

Computational Program for Determining the Heat Flow through the Furnace Walls

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ABSTRACT

Energy saving is a very topical issue. In these conditions, the reduction of heat losses through the walls of the furnaces (regardless of their nature: melting, heat treatment, etc.) is a priority right from the design phase. Knowing the thermal flow through the walls of the furnaces, they can be sized and the materials used to build them can be chosen so that the losses are reduced to the maximum. The paper presents a calculation program made in VisualBasic from Microsoft that allows determining the heat flow with a high enough precision for engineering calculations and not only. The main advantage is that a free platform is used and not specialized commercial software that is very expensive. The program can be used both for the design of industrial furnaces and for the modernization of existing furnaces by replacing the material of the insulating layer. It can also be used in other industries such as construction.

KEYWORDS: Heat flow, interval halving method, thermal conductivity

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I. INTRODUCTION

It is known that the heating aggregates used in industry (for melting materials or their thermal treatment) are large energy consumers. In today's conditions energy saving is a general priority. A number of researchers [1, 2, 3] are already analyzing the aspects related to the economic efficiency of thermal installations.

An important part of the energy consumption, in the case of furnaces, is the heat lost through the walls of the furnaces. From the design phase of the furnaces, the dimensioning of the walls and the materials from which these walls are built must be taken into account. The vast majority of manufacturers of such materials – refractory ceramic materials or thermal insulation materials – invest significant amounts in research related to improving the quality of these materials. Also, a number of researchers from universities and research institutes are dedicated to the study of these materials [4, 5, 6, 7].

In order to take into account the reduction of heat loss through the walls from the design phase, there are a number of specialized commercial software for simulation. All these programs have the disadvantage of high cost for a small business. There are numerous studies and researches of high scientific level dealing with the modeling of heat transfer in thermal installations that do not use these commercial software [1, 8, 9, 10, 11, 12]. Most of these researchers use finite element analysis in their research. This paper presents a software created by the author using the free VisualStudio – VisualBasic platform from Microsoft and using a combination between the iteration method and the interval halving method.

II. METODOLOGY

Heat losses through the walls of the furnaces can be determined by analytical relations depending on the type of wall: flat or cylindrical.

In the case of flat walls, fig 1a, the unit thermal flux, q [W/m^2], transmitted through the walls is determined with equation 1 [13]:

$$q = \frac{\Delta T}{\frac{1}{\alpha_{in}} + \sum \frac{\delta_i}{\lambda_i} + \frac{1}{\alpha_{out}}} \quad \left[\frac{W}{m^2} \right] \quad (1)$$

where $\Delta T = T_{in} - T_{out}$ is the temperature difference between the temperature inside the furnace (T_{in}) and the temperature outside (T_{out}), in Celsius degrees

α_{in} – the coefficient of convective heat transfer from the inside of the furnace to the wall, in W

δ_i – the thicknesses of the layers that make up the wall, in m

λ_i – the thermal conductivity of the material of layer i of the wall, in $W/m^{\circ}C$

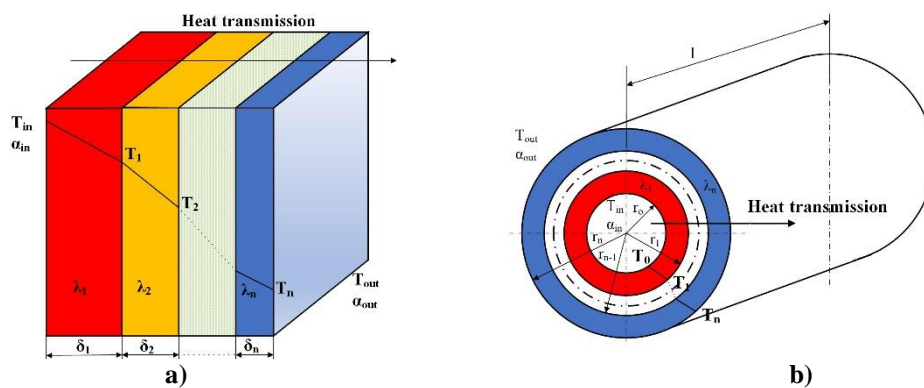
α_{out} – the coefficient of convective heat transfer from the wall to the outside environment, in W

In the case of cylindrical walls, fig 1b, the unit thermal flux, q [W/m], transmitted through the walls is determined with equation 2 [13] where:

$$q = \frac{\Delta T}{\frac{1}{\pi \cdot \alpha_{in} \cdot d_{in}} + \sum \frac{1}{2 \cdot \pi \cdot \lambda_i} \cdot \ln \left(\frac{d_{i+1}}{d_i} \right) + \frac{1}{\pi \cdot \alpha_{out} \cdot d_{out}}} \quad \left[\frac{W}{m} \right] \quad (2)$$

d_i – the diameters of the cylindrical layers of the wall, in m

d_{in}, d_{out} – the inner and outer diameter of the furnace, in m



b) Fig. 1. Heat transmission through the walls: a) flat walls; b) cylindrical walls

Regardless of the type of wall, determining the unit heat flux is difficult due to the fact that the values of λ depend on the temperature. For most materials $\lambda = \lambda_0 \pm a \cdot T_m$, where T_m is the average temperature of the material layer; a is a material constant. In the case of multi-layer walls, the difficulty arises because the interlayer temperatures are not known and thus the value of λ cannot be determined. An average value of λ can be used (considering the average of the internal and external temperatures in the furnace), but the accuracy of the calculation is quite low.

