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MATHEMATICAL MODEL OF ONE-DIMENSIONAL HEATING AND COOLING OF FLAT CERAMIC BODIES INSIDE THE TUNNEL KILN

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Heat transfer inside the tunnel kiln, which serves for producing ceramic bodies by reactive sintering of kaolinite raw material, has been modelled. The procedure for solving the model as well as adequate computer program have been suggested in order to achieve two goals: determining of (optimal) length of thermal treatment for required temperature in the center of the body and vice versa, calculating the temperature in the center of the body for given length of process. Also, correlation which defines temperature change in the center of the body along the tunnel was determined. Computer program was applied to the tunnel kiln already installed in IGM-Kanjiza and optimal length of thermal treatment was determined. The suggestion to shorten the process in the examined kiln was given.

1. INTRODUCTION

In order to provide all necessary conditions for sintering process inside the heavy ceramic elements they should be dried and after that heated, by combustion products, in a tunnel kiln up to achieving optimal temperature. An optimal regime should be kept, for a certain period of time, until all chemical as well as phase transformation were accomplished. At the end of the thermal treatment, products have to be cooled by the atmospheric air, with the aim to stop changes in the material and to obtain acceptable output temperature.

Many papers, which are dealing with mathematical modelling of heat transfer processes inside the industrial kilns, have been published till now. They shed the light upon the problem from the point of view of kiln design, simulation, optimization and/or control. In paper [1] a thorough review of well known methods for calculating (primary radiative) heat fluxes exchanged inside the kilns of different types and geometries has been given.

A procedure suggested in this paper is a kind of combination, obtained by uniting two methods: "long furnace" and "zone" method, applied to determining (convective and radiative) heat fluxes exchanged between gas and ceramic bodies, which are assumed flat. Conductive flux through bodies is modelled by Fourier's partial differential equation for unsteady conduction. Its solution corresponds to the temperature in the center of the ceramic body as a function of time. Once determined, temperatures can be correlated with the body position related to the entrance of the tunnel as the origin of coordinate system. Both results (temperature values and the model of their changes along the tunnel) are equally important; first shows the influence of the local thermal phenomena on the material itself while the second concerns the equation that generalizes thermal processes.

2. SYSTEM DESCRIPTION AND ACCEPTED ASSUMPTIONS

Mathematical model which has been suggested concerns a tunnel kiln for producing the roof tiles, which are assumed one – dimensional from the point of view of heat transfer (see Fig. 1.). Mentioned approximation enables the application of analytical unsteady state solution.

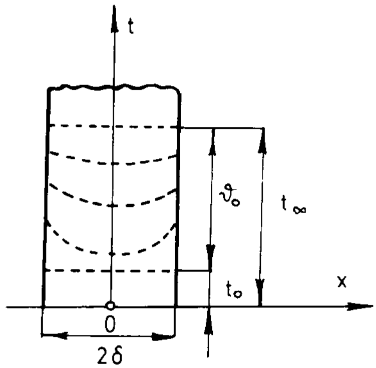

Fig. 1. Temperature evolution in time in a ceramic body.

Heating and cooling processes are supposed to be consisted of successive unsteady heat conduction steps through the ceramic bodies exposed to the influence of gas (air) at a constant temperature. Consequently, a tunnel of a kiln could be divided into the short zones, filled with the fluid at a constant temperature as well as a ceramic bodies which temperature asymptotically tends to the temperature of surrounding gas.

The heat exchange implies the ideal mixing of gas streams inside every tunnel zone, therefore the assumption that each ceramic body is exposed to the gas streams along both of its boundary surfaces equally might be accepted. Such zones also, give the opportunity for expressing the fluid and material physical properties in the form of parameters dependent on local temperatures, gas mixture composition etc.

3. MODELLING OF HEAT TRANSFER PROCESSES IN PARTICULAR ZONE

3. 1. Mathematical Model

3.1.1. Heat Transfer by Coupled Convection and Radiation

Heat energy is exchanged between environment and ceramic bodies by both convection and radiation. Mentioned phenomena define boundary condition for the partial equation (9) of the model i.e. Fourier equation for unsteady state conduction of thermal energy.

