to assess the temperature field. A TERMEK heater (120 cm long, 1000 W) with a Kanthal wire was used for heating the outer surface. The heater was appropriately bent to ensure its direct contact with a layer of an aluminium sheet approx. 1 mm thick, which made it possible to even out the temperature distribution and to heat the fins uniformly (Figure 9). A thermostat was also installed, whose thermocouple was located between the aluminium layer and the fins, which allowed control over the temperature of the aluminium sheet. The regulation range of the thermostat was from 50 °C to 320 °C. The ends of the copper tubes were adapted for the purpose of connecting to the water supply system, to ensure efficient cooling. It had been determined experimentally that, with the thermostat set to 170 °C, cooling with air blown by a fan was sufficient.

In the designed experiment, heat transfer occurs from the heat source, i.e., the aluminium sheet, across the fins, the steel tube bonded to the fins by means of a laser or MAG weld, the tin layer, and the copper tube (Figure 9). Air heated by the aluminium sheet rises and heats the side fin surfaces by natural convection, which reflects the actual service conditions (Figure 10).

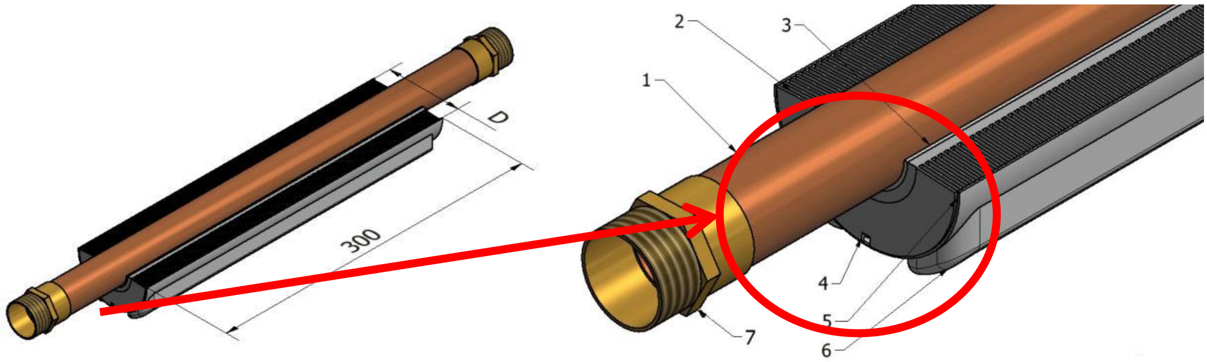


Figure 9. The heat exchange simulation system: 1—copper tube, 28 or 35 mm in diameter, 2—finned tube cut in half, 3—thin layer precisely filling the space resulting from the difference between the diameters of tube 1 and 2, 4—a space cut in the fins for placing the thermostat sensor, 5—1-mm thick aluminium sheet bent to contact with the fins, 6—heater bent to contact with the sheet surface, and 7—brass joint with an inch screw thread.

