Modeling of Radiation Heat Transfer in Indirect Heating Process

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Abstract. *Correct evaluation of radiation in modeling of indirect or induction heating process is discussed. A newly offered approach introduces so called generalized convection and experimentally-numerical determination of its coefficient. The suggested algorithm is illustrated by typical example.*

Keywords: indirect heating, induction heating, thermal convection and radiation, boundary element method, generalized convection.

1. Introduction

The boundary conditions of temperature field of bodies heated indirectly or by induction in common gaseous media (air) are mostly given by convection and radiation. The intensity of the convective heat transfer between the heated body and ambient gaseous medium depends on the local physical circumstances and thickness of the laminar boundary layer of fluid surrounding the solid body. The heat flow obeys the Newton law

$$q_\mathrm{c} = -\lambda \frac{\partial T}{\partial n} = \alpha_\mathrm{c}\left(T - T_0\right) \tag{1}$$

where q_c denotes the heat flow from the body to the ambient medium due to convection, λ the thermal conductivity of the body, n the outward normal, T the surface temperature of the body, T_0 the temperature of the distant gas medium and α_c the convective heat transfer coefficient. Coefficient α_c is usually found experimentally or from the theory of similarity.

For the solid body in an unbounded gas medium the heat transport by radiation may approximately be quantified by the Stefan-Boltzmann law in the form

$$q_\mathrm{r} = C_\mathrm{r1} C_\mathrm{r2} \sigma\left(T^4 - T_0^4\right) = \bar{C}_\mathrm{r12} \sigma\left(T^4 - T_0{}^4\right) \tag{2}$$

where q_r denotes the heat flow from the body to the ambient medium due to radiation, $\sigma = (5.67032 \pm 0.0071) \cdot 10^{-8}\,\mathrm{Wm^{-2}K^{-4}}$ is the Stefan-Boltzmann constant, T the absolute temperature of the surface of the radiating body and T_0 the absolute temperature of the distant gas medium. Symbol $C_\mathrm{r1} \in \left(0,1\right)$ stands for the emissivity of the surface of the radiating solid body and $C_\mathrm{r2} \in \left(0,1\right)$ the emissivity of the ambient medium. The product of both above quantities $\bar{C}_\mathrm{r12}$ may be interpreted as the “effective” emissivity of the interface between the body and ambient medium.

Now the principal question is whether it is necessary to consider both mechanisms in every case or neglect one of the mechanisms with respect to the other. In older references (i.e. [1]) we can often find the opinion that up to certain temperatures (about 200 °C) the radiation can be neglected in comparison with the natural convection. Nevertheless, the elementary experience (see, for example, a radiating body of central heating) provides another idea. This was demonstrated by an example described in [2]. In some cases, however, the problem of induction heating should be completed by analysis of multiple reflection phenomena describing heat transfer between the heated body and surrounding surfaces. Some examples are described in [3], [4].

2. Generalized convection

We can say that the total transfer of heat from the solid body into the unbounded gas medium is characterized by heat flow q_{tot} given by the sum of the convective (1) and radiation (2) flows (the third mechanism – conduction – being neglected due to very poor thermal conductivity of common gaseous media)

$$q_{\mathrm{tot}} = q_{\mathrm{c}} + q_{\mathrm{r}} = \alpha_{\mathrm{c}}\left(T - T_0\right) + \sigma \overline{C}_{\mathrm{r12}}\left(T^4 - T_0^4\right). \tag{3}$$

After a simple rearrangement we can formally write

$$q_{\mathrm{tot}} = \alpha_{\mathrm{tot}}\left(T - T_0\right),\ \ \alpha_{\mathrm{tot}} = \alpha_{\mathrm{c}} + \alpha_{\mathrm{r}},\ \ \alpha_{\mathrm{r}} = \sigma \overline{C}_{\mathrm{r12}}\left(T + T_0\right)\left(T^2 + T_0^2\right). \tag{4}$$

This relation can be found, for example, already in [5]. But only in association with a simple experimentally-numerical algorithm for determining of the generalized coefficient α_{tot} it becomes practically applicable.

