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THERMOELECTRIC HEAT RECUPERATORS FOR CEMENT KILNS

In the present work the results of the research aimed at the studies of the possibility of use of thermoelectric energy conversion for recuperation of the heat radiated by the preheated rotating surfaces of the cement kilns are presented. The temperature specifications of the kilns functioning remain unchanged, though. To reach this, the degree of emissivity of the kiln surface should be changed. The dependences were obtained of the maximum efficiency and temperature of the thermoelectric generator hot heat exchanger on the emissivity of the cement kiln surface. Both maximum efficiency of a thermoelectric generator and its designed capacity were estimated.

Key words: recuperation, cement kiln, thermoelectric module.

Introduction

General characterization of the problem. Nearly all equipment for the industrial technological processes, such as heat engines (turbines, combustion engines etc.) scatter huge amounts of waste heat during their operation, the said waste heat being a part and parcel of heat pollution of the environment [1]. Therefore, the elimination of waste heat as well as its utilization in order to obtain electric energy is a problem of the exceptional significance. The temperatures of such waste heat differ considerably and lie approximately in the range from 50 to 700 °C. For most cases within this range of temperatures, especially for those below 400 °C, it is unreasonable to apply heat engines. As the analysis has shown, the most favourable for heat recuperation at such temperatures is the thermoelectric method of direct thermal into electric energy conversion [2-4]. Moreover, the characteristics of heat sources (their dimensions, operation modes, heat carriers) are rather various. Of particular interest is here the problem of recuperation of the heat radiated from the cement kilns rotating surfaces. For conditions like those the most suitable is the thermoelectric method of energy conversion as thermoelectric converters are easy to adapt to various thermal energy sources [5]. The fact that such converters (modules) have been designed recently whose specific cost equals to 0.5 – 2 $/W thus ensuring the profitability of thermoelectric heat recuperators is also of great importance.

Analysis of the literature. Thermoelectric devices for combustion engines waste heat recuperation [6], gas rolling mill furnaces [7] and gas-pumping aggregate turbines [8]. For all cases considered a thermoelectric generator (its hot heat exchanging surface) is in contact with the heated heat-release surface. Such a construction, though, is inappropriate when the heat from the rotating cement kiln is used. Effective in this case is the utilization of heat radiation off these heated surfaces [9]. The fact that the presence of a thermoelectric generator causes changes in the temperature mode of the kiln itself, which is but undesirable for the technological process of cement production, is an obstacle to the said thermoelectric generators being used for cement kilns heat recuperation.

The purpose of the present work is the analysis of the possibility of employment of the thermoelectric energy conversion for recuperation of heat radiated by the rotating surfaces of cement kilns without changing temperature specifications of the said kilns operation.

Problem definition

The cement kiln appearance and diagrammatic view are presented in Figs. 1 and 2.

Fig. 1. A cement kiln appearance [10].

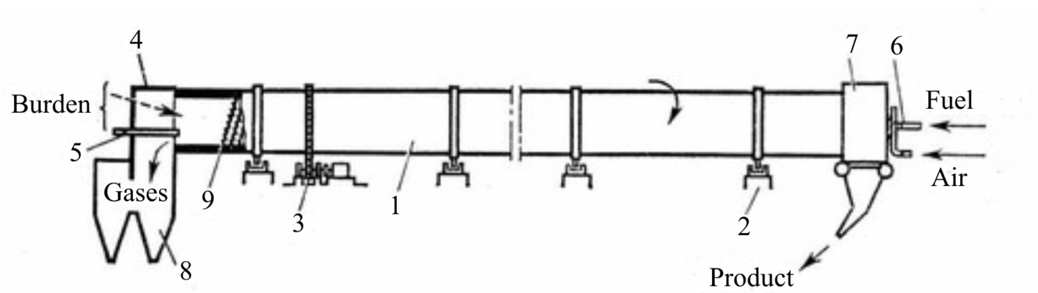

Fig. 2. A cement kiln diagrammatic view [11]. 1 – metallic cylinder, 2 – bearing rollers, 3 – electric motor with the reducer and gear, 4 – burden load cap, 5 – burden load injector, 6 – fuel input injectors, 7 – hot cap, 8 –dusting system, 9 – heat exchangers.

To reach the purpose of the present work, two physical models of the cement kiln heat exchange were used. The first one considers the kiln heat exchange without a thermoelectric generator (Fig.3). It was necessary for heat irradiation estimation in the absence of an external heat consumer. In the second model the thermoelectric generator was taken into account that introduces changes into both temperature and thermal modes of the cement kiln. The estimation was also performed for the increase in emissivity of the kiln surface required to preserve the unchanged heat irradiation from the kiln.

