An experiment on a cylindrical Ni-Al radiant burner with heat recuperation

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Abstract. This paper presents experimentally studied temperature and radiation parameters of a gas-fired luminous radiant heater based on a conical aluminium recuperator and a cylindrical Ni-Al burner. Two operation modes have been investigated: (i) with air preheating by means of heat recuperation when the air is supplied into the burner through the hollow recuperator, and (ii) without air preheating when the fuel mixture is directly supplied to the burner. The dependences of radiation efficiency on a burner firing rate in the range of 100-340 kW/m² are analyzed. The specific requirements to obtain the radiation efficiency up to 70% are discussed.

1. Introduction
Gas-fired luminous radiant heaters, also known as radiant burners, are widely used for generating infrared fluxes [1,2]. Currently, radiant burners are successfully used for heating industrial zones, as well as for drying and thermal processing of materials. This study has been motivated by the experimental findings about temperature and radiative characteristics of cylindrical burners made of Ni-Al alloy [3]. The findings reveal a significant improvement in the radiation efficiency of burners operated in an internal combustion mode. In this combustion mode, the flame stabilizes in an internal cavity of a cylindrical burner that allows achieving the radiation efficiency of about 60%. This type of infrared burners converts the enthalpy of combustion products into an IR flux with the efficiency close to the maximum possible [4]. It should be noted that the term "radiation efficiency" is understood as a fraction of heat power transferred to an infrared flux [5]. In order to obtain high radiation efficiency, it is important to use a lean fuel-air mixture with the composition as close to stoichiometry as possible and the only criterion is that of appropriate CO/NOX emission. Because of barrel-shaped design, the cylindrical burner emits the infrared flux into the solid angle of 4π [6]. For the purpose of heat treatment of flat surfaces, e.g. for conveyor drying, the IR flux from cylindrical burner has to be refocused into the solid angle of 2π by means of reflectors. The aim of this study is to investigate the functional characteristics of a luminous radiant heater with 2π solid angle based on a cylindrical Ni-Al burner operated in the internal combustion mode.

2. Experimental methods
To create a cylindrical burner, an intermetallic Ni-Al alloy is used, which is characterized by high oxidation resistance and high-temperature strength. The burner is made in the form of hollow cylinders with a hemispherical head by a combustion synthesis technique, with the diameter of d = 48 mm, total length of l = 77 mm (surface area of 116 cm²) and the wall thickness of 8.5 mm.
Porosity is 55%, the average size of the frame elements is 1000 μm. The burner was installed inside a conical hollow-type recuperator made from an aluminum alloy: diameters are 116 and 185 mm, height is 96 mm, exhaust aperture is 269 cm² (fig. 1). The burner dimensions were measured by a dial caliper with accuracy of 10⁻⁴ m.

![Figure 1. The diagram of a radiation burner. The points of temperature control are shown by black stars.](image)

The natural gas of the following composition was used as a fuel: methane 91.07 vol.%, ethane 4.05 vol.%, propane 1.69 vol.%, the rest (n-butane, i-butane, n-pentane, i-pentane, carbon dioxide, nitrogen) – 3.19 vol.%; the low heat value is $H_i = 35.62$ MJ/m³; the stoichiometric composition of gas with air is 1.0:10.0 by volume. The gas supply was maintained with the use of a mass flow controller RRG-12, accuracy of ± 0.03 nl/min (Eltechpribor, Russia). The power range of 1140-3900 W (burner firing rate of 98-335 kW/m², heater firing rate of 42-145 kW/m²) was investigated. An air compressor was used for supplying air. In this work the air-fuel ratio was 1.1, and the composition of a fuel-air mixture was controlled by flow meters Mass-View with accuracy of ± 2 % (Bronkhorst, Netherland). After the mass flow control, the air was supplied into a hollow conical recuperator and then into a gas mixer equipped with a flame arrester and a burner housing at the end. The mode without recuperation was also investigated, when the premixed mixture was supplied directly to the gas mixer; the orifices of the recuperator were sealed. The flame ignition was switched from the outer surface of the cylindrical burner. After 15-30 seconds of operation, a spontaneous flashback of the flame in the inner cavity of the burner occurred, consequently the internal combustion mode was realized. During the experiments the temperatures of preheated air, porous burner and aluminum recuperator were measured by R type thermocouples with the use of a controller Adam 4018+ (Advantech Co, Taiwan). The points of temperature control are shown by black stars on fig. 1.