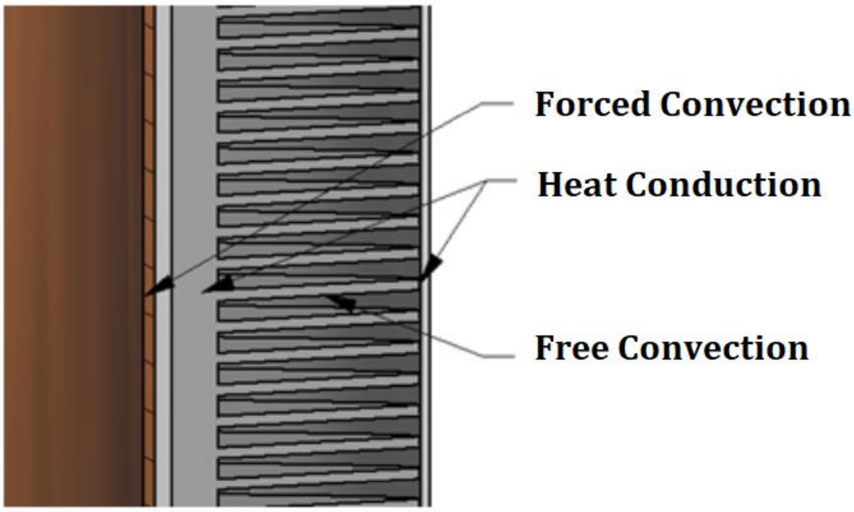
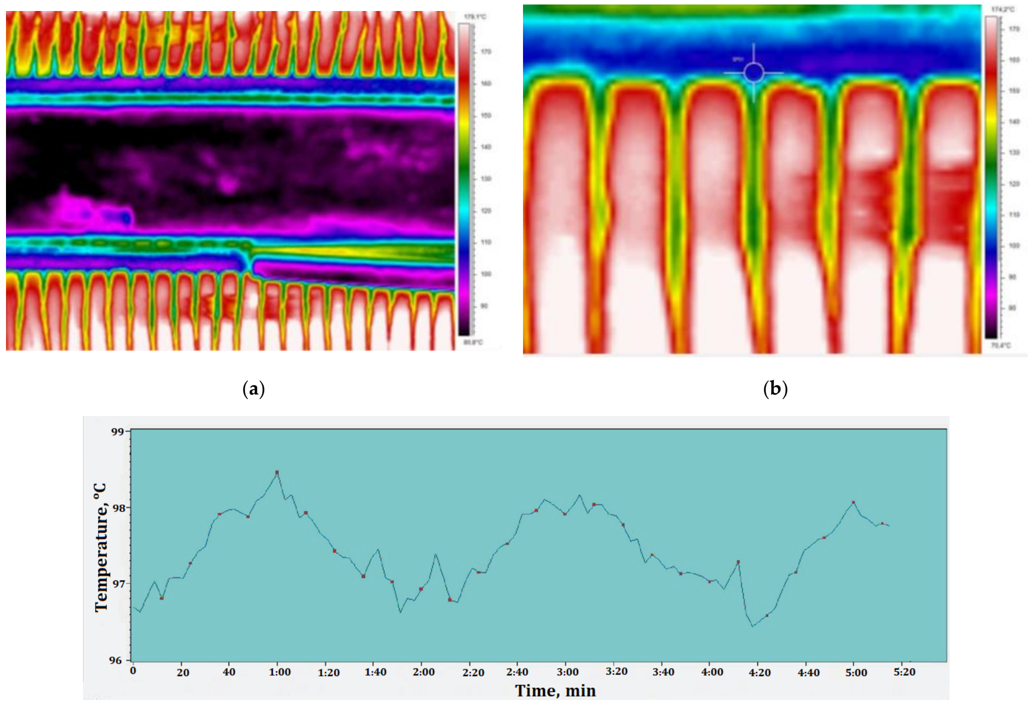


Figure 10. Identification of the heat exchange mechanisms in the test stand system.

With much cooler air flowing through the copper tube, heat is absorbed through natural convection and its exchange is accelerated, which makes the temperature difference clearly observable on the examined surface. Figure 11 shows the test results for a laser-welded tube in the form of temperature distribution maps, whereas Figure 12 presents the results for the MAG-welded tube.

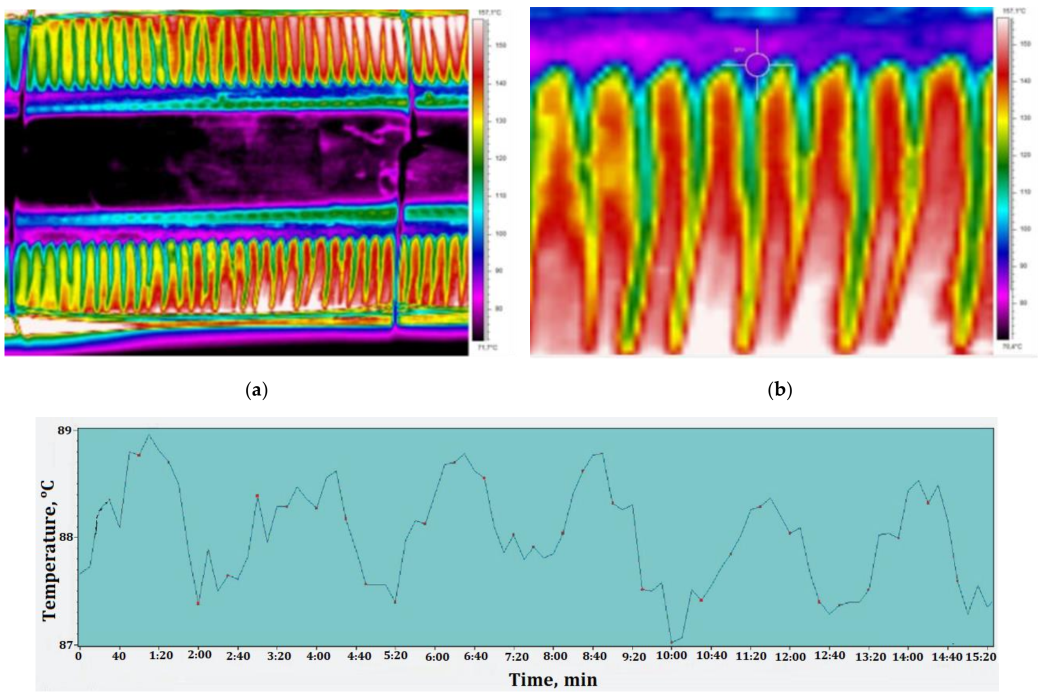
The result analysis revealed that the temperature at point SP01 stabilised at 97 °C for the laser-welded tube (Figure 11c). Based on the thermograms, it was found that, in the laser-welded tube, the heat transfer from the fin to the tube was uniform across the entire fin width. This stems from the complete penetration of the weld (Figure 11a,b). As for the MAG-welded tube, the temperature at point SP02 stabilised at 88 °C (Figure 12c).

