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Comparison of methods for determining the convective heat transfer coefficient for the induction-heated charge

Abstract. *This paper presents a comparison of convective heat transfer coefficients determined by use of different methods. The coefficients were estimated from dimensionless numbers (5 variants) and by numerical fluid dynamics simulation (4 variants). A computer simulation of induction heating process of a steel non-magnetic workpiece in a vertical induction heater was adopted as a calculation model. Except for the value of convective heat transfer coefficient also the influence of its changes on temperature distribution in the heated workpiece was monitored.*

Streszczenie*. W pracy porównano wartości współczynników konwekcyjnej wymiany ciepła wyznaczonych różnymi metodami. Współczynniki wyznaczono w oparciu o liczby kryterialne (5 wariantów) i bazując na symulacji numerycznej mechaniki płynów (4 warianty).Oprócz wartości współczynnika wymiany ciepła przez konwekcję kontrolowano także wpływ zmiany tego współczynnika na rozkład temperatury w nagrzewanym wsadzie. (****Porównanie metod wyznaczania współczynnika konwekcyjnej wymiany ciepła dla wsadu nagrzewanego indukcyjnie****).*

Keywords: convective heat transfer coefficient, dimensionless numbers, fluid dynamics, induction heating.
Słowa kluczowe: współczynnik wymiany ciepła przez konwekcję, liczby kryterialne, dynamika płynów, nagrzewanie indukcyjne.

Introduction

Numerical modelling of physical processes is becoming a method more and more frequently used to accelerate the design of many technical devices. In the case of some technologies a few physical fields have to be modelled simultaneously, and induction heating is one of the processes that require an analysis of at least two physical fields during modeling. Both electromagnetic field and temperature field have to be modelled in this case. The calculation model for each of these fields has its own specific characteristics. This article focuses on the temperature field model. A complete calculation model of temperature field for induction heating should include the whole heating system, i.e. the heated workpiece and inductor together with thermal insulation and cooling system. In order to conduct a proper analysis, the following factors have to be taken into consideration: radiative heat transfer between the system components (typically between the heated workpiece and thermal insulation of the inductor) and cooling of the workpiece by flowing air. The influence of the model of radiative heat transfer on temperature distribution in workpiece was discussed by the Authors in [1], whereas in this article the research was concentrated on the effect of the simplifications concerning heat transfer and connected with the convective motion of the air surrounding the workpiece. The process of induction heating of a cylindrical charge in a vertical heater was adopted as a model. Such calculation model should allow for an analysis of electromagnetic field and temperature field. In the latter the motion of air around the workpiece may pose some problems as its calculation requires a coupling of three fields: electromagnetic field, temperature field, and fluid dynamics field. Another problem is that it is symbolic calculations that are typically used in induction heating, while in the other two cases, i.e. in temperature field analysis and fluid dynamics analysis, these are calculation in the time domain. In order to avoid a coupled analysis of three physical fields, heat transfer between the workpiece and ambient air is modelled with the use of convective heat transfer coefficient. In this way a great amount of time can be saved because convective heat transfer coefficient is quite easily determined by methods based on dimensionless numbers, and owing to this the analysis of flow field can avoided. Additionally, using the boundary condition in the form of equation (1), the calculation model can be limited to the area of the heated workpiece.

$$(1) \qquad -\lambda \frac{\partial T}{\partial n}_P = \alpha (T - T_o) + \varepsilon \sigma (T^4 - T_o^4)$$

where: λ – thermal conductivity, W/(mK); T – temperature, K; α – convective heat transfer coefficient, W/(m^{2}K); ε – total emissivity, -; σ – Stefan-Boltzmann constant, W/(m^{2}K^4).

The presented experiment was focused on the influence that the value of convective heat transfer coefficient has on temperature distribution in the induction heated workpiece.

Calculation model

A cylindrical induction heater heating a steel non-magnetic workpiece was adopted as a calculation model. The basic dimensions of the system presented in Figure 1 are as follows: workpiece radius r_w = 20 mm, height of workpiece h_w = 100 mm, air gap a_g = 7 mm, thickness of inductor thermal insulation w_i = 5 mm, inductor coil height h_u = 12 mm, inductor wall thickness g_s = 2 mm, distance between coil turns h_{iw} = 5 mm.