3. Experimentally-numerical determination of coefficient α_{tot}

The thermal flux at an arbitrary point M on boundary Γ between the solid body and unbounded gas medium is given by relation

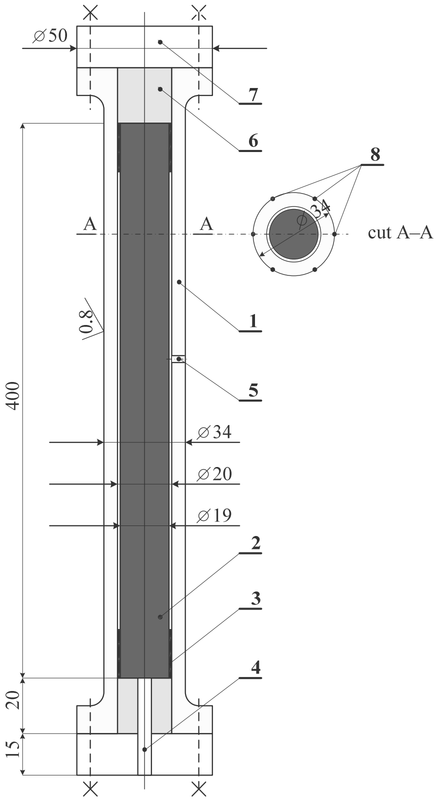
$$q_{\mathrm{tot}} = -\lambda \frac{\partial T}{\partial n} = \alpha_{\mathrm{tot}}\left(T - T_0\right). \tag{5}$$

Hence we can find the value of α_{tot} at point M provided that we know the values of T, T_0, λ and $\partial T / \partial n$. The experimental determination of the distribution of the surface temperature T, as well as temperature T_0 of the unbounded gas medium can sufficiently accurately be realized in any laboratory equipped with common apparatus. On the other hand, the direct measurement of $\partial T / \partial n$ on the surface of the same body is difficult by principle and always will be burdened by an error. More advantageous is to find this distribution by the Boundary Element Method (BEM) [6] that starts from the knowledge of the distribution of the surface temperature T. The particulars are described in [2].

4. Practical example of determination of α_{tot}

To simplify the description of the experiment, we will further work with temperatures in °C. Consider an unpolished steel shell in unmoving (steady) air, whose surface is heated to temperature $T_{\max}$ B 500 °C. The cylindrical shell **1** (see Fig. 1, left part) is assumed to be infinitely long, so that its temperature varies only in the radial direction, which can be expressed as $T = T\left(r\right)$. The aim of the experiment is to illustrate the experimentally-numerical algorithm for determination of coefficient $\alpha_{\mathrm{tot}}\left(T\right)$ described in the previous paragraph. Another partial aim is to compare the amount of heat transferred from the wall of the tube by convection and radiation.

The measuring device is depicted in Fig. 1, right part. It consists of the mentioned shell **2** on whose surface we investigate the values of α_{tot}, α_{c} and α_{r} as functions of the surface temperatures. These temperatures are measured by six thermocouples **1** placed on the surface of the measuring cylinder NiCr_NiAl and registered on the display of the measuring device **4**. The temperature of the ambient medium T_0 is measured by a mercury dilatation thermometer **3** that is not influenced by radiation from the measuring cylinder (combination glass + mercury is a very good reflecting surface for infrared radiation). The internal power heating the measuring cylinder **2** (and affecting also its surface temperatures) is controlled by temperature control unit **5** and evaluated by wattmeter **6**. The measuring cylinder used for the described experiment is depicted in details in Fig. 1 left. It consists of an electrical resistive heating element **2** of maximum power 500 W, inserted by means of the distance rings **3** (asbestos tape) into a steel (carbon steel, its thermal conductivity $\lambda(T)$ is shown in Fig. 2 left) cylindrical shell **1**. Its surface is equipped by six thermocouples NiCr_NiAl **8**. For suppressing the variations of temperature of the measuring cylindrical shell **1** in the axial direction both ends of the heating element **2** are equipped with thermal insulation **6** (fiberglass). The cylindrical shell **1** is also closed by asbestos insulating flanges **7**.