It was found that the heat flow from the rib to the tube occurred through the MAG fillet weld to a much greater extent (Figure 12a,b). This was caused by the shape of the fillet weld, affected by incomplete penetration. Operation under such conditions for a long time may cause damage and cracks due to the non-uniform temperature in the material, the overheating of the material on the weld root side, and potential high-temperature corrosion in the area of lack of penetration.



(c)

Figure 11. Results of the thermographic examinations of a laser-welded tube: (**a**) general thermogram of heat distribution in the tube, (**b**) detailed thermogram, and (**c**) temperature distribution at point SP01 for a period of 5.2 min.



(c)

Figure 12. Results of the thermographic examinations of the MAG-welded tube: (**a**) general thermogram of heat distribution in the tube, (**b**) detailed thermogram, and (**c**) temperature distribution at point SP02 for a period of up to 15.2 min.

4. Analysis of the Test Results

An analysis of the structural solutions applied in modern recovery boilers and gas boilers showed that finned tubes were usually manufactured based on tubes having diameters of from 31.8 to 63.5 mm and made of low-carbon steels (e.g., P235, P355) or low-alloy steels of the 15Mo3, 13CrMo4.4, and 10CrMo4.10 types, according to DIN 17175. Such steels are considered to have good weldability. On this basis, tubes made of steel grade P265GH, having a diameter of 51.0 mm and wall thickness of 3.6 mm, and a flat bar of steel grade DC01, measuring 19.5 mm × 1.0 mm, were selected for the purposes of the tests.

In order to evaluate the effect of weld continuity and shape on the thermal performance of the tubes, a model diagram of a tube/fin welded joint with incomplete penetration was developed (Figure 13). The contact resistance (Rs,[(m^2·°C)/W]) of a finned tube is defined as the ratio of the gap width (G_s) to the heat transfer coefficient on the flue gas side.

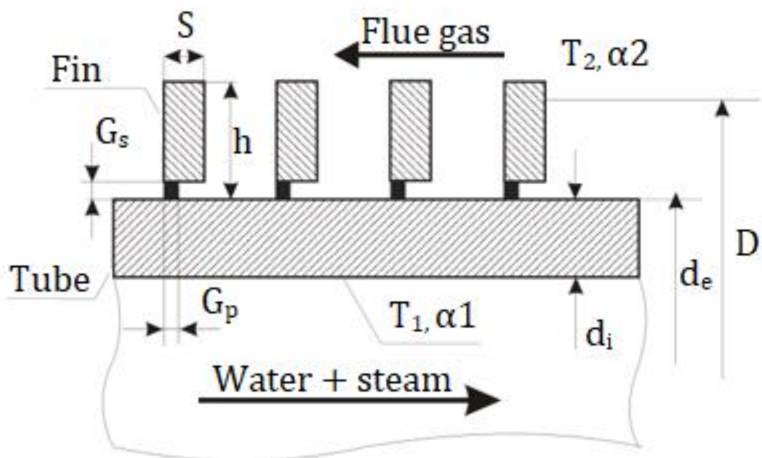


Figure 13. Diagram of a tube/fin joint with incomplete penetration [28].

The contact resistance for tube Rs with external transverse fins is a function of the gap width (G_s) between the tube and the fin, the gap length (δ—G_p) (Figure 13), and the heat transfer coefficient on the flue gas side (λ_2). The value of this resistance can vary from 0, in the case of complete penetration, to G_s/λ_2 [28,29].

