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# ANALYSIS OF ECONOMIC EFFECTS AND POSSIBILITIES OF REDUCING $CO_2$ IN AN INDUSTRIAL THERMAL TREATMENT SYSTEM

Mariusz WNĘK

Wydział Inżynierii Materiałowej i Cyfryzacji Przemysłu, Politechnika Śląska; mariusz.wnek@polsl.pl,
ORCID: 0000-0003-2485-7765

**Purpose:** The purpose of this article is to present the possibilities for the metallurgical industry to reduce burning gas consumption and thus reduce $CO_2$ emissions, which is a very important aspect at the moment.

**Design/methodology/approach**: This article presents the potential for reducing $CO_2$ emissions (in industrial burner systems for metallurgical heat treatment furnaces), which is currently highly desirable technologically and economically. The obtained results are the result of preliminary numerical modeling and subsequent laboratory tests.

**Findings:** The study determined that solutions that increase the preheat temperature of the combustion air supplied to the burners will have the greatest impact on reducing $CO_2$ emissions. Other elements also contribute to reducing $CO_2$ emissions, but on a comparative scale, they have less significant limitations and will not be considered in this publication.

**Originality/value:** For many years, recuperator-type air heaters have been used, and material particles discharged with exhaust gases have been observed to accumulate on their surfaces. These particles, bonding with the recuperator surface, increase thermal resistance, which results in a decrease in the heat transfer coefficient and reduced combustion air preheating. The originality of this topic is shows the extent to which this phenomenon affects the achieved combustion air preheating.

**Keywords:** reduction of $CO_2$ emissions, recuperator, compact gas burner regenerator, environmental protection.

**Category of the paper:** research paper.

## 1. Introduction

In the analysis of gas-fired furnaces, $CO_2$ emissions are primarily related to the amount of gas burned. For large industrial facilities (e.g., metallurgical furnaces 15-20 meters long and powered by 20-40 burners), switching to electricity, which is considered environmentally friendly, is either impossible or uneconomical.

Important parameters that also influence the reduction of $CO_2$ emissions are the excess air coefficient in the combustion process and the pressure in the furnace, which causes the exhaust gases to be expelled through leaks or by drawing in external air, changing the technological parameters and the burner system must cope with such disturbances – which usually results in excessive combustion of the gas fuel and is associated with excessive $CO_2$ emissions.

The presented parameters (air excess coefficient and pressure in the furnace chamber) influence the reduction of $CO_2$ emissions from the combustion of gas fuel in the burner by approximately 5-10%.

A recuperation system based on a tubular heat recovery unit is significantly more effective in reducing $CO_2$ emissions. It is simple and inexpensive compared to other type this systems. However, this solution only works effectively at the initial stage of installation (providing the highest heating). This is because in this type of heat recovery unit, the tubes are exposed to pollutants in the exhaust gases, which settle on them and reduce the heat transfer coefficient. This phenomenon results in a lower combustion air preheating temperature. This results in increased fuel combustion to maintain the furnace's process temperature (Puszer et al., 2021; Tomeczek et al., 2021; Gitzinger et al., 2010).

According to literature sources, tubular recuperators (metal or ceramic) enable heating of combustion air (i.e. recovery of thermal energy from exhaust gases) up to 500-600°C with an exhaust gas temperature of 1200°C.

The basis for process efficiency is achieving the highest possible combustion air preheating temperature, i.e., recovering as much thermal energy as possible from the exhaust gases. This reduces the amount of fuel supplied to the technological process and, consequently, $CO_2$ emissions.

The best solution for metallurgical furnaces fueled by gas burners is the use of regenerative systems. This type of solution can provide a much higher level of combustion air under the tree, resulting in a significant reduction in the chemical energy of the fuel and a significant reduction in $CO_2$ emissions (Ankel et al., 1987; Hasegawa et al., 2000; Fukushima et al., 2002; Georgiew, 2007).

Burner regenerators are characterized by an alternating fluid flow direction (exhaust gases - air) and are therefore not subject to such significant deposition of pollutants and reduction of the thermal energy transferred to the heated air.

With the appropriate design of burner regenerators, it is possible to obtain air heating close to (approx. 7-10% less) the exhaust gas temperature.

