Висновки

Розглянуто метод формування в термосенсорних ІС експоненційної характеристики перетворення. Досліджено залежність функції перетворення при заданих величинах опорної температури та діапазону вимірювання. Метод полягає у формуванні та подальшому перетворенні струму через прямозміщений p-n-перехід при фіксації на ньому температурно-незалежної напруги, або, з метою підвищення чутливості, – напруги з лінійною температурною залежністю. Крутість перетворення термосенсорних ІС становить відповідно 9%/К та 17%/К. Відрізняючись мінімальними структурними затратами, мінімальним енергоспоживанням та можливістю працювати з низьковольтним джерелом живлення, розроблені ІС можуть знайти широке застосування в сучасних системах керування термостатами, елементами захисту від перегріву, протипожежній сигналізації тощо.

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APPLICATION OF FINITE ELEMENTS METHOD FOR OPTIMISATION OF OPTICAL FIBRE PROBE DESIGNED TO OPERATE IN HARSH CONDITIONS

In the work we describe the process of design of fibre-optic probe for the flame monitoring system by method of finite elements. Probe made according to the design has successfully passed tests made in industrial boiler OP650.

Описано процес розробки волоконно-оптичного зонду для систем моніторингу полум'я методом скінченних елементів. Виготовлений зонд успішно пройшов випробовування в промисловому бойлері OP650.

1. Introduction

Burning of pulverised coal in power boilers produce important emission of pollution into atmosphere. In order to reduce it the combustion process was modified. The so called stage combustion was introduced, considerably decreasing NO_x emission. Installation of new generation, low-emission burners is the basic way to implement this method of combustion. In case of such burners combustion proceeds with an air deficiency in the first zones of the flame, what results in temperature decrease (comparing with older burners) preventing synthesis of the so called thermal NO_x. The combustion is incomplete. Then, in further zones of the flame, excess air is being supplied allowing completion of oxidation process i.e. full combustion. In such an organisation of combustion process the amount of unburned particles rises what means losses in combustion efficiency. In order to minimise such losses the reliable information about combustion, especially in its first stage, becomes necessary. This task is relatively difficult. One of methods (probably the cheapest) is application of optical fibre system for monitoring of chosen zones of flame in each burner in the boiler [7, 8]. In such system the probe is placed inside the burning chamber where harsh conditions exist (high temperature >400°C and dustiness). At least one month of reliable operation of the probe, with no maintenance (like cleaning) is required. Early designs allowed only few hours of operation. The elimination of dirt deposition on optical part was the most important problem. In order to solve this problem and design the probe which meets the requirements computer simulation was applied, using FLUENT software that implements the method of finite elements.

2. General description of method

Let us assume that we analyze the problem that is described in the area Ω by partial differential equation and the boundary conditions are given. Let the function Φ(P) be the solution, where P is a point of the considered area Ω. Procedure of searching of the solution in the method of finite elements consists of the following stages:

Stage 1

The considered area Ω is being divided into simple sub-areas – finite elements. In case of 2D problem they can be for example triangles or quadrangles. The elements cannot overlap or form gaps. The so called node points (nodes) are assigned to each element.

Stage 2

An approximation of searched function Φ is being selected for each element. Approximating function has to be chosen in such way to maintain continuity between adjacent elements [6]. When the area is divided into triangles the linear approximation can be applied

$$\Phi^{(e)}(x,y) = \alpha_1 + \alpha_2 x + \alpha_3 y \tag{1}$$

Values of parameters of approximation are assumed to be equal to node values of searched function Φ. The approximating function inside the element can be represented as linear combination of the shape function $N_i(P)$ and node values of searched function Φ as coefficients. For the two-dimensional element having *p* nodes an approximating function is assumed to be as follows:

$$\Phi^{(e)}(x,y) = N_1(x,y)\Phi_1 + N_2(x,y)\Phi_2 + \cdots + N_p(x,y)\Phi_p = \sum_{i=1}^{p} N_i(x,y)\Phi_i \tag{2}$$

For the expression (2) to hold true for arbitrary node point values Φ_i, the shape functions must have the value of one in the given node and zero in other nodes.

$$N_i(x_i, y_j) = \begin{cases} 1 \text{ dla } i = j \\ 1 \text{ dla } i \neq j \end{cases} \tag{3}$$

In every finite element the searched function Φ is therefore represented in the form of expression (2) with known functions $N_i(P)$ and unknown values of function Φ(*x*,*y*) in element's nodes.

