

EXPERIMENTAL STUDIES ON RADIATION HEAT TRANSFER ENHANCEMENT ON A STANDARD MUFFLE FURNACE

by

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One of the sources of increased industrial energy consumption is the heating equipment, e.g., furnaces. Their domain of use is very wide and due to its abundance of applications it is key equipment in modern civilization.

The present experimental investigations are related to reducing energy consumptions and started from the geometry of a classic manufactured furnace. During this experimental study, different cases have been carefully chosen in order to compare and measure the effects of applying different enhancement methods of the radiation heat transfer processes. The main objective of this work was to evaluate the behavior of a heated enclosure, when different radiant panels were introduced. The experimental investigation showed that their efficiency was influenced by their position inside the heating area. In conclusion, changing the inner geometry by introducing radiant panels inside the heated chamber leads to important time savings in the heating process.

Key words: *heat transfer, furnace, radiation, experimental*

Introduction

Furnaces are used in a wide variety of applications including power plants, nuclear reactors, refrigeration and other heating systems, automotive, heat recovery systems, chemical processing, and food industries [1-3]. One of the sources of increased industrial energy consumption is the heating equipment, e. g., furnaces used in industrial processes such as heat treatment at medium and high temperatures and forging. Furnaces are the most commonly-used equipment in the world, with an annual energy consumption exceeding a billion joules. Their domain of use is very wide starting from food and chemicals to the metallurgical industries and has been used since the early stages of civilization, and due to its abundance of applications it is key equipment in modern civilization.

The chamber furnace (electric or combustion heated) is the most widely used furnace and provides the backbone of most infrastructure.

The performance improvement of heating equipment is of major importance and must be correlated with energy consumption which is mainly reflected in the blank production price. The need to reduce energy consumption places high demand on re-designing the inner space of heating equipment. The modification of chamber geometry can potentially lead not only to energy savings but also reduced production costs for the furnaces. Previous studies as well as the

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larger community have already highlighted such potential [3, 4]; however these studies were largely based on smaller scale furnaces [5-7]. Besides the performance of the furnace being improved, the heat transfer enhancement enables the overall size of the furnace to be considerably decreased.

Improvement of heat transfer in energy systems allow to obtain more efficient energy saving [8]. In order to reach this heat transfer enhancement, ways are given by the employment of techniques which are enabling to realize high heat transfer in a small volume, *i. e.*, high heat transfer density. Then it needs to increase the heat transfer surface and/or the heat transfer coefficients between the fluid and the surfaces [9]. This need can be met in two ways: introducing new designs for heating devices and enhancing the heat transfer capability of the fluid itself.

The new techniques, the particular materials and the employment of new designs determine the need to evaluate new heat transfer behaviours. In the last years, research activities are very intensive to solve these problems and several novel techniques have been proposed and studied theoretically, numerically and experimentally [10-12].

Moreover, it is very interesting to observe that a new thermal design may give an improvement in heat transfer in energy system component. These topics have been studied recently and they could be very promising into the enhancement of thermal control, thermal design, and optimization. In this context, the research has been focused on the energy savings and improvement of heating equipments based on heat transfer augmentation.

Moreover, few simulation performed on different heated enclosures were tested for counter-flow configuration. It was revealed that the empirical correlation for constant temperature boundary condition is quite in agreement with the present data [13]. From the results of these studies it was found out that the total heating temperature is depending on the position of the radiant panels.

Takami *et al.* [14] considered high power reflector as a new heating solution for use in high power heating systems. Simulations of heat transfer were performed with different reflector configurations in the COMSOL[®] software environment. Optimum shapes and dimensions were found that produced the highest peak temperature, mean temperature, and uniform temperature distribution in the surface above the element. The results showed a satisfactory fit with average furnace temperatures.

Some studies are related to investigation of the heat transfer characteristics of air flowing through high-temperature silicon carbide ceramic foams in an electric air heating furnace heated by resistance wires and silicon-carbon sticks [15]. Authors found that for an air inlet flow rate of 200 m³/h, the air outlet temperature reached 981 °C after about 2 h when five silicon carbide ceramic foam panels were inserted inside the furnace, while it only reached about 650 °C when no ceramic foam was inserted. The heat transfer enhancement was due to that the ceramic foams enlarged the heat transfer area between air and hot solid surfaces. The results also showed that the position of the ceramic foam in the furnace played an important role in its effect on the heat transfer [15]. Also, the same authors investigates experimentally the heat transfer characteristics of air flowing through high-temperature silicon carbide ceramic foams in an electric air heating furnace The heat transfer enhancement was due to that the ceramic foams enlarged the heat transfer area between air and hot solid surfaces [16].