## 2. Sediments in the heat recovery system – tubular heat recovery unit

The main problem in heat recovery systems is the formation of a layer of deposits on the outer surface of the pipes, which affects the performance of these devices, i.e., increasing the resistance to exhaust gas flow in extended pipe bundles and decreasing the air preheat temperature.

The results of the tests on recuperators and the developed relationships, which allow for determining the thermal parameters of recuperators that are systematically contaminated during their operation, can be used in diagnostics and in the design of their structures for industrial furnaces.

The economics of recuperator use depends on properly solving design and operational challenges that contribute to achieving high efficiency. Recuperators constructed from extensive tube bundles are used in the exhaust gas ducts of industrial furnaces. The intensive heat flow from the exhaust gases through the tube walls allows for high-temperature heated combustion air and significant fuel savings. Exhaust gases discharged from the working spaces of metallurgical furnaces carry very fine dust, primarily particles of insulating materials and scale, which settle on the outer surface of the recuperator tubes (Figure 1a). The extent of this phenomenon depends on the type of insulating materials used, the tube bundle configuration, and the geometry of the exhaust gas extraction system. This significantly increases heat flow resistance and reduces the heat flux transferred in the recuperator (Fukushima et al., 2002; Georgiew et al., 2007; https://www.fivesgroup.com/energy-combustion). In the case of bundles with small inter-tube spacing, there is also a significant increase in exhaust flow resistance (Figure 2b).

a) b)

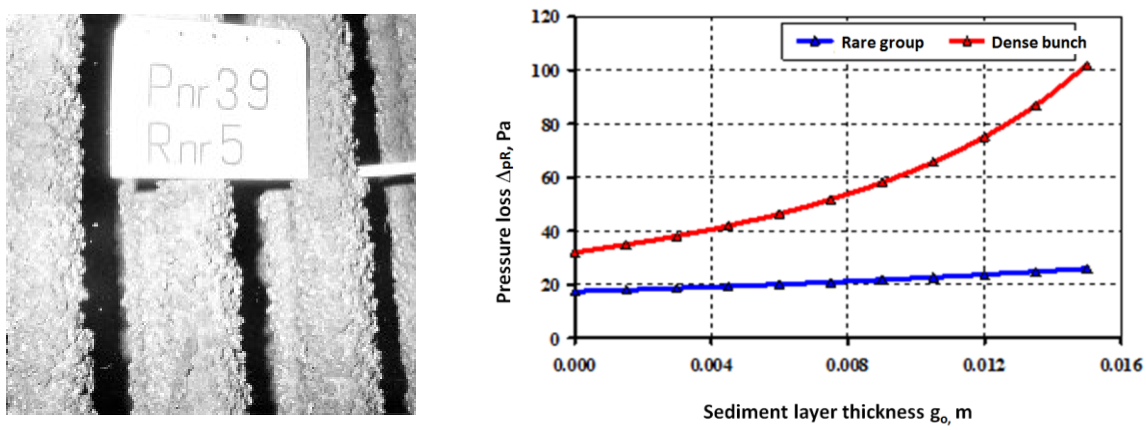


**Figure 1.** Recuperator pipes with deposits: a) recuperator pipes; b) exhaust gas pressure loss.

Dust in the exhaust gases positively affects the intensity of radiative heat flow in the recuperator, but the systematically growing layer of deposits from the beginning of the recuperator's construction increases the thermal resistance of the contaminated wall and, as a result, lowers the temperature of the heated air (Figure 2). This phenomenon ultimately leads to a deterioration of the energy and economic parameters of the furnaces and causes difficulties in their operation.