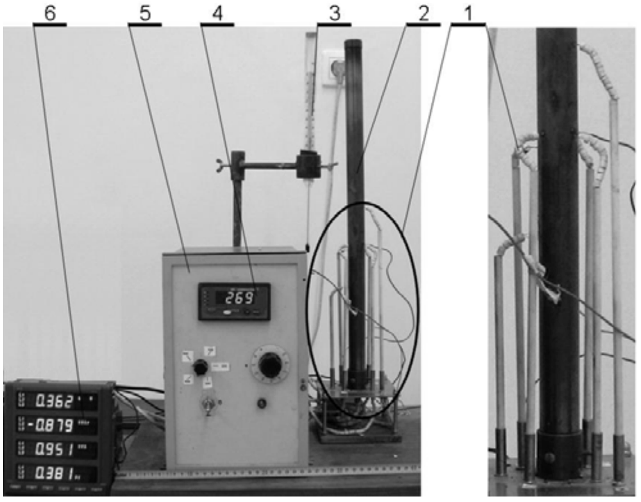


Fig.1 left: measured sample: **1** –cylindrical shell from carbon steel**,** **2** – heating element 500 W, **3** – distance rings (asbestos tape), **4** – inlet for feeding of the heating element, **5** – inlet for measurement of the internal temperature, **6** – thermal insulation (fiberglass), **7** – asbestos insulation flanges, **8** – thermocouples

Fig.1 right: measuring stand: **1** – thermocouples, **2** – measuring cylinder, **3** – mercury dilatation thermometer, **4** – measuring device, **5** – temperature control unit, **6** – wattmeter

With respect to the capabilities of the registration device, all measurements could always be carried out only in steady state. Therefore, the measuring cylinder was designed in such a manner that would ensure (at relatively uniform thermal field) low thermal inertia. Fig. 2 left shows the temperature dependence of thermal conductivity of the cylindrical shell, Fig. 2 right depicts the results of the experiment. As the distribution of temperature in the wall of the shell depends on radius r only, it is not necessary to apply the boundary element method to find $\partial T / \partial n$ because this value may easily be determined from the analytical solution.

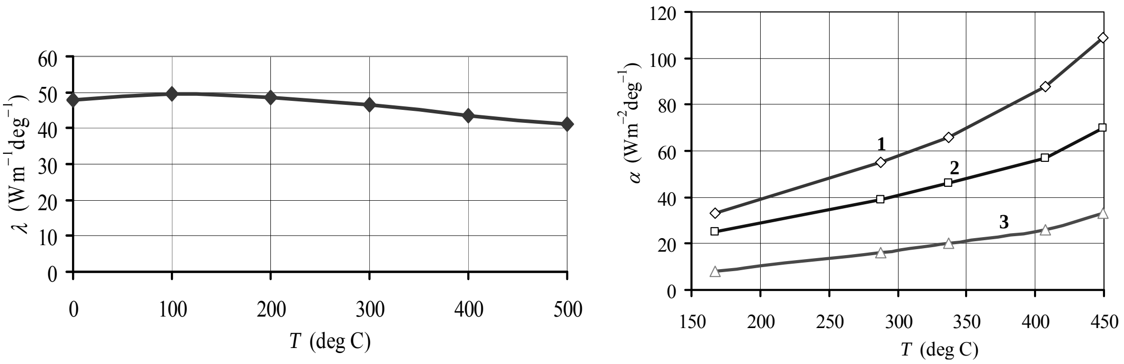


Fig. 2 left: the temperature dependence of thermal conductivity of the used steel shell

Fig. 2 right: measured temperature dependencies of particular coefficients of heat transfer

1 – α_{tot} (experiment), **2 –** α_{c} (see [7]), **3 –** α_{r} calculated from (4)

Fig. 2 right shows that the effect of radiation in the investigated range of the temperatures $T \in \langle 150, 450 \rangle$ °C is somewhat smaller than the effect of convection, but in no case negligible. All these mechanisms of heat transfer grow with the increase of the surface temperature T.

5. Conclusions

The above theoretical conclusions agree well with the results described in references. Nevertheless, in order to confirm their general validity, the authors prepare an experiment making possible to experimentally find the value of α_{tot}. But it would be also possible to prepare specific experiments providing (with a sufficient accuracy) the values α_{c} and $\overline{C}_{\mathrm{r12}}$.

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