Stage 3

On the grounds of procedure which optimises parameters of the approximating function the system of algebraic equations with unknown values of function $\Phi(x,y)$ in element's nodes is created. Boundary conditions have to be considered here also.

Stage 4

The system of algebraic equations is being solved. The solution is the set of values of searched function $\Phi(x,y)$ in element's nodes. [1,2,3,4]

3. Equations of the method

For the sake of simplicity the detailed analysis will consider two-dimensional problems in Cartesian co-ordinates.

Let us consider an equation

$$\nabla^2\Phi - q\Phi = -Q \tag{4}$$

which in Cartesian co-ordinates can be rewritten as follows

$$\frac{\partial^2\Phi}{\partial x^2} + \frac{\partial^2\Phi}{\partial y^2} - q\Phi = -Q \tag{5}$$

where Φ is the searched function that is assumed to be unequivocally defined in an area Ω with boundary Γ, q and Q are known position functions in the area Ω.

Problem description has to be competed with boundary conditions. Let us assume that function Φ on part of the boundary Γ meets the Dirichlet condition:

$$\Phi\big|_{\Gamma_1} = \Phi_0 \tag{6}$$

and the boundary condition of the third kind on the remaining part:

$$\left.\frac{\partial\Phi}{\partial n} - \alpha\Phi - \beta\right|_{\Gamma_2} = 0 \tag{7}$$

where Φ_0, α, β are known functions and n is the normal external to boundary to Γ_2.

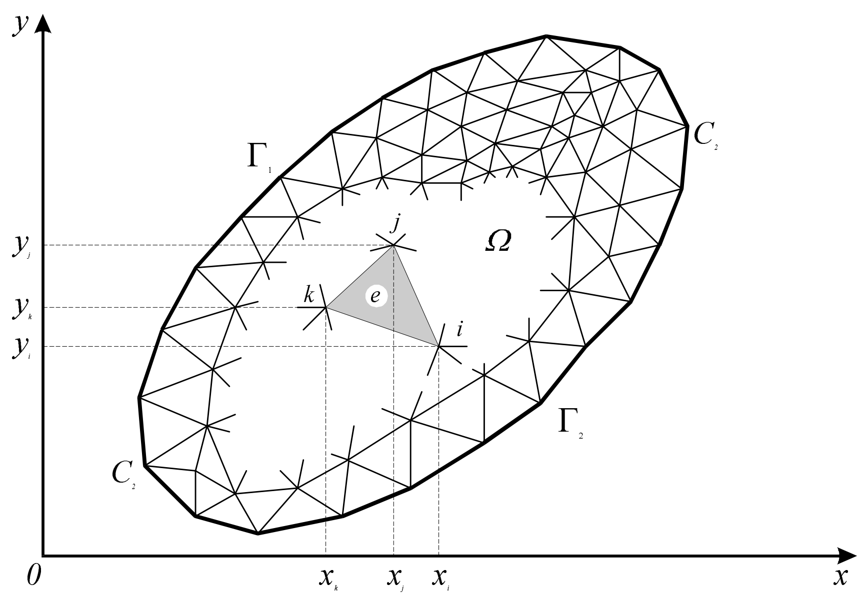

Fig. 1. Division of an area Ω into triangle elements

Let us assume that a flat area Ω has been divided into triangle elements of arbitrary dimensions (fig.1). Points C_1 and C_2 on the boundary Γ divides it into part Γ_1 on condition (6) and Γ_2 on condition (7). Let us consider the typical element *e* with nodes *i*, *j*, *k* numbered counterclockwise. Let us assume , that inside the element the searched field value is a linear function of co-ordinates x and y according to an approximation (1). In order to determine coefficients α_1, ,α_2 ,α_3, we assume that values of function Φ are given and equal to Φ_i, Φ_j, Φ_k. We obtain therefore the following system of equations:

$$\begin{aligned} \Phi_i &= \alpha_1 + \alpha_2 x_i + \alpha_3 y_i \\ \Phi_j &= \alpha_1 + \alpha_2 x_j + \alpha_3 y_j \\ \Phi_k &= \alpha_1 + \alpha_2 x_k + \alpha_3 y_k \end{aligned} \tag{8}$$