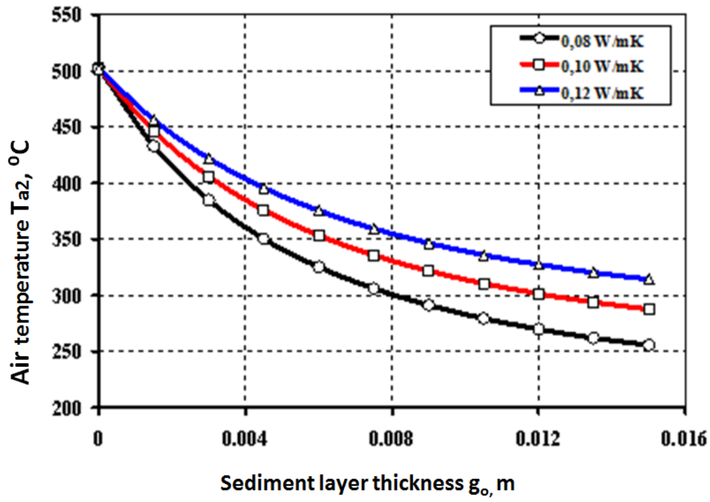


**Figure 2.** Temperature of heated air $T_{a2}$ in the recuperator with deposits.

Proper design of substrate and combustion product flow systems requires accurate calculations of their temperatures and pressure losses in recuperators. The impact of deposits on heat transfer and gas dynamics in recuperators intended for long-term operation should be considered in the design calculations for these devices. Identifying the parameters of deposits deposited on recuperator tubes allows for more reliable calculations of these devices.

During the tests, it was found that the exhaust gas flow in the exhaust gas channels is characterized by significant disturbances, causing instability of the measured pressure values. The results of tests on laboratory tubular recuperators and metallurgical furnaces, as well as the analysis of various data on pressure losses in recuperator tube bundles, allowed us to determine the relationship for determining the resistance number $\lambda_{fr}$.

$$\lambda_{fr} = 2{,}1 \cdot K_p^{-0{,}1} \cdot Re_s^{-0{,}1} \tag{1}$$

for pipe bundles with parameters $S_1/d_z$ and $S_2/d_z$ of 1.5-3.5, in which the pipe bundle design parameter $K_p$ is determined as:

$$K_p = \frac{S_1 \cdot S_2}{d_Z^2} \tag{2}$$

and it depends on the outer diameter of the pipes $d_z$ and their spacing within row $S_1$ and between rows $S_2$.

Determining the resistance number $\lambda_{fr}$ (1) is necessary to determine the exhaust gas pressure loss in the recuperator $\Delta_{psR}$ (Figure 1).

## 3. Heat flow studies

The scale of the phenomenon of the build-up of a layer of deposits impairing heat transfer was identified by measurements in several dozen recuperators of pit furnaces.

Operational measurements of the effects of long-term operation of recuperators have shown a very significant effect of increasing the thickness of the deposit layer on lowering the temperature of the heated air. Changes in heat transfer conditions and gas dynamics on the exhaust side of pipes with increasing thermal resistance of deposits significantly influence changes in the heat transfer coefficient k.

Practical experience with these devices shows that a significant drop in air temperature of approximately 100°C occurs after approximately 1.5 years of operation. Measurements of the heat recovery units in the flue gas ducts allow us to determine the average thickness of the deposit layer on the pipes of the considered heat recovery units after approximately 3-4 years of operation at 4-6 mm.

The analysis of the collected source information and the results of the recuperator tests allowed us to determine the dependence of the change in the ratio of heat transfer coefficients $n_k = k/k_{rn}$ on their operation time t for the considered cases of using these devices in heating furnaces

$$n_k = e^{-C\cdot t} \tag{3}$$

in which for recuperators of pit furnaces C=0.28 $yr^{-1}$, and for recuperators of pusher furnaces C=0.12 $yr^{-1}$. Measurement data of recuperators allow determining the changes in the ratio of the thermal resistance of the pipe wall ro with a layer of deposits of thickness so to the thermal resistance $r_m$ of a clean metal wall of thickness $s_m$, occurring over time (0). Assuming for calculation purposes $r_m=s_m/\lambda_m=0.0002$ $m^2K/W$, the relationship was established

$$\frac{r_0}{r_m} = C \cdot t \tag{4}$$

in which: for recuperators of pit furnaces C = 74 $yr^{-1}$, for recuperators of pusher furnaces C = 48 $yr^{-1}$ and $r_o = (s_m/\lambda_m) + (s_o/\lambda_o)$.