Welding irregularities offer contact resistance to heat flow and affect the thermal performance of a tube/fin joint, understood as the ratio of the heat flux in a tube with welding irregularities to the heat flux in a tube of the same geometric dimensions, but unaffected by irregularities:

$$\eta_s == \frac{\dot{Q}}{\dot{Q}_X} \cdot 100\% \tag{22}$$

where: η_s—thermal performance of the joint, $\dot{Q}$—heat flux measured for a finned tube with welding irregularities, and $\dot{Q}_X$—heat flux measured for a finned tube without welding irregularities.

The following values were applied to the calculations of h thermal performance: fin heat transfer coefficient λ_1 = 52 W/m °C, air heat transfer coefficient λ_2 = 0.025 W/m °C, fin thickness s = 1.0 mm, and fin height h = 19 mm (Figure 14). Figure 14 shows the results of the calculations depending on the heat flux flowing through a tube/fin joint with incomplete penetration in relation to the heat flux flowing through a tube/fin joint with complete penetration, i.e., $G_{p/s}$ = 100%.

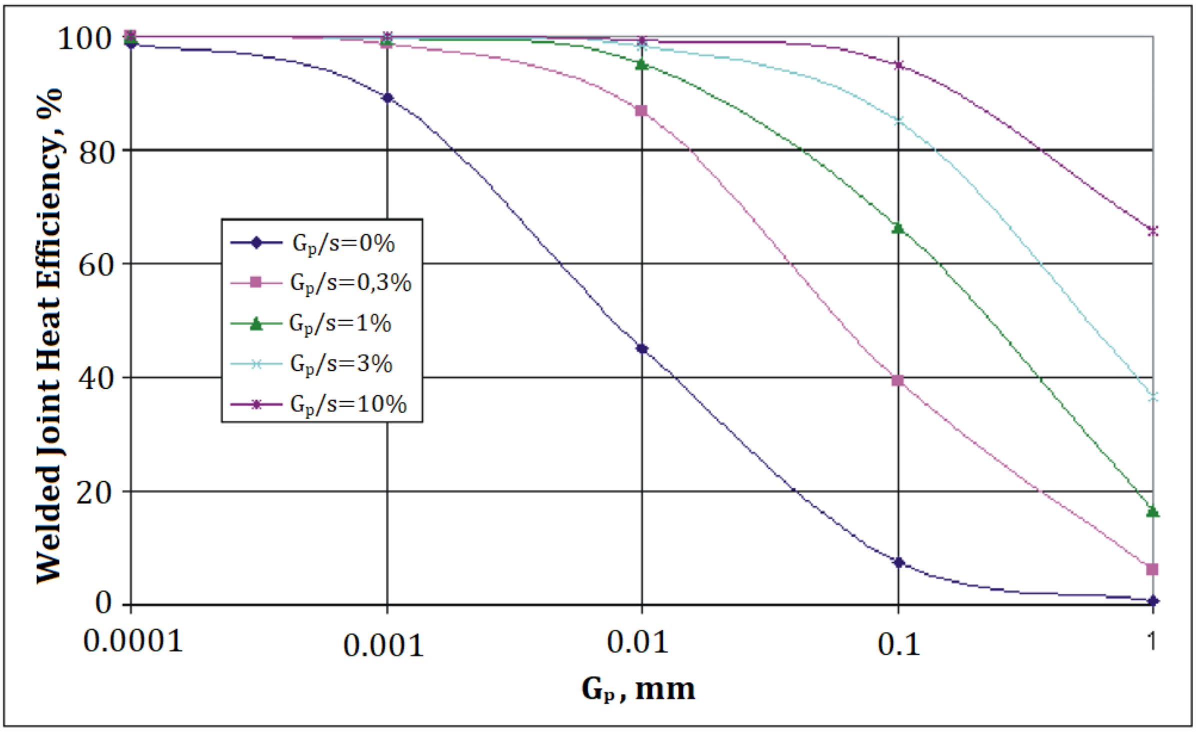


Figure 14. The relative heat flux flowing through a fin bonded to a tube by means of a welded joint with incomplete penetration in the function of the gap width between the fin and the tube (G_p).

