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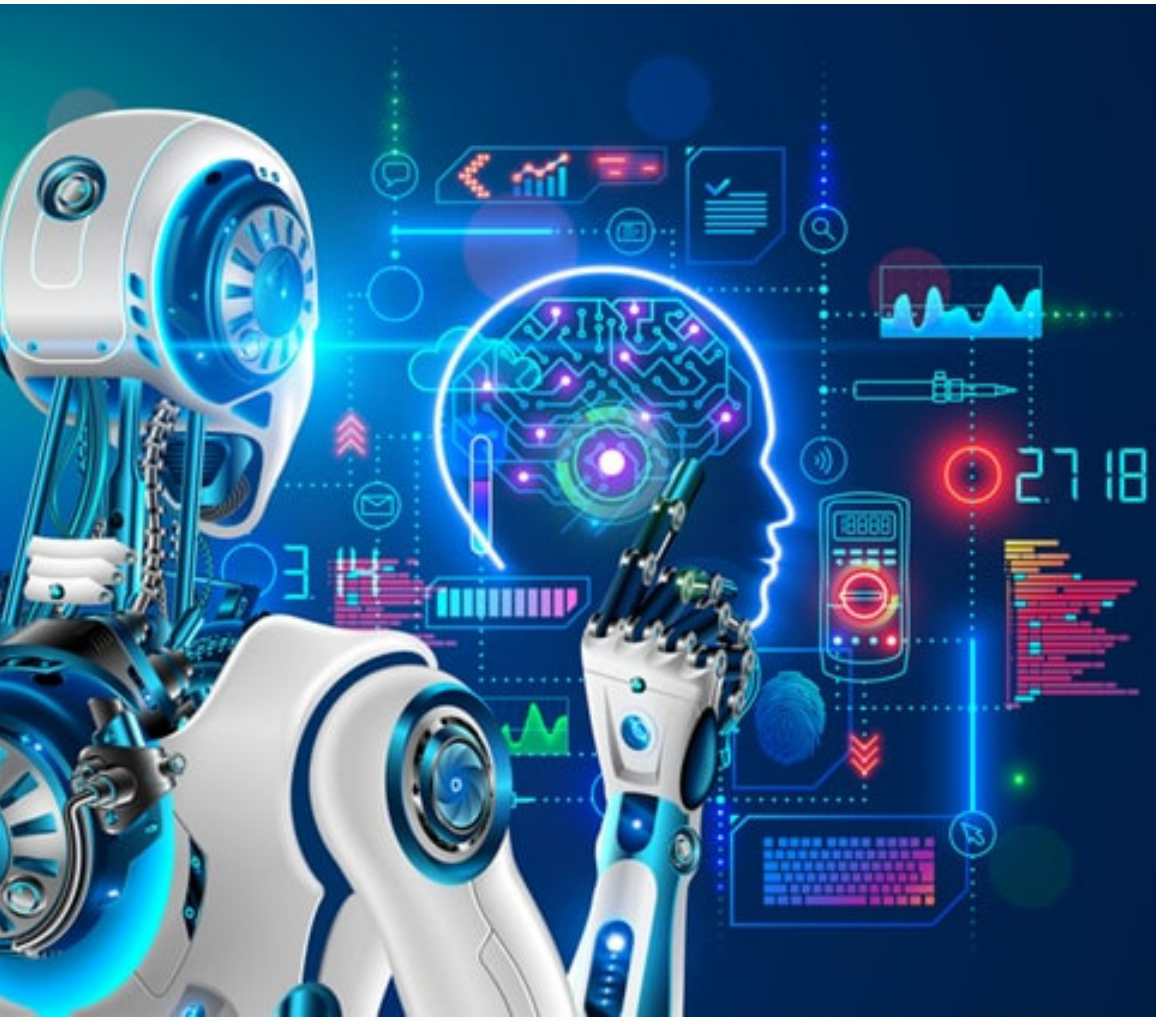

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MODELING OF HEAT FLOWS IN GAS-FIRED CHAMBER FURNACES

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Abstract: This paper presents the specific features of developing material and energy balances for technological processes and industrial systems based on the laws of mass and energy conservation, as applied to gas-fired chamber furnaces. It is shown that the heat balance relies on a number of assumptions regarding linear variations of heat flows, which can be further refined through modeling techniques.

Key words: gas-fired chamber furnaces; heat and material balance; transfer and removal of a specified amount of heat; conjugate heat transfer.