From the system of equations (8) we determine coefficients α_1, ,α_2 ,α_3:

$$\begin{aligned} \alpha_1 &= \left(a_i\Phi_i + a_i\Phi_i + a_k\Phi_k\right)/(2\Delta), \\ \alpha_1 &= \left(b_i\Phi_i + b_i\Phi_i + b_k\Phi_k\right)/(2\Delta), \\ \alpha_1 &= \left(c_i\Phi_i + c_i\Phi_i + c_k\Phi_k\right)/(2\Delta), \end{aligned} \tag{9}$$

where: $a_i=x_jy_k-x_ky_j$, $b_i=y_j-y_k$, $c_i=x_k-x_j$, and the remaining coefficient can be obtained by cyclic substitution of indexes *i*, *j*, *k*, while Δ is an area of triangular element.

After the substitution of coefficients (9) into (1) and simple algebraic transformations we obtain the following form of function Φ inside an element *e*:

$$\Phi^{(e)}(x,y) = N_i\Phi_i + N_j\Phi_j + N_k\Phi_k = \begin{bmatrix} N_i & N_j & N_k \end{bmatrix} \begin{Bmatrix} \Phi_i \\ \Phi_j \\ \Phi_k \end{Bmatrix} = [N]^{(e)}\{\Phi\}^{(e)} \tag{10}$$

where: $N_m = \left(a_m + b_m x + c_m y\right)/(2\Delta), \quad m = i, j, k$.

It is easy to verify that the shape functions N_m meet the condition (3). When the shape functions N_m are linear the continuity of function Φ is ensured on the boundary between adjacent elements because its values in two nodes defining element's boundary unequivocally determine the linear variation along this boundary, common for both elements. The problem of determination of function $\Phi(x,y)$ in an area Ω with boundary *Γ*, was reduced to the problem of finding its value in all nodes of finite element pattern. The adequate system of algebraic equations, from which we determine these values can be formulated using the variance principle or the weighted reminder method [5,6].

4. Application of finite elements method for optimisation of optical fibre probe designed to operate in harsh conditions

The above described method was applied to design an air flow inside the probe. As it was meant before the FLUENT/UNS software was used, which solves the Navier-Stokes equation: for conservation of mass and momentum when it calculates laminar flow with no heat transfer or other additional models. For flows involving heat transfer, an additional equation for energy conservation is solved (Equation 11). For flows involving species mixing or reaction, a species conservation equation is solved or, if the PDF model is used, conservation equations for the mixture fraction and its variance. Additional conservation equations are solved when the flow is turbulent. Because in our case we assumed that the flow is laminar, the conservation equations for laminar flow are presented.

4.1. The Mass Conservation Equation

The equation for conservation of mass, or continuity equation, can be written as follows:

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_i}\left(\rho u_i\right)=S_m \tag{11}$$

Equation 11 is the general form of the mass conservation equation and is valid for incompressible as well as compressible flows. The source S_m is the mass added to the continuous phase from the dispersed second phase (e.g. due to vaporisation of liquid droplets) and any user defined sources

For 2D axisymmetric geometries the continuity equation is given by

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x}(\rho u)+\frac{\partial}{\partial r}(\rho v)+\frac{\rho v}{r}=S_m \tag{12}$$

where x is the axial co-ordinate, r is the radial co-ordinate, u is the axial velocity, and v is the radial velocity.