The analysis of the heat flux flowing through the welded tubes, taking into account welding defects in the form of discontinuities or incomplete penetration, indicates that weld continuity is crucial to the correct heat flow through a finned tube. The analysis of the influence of the joint penetration level on the thermal performance of a finned tube revealed that even penetration covering approx. 1% of the fin width ensured an appropriate heat transfer of more than 95% (G_p = 0.01 mm). However, insufficient joint penetration reduces its durability due to the rate of corrosion in a flue gas atmosphere and thermal and fatigue deformations. A discontinuity in the joint (G_p/s = 0%) leads to immediate overheating of the fin and a 50% decrease in thermal efficiency, even if the gap is 0.01 mm wide (Figure 14).

The main reason for the use of welded finned tubes is their thermal performance, i.e., the ratio of the heat flux passing through a finned tube to the heat flux passing through a plain tube. The evaluation of the heat flux transferred from steam to air by the laser-welded finned tubes showed that it was similar to the case of the MAG-welded finned tubes (Figure 6). The thermal performance of the welded finned tubes is over three times higher than for the plain tube (Figure 5).

5. Conclusions

The welded finned tubes are among the main components of heat exchangers, which determine the thermal performance of the entire exchanger. A very important factor determining the ability of finned tubes to conduct heat is the quality of the welded tube–rib joint. Welding technologies for this type of pipe are numerous, both by arc methods and laser welding. Based on the tests performed, it was found that the heat efficiency of welded finned tubes was three times higher than that of plain tubes, which confirms the validity of using a rib along the entire length of the tube.

The welding technology used very often determines weld discontinuities. The number of discontinuities in the weld determines the degree of connection between the tube and the rib. However, the heat efficiency was not found to be affected by the welding technology if the joints are constructed correctly. The correct heat flow at the level of 95% occurs in the tube/fin joint, even with joint penetration of 0.01 mm; however, the absence of metallic continuity in a joint results in a drastically reduced heat efficiency (by 50%) and the overheating of fins, which affects their durability. These results confirm the need to connect a permanent rib to the pipe along its entire length so as to ensure metallic continuity in the joint.

However, a detailed analysis of the temperature distributions in the tests showed slight differences in MAG-welded pipes and laser-welded pipes. Due to the shape of the joint, a more homogeneous heat flux distribution was observed for laser-welded pipes, which is related to the symmetrical weld in relation to the fillet weld made by the MAG method. It should therefore be concluded that the tests have shown that laser-welded finned tubes have a more uniform heat flow compared to MAG-welded tubes with a fillet weld. This results in less stress and deformation of the fin.

Author Contributions: Conceptualization, J.A. and M.U.; methodology, J.A. and M.U.; writing—original draft preparation, J.A. and M.U. All authors have read and agreed to the published version of the manuscript.