As part of the experiment, convective heat transfer coefficient was determined by different methods. Two families of methods were used. The first group encompasses the methods based on dimensionless numbers, and they were used to determine the coefficient value for the edge (surface) bc. The other technique to determine the coefficient was a numerical fluid mechanics simulation, which made it possible to determine the coefficient value for edges ab, bc and cd (Fig.1).

The methods of determining convective heat transfer coefficient based on dimensionless numbers require that the conditions of heat release should be stipulated. However, these conditions are defined with different degrees of precision, starting from very general, including the Rayleigh number and unspecific information about the surface (vertical, horizontal), to more precise stipulations. The system under consideration corresponds to a configuration called annular gap [2]. The division selection criteria on which to decide what kind type of arrangement should be chosen are not very precise. For this reason, as part of the experiment, convection coefficients were also determined based on the model of heat release with free liquid flow in an open system in three different configurations: a vertical surface, a vertical cylinder with a height much bigger than diameter, a vertical cylinder of a given diameter and height.

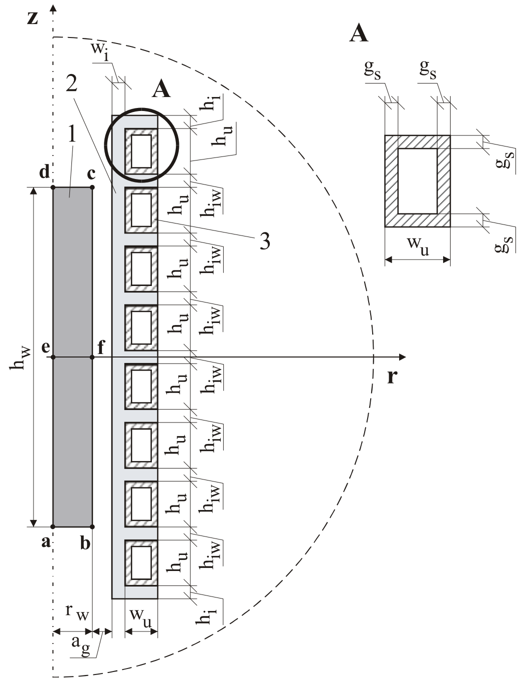

Fig.1. Model of induction heater

In conclusion, the value of heat release was determined for 5 calculation models based on dimensionless numbers: 4 for open system and 1 for closed system.

- A1 vertical surface model for transition flow;
- A2 verticalsurface model for turbulent flow);
- A3 vertical cylinder with diameter d < 0.61 m and height much bigger than diameter;
- A4 short vertical cylinder with diameter d < 0.31 m;
- A5 vertical cylindrical annulus.

Apart from the calculations of the convective heat transfer coefficients based on dimensionless numbers, the same coefficient was determined based on a numerical analysis of the flow and temperature fields. Depending on the expected type of flow, the calculations are carried out for a calculation model of laminar flow or turbulent flow. The assessment of the flow characteristics regime is again based on dimensionless numbers, and in this particular case on the Reynolds number. For the model considered the Reynolds number ranges from 5 to 2500, depending on the estimated flow speed, which means that it takes on the values characteristic of laminar and transition flows. All in all, four calculation variants were conducted using numerical analysis of flow field [3], [4] and temperature field. They differed in the type of the flow modelled, which was either laminar or turbulent flow, and in intensity of heating, which could be either intensive or less intensive.

- A6 less intensive heating, laminar calculation model;
- A7 less intensive heating, turbulent calculation model;
- A8 intensive heating, laminar calculation model;
- A9 intensive heating, turbulent calculation model.

Calculation model based on dimensionless numbers

Heat flow modelling for free liquid flow in open systems is based on dimensionless Nusselt number [2]. The Nusselt number is determined as a function of the Rayleigh number, which in turn is determined from the product of the Grashoff and the Prandtl numbers [2].

$$\alpha_k = \frac{C\left(\frac{g\delta^3 \beta \Delta T}{a\nu}\right)^n \lambda}{\delta} \tag{2}$$

where: α_k – convective heat transfer coefficient, W/(m^{2}K); δ – characteristic dimension; C, n – constants adopted depending on the assumed geometry of the system and flow conditions; g – gravitational acceleration, m/s^2; β – volumetric thermal expansion coefficient, for temperature T expressed in ^{o}C is $\beta = \frac{1}{T+273}$; a – thermal diffusivity, m^2/s; ν – kinematic viscosity, m^2/s.