In this paper simplified models based on experimental methods are proposed to estimate radiation heat transfer in heating processes. The investigations were done to understand radiation enhancement when panels are introduced. These panels, showed in fig. 1, were used in the experiment carried out for the validation of the system. As an explanation, classical radiant panels were used, some provided with 8 mm holes. In order to study heat transfer enhancement

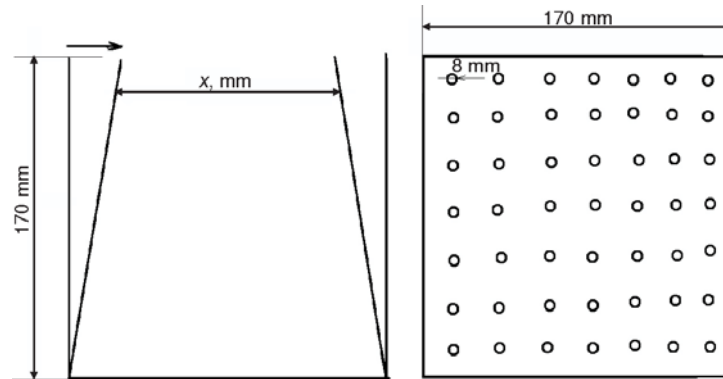


Figure 1. Radiant panels set-up

49 holes were made. In this situation the heat transfer surface is decreased and convection influence is studied along with radiation [17].

Experimental

The investigations were started from the geometry of a classic manufactured furnace. The furnace is having a rectangular chamber and its details are in tab. 1.

Table 1. Furnace parameters

Maximum work temperature	Work medium	Thermal uniformity	Inner dimensions	Exterior dimensions	Useful volume	Power	Supply tension
1100 °C	Circulating air	8 °C at maximum temperature	230 × 340 × 170 mm	480 × 650 × 570 mm	15 l	3.6 kW	230 V

The heated enclosure includes two metallic (from regular INOX type steel) radiant panels vertical oriented. The radiant panel geometry is rectangular with a 0.58 mm width and their dimensions are depicted in fig. 1. Figure 2 is a sketch of the considered case along with thermocouples position.

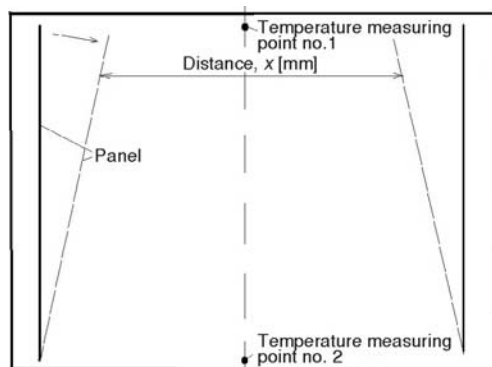


Figure 2. Sketch of the experiment

The temperatures were recorded automatically using two thermocouples inserted in the furnace and sealed to prevent any leakage. Also, all the connections between the temperature measuring stations and heated chamber were duly insulated. Experiments were carried out in the same initial conditions (temperature, humidity) for every case and identical heating conditions (furnace power, heating diagram) were considered.

The temperature measuring equipment consists in two type K heavy duty stainless steel thermocouples. Their accuracy is of ± 1.6 °C at

500 °C and ± 1 °C at 400 °C according to USA National Institute of Standards and Technology (NIST) as it is specified in probes technical data's. Respectively, furnace temperature control accuracy is ± 0.25 °C, as it is mentioned in furnace operator's manual and, further, experimental system accuracy goes to ± 1.25 - ± 1.85 °C, according to USA NIST.

In order to acquire trustable experimental data's, three experiments were performed for each panel position and surface. In these conditions, the experimental investigation uncertainty is diminished as much as is possible.

As was stated before, for each panel position three experiments were conducted, in the tables being written the arithmetic medium of the registered values.

Two variables were established for this study: the panel position, x , and the panel surface, S . The experimental results are in tab. 2, which represents the furnace heating behaviour for all of the considered cases. If it refers to tab. 2, regular surface means the initial panel surface and the decreased surface is for the perforated panels, as shown in fig. 1.