4.2. Momentum Conservation Equations

Conservation of momentum is the i-th direction in an inertial (non- accelerating) reference frame is described by:

$$\frac{\partial}{\partial t}\left(\rho u_i\right)+\frac{\partial}{\partial x_j}\left(\rho u_i u_j\right)=\frac{\partial p}{\partial x_i}+\frac{\partial r_{ij}}{\partial x_j}+\rho g_i+F_i \tag{13}$$

where p is the static pressure, r_{ij} is the stress tensor (described below), and ρg_i and F_i are the gravitational body force and external body forces (e.g., that arise from interaction with the dispersed phase) in the i direction, respectively. F_i also contains other, model-dependent source terms such as centrifugal and Coriolis force and porous-media and user defined sources.

The stress tensor is given by

$$r_{ij}=\left[\mu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\right]-\frac{2}{3}\mu\frac{\partial u_l}{\partial x_l}\delta_{ij} \tag{14}$$

where: μ is the molecular viscosity and the second term on the right hand is the effect of volume dilation.

For 2D axisymmetric geometries the axial and radial momentum conservation equations are given by

$$\begin{aligned}\frac{\partial}{\partial t}(\rho u)+\frac{1}{r}\frac{\partial}{\partial x}(r\rho uu)+\frac{1}{r}\frac{\partial}{\partial r}(r\rho vu)=\frac{\partial p}{\partial x}&\\ +\frac{1}{r}\frac{\partial}{\partial x}\left[r\mu\left(2\frac{\partial u}{\partial x}-\frac{2}{3}(\nabla\cdot\vec{v})\right)\right]&\\ +\frac{1}{r}\frac{\partial}{\partial r}\left[r\mu\left(\frac{\partial u}{\partial r}+\frac{\partial v}{\partial x}\right)\right]&\\ +F_i&\end{aligned} \tag{15}$$

and

$$\frac{\partial}{\partial t}\left(\rho v\right)+\frac{1}{r}\frac{\partial}{\partial x}\left(r\rho uv\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(r\rho vv\right)=\frac{\partial p}{\partial r}$$
$$+\frac{1}{r}\frac{\partial}{\partial x}\left[r\mu\left(\frac{\partial v}{\partial x}+\frac{\partial u}{\partial r}\right)\right]$$
$$+\frac{1}{r}\frac{\partial}{\partial x}\left[r\mu\left(2\frac{\partial v}{\partial r}-\frac{2}{3}(\nabla\cdot\vec{v})\right)\right] \qquad (16)$$
$$-2\mu\frac{v}{r^2}+\frac{2}{3}(\nabla\cdot\vec{v})+\rho\frac{w^2}{r}$$
$$+F_i$$

where

$$\nabla\cdot\vec{v}=\frac{\partial u}{\partial x}+\frac{\partial v}{\partial r}+\frac{v}{r} \qquad (17)$$

and w is the swirl velocity.

5. Results of simulation

As it was mentioned before, the measurement probe is placed inside the burning chamber, where the temperature rises above 400°C. The maximum working temperature of PCS optical fibres applied in the probe is 130°C so cooling is necessary. Clean air was used as cooling media. It was also used as cleaning media for optical part of the probe. Six different designs was considered (fig.2). Each one provides same angle of view (γ=30°) for system of optical fibres.