After putting the adequate values into the formula, the convective heat transfer coefficient is expressed by formula (2), in which beside the characteristic dimension and material properties are parameters C and n, which are dependent on the geometry of the system and conditions of the flow. For these two cases the surface height is the characteristic dimension, while parameters C and n depend on the Rayleigh number expressed by formula (3)[2], [5].

$$\mathrm{Ra} = \frac{g\delta^3 \beta \Delta T}{a\nu} \tag{3}$$

Depending on the expected workpiece temperature (temperatures from 30 to 1000^{o}C were considered), the Rayleigh number ranged from $6.37 \cdot 10^6$ to $2.59 \cdot 10^7$, which means that it encompassed the range of transitional (*A1*) and turbulent (*A2*) flow types. The values of convective heat transfer coefficient for variants A3 and *A4* are also determined on the basis of equation (1), but the values of coefficients C and n as well as of characteristic dimension are different. In this case the diameter of the cylinder is taken as characteristic dimension, and the values of coefficients are the following: for variant *A3* C = 0.45, n = 1/4, and for variant *A4* C = 0.55, n = 1/4.

The determination of heat transfer for free liquid flow in closed systems is based on different criteria. The basic quantity determined is effective thermal conductivity λ_z taking form (4) [2].

$$\lambda_z = \left(1 + \frac{C_1 Ra^n}{Ra + C_2}\right)\lambda_p \tag{4}$$

where: λ_z – effective thermal conductivity, W/(mK); λ_p – specific thermal conductivity of fluid in gap, W/(mK); Ra – Rayleigh number, -; C_1, C_2, n – constants adopted depending on geometric configuration.

The determination of convective heat transfer coefficient on the basis of the determined effecitve thermal conductivity again makes use of the known temperature of the surfaces washed by the fluid and is expressed in formula (5).

$$\alpha_k = \frac{\lambda_z (T_1 - T_2)}{\ln\left(\frac{(r_w + a_g)}{r_w}\right) r_w (T_1 - T_f)} \tag{5}$$

where: α_k – convective heat transfer coefficient, W/(m^{2}K); λ_z - effective thermal conductivity, W/(mK); T_1 – workpiece temperature, ^{o}C; T_2 – temperature of inductor's thermal insulation, °C; T_f – air temperature, °C; r_w – workpiece radius, m; a_g – air gap thickness, m;

For the annular gap the values of constants are: C_1= 0.1190, C_2 = 1,45·10^4, n = 1.270. The value of effecitve thermal conductivity is determined with the assumption that the temperature of the surface emitting and receiving heat to/from the flowing liquid is known (in our case it is the temperature of the workpiece and thermal insulation of the inductor).

Calculation model based on a numerical analysis of the flow field and temperature field

The calculation experiment consisted of two basic variants differing in the intensity of heating the workpiece, which was less intensive (inductor current of 1 kA) for variants *A6* and *A7* and intensive (inductor current of 3 kA) for variants *A8* and *A9*.

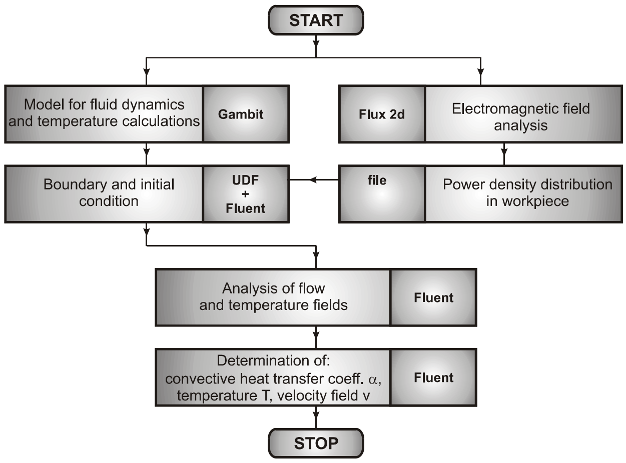

Fig.2. Block diagram for calculations using numerical analysis

The electromagnetic analysis was conducted by program Flux 2d [6], the temperature field analysis by program Fluent [3]. The coupling of electromagnetic field and temperature field analyses is a weak coupling, and power density determined by Flux was applied as the initial condition for the calculations of temperature field by use of own procedure UDF. The block diagram for the calculations can be seen in Figure 2.