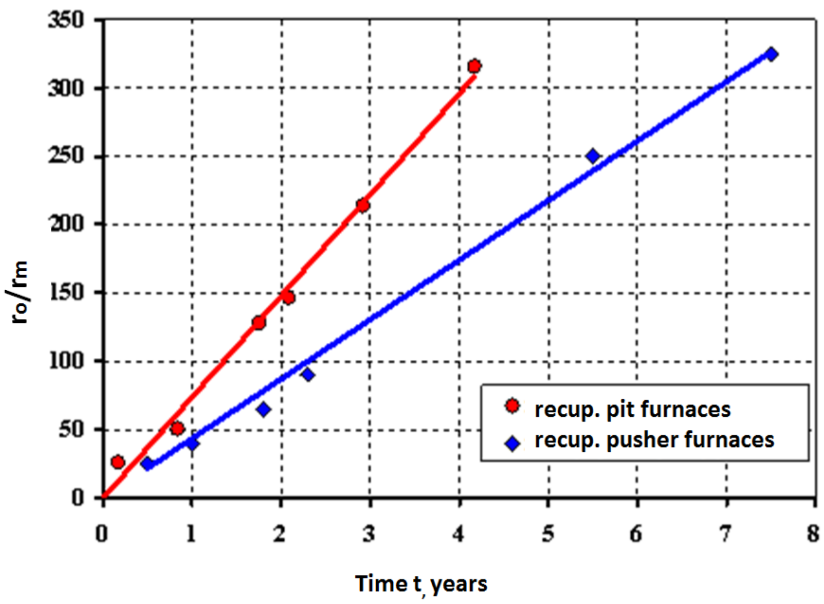


**Figure 3.** Thermal resistance measurements of pipes with deposits.

The physical properties of the solid and gas components of the porous sediment layer show that their thermal conductivity increases with temperature and density. Taking this trend into account, a relationship was formulated for calculating the thermal conductivity coefficient λo of the sediment (5).

$$\frac{\lambda_O}{\lambda_g} = \left[1 + 0{,}018\left(\frac{T_O}{T_n}\right)^{0{,}8}\left(\frac{\rho_O}{\rho_{ng}}\right)^{0{,}78}\right] \tag{5}$$

where: λo is the density of the sediment layer at temperature $T_o$ expressed in K.

For calculation purposes, the gas parameters under standard conditions were assumed:

$\lambda_{ng} = 1.3$ kg/m$^3$N, $\lambda_g = 0.0234$ W/mK, and $T_n = 273$ K.

The given equations (4) and (5) can be used to calculate recuperators for metallurgical heating furnaces, such as pusher furnaces. For the assumed service life of these devices, the thickness and conductivity coefficient of the deposit layer λo deposited on the tube surface can be determined. Their values can be varied depending on the relative distances between the tube bundle elements (e.g., tube rows or modules), assuming in equation **Błąd! Nie można odnaleźć źródła odwołania.** that the initial element is C = 60 yr$^{-1}$ and the final element is C = 36 yr$^{-1}$. For pit furnace recuperators, the given C parameter values can be increased by 25%.

## 4. Summary of problems related to sediment in the recuperation system

The design problem is to calculate the exhaust gas flow resistance in the extended tube bundles and determine the exhaust gas pressure losses. An important issue is to determine the heat flow and thermal conductivity of the deposits based on measurements of the deposit layer thickness and parameters, as well as to identify the temperature drop due to air heating.

A tubular heat recovery unit is a relatively simple structure. As the name suggests, it consists of a bundle of tubes made of various types of steel or ceramic. Ceramics can achieve higher air heating rates, but contamination deposited on the tube walls makes cleaning this structure very difficult, potentially damaging the structure, which in such cases would result in very high repair costs.

## 5. Burner regenerators system

In industrial heating furnaces with gas-fired burners, the most important control parameter is the process temperature. Due to high energy prices, efforts are being made to reduce gas fuel consumption by optimizing the efficiency of heating devices. One way to reduce gas fuel consumption is to optimize control processes 1 and 11. Using effective combustion air preheating methods is one way to significantly reduce fuel consumption in metallurgical thermal processes.

Regenerative systems are the most efficient, considering the temperature of the heated air. The latest burner designs can achieve air heating temperatures above 1100ºC, with exhaust gas temperatures reaching 1200ºC.

Currently, modern multi-burner furnace firing systems use individual air preheaters for each burner. One possible solution involves attaching these preheaters to the burners (0) or using individual regenerators housed in a single housing with the burner (https://www.fivesgroup.com/energy-combustion; https://www.bloomeng.com; Manatura, Tangtrakul, 2010; Wnęk, 2014).