A cement kiln heat exchange without a thermoelectric generator

The cement kiln model under study is a cylinder 1 with the diameter of $d = 4.8$ m and the length of $L = 76$ m, the temperature of which is constant and equals $T_1 = 300$ °C (Fig. 3).

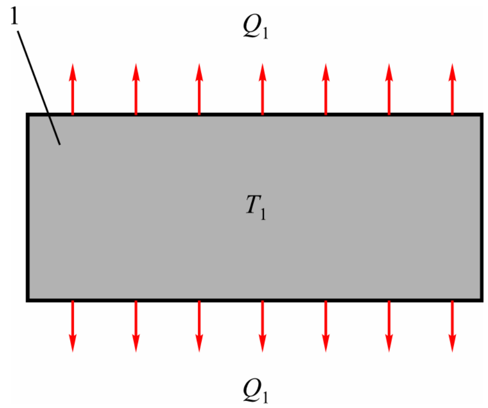

Fig. 3. A cement kiln model without a thermoelectric generator.

The kiln temperature is set due to the balance of heat released inside it and heat transfer into the environment. At the same time heat transfer into the environment takes place by way of free convection and radiation. The total heat flux off the lateral surface of such cylinder can be written in the form of

$$Q_1 = Q_{conv} + Q_{rad}, \tag{1}$$

where: Q_{conv} is the convections heat flux, Q_{rad} heat flux radiated from kiln surface.

The heat flux radiated from kiln surface can be determined proceeding from the Stefan-Boltzmann law

$$Q_{rad} = \varepsilon_1 \sigma S \left(T_1^4 - T_0^4\right), \tag{2}$$

where: ε_1 is the surface emissivity, $\sigma = 5.67 \cdot 10^{-8}$ W·m^{-2}·K^{-4} is the Stefan-Boltzmann constant, $S = \pi d L$ is the kiln lateral surface area, T_0 is the ambient temperature.

To estimate a convection component, it is necessary to define the Nusselt number which is a function of the Prandtl and Grashof numbers under free convection and depends but slightly on the shape of the body [12, 13].

$$\frac{\alpha l}{\kappa} = f\left(\frac{\nu}{a};\ \frac{g l^3}{\nu^2}\beta\Delta t;\ \text{shape of body}\right). \tag{3}$$

Here β [1/degree] is the medium expansiveness; Δt is thermal head;

$$\frac{\nu}{a} = Pr,\ \frac{g l^3}{\nu^2}\beta\Delta t = Gr. \tag{4}$$

Thermal resistance in gases is concentrated in the narrow wall layer where molecular friction prevails. The system of equations will thus contain only four independent variables instead of five (a, $g\rho\beta\Delta t$, μ, l) ρ – density, μ – dynamic viscosity, and give only one key criterion:

$$Pr\, Gr = \frac{g l^3}{a\nu}\beta\Delta t. \tag{5}$$

The diameter of the horizontal pipe is taken to be its linear dimension l. Calculation formulae have the form of:

a) at $10^{-3} < Pr\ Gr < 5\cdot10^{2}$

$$\alpha = A_1\left(\frac{\Delta t}{l^5}\right)^{1/3}. \quad (6)$$

b) at $5\cdot10^{2} < Pr\ Gr < 2\cdot10^{7}$

$$\alpha = A_2\left(\frac{\Delta t}{l}\right)^{1/4}. \quad (7)$$

c) $Pr\ Gr > 2\cdot10^{7}$

$$\alpha = A_3\Delta t^{1/3}. \quad (8)$$

For the air at the average temperature being $T_{av} = \frac{1}{2}(T_1 + T_0)$ the values of coefficients $A_{1\text{-}3}$ are the following: $A_1 = 0.28$, $A_2 = 1.07$, $A_3 = 1.05$.

For the case considered here $Pr\ Gr = 1.3\cdot10^{12}$ and, correspondingly, $\alpha = 6.8$ W/(m^2·K). Therefore, the total heat flux Q_1 from the kiln lateral surface will be equal to 5.07 MW, 2.1 MW due to convection and 2.97 MW due to radiation included.

A cement kiln heat exchange with a thermoelectric generator placed around its lateral surface

When a set of thermoelectric generators is placed around the lateral surface of the kiln (Fig. 2) whose hot side temperature should be higher than that of the environment, the heat flux off the kiln surface will decrease which is impermissible. Therefore, to ensure the initial heat removal, it is necessary to increase the kiln emissivity.