Results

The first stage of the experiment consisted in determining the heat transfer coefficients using different methods. Next, a coupled analysis of the electromagnetic and temperature fields was conducted for the determined range of coefficients values in order to examine how a change in the value of convective heat transfer coefficient affects the temperature. In Figure 3 can be seen a change in convective heat transfer coefficient for variants *A1* to *A5* (determined based on dimensionless numbers). As mentioned in the introduction, the models adopted for analysis do not always correspond to the real objects precisely. The model most similar to the considered case was variant *A5*. In this case, the values of convective heat transfer coefficient, depending on temperature, range from 9.18 W/(m^{2}K) for 100°C to 14.4 W/(m^{2}K) for 1000°C. In this variant the highest values of α_k coefficient were obtained. The lowest were obtained for variant *A2* and *A1*, that is for the model corresponding to a plane surface. In this last case the values α_k range from 6 W/(m^{2}K) to 9.7 W/(m^{2}K). It must be stressed that the time needed to determine the convective heat transfer coefficient by use of methods based on dimensionless numbers is so short that it can be ignored in calculations process.

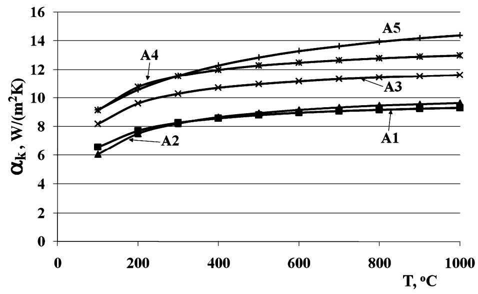

Fig.3. Values of convective heat transfer coefficient determined by models based on dimensionless numbers

The convective heat transfer coefficients for the numerical experiment are presented in Figure 4.

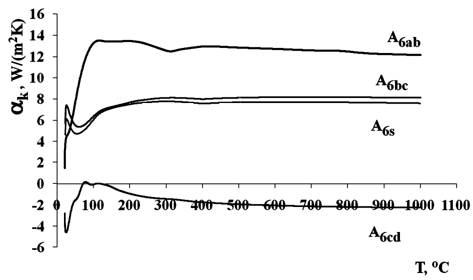

Fig.4. Values of alpha coefficients determined from the numerical laminar model – variant *A6*

In the experiment, these coefficient values were controlled for particular edges (surfaces plane) of the calculation model, that is the bottom edge of the workpiece (index ab), lateral edge (index bc) and upper edge (index cd). The average value of convective heat transfer coefficient was additionally determined as the weighted mean dependent on the surface (index s). Figure 4 indicates that the heat is collected from the lower and lateral surfaces of the workpiece, while the upper surface is heated because it is washed by the air that warmed by the lateral edge (sufrace) of the workpiece. For the lateral edge the values of convective heat transfer coefficient for laminar and turbulent models do not differ significantly, (they are about 7 W/(m^{2}K)). Determining the heat transfer coefficient by use of numerical methods of fluid mechanics is a time-consuming activity. The calculation time for a given variant was about four days. The results obtained are precise so that the differences in the values of convection on particular edges (surfaces) boundaries of the calculation model can be taken into consideration. Maximum difference in the α_k values determined for variants *A1* to *A9* is about 7 W/(m^{2}K). Similar results were obtained in [4].

Electro-magneto-thermal calculations by program Flux 2d were the last stage of the research. Sixteen variants were calculated. They differed in the value of coefficient α_k (its values being 5, 8, 10, 15 W/m^{2}K), in the radiative heat transfer being allowed for ε = 0 or 0.6, and in the heating intensivity (I = 1 kA or 3 kA). Maximum and minimum temperatures and temperature distribution for cross section ef (Fig.1) were controlled. List of variants can be seen in Table 1.