Typical of gas regime inside the tunnel of a kiln is: $GrPr<10^9$ so that natural convection could be assumed as dominant. Consequently, Nu-criterion should be calculated by applying one of very well known correlations, such as [2]:

$$\mathrm{Nu} = 0.421\,(\mathrm{Gr_H Pr^2})^{1/4}, \tag{1}$$

which lead to:

$$\alpha_{\mathrm{con}} = \mathrm{Nu_H}\lambda/H. \tag{2}$$

As a characteristic dimension (*H*), a height of a ceramic bodies pile has been accepted.

As far as radiation heat exchange between working fluid and ceramic bodies is concerned, it has to be emphasized that the radiation should be taken into consideration (especially because of the presence of CO_2 and H_2O molecules) inside the heating zone while in the zone of cooling by air it can be neglected.

The "mean beam length" concept is suggested for determining of emissive characteristics of gas mixture which composition (p_{CO_2} and p_{H_2O}) is known. Namely, if a mean beam length is determined for a given system geometry [1–4] then the emissivity of each gas component will be expressed as a function of so called "optical depth" $(X = p \cdot l) : \varepsilon_{CO_2} = \mathrm{f}_1(p_{CO_2} \cdot l)$ and $\varepsilon_{H_2O} = \mathrm{f}_2(p_{H_2O} \cdot l)$.

Total emissivity of gas mixture couldn't be obtained by simple addition of emissivities determined for partial gas components because of the fact that certain parts of two gas compounds spectra are overlapped one by another. So, a correction should be applied:

$$\varepsilon_{\mathrm{g}} = \varepsilon_{CO_2} + \beta\varepsilon_{H_2O} - \Delta\varepsilon. \tag{3}$$

Once defined, total emissivity determines total energy emitted by gas (in accordance with Stephan-Boltzmann law):

$$E = \varepsilon_{\mathrm{g}} C_0 \left(\frac{T_{\mathrm{g}}}{100}\right)^4. \tag{4}$$

On the other hand, the energy emitted by ceramic bodies and absorbed into gas molecules must be in proportion with gas absorptivity. There is a general relation among mentioned parameters:

$$\alpha_{\mathrm{g}} = \left(\frac{T_{\mathrm{g}}}{T_{\mathrm{m}}}\right)^{\beta} \varepsilon_{\mathrm{g}}(T_{\mathrm{m}}, X), \tag{5}$$

where T_{g} and T_{m} denote absolute temperature values of gas and material respectively.

Relation (5) is in agreement with Hottel's empirical expression for CO_2 (where $\beta = 2/3$) and H_2O (in which case $\beta = 1$). Total absorptivity of gas mixture is equal to the sum of particular absorptivity values.

In the case when material emissivity (ε_{m}) is greater than 0.8 energy exchanged between hot fluid and ceramic bodies can be estimated by applying the approximative relation [1–4]:

$$\Phi = \frac{1}{2}(\varepsilon + 1)C_0\left[\varepsilon_{\mathrm{g}}\left(\frac{T_{\mathrm{g}}}{100}\right)^4 - \alpha_{\mathrm{g}}\left(\frac{T_{\mathrm{m}}}{100}\right)^4\right] = \alpha_{\mathrm{rad}}(t_{\mathrm{g}} - t_{\mathrm{m}}), \tag{6}$$

that can be used for calculation of radiative heat transfer coefficient:

$$\alpha_{\text{rad}} = \frac{\Phi}{t_g - t_m}. \tag{7}$$

The total heat transfer coefficient of coupled convection and radiation should be obtained by addition:

$$\bar{\alpha} = \alpha_{\text{con}} + \alpha_{\text{rad}}. \tag{8}$$

In that form it can be applied in the boundary condition for analytical solving of heat conduction equation (9).

3.1.2. One-dimensional Conduction through Ceramic Bodies

Fundamental equation which describes unsteady state conduction of heat through a ceramic body (thin enough to be treated like one-dimensional system) is Fourier's equation:

$$\frac{\partial \vartheta}{\partial \tau} = \frac{\partial^2 \vartheta}{\partial x^2}. \tag{9}$$

From Fig. 1 it is obvious that ϑ represents a temperature difference:

$$\vartheta = t - t_\infty, \tag{10}$$

which initial value starts from maximum

$$\vartheta_0 = t_0 - t_\infty \tag{11}$$

and (exponentially) approaches zero during a heat treatment.