To increase the accuracy of the calculation, the iteration method is generally used. The iterative method is an approach to problem solving that involves repeating a set of instructions or operations to obtain a solution or to get closer to a desired solution. The iterative method can be applied in a variety of contexts, including solving mathematical equations, optimizing algorithms, numerical simulation, or dealing with practical problems that require repeated adjustment of parameters until a desired or optimal state is reached. This type of approach is often used when finding a direct solution is not possible or efficient.

The thermal flow is calculated using the values of λ at 0 Celsius degrees for the materials from which the wall is made [14]. After calculating the thermal flow, the temperatures between layers T_1, T_2, \dots, T_n are calculated according to the equation 3 for flat walls and equation 4 for cylindrical walls:

$$T_i = T_{in} - q \cdot \sum \frac{\delta_i}{\lambda_i} \quad [^{\circ}C] \quad (3)$$

$$T_i = T_{in} - q \cdot \sum \frac{1}{2 \cdot \pi \cdot \lambda_i} \cdot \ln \left(\frac{d_{i+1}}{d_i} \right) \quad [^{\circ}C] \quad (4)$$

With the resulting values for the interlayer temperatures, the values for λ_i are calculated and the heat flux is recalculated. The interlayer temperature values are determined again. These are compared with the previous results. If the difference between them is greater than a certain threshold, previously set, set for the calculation is restarted with the new temperature values and the procedure is repeated until the differences between the considered and calculated temperature values are lower than the value set for accuracy (in engineering calculations $<2\%$). The disadvantage of the method is that it may take many iterations to achieve the desired accuracy.

If the working speed offered by computers is used, this inconvenience disappears. In addition to this, if the iteration method is combined with the interval halving method, the calculation can be performed with very high precision.

The interval halving method, also known as the bisection method, is a technique for finding the roots of a continuous function on a given interval. The method starts with an initial interval $[m, n]$ in which a root is

assumed to be found. The root must be included in this interval, and the function must be continuous over the entire interval. The halfway point, p , of the interval is chosen, given by the formula $p = (m+n)/2$. This halfway point becomes an estimate of the root. The process continues until a certain precision is reached or the interval becomes small enough. Often, the stopping condition is $|f(p)| < \epsilon$, where ϵ is a specified tolerance (in the developed program in this paper the allowable error was considered to be $\epsilon < 0.1\%$). The process of choosing the new range and calculating the halfway point is repeated until the stopping condition is met.

The particularities is that it no longer starts from values of λ_i at 0 Celsius degrees temperature. Some interlayer temperatures T_1, T_2, \dots, T_n are arbitrarily chosen so that values of λ_i can be calculated according to the relation $\lambda_i = \lambda_0 \pm a \cdot T_{mi}$. With these values, the thermal flow is determined, after which the resulting T_1, T_2, \dots, T_n values are calculated. According to the principle of the interval halving method, if the difference between the chosen and calculated temperatures exceeds the set error level, the new temperatures are chosen as their arithmetic mean:

$$T'_i = \frac{T_{i \text{ chosen}} + T_{i \text{ calculated}}}{2} \tag{5}$$

and the process is repeated until the desired precision is reached.

Based on the considerations presented, a program was written, using the Visual Basic platform, to allow the determination of heat flow and interlayer temperatures for walls with up to 5 different layers (flat or cylindrical walls). The figure 2 shows the algorithm flow chart based on which the program was written.