The radiation efficiency of the burner was measured with the use of a 12A P/N 7Z02638 power sensor (Ophir, Israel): a spectral range of 0.19 – 20 μm, a specific power measurement range of 10⁻² - 60 kW/m², and measurement accuracy of ± 3%. The burner was located in such a way that the origin of coordinates was in the center of the emitter, and the OX axis coincided with its symmetry axis (Fig. 2). The radiation efficiency was determined as the ratio of the radiation flux across the semi spherical layer (pointing angle $\beta = (0, +90)^\circ$ and $\beta = (0, -90)^\circ$ at a pitch of 15°) to the burner power:

$$\eta_R = \frac{Z \pi r^2}{H_{air} Q_f} \sum_{i=1}^{N-1} (J_i + J_{i+1}) \left| \cos \beta_i - \cos \beta_{i+1} \right|$$

where $Z$ – correction factor calculated in accordance with chapter C5.5 of AHRI Standard 1330-2014 in order to account for the radiation losses in the air layer between the burner and the power sensor,
r – distance from the origin of coordinates to the power sensor aperture, \( Q_f \) – natural gas flow rate, \( J_i \) – radiation power density measured by the power sensor at the position corresponding to the angle \( \beta_i \).

Figure 2. – The scheme of measuring the radiation efficiency.

2.1 Experimental uncertainty analysis
Uncertainty of indirectly measured parameters was calculated with the use of a root-sum square combination of the effects of each of the individual inputs in accordance with [7]. All uncertainties are summarized in table 1.

Table 1. – Uncertainty of parameters.

| Parameters                      | Function                                      | Uncertainty, % |
|---------------------------------|------------------------------------------------|----------------|
| Fuel and air flow rate, \( Q_f, Q_a \) | –                                              | 2              |
| Radiation power density, \( J \)     | –                                              | 3              |
| Firing rate, \( F_R \)           | \( F_R = f \left( Q_f, d, l \right) = \frac{H_i \cdot Q_f}{\pi \cdot d \cdot l} \) | 2              |
| Radiation efficiency, \( \eta_R \) | \( \eta_R = f \left( r, Q_f, J_1, ..., J_n \right) = \text{Eq. 1} \) | 3.6            |

To account for a random error, a series of three independent measurements under the same experimental conditions were carried out, and the measured value of \( \eta_R \) was calculated for each experiment separately. The relative uncertainty was calculated for a confidence level of 0.95 as the root-sum square combination of a bias limit and a precision index of the result:

\[
\frac{\Delta \eta_R}{\eta_R} = \sqrt{(3.6\%)^2 + \frac{4.3^2}{\eta_R^2} \cdot \sum_{i=1}^{3} \left( \eta_{R_i} - \eta_R \right)^2},
\]

where \( \eta_{R_i} \) – mean of a set of 3 experiments.

3. Experimental results and discussion
Figure 3 shows the dependences of the burner temperature on the firing rate. It was established that the temperature difference between the semispherical head and the cylindrical part of the burner was from 20 to 50 K. In the mode of heat recuperation, the semispherical head was the most heated part of the burner, and vice versa in the mode without the heat recuperation. It was also established that in the mode of heat recuperation the turndown range of the burner was from 100 to 340 kW/m². With a firing rate over 340 kW/m², the burner temperature exceeds 1400 K, which is a limit condition for the Ni-Al alloy used. In the mode without recuperation, the upper range was much lower, about 220 kW/m². In that case, the upper range was limited by the operating temperature of the aluminum recuperator,
which was about 800 K (fig. 4). In the mode of heat recuperation, the temperature of the recuperator was significantly lower, about 450-550 K. Here the effective cooling of the recuperator took place with simultaneous preheating of combustion air by the value of $\Delta T$ up to 250 K (fig.5).

**Figure 3.** Dependences of the temperatures of the cylindrical burner on firing rate $F_R$. 
\(a\) – preheated combustion air by means of recuperation. \(b\) – without preheating and recuperation. Solid and empty markers correspond to temperatures of the semispherical head and cylindrical part of the burner correspondingly. Dashed lines correspond to maximal possible temperature $T = T_S = T_G$, calculated for given preheating of fuel mixture $\Delta T$.

