A GENERAL CONCEPT OF FIRE HYBRID MODELLING IN COMPARTMENTS

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Abstract. A general concept of a hybrid modelling of fire dynamics in the compartments is presented. The hybrid fire model combines the advantages of both zone and field models. The assumptions applying to physical model of fire and its mathematical description are given. Some problems related to application and development as well as verification and validation of the model are discussed.

Keywords: modelling of fire, computer simulation, zone fire model, field fire model, hybrid fire model, combustion.

1. Introduction

Although fire is one of the most complex phenomena, from early eighties scientists tried to create a digital model, which could be used for simulation of different fire scenarios. Actually, there are over 200 documented models of fire in the world (Konecki 2007). The following three main types of models can be distinguished: (1) integral, (2) zone and (3) field models. The first type is simple but the least accurate; it is used only in case of fires in well ventilated small rooms. This approach is especially applicable to analytical or fast numerical methods. The remaining two models are widely used all over the world. The most commonly applied and universal two models, invented and developed by National Institute of Standards and Technology (NIST), are zone model CFAST (last version 6.0.10 finished in 2005) and field model FDS (last version 4.0 finished in 2004, 5.0 in preparation) based on CFD procedures. The selected results of a digital simulation of the zone model of fire, carried out by Piórczyński, Gałaj (1998), were presented at VII, VIII and IX International Conferences "Modern Building Materials, Structures and Techniques in Vilnius" and can be found in the conference materials (Gałaj 2001, 2004, 2007).

Most of the models are applied for special purposes. As an example, models such as EGRESS, ELVAC or EVACS are used to solve the evacuation problems. The other like SMARTFIRE and KOBRA-3D are used to trace the smoke movement, while DETACT, LAVENT or JET are used to determine the time of sprinkler activation. Each of the above models have some disadvantages which limit their applicability. In case of the zone models only a few homogenous zones in the compartment are assumed (hot, cold and convection column). Therefore, it can be applicable only to small well-ventilated rooms, while in many other cases the accuracy is too low.

Some results of a research work on fire hybrid models of fire, performed at Leeds University, where program FACIT software and its 3-D version (FAS3D) was applied to simulate fires in the tunnels and compartments, are available in literature (Charters *et al.* 1994; Charters, Mcintosh 1995; Rylands, Mcintosh 2000). Like in the zone model, space of the compartment was divided into specified volumes: combustion and convective zones as well as hot, cold and mixing layers. On the top of that, each layer was divided into many cells for using the CFD method like in the field model. This model enables to simulate fire more accurately than zone models with considerably shorter time of calculation in comparison with the field models. However, in spite of introducing the control volumes, the presented model has the following weak points: significant simplification of parameters calculations, omitting of ventilation and extinguishing sub-models and no possibility to determine the species concentrations.

Chow (1996, 1997) applied CFAST zone model to simulate fire in big enclosures. He subdivided a bigger space into smaller cells (cases with 3, 9 and 15 cells were studied) and then applied to every cell the same procedure such as for the whole room. The obtained results showed, that a relative difference between flows in the model with 1 and 15 cells is significant and in some cases exceeds 30%. Despite a higher accuracy of this approach, the control volumes are still too big to get the values of fire parameters close enough to the measured values.

A multi-layer model was proposed by Suzuki *et al.* (2002). In this approach a fire compartment was divided into horizontal layers of the same height, in which the same fire parameters were assumed. These parameters were calculated by standard equations resulting from the law of mass and energy conservation. Extra modules of combustion, heat transfer and ceiling/wall flows were applied in the model. Theoretical results observed during

simulation are consistent with those obtained during the experiments conducted by Steckler *et al.* (1982) and Christian (2000). However, it has been suggested that the accuracy of the proposed model is still insufficient due to the fact that the changes in fire parameters at different points of the horizontal layer are not taken into consideration. It has been shown, that the relative difference between temperatures, measured on the same horizontal plane, can be even up to 30% (Gałaj, Zowada 2008).