Annotatsiya: Mazkur maqolada massa va energiya saqlanish qonunlariga asoslangan holda texnologik jarayonlar va sanoat tizimlari uchun material va issiqlik balanslarini ishlab chiqishning o‘ziga xos jihatlari gaz yoqiladigan kamerali pechlar misolida ko‘rib chiqilgan. Issiqlik balansi issiqlik oqimlarining chiziqli o‘zgarishi haqidagi bir qator farazlarga asoslanishi hamda ularni modellashtirish usullari orqali yanada aniqlashtirish mumkinligi ko‘rsatib berilgan.

Kalit so‘zlar: gaz yoqiladigan kamerali pechlar; issiqlik va material balansi; belgilangan miqdordagi issiqlikni uzatish va chiqarish; bog‘langan issiqlik almashinuvi.

Аннотация: В статье рассматриваются особенности разработки материального и теплового балансов технологических процессов и промышленных систем на основе законов сохранения массы и энергии применительно к газовым камерным печам. Показано, что тепловой баланс основывается на ряде допущений о линейном характере изменения тепловых потоков, которые могут быть уточнены с использованием методов моделирования.

Ключевые слова: газовые камерные печи; тепловой и материальный баланс; подвод и отвод заданного количества теплоты; сопряжённый теплообмен.

INTRODUCTION

Chamber furnaces fired by natural gas are widely used in thermal engineering and industrial heat-treatment processes due to their operational flexibility, controllability, and capability to ensure uniform temperature fields within the working volume. At the same time, such furnaces are among the most energy-intensive units in industrial practice, which makes the problem of rational fuel utilization and accurate assessment of thermal efficiency particularly relevant. Under modern conditions of rising energy costs and increasing requirements for energy efficiency, the development of scientifically grounded methods for analyzing and optimizing furnace thermal regimes becomes a priority task.

A key tool for evaluating the performance of gas-fired chamber furnaces is the heat balance, which reflects the distribution of supplied thermal energy among useful heat consumption and various losses. Classical heat

balance approaches are usually based on averaged or integral values over the entire firing cycle. However, such methods do not fully capture the transient nature of thermal processes occurring in the furnace, especially under non-stationary operating regimes characterized by continuously changing temperatures, fuel flow rates, and heat loads. As a result, important information about instantaneous heat flows and their influence on fuel consumption and thermal efficiency may be lost.

In recent years, increasing attention has been paid to dynamic and time-dependent modeling of thermal processes in furnaces. These approaches allow the consideration of instantaneous values of energy flows and provide a more detailed description of the interaction between fuel combustion, heat transfer to the product, refractory materials, and exhaust gases. Within this context, matrix-based formulations of heat balance equations offer significant advantages, as they enable a compact and systematic representation of multiple interacting heat flows and their evolution over time.

This paper focuses on the formulation and analysis of the heat balance of gas-fired chamber furnaces based on the law of conservation of energy for an open thermodynamic system, with explicit consideration of instantaneous heat flow values throughout the firing cycle. A matrix form of the heat balance equation is proposed, allowing fuel consumption, air and flue gas enthalpies, heat absorption by the product and refractory lining, and heat losses to be evaluated in a unified framework. The adopted approach makes it possible to link heat flows with temperature curves of the firing regime and to determine fuel consumption through numerical integration, providing a more accurate and physically consistent assessment of furnace performance.

The relevance of the study lies in its potential application to the optimization of thermal operating regimes, reduction of specific fuel consumption, and improvement of overall energy efficiency of chamber furnaces. In addition, the proposed methodology creates a foundation for further development of advanced mathematical models, digital twins, and simulation tools aimed at both process optimization and operator training in thermal engineering systems.

REVIEW OF LITERATURE ON THE SUBJECT

Issues of energy efficiency and rational energy use in industrial thermal units have long been the subject of scientific research, particularly in relation to chamber furnaces and high-temperature technological processes. One of the earlier systematic studies in this field was conducted by L. Zashkova, who analyzed the rational use of energy in gas-fired chamber furnaces for firing technical ceramic products. In her work, special attention was paid to the distribution of heat flows within the furnace volume, the role of refractory linings, and the influence of operating regimes on fuel consumption. The results demonstrated that a significant share of energy losses is associated with non-optimal firing schedules and insufficient consideration of transient thermal processes, which directly affects the overall energy efficiency of chamber furnaces.

The theoretical foundations for analyzing energy dissipation and irreversibility in thermomechanical systems were further developed by J. Royo, A. Valero, and A. Zaleta, who introduced the concept of dissipation temperature as an analytical tool for identifying malfunctions and inefficiencies. Their approach extends beyond traditional energy balances by incorporating thermodynamic irreversibility, allowing a deeper understanding of how energy degradation occurs within complex systems. Although their study focused on thermomechanical systems in general, the proposed methodology is highly relevant for furnace analysis, where combustion, heat transfer, and exhaust processes are inherently irreversible and strongly time-dependent.