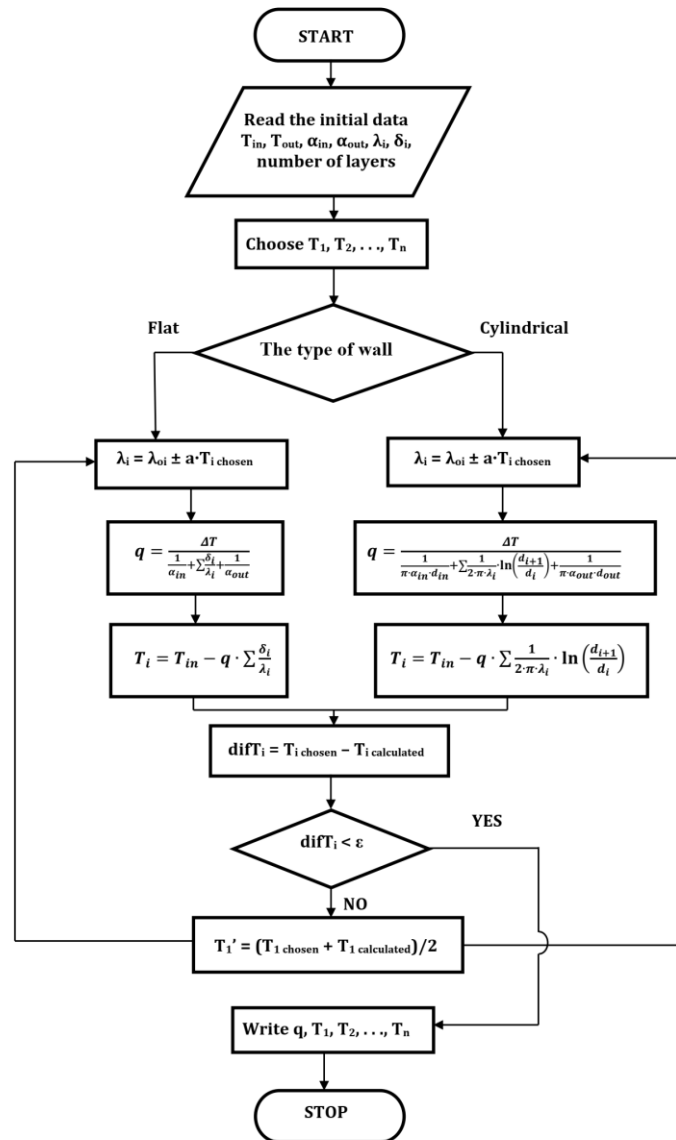


Fig. 2. The algorithm flow chart

III. CASE STUDY

A great advantage (and at the same time a paradox) is the fact that the chosen temperatures do not even have to fulfill the real condition $T_{in} \geq T_1 \geq T_2 \geq \dots \geq T_n \geq T_{out}$ but are actually chosen arbitrarily.

Using the program created and whose interface is shown in fig. 3 simulations were carried out for 2 situations that are frequently encountered in practice. A flat wall consisting of 4 layers of different materials was analyzed as follows: the inner layer of chamotte with a thickness of $\delta_1 = 200$ mm; layer 2 of diatomite with a thickness of $\delta_2 = 120$ mm; layer 3 of mineral wool with a thickness of $\delta_3 = 100$ mm and on the outside a protective layer of steel sheet with a thickness of $\delta_4 = 4$ mm. For reasons of labor protection, the outside temperature T_{out} was limited to 50 Celsius degrees. For T_{in} , the temperatures of 600, 800, 1000, 1200, 1400 and 1500 Celsius degrees were chosen. After running the program, the values for T_1 , T_2 , T_3 and q corresponding to each internal temperature taken into account were recorded. The variation mode of these quantities is shown in fig. 4.