**Figure 4.** Dependences of the recuperator temperature on the burner firing rate $F_R$. ■ – combustion air was preheated by means of recuperation. ● – without recuperation.

**Figure 5.** Dependences of the combustion air temperature rise $\Delta T$ on the burner firing rate $F_R$.

Fig. 3 also presents the calculated values of the maximum possible burner temperature for the case of radiation burners with an emissivity factor of 0.9 operated on a methane-air mixture with the air-fuel ratio of 1.1 at different preheating $\Delta T$. The calculations were made in accordance with the procedure described in [6]. This approach is based on the thermodynamic calculations of the
achievable radiation efficiency of burners under the assumption that the temperatures of the outgoing combustion products $T_G$ and the temperature of the burner surface $T_S$ are equal. It was established that for the recuperation mode the burner temperatures correspond to the preheating conditions of about $\Delta T = 200-600$ K. In the mode without recuperation, the temperature of the cylindrical part of the burner corresponds to the operation without preheating, i.e. $\Delta T = 0$.

Fig. 6 shows the dependences of the radiation efficiency on the luminous heater firing rate. It was found that in the mode of heat recuperation, the radiation efficiency varies from 60 to 70% in the range of firing rates from 42 to 145 kW/m$^2$. The dotted line in fig.6 shows the theoretical level of possible radiation efficiency of the methane-air burner operated without preheating, i.e. $\Delta T = 0$. From there, the radiation efficiency of the heater under consideration is close to the maximum possible efficiency of a flat porous burner with the surface area of 269 cm$^2$ operated at the same power range. It was found that the radiation efficiency in the combustion mode without heat recuperation is the same within the measurement accuracy. It was established that the values of radiation efficiency calculated with the use of the power data measured in the angels of $\beta = (0, +90)^\circ$ and $\beta = (0, -90)^\circ$ are the same, which proved that the conical recuperator used is symmetrical. It was established that about 80% of the radiation energy was focused between angles $\beta$ from -45 to +45 degrees (fig. 7). Despite significant differences in the temperature state of the burner in the studied modes (fig. 3), IR flux intensities are the same within the measurement accuracy.

Figure 8 shows the dependence of the radiation efficiency of the gas fired luminous radiant heater on the temperature of outgoing gases, calculated according to the methodology described in [6]. It follows that the radiation efficiency of 55-70% can be realized if only the temperature of the flue gases leaving the recuperator orifice is within the range of 900-1200 K.
Temperature of flue gases, K
Rad. Efficiency, %

Figure 8. Dependence of radiation efficiency of the gas fired luminous radiant heater \( \eta_R \) on the temperature of flue gases. For the case of methane-air mixture with air-fuel ratio of 1.1

For this heater design the sources of IR flux are (i) heat radiation of the porous burner and (ii) heat radiation of the recuperator inner wall. In the recuperation mode the main source of heat radiation is the burner. The upper estimate of the heat radiation from the reflecting surface is 30-75 W for the temperature of the aluminium recuperator in the range of 450-550 K assuming that emissivity is 0.3 (fig. 4). This is a 2-3% additional increase in terms of the radiation efficiency. In the combustion mode without recuperation the heat flux from the recuperator wall is increased: 200-340 W for the temperature of the aluminium recuperator in the range of 700-800 K, which is responsible for the increase in radiation efficiency on the value of 13-17% for the heater firing rates of 42-100 kW/m². It is assumed that this effect is of a practical importance since a simple reflector can be used to provide high radiation efficiency of the heater. Moreover, for non-recuperative combustion mode it is no need to construct any hollow-core reflectors, and NO\(_X\) emission appears to be lower since the temperature in the combustion zone is restricted.

4. Concluding remarks
The experimental findings have suggested that in both combustion modes, i.e. with and without heat recuperation, the radiation efficiency of the heater varies from 60 to 70%. The combustion mode with heat recuperation is characterized by increased temperature of the cylindrical burner. The combustion mode without heat recuperation is characterized by increased temperature of the reflector wall. From the viewpoint of the radiation efficiency value maximization, it makes no difference what emits the IR flux – burner or reflector. However, the heater under consideration do not allows to apply high firing rates that is why the only option is to use recuperation mode. It is of interest to investigate heaters with recuperators from higher-melting-point and higher-emissivity materials, for instance made from steels.

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