Due to the symmetry of heating (cooling) process and if λ = const it is possible to solve the problem only for one half of a plate, using following boundary conditions:

$$\begin{aligned} &\text{a) IN A CENTER OF A PLATE} \quad (x=0): \quad \left(\frac{\partial \vartheta}{\partial x}\right)_{x=0} = 0 \ \text{(symmetricity)} \\ &\text{b) AT A SURFACE OF A PLATE} \quad (x=\delta): \quad \left(\frac{\partial \vartheta}{\partial x}\right)_{x=\delta} = -\frac{\alpha}{\lambda}\vartheta_{x=\delta}. \end{aligned} \tag{12}$$

It is well known that so simplified model, accompanied with adequate initial and boundary conditions (11) and (12), has an analytical solution. For the central plane of a plate it can be expressed as a sum of infinite series:

$$\Theta(\tau) = \frac{\vartheta}{\vartheta_0} = \sum_{i=1}^{\infty} \frac{2\sin\alpha_i}{\alpha_i + \sin\alpha_i \cos\alpha_i} \mathrm{e}^{-\alpha_i^2 \mathrm{Fo}(\tau)} = \sum_{i=1}^{\infty} \mathrm{f(Bi)}_i \mathrm{e}^{-\alpha_i^2 \mathrm{Fo}(\tau)}, \tag{13}$$

whose terms are functions of both Bi– and Fo– criteria. The first represents the ratio of inside material resistance

$$R_\lambda = \delta/(\lambda S) \tag{14}$$

and outside gas layer resistance

$$R_\alpha = 1/(\bar{\alpha} S). \tag{15}$$

Building materials with high content of clay (kaolinite) posses thermal conductivities ($\lambda < 1$ [W/mK]) between conductivity values typical of metals and insulators. Having in mind possible $\bar{\alpha}$– values (for natural convection coupled with heat radiation) as well as small thickness of treated samples it can be concluded that building ceramic materials are characterized by: $0 < \mathrm{Bi} < 10$, i.e. Bi– criterion differs from the values typical of both metals ($\mathrm{Bi} \to 0$) and insulators ($\mathrm{Bi} \to \infty$). Fo– criterion, which contains time as a parameter, influences the body temperature (Eq. (13)) exponentially.

It was proven that summarizing four terms (usually presented in tabular form [3]) gives quite acceptable analytical solution of the time - developed process.

3.2. Computer Program

3.2.1. Data

For successful solving of mathematical model a computer program was developed, which requires several groups of input - data.

Firstly, it is necessary to know thermophysical properties of material itself where λ and C_p can be specified either as the constants, for all the kiln, or as the functions of local temperature (constants for each zone, but variable for the kiln). The second alternative is better, because it allows more precise predicting of material properties, primary dependent on temperature.

Geometrical characteristics of a particular ceramic body, pile of bodies as well as a crossection and length of a tunnel have to be given. Also, data referred to gas mixture emissivity and absorptivity should be known. Finally, vectors of gas and air measured temperatures for each particular zone have to be specified.

Unvariable data were given in a form of three following matrices:

- thermophysical characteristics of combustion products for a relevant temperature interval;
- thermophysical characteristics of air, for a relevant temperature interval either;
- parameters to define analytical solutions in terms of Bicriterion.

Besides necessary physical data, the procedure requires a certain number of "numerical data" (space and time steps, tolerated calculating error etc.).

3.2.2. The Structure of the Program

General algorithm for solving a heat transfer mathematical model is presented in Fig. 2. The algorithm starts from reading all relevant data for material, the ceramic body, the pile of bodies and the kiln itself. It is followed by specifying the temperature distribution of working fluid along the tunnel.