Funding: J.A. acknowledge the partial financial support of this study by the Silesian University of Technology, Faculty of Materials Science, Department of Metallurgy and Recycling within the project No 208/RM2/2022; 11/020/BK_22/0088.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Voss, W.; Adamiec, P. *Welding of Finned Tubes*; Welding Technology Review No. 4.; Publishing Agency SIMP: London, UK, 1994.
2. Sobbe, W.; Janzen, J.; Schiemann, M.; Braun, H. Effiziente Dampfkesselanlagen fur industrielle Heiz-und Heizkraftwerke sowie Hilfskesselanlagen fur Kraftwerke. *VGB Powertech* **2011**, *91*, 54–59.
3. Kogeneracja Technologią dla Przemysłu-Skojarzona Produkcja Energii Elektrycznej, Ciepła i Chłodu, Część 1. Available online: http://automatykab2b.pl/tematmiesiaca/3254-kogeneracja-technologi-dla-przemysu-skojarzona-produkcja-energii-elektrycznej-ciepa-i-chodu-cz-1?start=1# (accessed on 17 September 2014).
4. Pudlik, W. *Wymiana i Wymienniki Ciepła*; Publishing Gdańsk University of Technology: Gdańsk, Poland, 2012.
5. Mitrovic, J. *Heat Exchanger and Condenser Tubes, Tube Types–Materials–Attributes–Machning*; Publico Publications: Lisbon, Portugal, 2004.
6. Pasierb, A. New solutions in the technology of rolling finned tubes. *Rudy Met. Nieżelazne* **2002**, *47*, 505–507.
7. Belinskiy, B.; Hiestand, J.; Weerasena, L. Optimal design of a fin in steady-state. *Appl. Math. Model.* **2020**, *77*, 1188–1200. [CrossRef]
8. Xia, W.; Wu, B.; Tang, Y.; Ye, B. On chopping–Extrusion of integral-fin copper tubes. *J. Mater. Process. Technol.* **2003**, *138*, 385–389. [CrossRef]
9. Tang, Y.; Xia, W.; Liu, S.; Zeng, Z.; Ye, B. Fin formation during pre-roll ploughing of copper 3D outside fin tube. *Trans. Nonferrous Mater. Soc. China* **2001**, *11*, 712–716.
10. Nemati, H.; Moghimi, M.A.; Sapin, P.; Markides, C.N. Shape optimisation of air-cooled finned-tube heat exchangers. *Int. J. Therm. Sci.* **2020**, *150*, 106233. [CrossRef]
11. Unger, S.; Matthias, B.; Gruber, S.; Willner, R.; Hamper, U. Experimental study on the air-side thermal-flow performance of additively manufactured heat exchangers with novel fin designs. *Int. J. Therm. Sci.* **2019**, *146*, 106074. [CrossRef]
12. Ryan, J.E. Laser Assisted High Frequency Welding. U.S. Patent No. 5,343,015A, 30 August 1994.
13. Stolecki, M.; Bijok, H.; Kowal, Ł.; Adamiec, J. Laser welding of finned tubes made of austenitic steels. *Arch. Metall. Mater.* **2015**, *60*, 1807–1811. [CrossRef]
14. Stewart, S.W.; Shelton, S.V.; Aspelund, K.A. Finned-Tube Heat Exchanger Optimization. In Proceedings of the HEFAT2003 2nd International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics, Victoria Falls, Zambia, 23–26 June 2003.
15. Kocurek, R.; Adamiec, J. Manufacturing technologies of finned tubes. *Adv. Mater. Sci.* **2013**, *13*, 26–35. [CrossRef]
16. Kitzberger, R.; Schmidt, R.-R. Thermodynamischen Untersuchungen in Kraftwerken. *VGB Powertech* **2011**, *91*, 70–74.
17. Adamiec, P. *Technological Instruction for the Production of Finned Pipes*; Company Materials; Energoinstal S.A.: Katowice, Poland, 1997.
18. Pikos, I.; Kocurek, R.; Adamiec, J. Perspectives of materials for fin tubes. *Adv. Mater. Sci.* **2013**, *13*, 17–25. [CrossRef]
19. Gawrysiuk, W.; Adamiec, J.; Więcek, M. Possibilities of laser and hybrid welding of sheet piling and finned pipes. In *Bulletin of the Welding Institute in Gliwice, Proceedings of the Welding in Energetics Conference, Sosnowiec, Poland, 21–23 October 2008*; Welding Institute: Gliwice, Poland, 2008; Volume 52, pp. 54–58.
20. Centre of Innovative Laser Technologies in Energoinstal. Production Hall and Laser. Available online: https://citl.energoinstal.pl/en-GB/production_hall_and_laser.html (accessed on 28 December 2022).

21. Adamiec, P.; Ochman, J.; Polubniok, H.; Voss, W. *Influence of Defective Finned Tubes on Their Thermal Efficiency. New Technologies and Materials in Metallurgy and Materials Mcience. 2nd Scientific Seminar;* Faculty of Materials Science and Metallurgy, Silesian University of Technology: Katowice, Poland, 2004.
22. Stano, S. YAG lasers in robotic welding stations. In *Seminar Materials: Development of Welding and Cutting with CO_2 and YAG Lasers and Possible Use*; Welding Institute: Gliwice, Poland, 2005.
23. Power Plants for Energy Supply. Available online: www.standardkessel-baumgarte.com (accessed on 17 September 2014).
24. Pudlik, W. *Exchange and Heat Exchangers*; Publishing house of the Gdańsk University of Technology: Gdańsk, Poland, 1988.
25. Wang, Y.; Liu, Y.; Wang, X.; Zhao, Q.; Ke, Z. Experimental study on the heat transfer and resistance characteristics of pin-fin tube. *Therm. Sci.* **2019**, *25*, 59–72. [CrossRef]
26. Hobler, T. *Heat Movement and Exchangers*; Scientific and Technical Publishing House: Warszawa, Poland, 1974.
27. Stephan, K. Wärmeleistung von Rippenrohren bei unvollkommener Befestigung der Rippen. Kältetechnik-Klimatisierung 18 Nr. 2 (1966) 41-48 Mannesmann-Forschungsbericht Nr. 338. 1996.
28. Staniszewski, B. *Heat Transfer Theoretical Basis*; PWN: Warszawa, Poland, 1979.
29. Kostowski, E. *Heat Flow*; University Script; Silesian University of Technology: Gliwice, Poland, 2000; No. 1293.