Table 1. Calculation variants checking the influence of the values of α_k on the value and distribution of temperature

Variant	Value ε, -	Value α_k W/(m^{2}K)	Inductor current I, A
et1/et9	0	15	1000/3000
et2/et10	0	10	1000/3000
et3/et11	0	8	1000/3000
et4/et12	0	5	1000/3000
et5/et13	0.6	15	1000/3000
et6/et14	0.6	10	1000/3000
et7/et15	0.6	8	1000/3000
et8/et16	0.6	5	1000/3000

As expected, the differences in temperatures among the variants were bigger for less intensive heating than for intensive heating. In the cases where radiation was not allowed for (Fig. 5) the maximum differences in the minimal temperature were 93^{o}C, which is about 10% of the final heating temperature. After the radiation having been considered, the values of deviations decreased to about 40^{o}C. In intensive heating the influence of the convective heat transfer coefficient was rather slight and did not exceed 1% (Fig. 6).

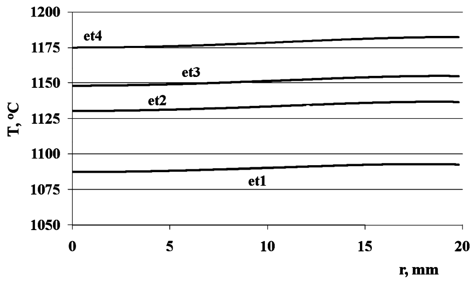

Fig.5. Temperature distribution at cross section *ef* calculated over the heating time of 400 s for variants *et1* to *et4*

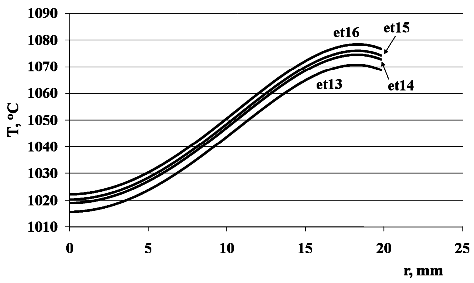

Fig.6. Temperature distribution at cross section *ef* calculated after the heating time of 40 s for variants *et13* to *et16*

As expected, the differences in temperatures among the variants were bigger for less intensive heating (Fig.5) than for intensive heating. In the cases where radiation was not allowed for (Fig.6) the maximum differences in the minimal temperature were 93^{o}C, which is about 10% of the final heating temperature. After the radiation having been considered, the values of deviations decreased to about 40^{o}C. In intensive heating the influence of the convective heat transfer coefficient was rather slight and did not exceed 1% (Fig.6).

From the conducted experiment it can be concluded that in the case of intensive heating it is sufficient to determine the convective heat transfer coefficient by an approximate method based on dimensionless numbers, but in the case of less intensive heating a coupled elektromagnetic-temperature-fluid mechanics analysis should be considered. Otherwise, the convective heat transfer coefficient must be determined by the numerical methods of fluid mechanics.

Conclusion

The calculation experiment presented in this paper focused on a comparison of the values of convective heat transfer coefficients obtained by different methods and on the influence of the changes in the coefficient on the temperature distribution in the induction heated workpiece. The obtained values of convective heat transfer coefficient ranged from about 6 to 15 W/(m^{2}K).

In order to compare the influence of the change in α_k coefficient on temperature distribution in the heated workpiece 16 calculation variants were prepared. These variants differed in the value of the adopted convective heat transfer coefficient ranging from 5 to 15 W/m^{2}K, in heating intensivity, and in the radiative heat transfer being allowed for or not. In variants *et1* to *et8* (less intensive heating), a significant influence of coefficient α_k on the workpiece temperature was observed. The differences in temperatures were about 90^{o}C. When radiative heat transfer was taken into account, the difference was decreased by half, to about 40^{o}C, which is about 10 and 4% of the final temperature of the workpiece. In variants *et9* to *et16* (intensive heating) the influence of the change in the convective heat transfer coefficient on the temperature of the heated workpiece was far smaller, that is around 10^{o}C , which is about 1% of the final temperature of the workpiece.

On the basis of the results obtained it can be concluded that for intensive heating it is sufficient to determine the convective heat transfer coefficient by approximate methods based on dimensionless numbers, while for less intensive heating one should consider heat transfer modeling by fluid mechanics numerical simulation.

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