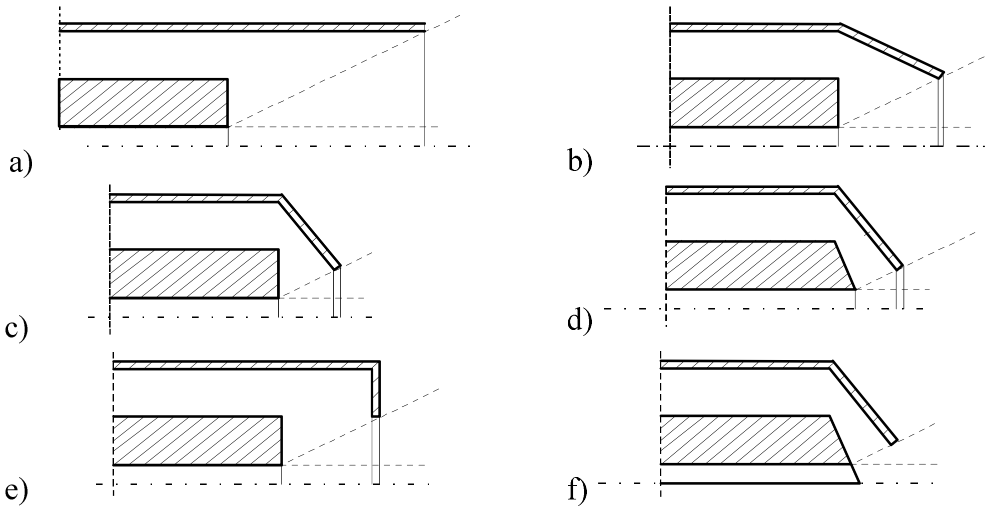

Fig. 2. Six design variants considered in the simulation

The applied pattern of division into finite elements is shown on fig 3. The following principle was applied: areas where big variation of searched function is expected are divided into smaller elements and, areas where small changes are supposed are divided into larger elements [4].

Results of simulation for each design of the probe are shown at fig.4 to fig.9 It can be seen that only in two cases (fig. 7 and 9) whirls, that in dusty environment would cause dirt deposition on optical head, does not appear. This is why design shown at Fig.2f was accepted as practical solution. Further simulations were made for the chosen design, were different supply air pressure was considered. Results obtained for the range 0,1 to 5 kPa confirmed the absence of whirls. The optical head of the probe is ended with specially designed quartz sphere, which also protects fibre endings from hot particles of coal.

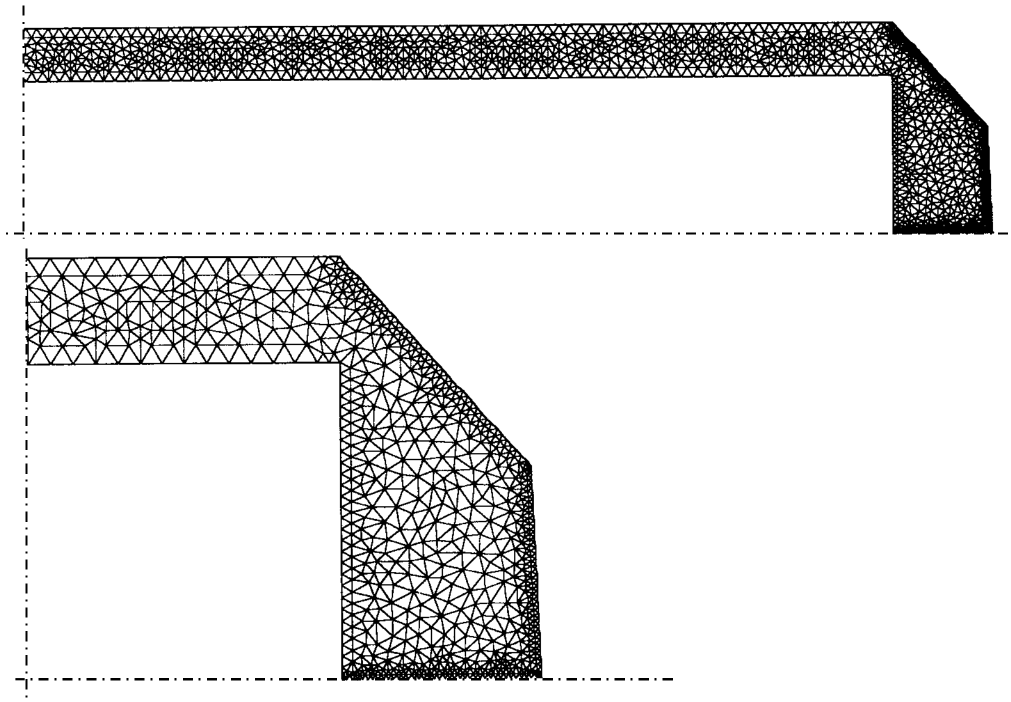

Fig. 3. The pattern of division into finite elements, below the detailed view of a nozzle is shown