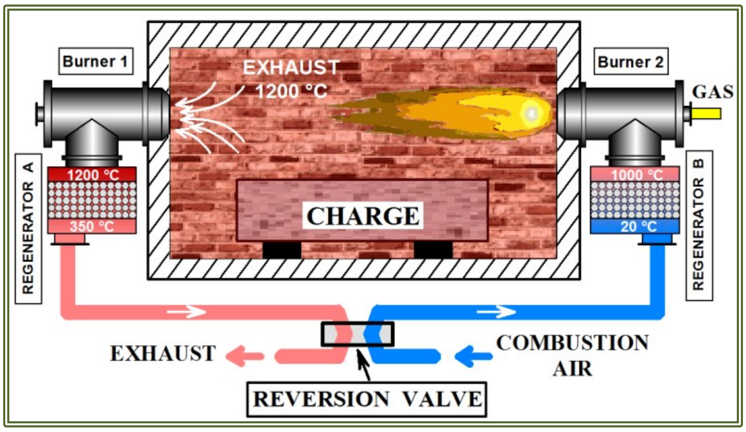


**Figure 4.** Operation diagram of compact regenerative burners.

## 6. Computer-aided regenerator selection

The scope of the work involved determining a set of ceramic materials suitable for producing regenerative packing, and one of them was selected (0). The regenerator's design parameters were selected based on, among other things, the assumed burner power, and the geometric dimensions of the regenerative packing structure were determined with a view to intensifying heat transfer. The heat regenerator packing structure was selected for a low-power burner of 20-50 kW, fueled by natural gas, assuming an excess combustion air ratio of 1.05-1.1 (air flow rate of approximately 26-68 kg/h). Numerical modeling using proprietary Reg-Optimum software was used to determine the key structural dimensions of the regenerator packing (Wnęk, 2012).

The solution had to meet the following criteria: large heat transfer surface, minimum mass, and the highest possible ratio of heat transfer surface to volume (A/V)→ max. A solution that meets these criteria guarantees the possibility of achieving high combustion air preheating temperatures, thus reducing gas fuel consumption and limiting $CO_2$ emissions.

**Table 1.**
*Properties of the regenerative filling material*

| **Lp.** | **Regenerator material** | **Density ρ, kg/m³** | **Thermal conductivity coefficient λ, W/(m K)** | **Specific heat capacity $c_p$, J/(kg K)** | **Volumetric heat capacity $\rho c_p$, MJ/(m³ K)** | **Diffusivity $k \cdot 10^7$, m²/s** | **Melting point, °C** |
|---|---|---|---|---|---|---|---|
| *1* | *2* | *3* | *4* | *5* | *6* | *7* | *8* |
| 1 | Aluminum trioxide | 1900 | 0.6 | 500 | 0.95 | 6.6 | 2040 |

## 7. Research station

Experimental studies were conducted on a stand enabling analysis of the operation of one regenerator section (0, 0). The stand consisted of: a compact and metered regenerator, a heating chamber, a hot and cold fluid flow measurement system, and air supply and exhaust gas discharge systems. The measurement, control, and regulation system was managed by an industrial controller with I/O modules and a proprietary program written in the industrial LabView programming environment.