A comparative perspective based on both energy and exergy analyses was presented by A. Folorunso and C.J. Diji in their study of a cement manufacturing plant. Their results confirmed that energy analysis alone may mask critical inefficiencies that become evident only when exergy losses are evaluated. The authors emphasized that high-temperature processes, such as clinker production or firing operations, are characterized by substantial exergy destruction in combustion chambers and heat exchange equipment. These findings underscore the importance of integrating advanced thermodynamic approaches into the assessment of industrial furnaces to achieve meaningful reductions in fuel consumption.

The methodological and applied aspects of industrial heat engineering were comprehensively addressed in the habilitation work of L. Zashkova, devoted to the scientific field of industrial thermal engineering. This research generalized long-term experimental and analytical investigations of industrial furnaces, heat treatment installations, and energy-saving measures. The author highlighted the necessity of moving from stationary heat balance calculations toward more detailed descriptions that account for variable operating conditions, transient heating of products and refractory materials, and dynamic control of fuel and air supply. These conclusions provide a solid scientific basis for the development of time-dependent and matrix-based heat balance models.

Thermoeconomic modeling approaches were explored by J.J. Santos, M.A. Nascimento, and E.E.S. Lora in their analysis of a gas turbine cogeneration system with steam injection. Their work demonstrated how the integration of thermodynamic and economic criteria allows the identification of optimal operating regimes

that minimize both energy losses and production costs. Although the object of their study was a cogeneration system, the methodological framework they proposed is applicable to gas-fired furnaces, where fuel costs constitute a major component of operating expenses and where optimization of thermal regimes has direct economic implications.

Overall, the reviewed studies indicate a clear evolution from traditional integral heat balance methods toward more advanced energy, exergy, and thermoeconomic analyses. At the same time, there remains a need for practical modeling approaches that can capture the instantaneous behavior of heat flows in chamber furnaces under real firing regimes. This gap in the literature justifies the development of matrix-based, time-dependent heat balance models aimed at improving the accuracy of fuel consumption assessment and enhancing the energy efficiency of gas-fired chamber furnaces.

RESEARCH METHODOLOGY

The research methodology is based on analytical and numerical approaches to the study of heat balance in gas-fired chamber furnaces. Initial data on fuel, air, flue gas, and temperature regimes are obtained from design parameters and calculated thermophysical properties. Instantaneous heat flows are evaluated using a matrix-based heat balance model, while fuel consumption and total heat quantities are determined through numerical integration of time-dependent functions over the firing cycle.

ANALYSIS AND RESULTS

The heat balance is formulated on the basis of the law of conservation of energy for an open thermodynamic system and is expressed as follows: the sum of incoming (input) energy/heat flows $\dot{Q}_i^{in}$ is equal to the sum of outgoing (output) energy/heat flows $\dot{Q}_i^{out}$.

$$\sum_{i=1}^{n} \dot{Q}_i^{in} = \sum_{i=1}^{n} \dot{Q}_i^{out} \quad (1)$$

Individual components of the heat balance of chamber furnaces are taken in terms of their instantaneous values, and for their evaluation it is proposed to consider the balance equation in a matrix form [1]:

$$[B]\left(\left[Q_{\text{ä}}^{p}\right] + V_{\alpha}[h_{air}] + [h_{fuel}] - V_{\alpha}^{\text{ë}\text{ë}}\ [h_{\text{ë}\text{ë}}]\right) = \left[\dot{Q}_{heat}\right] + \left[\dot{Q}_{prod}\right] + \left[\dot{Q}_{ref}\right] + \left[\dot{Q}_{chem}\right] \quad (2)$$

where:

$[B] = \begin{bmatrix} B_1 & 0 & . & 0 \\ 0 & B_2 & . & 0 \\ . & . & . & . \\ 0 & 0 & 0 & B_n \end{bmatrix}$ – a diagonal matrix containing the instantaneous values of the fuel quantity;

$[Q_{\partial}^{p}] = \begin{bmatrix} Q_{\text{ä}}^{p} \\ . \\ . \\ Q_{\text{ä}}^{p} \end{bmatrix}$ – a column matrix containing the values of the lower working calorific value of the fuel;