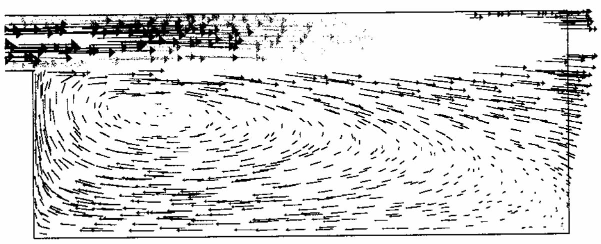

Fig.4. Result of simulation design 2a

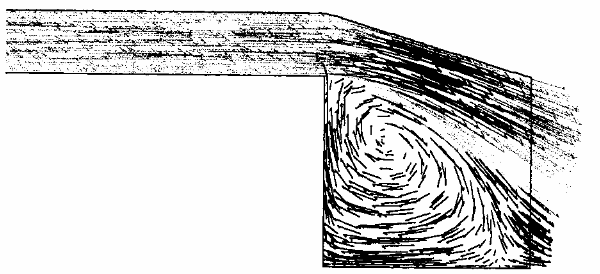

Fig.5. Result of simulation design 2b

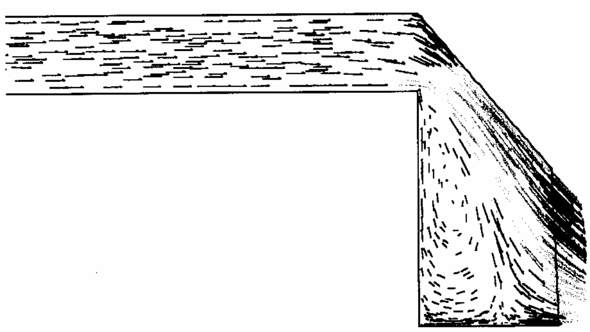

Fig.6. Result of simulation design 2c

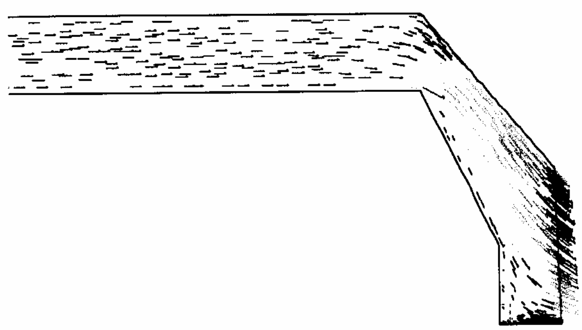

Fig.7. Result of simulation design 2d

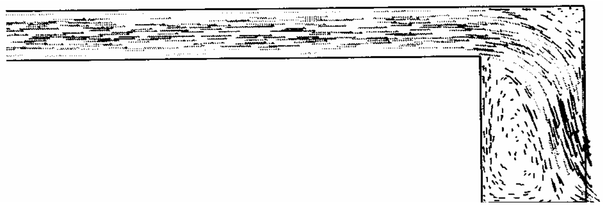

Fig.8. Result of simulation design 2e

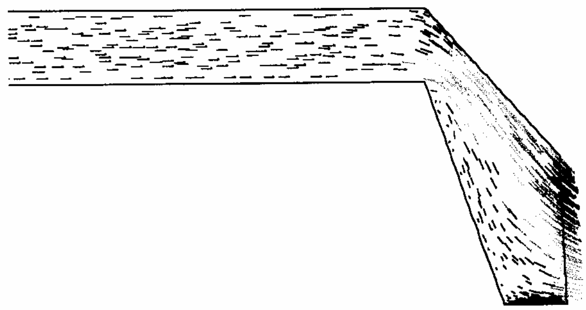

Fig.9. Result of simulation design 2f

6. Conclusions

The real measurement probe was made according to a solution shown at fig. 6f. It was equipped with a thermocouple that controls the temperature of an optical head. The cleaning/cooling air is supplied from a special system that ensure adequate pressure (about 3kPa) and purity. The probe was installed in a power unit and operates already more than three months with no need of maintenance. So, as it can be seen the design was positively verified in industrial conditions.

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