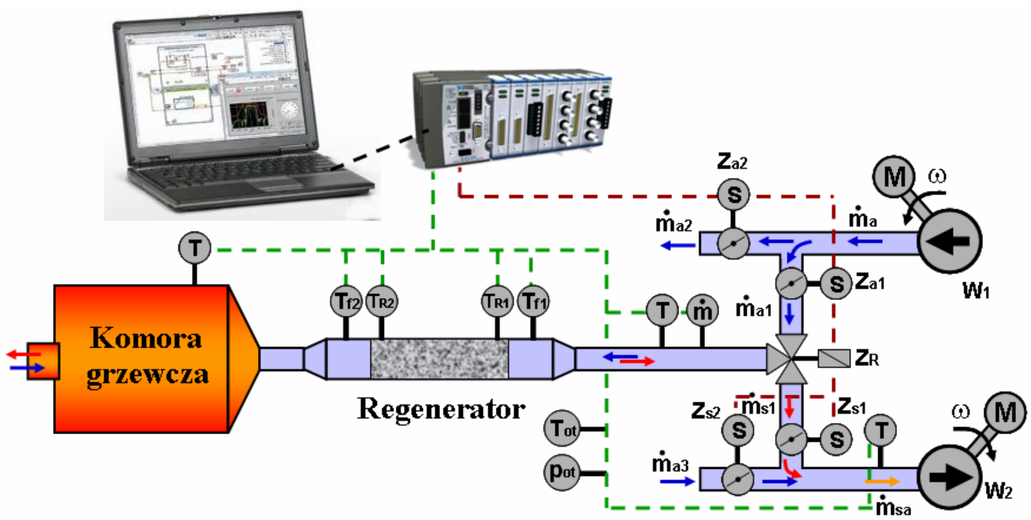


**Figure 5.** Schematic of the regenerator characteristics testing stand.

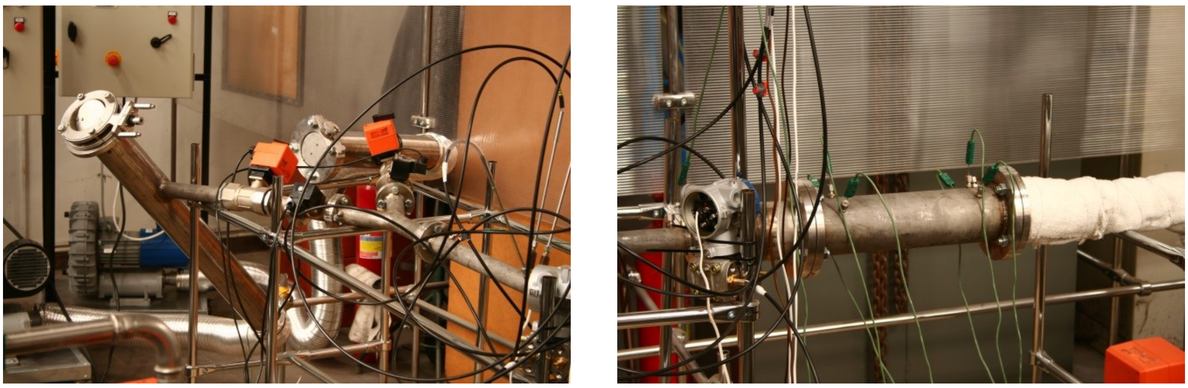

**Figure 6.** Gas burner regenerator test stand.

## 8. Research object

A regenerator made of $Al_2O_3$ (0) was used in the bench tests. The designed regenerator consisted of several segments, each 12 mm thick and 90 mm in diameter, with 325 circular flow channels each 3 mm in diameter.

The mass of the entire regenerative filling for the developed structure was approximately 3.7 kg and the coefficient (A/V) = 1320 $m^2/m^3$ (0) is comparable to the best solutions in the industry and presented in the world literature.

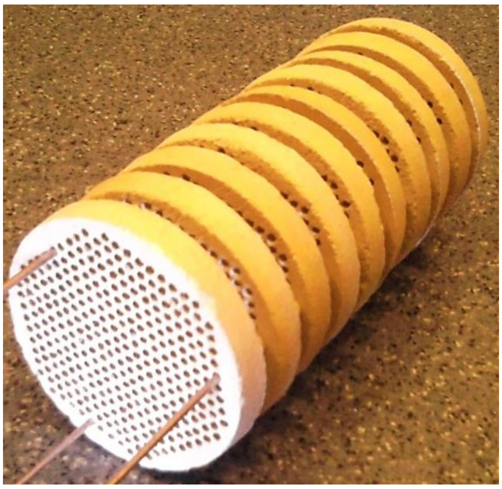

**Figure 7.** Ceramic filling of the burner regenerator.

## 9. Economic and environmental effects of using a regenerative system in industry

Selecting the right material for the regenerator fill to achieve high heated air temperatures is crucial. It is well known that increasing combustion air temperature leads to reduced fuel consumption and, at the same time, reduced $CO_2$ emissions.

The ability of a regenerator constructed from the selected material to achieve high air preheating (approximately 1100°C for exhaust gases at 1200°C), confirmed in bench tests, allows for significant savings in fuel consumption and, consequently, increases the efficiency of the heating furnace. An additional benefit is reduced $CO_2$ emissions, which is a very important environmental aspect.

The use of modern regenerative burners with the demonstrated combustion air preheating capabilities in a metallurgical heating furnace (with a capacity of 8.5 MW) resulted in a reduction in fuel consumption by over 30%, resulting in significant annual savings and avoiding the emission of over 4400 Mg of $CO_2$ per year, which has a significant and positive environmental impact (0).