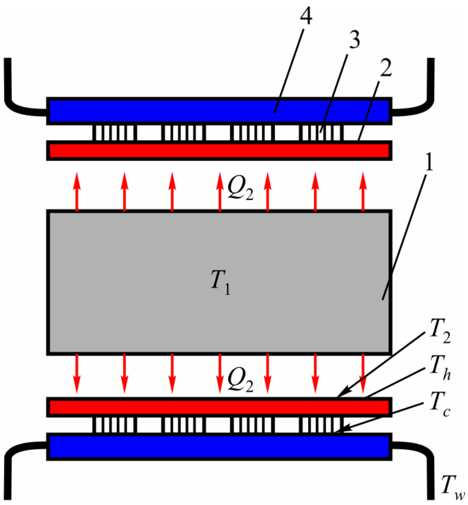

Fig. 4. A cement kiln model with a thermoelectric generator. 1 – a part of the kiln surface, 2 –a hot heat exchanger, 3 –thermoelectric modules, 4 – a cold water heat exchanger.

The total heat flux off the lateral surface of the kiln can be written in the form of

$$Q_2 = \varepsilon_1'\varepsilon_2\sigma S\left(T_1^4 - T_2^4\right) + Q'_{conv}, \quad (9)$$

Heat transfer due to convection Q'_{conv} can here be considered according to the formulae for thermal conductivity for a solid wall by way of introducing the equivalent air space heat conductivity factor.

The equivalent air space heat conductivity factor when heat emission due to radiation from one wall to another is neglected can be determined from the formula

$$\kappa_{eq} = \varepsilon_{conv}\kappa. \tag{10}$$

where κ is heat conductivity factor of the medium filling the air space (κ = 0.0355 W/(m·K) for the air average temperature of 150 °C); $\varepsilon_{conv} = f\,(Pr\ Gr)$ is the factor considering convection impact.

Calculation formulae for the convection factor are:

a) at $10^4 < Pr\,Gr\left(\frac{L_1}{L_2}\right)^k\left(\frac{d}{\delta}\right)^n < 10^7$

$$\varepsilon_{conv} = 0.062\left[Pr\,Gr\left(\frac{L_1}{L_2}\right)^k\left(\frac{d}{\delta}\right)^n\right]^{1/3} \tag{11}$$

b) at $10^7 < Pr\,Gr\left(\frac{L_1}{L_2}\right)^k\left(\frac{d}{\delta}\right)^n < 10^{10}$

$$\varepsilon_{conv} = 0.22\left[Pr\,Gr\left(\frac{L_1}{L_2}\right)^k\left(\frac{d}{\delta}\right)^n\right]^{1/4} \tag{12}$$

where: δ is the layer thickness, L_1/L_2 is the relation between the convection flux path length from the lower boundary of the heater to the cooler and the height of this path, *d* to the heater diameter. For the inclined cylindrical layer $L_1/L_2 = 1$, $k = 3$, $n = 0$. For the horizontal cylindrical layer $\frac{L_1}{L_2} = \frac{\pi r + \delta}{d + \delta}$, $k = 3$, $n = 0$.

At the value of the combination $Pr\,Gr\left(\frac{L_1}{L_2}\right)^k\left(\frac{d}{\delta}\right)^n < 10^3$ the impact of convection inside the gap is actually absent and only thermal conductivity is considered in calculations.

While defining the criteria the average temperature is taken as the determinant one

$$T_{av} = \frac{1}{2}\left(T_1 + T_0\right), \tag{13}$$

and the layer thickness δ (5 cm) is taken as the determinant, respectively.

For this case the value of $Pr\,Gr\left(\frac{L_1}{L_2}\right)^k\left(\frac{d}{\delta}\right)^n = 7.6\cdot 10^5$, and $\varepsilon_{conv} = 2.62$. Correspondingly, $\kappa_{eq} = 0.093$ W/(m·K), whereas the heat flux due to convection from the kiln lateral surface to the hot heat exchanger of the thermoelectric generator will surely depend on the temperature T_2 thus set.

The effect of the internal cylinder rotation on the heat emission in the problems like this, the Couette-Taylor problems, is considered via dimensionless parameters, namely, the Reynolds number Re_h which characterizes the forced circular flow, or the Taylor number. A modified Taylor number is highly convenient to use for these purposes [14].

$$Ta_m = \frac{\Omega^2 d^2 \delta^3}{2\nu\left(d + \delta\right)}\left(\frac{1697}{\pi^4}C\right), \tag{14}$$

$$C = 0.0571\left(1 - 0.652\frac{2\delta}{d}\right) + 0.00056\left(1 - 0.652\frac{2\delta}{d}\right)^{-1} \tag{15}$$

where Ω is the angular rotational velocity.