The next step of the procedure is providing the boundary condition for fundamental equation of the model (Eq. (13)) i.e. thermal characterization of fluid in the tunnel. So, algorithm proceeds by taking the data stored in adequate files for working fluids (combustion products for the first and air for the second stage of

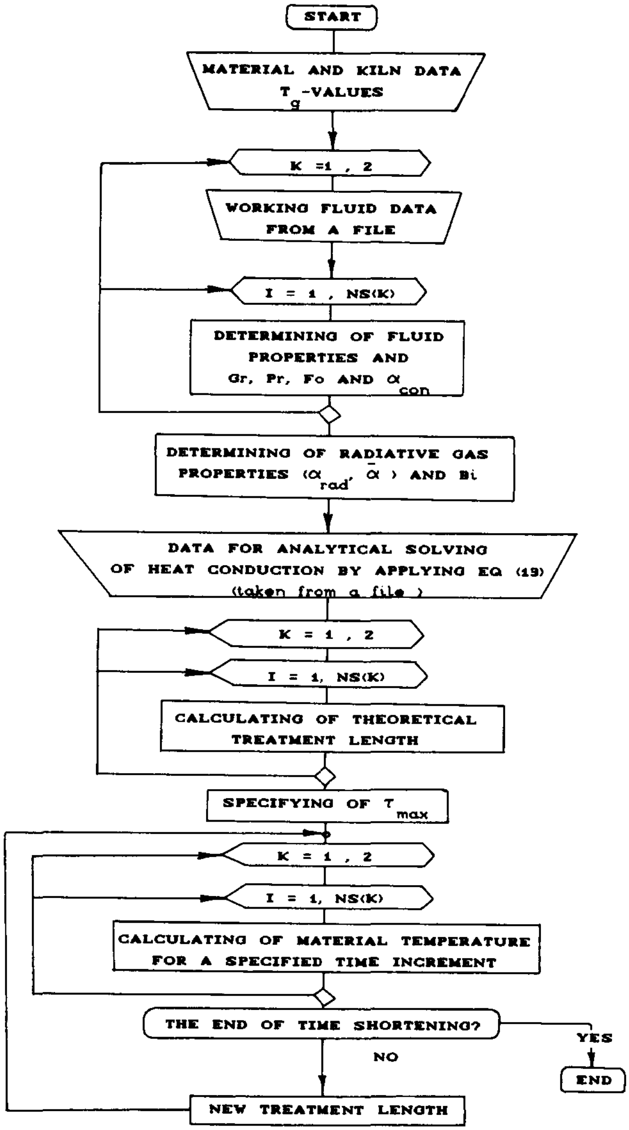

Fig. 2. General algorithm for solving of heat transfer model.

the process). By employing linear interpolation of tabulated values ϱ, C_p, μ and λ are determined, as the parameters dependent on local temperatures (constants in a zone, but variable along the kiln). Based on thermophysical properties of fluids Gr–, Pr– and timeless part of Fo– criteria as well as α_{con} are calculated, for every zone of a kiln. After that, the convective-radiative characterization of combustion products, only for the zones in the heating regime, is performed.

The main part of the algorithm is solving of Fourier equation in order to determine optimal length of thermal treatment which guarantees achieving the material temperature (in the center of the body), for all zones of the tunnel kiln, so that predetermined sintering temperature can be reached. This part of the procedure consists of two steps.

Firstly, hypothetical process is analyzed that lasts long enough to enable achieving the temperature of the material which approaches the temperature of the surrounding gas (see Fig. 3.) to a small specified difference. So, by applying equation (13), for defining material temperature in all zones of the tunnel, "theoretical value" of thermal treatment length is determined. Because of different thermal conditions inside particular zones it is obvious that so calculated lengths of treatment differ among zones. The longest period of time should be found. It is unnecessary to say that total length of the process will be obtained by multiplying the number of zones and the calculated time length.

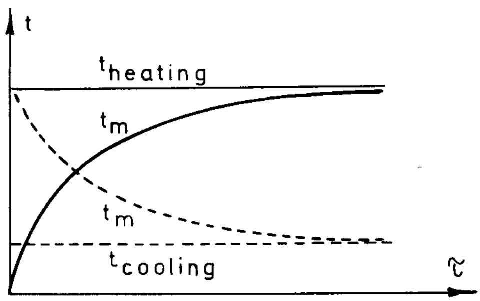

Fig. 3. Temperature changes in the center of ceramic body during heating and cooling by fluid at a constant temperature.