Table 2. Furnace heating regime for all the experimental cases

Panel position, [mm]	Panel surface, [m ²]	Heating time up to 500 °C, [s]	Energy consumption, [Wh]	Energy variation with panel surface, [Wh]
200	regular surface	1290	645	1.5
	decreased surface	1293	646.5	
180	regular surface	1339	669.5	-8.1
	decreased surface	1177	588.5	
160	regular surface	1320	660	21.5
	decreased surface	1363	681.5	
140	regular surface	1340	670	16
	decreased surface	1372	686	
120	regular surface	1210	605	49
	decreased surface	1308	654	
100	regular surface	1280	640	37.5
	decreased surface	1335	667.5	
80	regular surface	1289	644.5	17
	decreased surface	1323	661.5	
60	regular surface	1190	595	61
	decreased surface	1312	656	

The experiment was rigorously conducted in order to assure its repeatability. As a study charge, a cylindrical part with dimensions $\varnothing 24$ mm x 100 mm, made of AlMgSi has been used.

Results and discussion

The interpretation of the experimental results consists in establishing the experimental variation curves of the radiant panels' position vs. energy consumption. The interpretation of the experimental results will be finalized by a statistical analysis of the registered values of energy consumption [18].

In tab. 3 the outcome for the centralized experiment is presented. The registered parameters were heating rate and energy consumption for a heating program until 500 °C.

Table 3. Centralized results

Panel position, [mm]	Panel surface, [m ²]	Energy consumption, [Wh]	Heating rate, [°C/s]
200	0.0289	645	0.387597
200	0.02644	646.5	0.386698
180	0.0289	669.5	0.373413
180	0.02644	588.5	0.424809
160	0.0289	660	0.378788
160	0.02644	681.5	0.366838
140	0.0289	670	0.373134
140	0.02644	686	0.364431
120	0.0289	605	0.413223
120	0.02644	654	0.382263
100	0.0289	640	0.390625
100	0.02644	667.5	0.374532
80	0.0289	644.5	0.387898
80	0.02644	661.5	0.377929
60	0.0289	595	0.420168
60	0.02644	656	0.381098

The interpretation of the results has as purpose finding an experimental equation that can describe as precisely as possible the physical processes that take place in the considered situations. Thus, for fitting the experimental data's a Table Curve 3D commercial code was used. This program has wide capabilities to fit the experimental data with different equations and to calculate all of the numerical data needed in order to establish its accuracy. Data analysis starts with the most trustable equations available in the code database [19]. Final results are presented on each diagram.

Figure 3 represents the 3-D diagram of the energy consumption experimental data vs. panel position and surface. Moreover, in fig. 4 are two sections from fig. 3 that are useful in revealing the optimum panel position and/or surface. Heating rate experimental points and surface along with the polynomial fitted surfaces are not presented graphically because the points are depending on energy consumption.

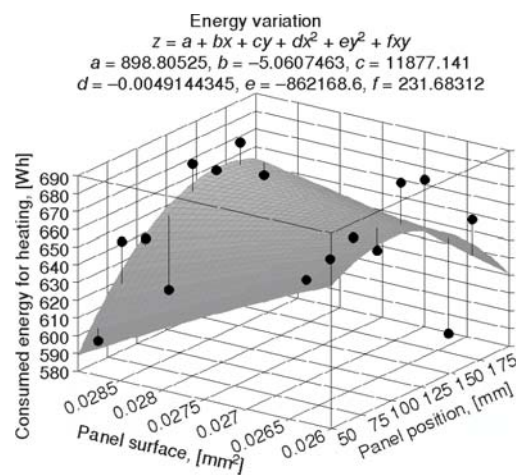


Figure 3. 3-D data fitting for energy consumption

The fitting surfaces were obtained by polynomial fitting method and can represent an experimental correlation between panel position and energy consumptions [18].

From fig. 3 it will consider the trend line surface:

$$E = 898.81 + 5.06 x + 11877.14 S - 0.0049 x^2 - 862168.6 S^2 + 231.68 x S \quad (1)$$

with the notations E is the energy consumption for heating up to 500 °C, S – the panel radiation surface, and x – the panel position, mm.