Before the secondary flows appear ($Ta_m < 1700$), the Nusselt number Nu^* is defined by the equation

$$Nu^* = 2 \tag{16}$$

and does not depend on either gas properties or the size and rotation velocity of the cylinder.

At the emergence of macro eddy secondary flows the Taylor number should be considered. Within the range of $Ta_m \approx 1700\ldots1\cdot10^5$ the heat transfer factor for the air is described by the empiric formula

$$Nu^* = 0.128 Ta_m^{0.367} \tag{17}$$

Within the range of $Ta_m \approx 10^4\ldots2\cdot10^8$

$$Nu^* = 0.42 Ta_m^{0.25} Pr^{0.25} \tag{18}$$

Within the range of $Ta_m \approx 10^7\ldots2\cdot10^9$

$$Nu^* = 0.28 Ta_m^{0.285}. \tag{19}$$

Therefore, when the kiln rotation is taken into consideration, the heat emission due to convection increases up to 2.2 times.

To find a new emissivity value for the kiln lateral surface ε'_1, required for the preset heat sink, it is necessary to obtain the balance between Q_1 and Q_2. In so doing, the temperature of the hot heat exchanger becomes the function of ε'_1. According to calculations, the value of hot heat exchanger temperature T_2 when the surface of the kiln is covered with a special paint with the emissivity from 0.80 to 0.99 is in the range from 80 to 172 °C (Fig. 5.).

The dependence of the thermopile efficiency on ε'_1 derived from the experimental dependences of η on the temperature difference ($T_h - T_c$) is presented in Fig. 6.

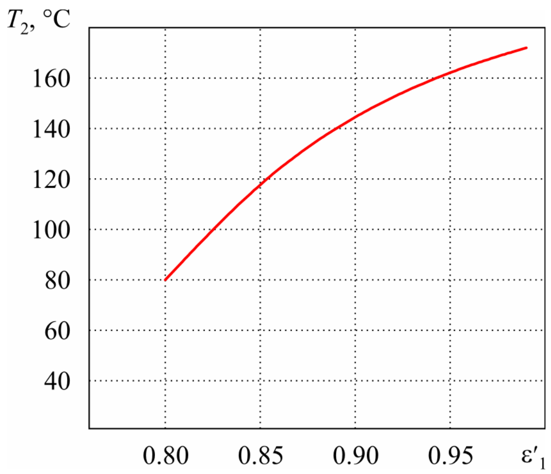

Fig. 5. Temperature of the hot heat exchanger as a function of kiln emissivity.

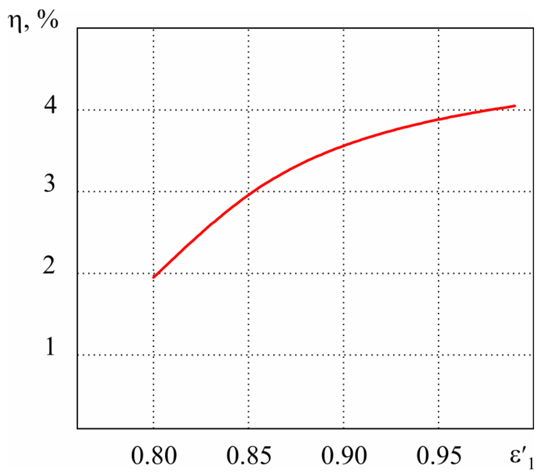

Fig. 6. Maximum efficiency of a thermopile as a function of kiln emissivity.

Thus, the maximum efficiency of dedicated thermoelectric modules of "Altec-M" company (Ukraine) will be 4.05 % taking into consideration that with the use of water cooling their cold side temperature $T_c \approx 30$ °C. In this case, the generator design capacity with account of the expenditures on the power supply of thermoelectric modules cooling system will be 130 W/m^2.

Conclusions

1. Mathematical modeling was obtained that allows estimating the impact of a thermoelectric generator on the cement kiln heat exchange, its rotation considered. The possibility of such impact elimination by way of changing the surface emissivity was determined.
2. The dependences were obtained of the maximum efficiency and temperature of the thermoelectric generator hot heat exchanger on the emissivity of the cement kiln surface.
3. The thermoelectric generator maximum efficiency was computed for the design of the cement kiln under discussion, the said efficiency being 4.05 %.
4. The generator designed capacity where the expenditures on the power supply of the thermoelectric modules cooling system are taken into account will equal to 130 W/m^2.

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