Secondly, hypothetical process will be shortened with the aim to increase of total annual production. So, in the last part of the algorithm the length of thermal treatment in every zone will be reduced, under permanent calculation (control) of material, temperature and a minimum of treatment length will be found so that material in sintering zone reaches acceptable value.

4. TEMPERATURE – TIME EVOLUTION IN THE CENTER OF A CERAMIC BODY

When the optimal temperature values in a center of a body (in every particular zone) were determined and stored it might be useful to determine a model of their change during the time, i.e. a function which brings into relation material temperatures and the position of ceramic body in the tunnel. Therefore, the calculated temperature values should be correlated with time (equivalent to the position) as independent variable, in order to gain the expression: $t_{mat}(\tau)$.

At first a type of function should be chosen, starting from linear polynomial to other more complicated functions. Secondly, polynomial coefficients have to be determined by applying the least squares method. For this purpose either original [5] or one of many published computer programs [6] can be used.

5. TEST EXAMPLE

5.1. Optimization of Thermal Treatment Length in a Real Equipment

Procedure and computer program were applied to optimization of thermal treatment length for an already installed tunnel kiln characterized by following data:

– *for material:*
$\varrho = 1800$ [kg/m^3]
$C_p = 0.88 + 0.023\, t_m$ [kJ/kg K]
$\lambda = 2 \times 10^{-4}\, \varrho$ [W/m K]
– *for a kiln:*
$S_k = 1836.7$ [m^2]
$V_k = 1422.75$ [m^3]
$P_{tot} = 98$ [kPa]

– *for a ceramic body:*
$\delta = 0.0115$ [m]
$S = 0.23287$ [m^2]
$V = 2.45255 \times 10^{-3}$ [m^3]
$t_1 = 29.7$ [°C]
$t_2 = 1000$ [°C]
– *for a pile of bodies:*
$H = 1.5$ [m]

– *for working fluids:*
temperature distribution
$P_{CO_2} = 5.4$ [kPa]
$P_{H_2O} = 9.8$ [kPa]

ϱ, C_p, μ, λ for combustion products and air.

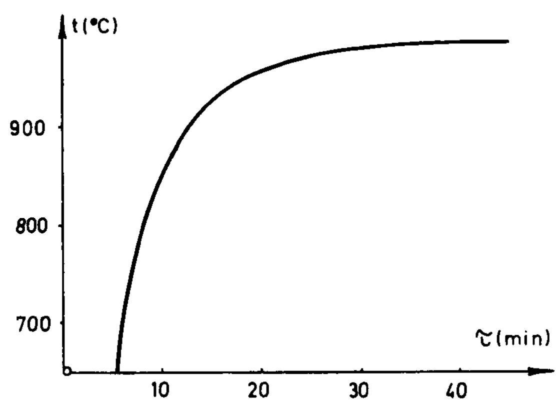

Fig. 4. Material temperature in last heating zone as a function of treatment period length.

Temperature distribution of working fluid was obtained by measuring in both directions (axial and radial) [7], whereas an average gas temperature, at one cross-section, was estimated as an arithmetical mean value.

"Theoretical time period length" was calculated for each zone of the tunnel and 25 [min] as a minimum and 104 [min] as a maximum were obtained (with tolerated deviation: $\Theta \leq 0.02$).

Maximal value was adopted and material temperatures were recalculated. Finally, by shortening of time period the optimal value $\tau_{opt} = 35$ [min] was found so that the temperature in the center of a body, for last zone of heating, reaches acceptable 990 [°C] (see Fig. 4).

Having in mind that time need in a real process, determined by experience, has almost 40 % greater value than the optimal one ($\tau_{real} = 48$ [min]), it is obvious that shortening of thermal treatment can be suggested.