$[h_{air}] = \begin{bmatrix} h_a^1 \\ h_a^2 \\ . \\ h_a^n \end{bmatrix}$ – a column matrix containing the instantaneous values of the enthalpy of the combustion air;

$$[h_{fuel}] = \begin{bmatrix} h_g^1 \\ h_g^2 \\ . \\ h_g^n \end{bmatrix}$$ – a column matrix containing the instantaneous values of the fuel enthalpy;

$$[h_{f.g}] = \begin{bmatrix} h_{f.g}^1 \\ h_{f.g}^2 \\ . \\ h_{f.g}^n \end{bmatrix}$$ – a column matrix containing the instantaneous values of the enthalpy of flue gases[2];

$$h_{f.g}^i = c_{p,g}^i t_g^i \; ; \quad h^i air = c_{p,air}^i t_{air}^i . \tag{3}$$

The specific heat capacities of air and flue gases are determined using the following relationships:

$$c_{air}^i = 1298 + 0{,}233 t_{air}^i \; ; \; c_g^i = 1354 + 0{,}343 t_g^i \; . \tag{4}$$

The temperature of the gases leaving the furnace can be determined from the following expression:

$$T_a^i = \sqrt{T_{\max}^i T^i} = \sqrt{T_a^i T^i} . \tag{5}$$

The variation of the temperature in the furnace space T_i under the investigated operating conditions is determined by temperature curves. For $T_{\max}$ in equation (5), the actual combustion temperature T_∂ in the furnace is adopted, which, within the framework of the studied regimes, is calculated using the following formula[3]:

$$T_a^i = 273.15 + k \frac{Q_\partial^D + c_{fuel} t_{fuel} + V_\alpha t_{air}^i c_{air}^i}{V_\alpha^a}, \tag{6}$$

where $k = 0.8$ is a coefficient accounting for combustion losses in furnaces of this type.

$$\left[\dot{Q}_{heat}\right] = \begin{bmatrix} \dot{Q}_{heat}^1 \\ \dot{Q}_{heat}^2 \\ . \\ \dot{Q}_{heat}^n \end{bmatrix}$$ – a column matrix containing the instantaneous values of the heat flow used for heating the furnace and the railcar;

$$\dot{Q}_{heat}^i = \dot{Q}_{ka}^i + \dot{Q}_{ka}^i \tag{7}$$

$$\left[\dot{Q}_{chem}\right] = \begin{bmatrix} 0 \\ . \\ \dot{Q}_{chem1} \\ 0 \\ \dot{Q}_{chem2} \\ 0 \end{bmatrix}$$ – a column matrix containing the instantaneous values of the heat flows required for the progression of chemical reactions in the product.

These heat flows are introduced into those rows of the matrices that correspond to the time at which temperatures are reached at which phase-forming reactions become possible;

$$\left[\dot{Q}_{prod}\right]=\begin{bmatrix}\dot{Q}^1_{prod}\\ \dot{Q}^2_{prod}\\ .\\ \dot{Q}^n_{prod}\end{bmatrix}$$ – a column matrix containing the instantaneous values of the heat flow for heating the product.

$$\left[\dot{Q}_{ref}\right]=\begin{bmatrix}\dot{Q}^1_{ref}\\ \dot{Q}^2_{ref}\\ .\\ \dot{Q}^n_{ref}\end{bmatrix}$$ – a column matrix containing the instantaneous values of the heat flow for heating the refractory material.

The superscript of the matrix elements corresponds to the end of the intervals $1\Delta\tau;\ 2\Delta\tau \dots n\Delta\tau$ of the firing cycle.

To determine the instantaneous values of the flows, this study proposes a relationship analogous to the temperature curve of the firing regime, linking their instantaneous values to time τ :

To determine the instantaneous values of the last two heat flows, the present work proposes a dependence between their instantaneous values and time τ , similar to the temperature curve for the baking mode:

$$Q^i_{prod}=\begin{cases}\dfrac{\dot{Q}^{\tau_{heat}}_{prod}}{\tau_{heat}}\tau & \tau\le\tau_{íàãð}\\ \dot{Q}^{\tau_{heat}}_{prod} & \tau_{heat}\le\tau\le\tau_{bak}\end{cases} \quad (8)$$

and

$$Q^i_{ref}=\begin{cases}\dfrac{\dot{Q}^{\tau_h}_{ref}}{\tau_h}\tau & \tau\le\tau_{fuel}\\ \dot{Q}^{\tau_h}_{ref} & \tau_h\le\tau\le\tau_{bak}\end{cases} \quad (9)$$

After numerically solving equation (2), the instantaneous values of the required fuel amount B_{ii} are obtained. The total values of the supplied and removed heat flows, as well as the fuel consumption, are determined by numerical integration of the time-dependent matrix elements over the cycle interval.

$$B=\int_0^{n\Delta\tau}B(\tau)d\tau. \quad (10)$$

A limitation for implementing the investigated thermal operating regime of the furnace is the condition that the maximum calculated instantaneous fuel value $B_{\max}$ must be lower than the maximum permissible value for the given burner installation [4]. This approach is based on a number of assumptions regarding linear variations of heat flows, which can be further refined through modeling.