Based on the test results, the regenerator's quality was assessed. The relative air preheating coefficient was calculated based on the air temperature at the regenerator outlet. It can be seen that it is approximately 95% – the average coefficient for a recuperation system is typically in the range of 30-40%. A high combustion system efficiency of approximately 86% was achieved. All obtained regenerator quality results indicate that the regenerator under consideration is an interesting solution, capable of significantly reducing fuel consumption and $CO_2$ emissions (https://enerad.pl/gaz-dla-firmy-jaka-taryfe-i-oferte-wybrac/).

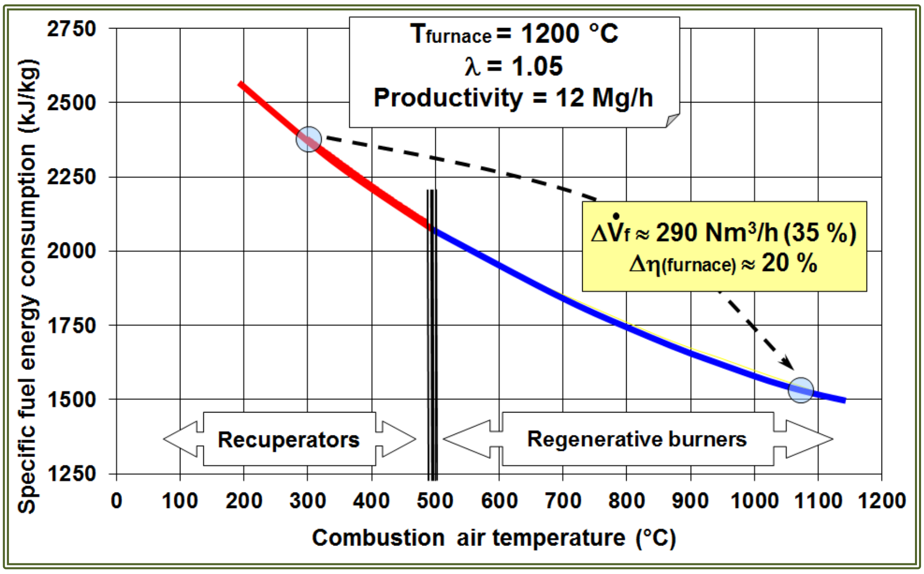


**Figure 8.** The fuel consumption as a function of the air preheat.

## 10.Conclusions

- A tubular recuperator is a simple solution for heating combustion air. However, the heating temperatures achieved differ significantly from the exhaust gas temperature, resulting in relatively low fuel consumption and, therefore, carbon dioxide emissions.
- Tubular heat recovery units can be difficult to clean due to the deposition of contaminants in the exhaust gases. It is easier to clean a heat recovery unit with a steel pipe system, but with a ceramic system, it is very difficult and can be damaged, which can result in high repair costs.
- Burner regenerators (individual and compact) are a much more efficient energy recovery system compared to a recuperative system. This solution allows for a much higher combustion air preheating temperature, which, for a well-designed regenerator, significantly approaches the exhaust gas temperature.
- Regenerators, due to their alternating operation, are not subject to such significant pollution as recuperators, it could be said that they are self-cleaning.

- Using a regenerative system allows for very high air heating temperatures, which significantly reduces fuel consumption and CO2 emissions (without changing the technological parameters of the process). This is a very attractive solution from an environmental perspective.
- Selecting the design parameters of the regenerator filling is not easy and computer support is necessary.
- Regenerators for low-power burners (up to 50 kW) were considered.
- The regenerator quality was checked. A relative fuel economy factor of approximately 0.5 was recorded. Relative air preheating factor and combustion system efficiency were achieved at levels of 95% and 86%, respectively. All factors achieved very high and satisfactory values. These values guarantee significant fuel savings and a reduction in $CO_2$ emissions.
- Using a regenerative system allows for very high air heating temperatures, which significantly reduces fuel consumption and $CO_2$ emissions (without changing the technological parameters of the process). This is a very attractive solution from an environmental perspective.
- Based on simulation tests, it was determined that the material intended for filling the regenerator should have properties that meet the following conditions: volumetric heat capacity $\rho c_p > 1$ MJ/(m$^3$ K), diffusivity k = (2-10)·10-7 m$^2$/s.
- The computer-aided selection of the regenerator design parameters indicated a solution that, in bench tests, confirmed the high temperature of the heated combustion air and thus reduced gas fuel consumption and a significant reduction in $CO_2$ emissions.

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