5.2. Determining of Material Temperature Distribution along the Kiln

Calculated values of material temperatures after its heating for 35 [min] inside every kiln zone are presented in Fig. 5. Their correlating in order to determine $t_m(\tau)$ models (linear as well as quadratic polynomial) gives following expressions; linear equation for heating

$$t = 21.774 + 0.9344\tau \tag{16}$$

and cooling

$$t = 1063.611 - 1.0288\tau\,, \tag{17}$$

together with quadratic equation for heating

$$t = 176.4795 - 0.1386\tau + 0.001181\tau^2 \tag{18}$$

and cooling

$$t = 916.4998 - 0.1963\tau - 0.0008372\tau^2. \tag{19}$$

It should be noticed that time and temperature units are [min] and [°C] respectively.

At a first glance can be observed that quadratic model fits material temperatures better than the linear one. Searching for correlation better than quadratic one might be continued if necessary.

6. CONCLUSION

As a result of reported investigations a mathematical model, which defines heat transfer phenomena between surrounding gas and treated one- dimensional ceramic bodies inside a tunnel kiln, was formulated. Its main part is Fourier's equation for unsteady heat conduction through ceramic bodies accompanied with adequate

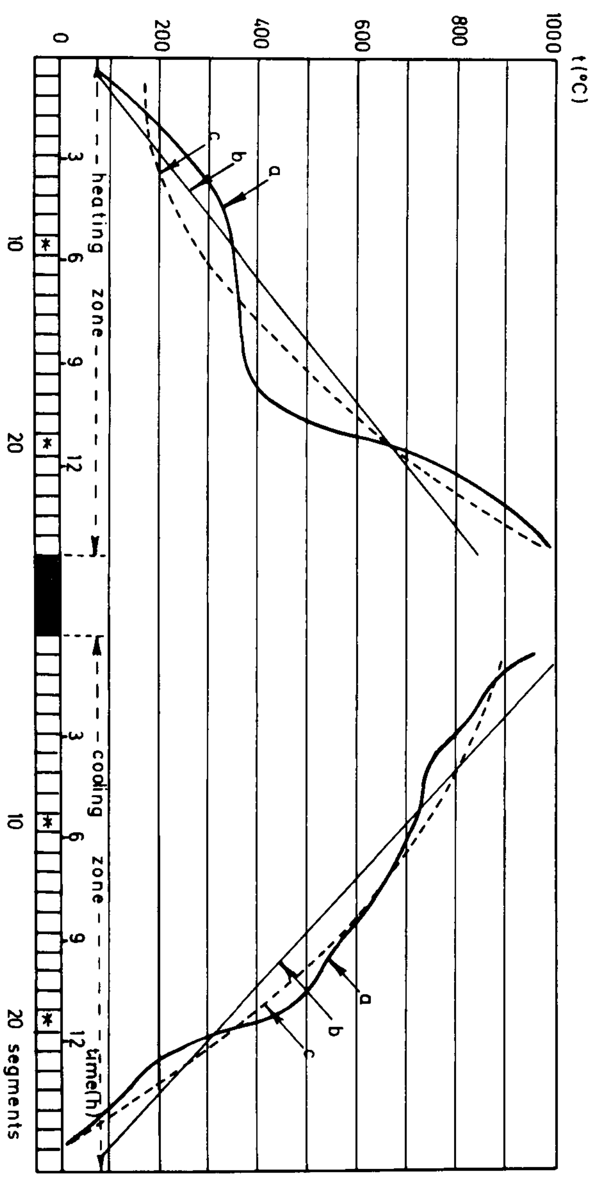

Fig. 5. Distribution of material temperature along the kiln:
a) calculated by applying a model; b) calculated by using linear correlation;
c) calculated by using quadratic correlation.

boundary condition; convective- radiative for heating zone and pure convective for cooling zone.

Numerical procedure as well as computer program were developed in order to solve the model. They imply analytical solving of conduction – equation by summarizing four terms of infinite series which represents the solution. The error in calculating made because of cutting the series is significantly less than 1 %.

Boundary condition for main equation is defined on the basis of arithmetical mean temperature of working gas, for each tunnel zone. Obviously, error made in this way decreases by decrease of zone volume. Also, all other assumptions (see Chapter 2.) contribute to the increase of total error in a degree which value is difficult to predict. Finally, unavoidable error is caused by accumulating during the numerical procedure, where calculated (final) temperature value for one segment is accepted as the initial value for the next one.