Based on equation (2), the hourly values of natural gas consumption at a temperature of 20 °C and combustion air at a temperature of 150 °C were determined (Fig. 1).

The heat flows for heating the refractory material, the product, and the masonry in the corresponding matrices were determined by modeling their transient heating along the temperature curve using appropriate models (Figure 1) [5].

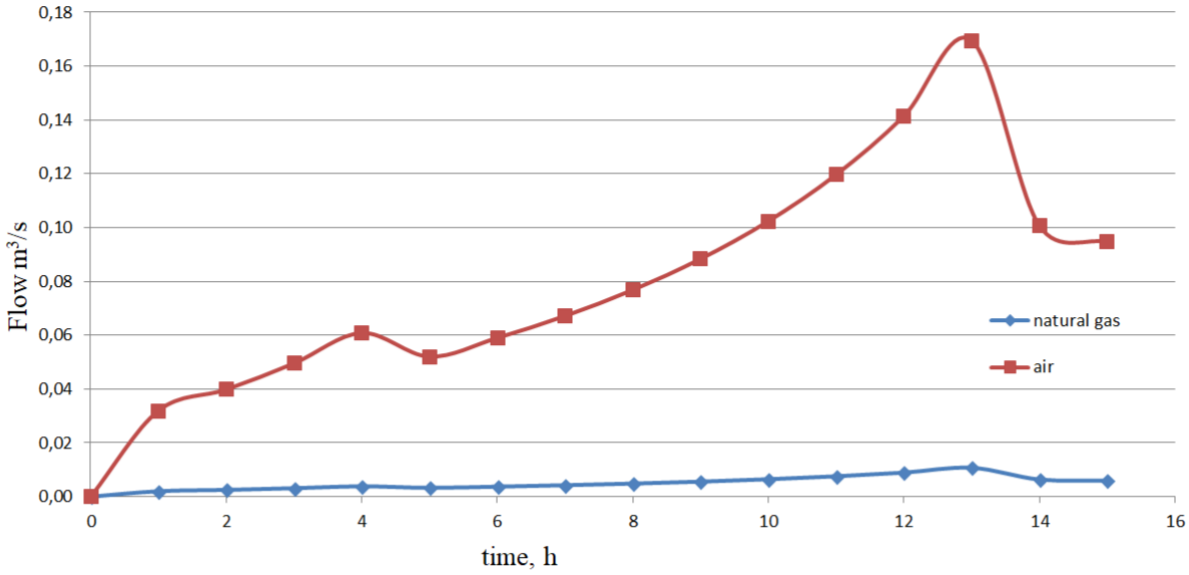

Figure 1. Heat flows of natural gas and air

Based on the recalculated fuel and air flow rates, their velocities at the inlets of the burner nozzles were determined. Using the numerical values of these velocities, time-dependent relationships describing their variation were derived in the MAPLE environment.

The uniqueness conditions for solving the system of conjugate heat transfer equations reflect the adopted process conditions and the time-dependent variations in air and fuel flow rates.

CONCLUSIONS AND SUGGESTIONS

The paper addresses the formulation and analysis of the heat balance of gas-fired chamber furnaces based on the law of conservation of energy for open thermodynamic systems. Within the scope of the study, the main components of the heat balance were identified, and a matrix-based approach to their representation was proposed, enabling the consideration of instantaneous heat flow values throughout the entire firing cycle.

The graphs constructed on the basis of analytical relationships showed that the temperature of the exhaust gases exhibits an almost linear dependence on the supplied heat flow. This confirms the validity of the assumption adopted in this study regarding the linear nature of heat flow variations under the investigated operating regimes of chamber furnaces. In addition, the linear time variation of the heat flow corresponds to the temperature curves of the firing regimes and allows numerical integration methods to be effectively applied to determine the total heat input and fuel consumption.

The obtained results are of practical significance for the analysis and optimization of thermal operating regimes of chamber furnaces aimed at reducing specific fuel consumption and improving the energy efficiency of thermal engineering installations. The proposed heat balance model can serve as a scientific basis for the development of mathematical models, digital twins, and computer-based training simulators for operator training, as well as for further refinement of thermal processes using numerical modeling methods.

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