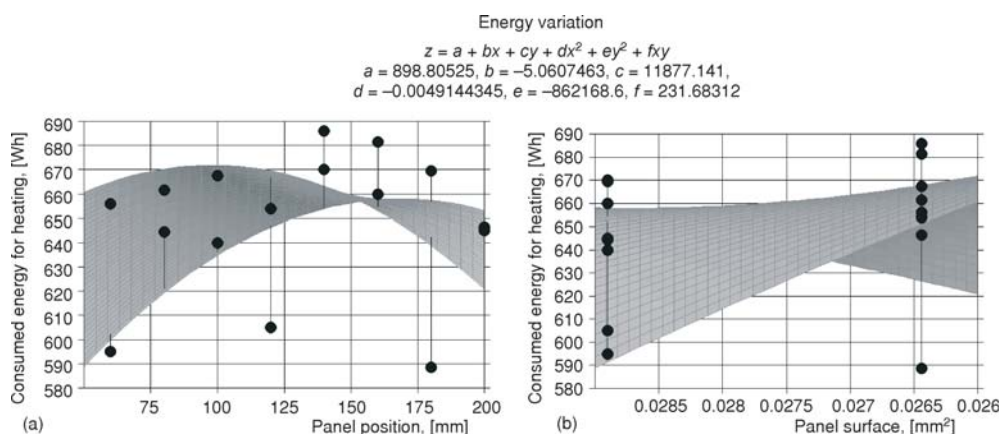


Figure 4. Sections through fig. 3, (a) Consumed energy vs. panel surface; (b) Consumed energy vs. panel position

The regression was obtained by computer, by least squares method and represents a correlation between panel position (x), energy consumption (E), and panel radiation surface (S). So, eq. (1) serves for the correlation of the working space shape with the technological objectives of the aluminum alloys heating and is considered to be the most important, offering precise quantitative information regarding the energy saving that is obtained with the help of the proposed solution concerning the changing of the working space.

This equation can be used only according to technological needs reflected in the parts dimensions.

Moreover, if it refers to tab. 2, for every panel position, the lower energy consumption was observed for the regular surface panels, even if the differences in some cases were not notable. The physical explanation of this phenomenon is that by introducing the radiant panels inside the heating chamber, radiation is increasing accordingly to the irradiative panel area. But, when the panel surface is decreasing, the reflected heat is decreasing too. An exception is case 2, where an 8.1% energy saving for the perforated panel was noticed. If it refers to this situation, the inclined panel position is influencing the convection inside the heating area by increasing air rate due to the panel holes. This idea, of the hole position influence worth to be studied on simulation basis.

Furthermore, an optimum position can be estimated at $x = 50$ mm and $S = 0.029$ mm². This graphical position correspond to an energy consumption $E = 590$ Wh, if it refers to fig. 3.

Conclusions

An experimental investigation was carried out to study radiation heat transfer enhancement in a modified closed enclosure of a classic furnace.

From the results of the present study, it was found out that both the heating rate and energy consumption are depending on radiant panel position and surface. The most suitable case is to use regular panels as large as is possible.

Moreover, if it compares data from tab. 3 it can remark a higher heating time for using the perforated panels at 140 mm, thus the highest energy consumption. Figure 3 shows the efficiency of placing different panels inside the working chamber, for heating up to 500 °C. Precisely, it obtains a maximum of 17% energy saving by using the perforated panels at 180 mm. Also, if it considers the optimum position revealed from the interpretation of figs. 3 and 4, the geometrical condition of choosing a furnace may be not accomplished if it heats large parts. This optimum position is for panels at 50 mm, so the available inner space for heating is substantially decreasing.

Moreover, if it considers panels at 140 mm, in relationship with tab. 2, it results the highest energy consumption despite the increased radiation area of the panel.

Thus, changing the furnace chamber geometry by introducing radiant panels leads to energy savings in the heating process by increasing the radiation heat transfer inside the furnace. Also, panel position optimization has to be based on three major aspects:

- technological need for heating, reflected through charge heating rate,
- geometrical need, reflected through charge configuration, and
- economical need, reflected in the final energy consumption that leads to the final product price.

As a final consideration, if it thinks about all the experimental data, along with all major aspects to be considered in industrial heating it can conclude that introducing panels can improve global heat transfer in the heated enclosure. The dimensions, surface and panel position is depending on the charge dimensions and requires more experimental and numerical studies regarding their optimum shape. This particular study revealed that a suitable case for energy saving is to use perforated panels at 180 mm.

Nomenclature

E	– energy consumption, [Wh]
S	– panel surface, [m ²]
T	– temperature, in [°C]
x	– panel position, [mm]

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