Having all facts in mind, temperature in last heating zone might be underestimated up to 5 %.

By introducing the computer program it is possible both to optimize and to simulate thermal treatment in the tunnel kiln. Namely, for required temperature in the center of the ceramic body it is possible to calculate optimal duration of the process, while for the specified treatment length one can predict the temperature in the center of ceramic body.

On the other hand, program enables defining the model of material temperature change along the tunnel kiln, which combines processes of particular zones and allows investigating of thermal treatment at a general level.

Developed program can also be used for carrying numerical experiments on under the conditions when changes of relevant parameters occur (such as composition and characteristics of available raw material, composition and quality of used fuel, dimension of ceramic bodies etc.). By applying the computer program it is possible to recalculate actual process parameters permanently in order to keep equipment capacity at optimal level.

Symbols

Bi	– Biot number
C_p	– Specific heat capacity [J/kg K]
C_0	– Boltzmann constant [W/m^2K^4]
E	– Energy emitted by radiation [W/m^2]
Gr	– Grashof number
H	– Height (characteristic dimension) [m]
l	– Mean beam length [m]
Nu	– Nusselt number
R	– Thermal resistance [K/W]
S	– Surface [m^2]
T, t	– Temperature [K, °C]
V	– Volume [m^3]
X	– Optical depth [m]
α	– Heat transfer coefficient, eigen value in equation (13) [W/m^2 K]

α_g	– Absorptivity
β	– Empirical coefficient
δ	– Ceramic body (plate) thickness [m]
ε	– Relative emissivity
Φ	– Thermal flux [W/m^2]
λ	– Thermal conductivity [W/m K]
μ	– Viscosity [N/m^{2}s]
Θ	– Dimensionless temperature
ρ	– Density [kg/m^3]
τ	– Time [s, min]
ϑ	– Temperature difference [°C]

Indices

0	starting	k	kiln
∞	final	m	material
con	convective	rad	radiative
g	gas	s	surface
H	height	tot	total

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MATEMATICKÝ MODEL JEDNOSMĚRNÉHO OHŘEVU A OCHLAZOVÁNÍ PLOCHÝCH KERAMICKÝCH TĚLES V TUNELOVÉ PECI

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V článku je rozpracován model přenosu tepla v tunelové peci, která se používá při výrobě plochých keramických těles reaktivním slinováním kaolinitové suroviny.

Za účelem zjednodušení matematického modelu bylo zavedeno několik předpokladů. Nejdůležitější je předpoklad jednorozměrnosti těles (obr. 1). Také se předpokládá, že k ohřevu a ochlazování dochází ve zvláštních pásmech – částech tunelu. Toto přiblížení umožňuje použít jednorozměrnou Fourierovu rovnici pro neustálené vedení tepla testovanými tělesy, která je řešena analyticky.

Nezbytné okrajové podmínky se získaly určením konvektivního a radiačního přenosu tepla v pásmu ohřevu a stanovením pouze konvektivního přenosu v pásmu chladnutí, a to pro všechna pásma tunelu. Stanovení konvekčního koeficientu bylo provedeno na základě příslušného vztahu. Průměrný radiační koeficient se získal uplatněním koncepce „střední vlnové délky".

Pro zdárné řešení matematického modelu byl vyvinut počítačový program. Jeho algoritmus zachycuje obr. 2.

Program začíná čtením všech nezbytných údajů o materiálu, keramickém tělese, ložení keramických těles a o vlastní peci. Dále následuje přesné určení rozložení teploty pracovního plynu po délce pece. V dalším kroku algoritmu se počítá okrajová podmínka a poslední krok slouží k řešení Fourierovy rovnice, jehož cílem je definování optimální doby tepelného působení pro danou teplotu ve středu tělesa a výpočet teploty uprostřed materiálu za daného průběhu procesu. Teplota ve středu materiálu se asymptoticky blíží teplotě okolního plynu (obr. 3). Je též vhodné stanovit změny teploty materiálu.

Vypracovaný počítačový program byl aplikován na již instalované peci. Výsledky výpočtu uvádí obr. 4. Na základě nich bylo navrženo zkrácení doby výpalu.