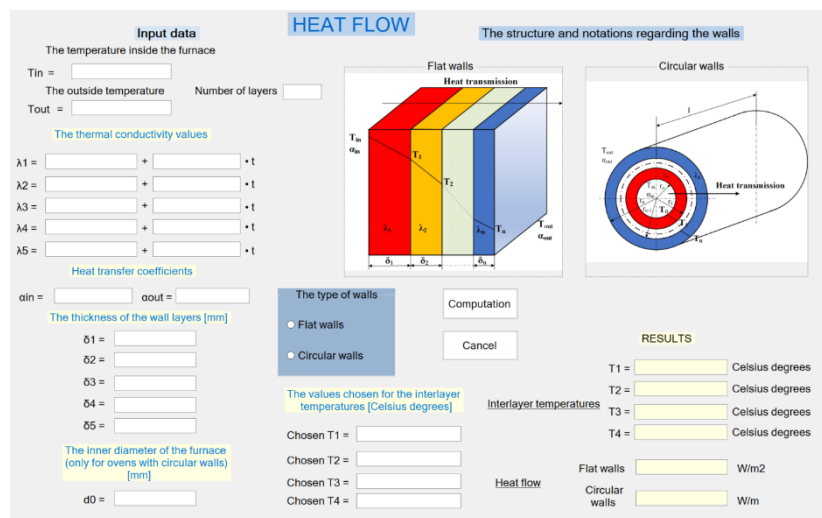


Fig. 3. The interface of the computational program

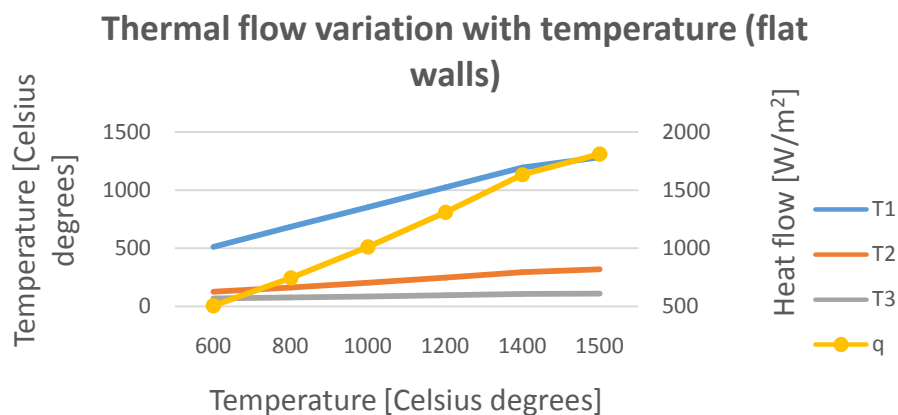


Fig. 4. Thermal flow vs temperature in case 1

An increase in the heat flux q with the increase of the internal wall temperature is clearly observed.

In the next stage, the situation was simulated in which the layer of diatomite and mineral wool were replaced by a layer of porous chamotte (it is increasingly used as a thermal insulation material in furnaces) keeping the same thickness of the final layer ($\delta_{porous\ fireclay} = \delta_{diatomite} + \delta_{mineral\ wool} = 220$ mm). The relations that describe the dependence of λ on temperature for the considered materials were taken from [15] and for porous chamotte from the manufacturers' websites.

From the analysis of the obtained results, a significant reduction of the thermal flow through the wall can be observed, regardless of the internal temperature of the wall – fig. 5. The reduction is around 50 percent, a fact presented in the fig. 6.

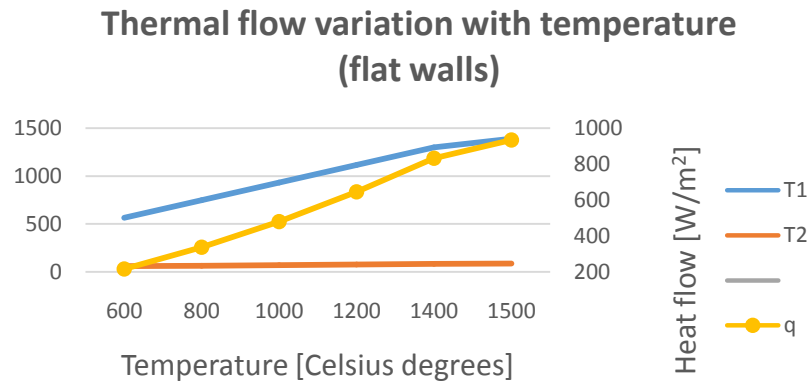


Fig. 5. Thermal flow vs temperature in case 2

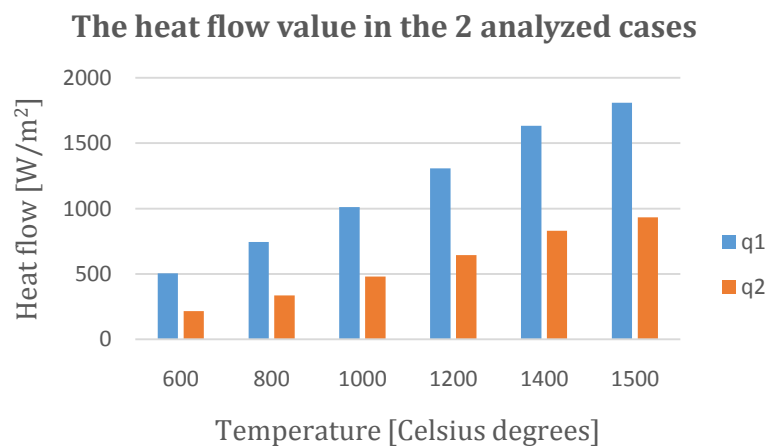


Fig. 6. The variation of the thermal flow in the 2 analyzed cases

IV. CONCLUSION

The work demonstrates the fact that, using a free software platform, a calculation program can be created to determine with a sufficiently high precision the heat flow transmitted through the walls. In the calculation program, a combination of the iteration method and the method of halving the interval was made in order to be able to perform the calculations with great accuracy. Classical analytical mathematical expressions regarding the complex heat transfer through plane or circular walls were used. In addition to calculating the value of heat flow and interlayer temperatures (in the case of multilayer walls), the program can also be used to simulate various situations and obtain useful information in the design or redesign phase of thermal installations.

It was demonstrated in the work that, by using new materials with superior characteristics, a reduction in energy consumption can be achieved even in the case of old aggregates through modernization. The applicability of the program is not limited to metallurgical furnaces but can be extended to a wide range of applications involving heat transfer.

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