Závěrem byly modely teplotních změn vyjádřeny odpovídajícími lineárními a kvadratickými vztahy (obr. 5).

Uvedený program je obzvláště vhodný pro numerické hodnocení systému, ve kterém nastávají změny základních parametrů jako je složení a vlastnosti použitých surovin, složení a kvalita použitého paliva, tloušťka keramického tělesa atd. Cílem použití programu je také udržení optimální kapacity zařízení.

Obr. 1. Časový vývoj teploty v keramickém tělese.
Obr. 2. Všeobecný algoritmus pro řešení modelu přenosu tepla.
Obr. 3. Teplotní změny ve středu keramického tělesa během ohřevu a ochlazování plynem o konstantní teplotě.
Obr. 4. Teplota materiálu v posledním pásmu ohřevu jako funkce doby tepelného působení.
Obr. 5. Rozložení teploty materiálu po délce pece: a) vypočítaná na základě modelu; b) vypočítaná z lineárního vztahu; c) vypočítaná z kvadratického vztahu.

МАТЕМАТИЧЕСКАЯ МОДЕЛЬ НАГРЕВАНИЯ И ОХЛАЖДЕНИЯ ПЛОСКИХ КЕРАМИЧЕСКИХ ТЕЛ В ОДНОМ НАПРАВЛЕНИИ В ТУННЕЛЬНОЙ ПЕЧИ

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В предлагаемой статье разрабатывается модель теплопередачи в туннельной печи, служащей для производства плоскостных керамический тел реактивным спеканием каолинитового сырья.

С целью упрощения математической модели авторами водится несколько предположений. Самым важнымиз них является одноразмерность тел (рис. 1). Далее предполагается, что нагревание и охлаждение происходят в особых зонах – частях туннеля. Данное приближение предоставляет возможность использования одноразмерного уравнения Фуриера для теплопроводности тестированными телами, которое авторами решается аналитическим путем.

Необходимые краевые условия получались установлением конвективной и радиационной теплопередачи в зоне нагрева, а установлением только конвективной теплопередачи в зоне охлаждения, а именно в случае всех зон туннеля. Установление коэффициента конвекции проводили на основании соответствующего отношения. Средний коэффициент радиации получили использованием концепции «средней длины волны».

Для успешного решения математической модели была разработана программа вычислительной машины. Её алгоритм изображается на рис. 2.

Программа начинается чтением всех необходимых данных относительно материала, керамического тела, укладки керамических тел и относительно используемой печи. Далее приводится точное распределение температуры рабочего газа вдоль длины печи. Дальнейший шаг алгоритма представляет собой краевое условие и последний шаг предназначен для решения уравнеия Фуриера и его целью является определение оптимального времени теплового воздействия для данной температуры в середине тела и расчет температуры в середине материала при данном ходе процесса. Температура в середине материала асимптотически приближается к температуре окружающего газа (рис. 3). Оказывается также пригодным установление изменения температуры материала.

Разработанная программа вычислительной машины была использована уже на установленной печи. Результаты расчета приводятся на рис. 4. На их основании было предложено уменьшение времени обжига.

В заключение приводимой работы модели температурных изменений приводятся в виде соответствующих линейных и квадратических отношений (рис. 5).

Приводимая программа оказывается весьма пригодной для нумерической оценки системы, в которой происходят изменения основных параметров, как напр. состав и свойства используемого сырья и состав и качество используемого топлива, толщина керамического тела и т. д. Цель использования программы – использование оптимальной мощности установки.

Рис. 1. Временное развитие температуры в керамическом теле.

Рис. 2. Общий алгоритм, служащий для решения модели теплопередачи.

Рис. 3. Температурные изменения в середине керамического тела во время нагрева и охлаждения газом при постоянной температуре.

Рис. 4. Температура материала в последней зоне нагрева в виде функции времени теплового воздействия.

Рис. 5. Распределение температуры материала вдоль длины печи:
a) температура, расчитанная на основании модели,
b) температура, расчитанная на основании линейного отношения,
c) температура, расчитанная на основании квадратического отношения.