Another approach to the hybrid modelling was proposed by Hua *et al.* (2005). In this approach a combination of the zone and field model was applied for investigating a growth of fire in multi-story building. A field model was used in the rooms with more complex dynamics of fire (e.g. with burning flammable object), while zone model was used in the compartments, where hot and cold zones were better stratified (e.g. in corridors, rooms situated far enough from the fire). Additionally, a transition model between the rooms with zone and field models was also applied. Changes in a thickness of the hot layer during the fire in the proposed hybrid model were compared with corresponding characteristics obtained for typical zone and field models. It can be concluded that the presented above method is very interesting and applicable for many fire scenarios. However, it should be noticed that even in a room, where the zone model was assumed a significant difference between temperatures and other fire parameters could occur as a result of the local whirls, wall airflows etc.

Requirements for acceptable model use can be found in a paper (Beard 2005). The problems connected with fire modelling, experiments with full-scale fires etc. were often discussed in the papers published last few years. We can give the examples of them: Himoto, Tanaka 2008; Kang 2009; Li *et al.* 2009; Merci, Van Maele 2008; Nilsen, Log 2009; Pierce, Moss 2007; Półka 2008; Rusch *et al.* 2008; Wu *et al.* 2007; Yoon *et al.* 2007; Yeoh *et al.* 2003; Yuen *et al.* 2006.

In this paper a more accurate hybrid model of the fire (HMF) in the compartments is proposed. This approach assumes application of the elementary volume controls, which is similar to the field model concept, while the calculation algorithms are based on the zone model. This method of calculation is simpler than the one used in the field model presented by Novozhilov (2001). Additionally, in the concept proposed by the author the application of advanced ventilation and extinguishing sub-models (sprinkler and mist systems) is discussed.

2. Description of hybrid fire model

A division of the compartment into $n[i]$ elementary structural cells of the same volume $V_k[i]$ with identical values of the fire parameters in all points of every cell was a main idea of proposed HMF. The accuracy of HMF depends among others on the volume $V_k[i]$. For the smaller value of $V_k[i]$, we get a greater accuracy, but simultaneously a longer time of calculations. The accuracy of the proposed model depends also on many other factors like mathematical model of the fire and input data. A reasonable compromise should be taken here resulting from the

assumptions and experimental data. The same widths and heights of the cells in the compartments situated on the same level were assumed to simplify the model of mass flow between adjacent cells. It results in the same widths and heights of the compartments. However, later in the next versions of HMF, we can omit this assumption introducing cells of different volumes $V_k[i,j]$ for the same compartment. Some horizontal and vertical views of 3 compartments connected by vertical openings (doors) are shown in Figs 1, 2. For the cells positioned within vertical vents connecting 2 compartments (e.g. doors or windows), its size along Ox axis, equal to the thickness of the opening was taken (Fig. 1). Similarly, for the horizontal vents the size of the cells along Oz axis equal to the height of the opening was accepted (Fig. 2). The number of the elementary cells along axis Ox, Oy and Oz of i-th compartment is determined from the following expressions:

$$n_x[i] = \min\left\{n_x \in N : n_x \ge \frac{D[i]}{\Delta x_{\max}}\right\},$$

$$n_y[i] = \min\left\{n_y \in N : n_y \ge \frac{S[i]}{\Delta y_{\max}}\right\}, \qquad (1)$$

$$n_z[i] = \min\left\{n_z \in N : n_z \ge \frac{H[i]}{\Delta z_{\max}}\right\},$$

where*: D[i]* – length of i-th compartment [m], *S[i]* – width of i-th compartment [m], *H[i]* – height of i-th compartment [m], $\Delta x_{\max}$ – maximum dimension of the elementary cell along the axis Ox [m], $\Delta y_{\max}$ – maximum dimension of the elementary cell along the axis Oy [m], $\Delta z_{\max}$ – maximum dimension of the elementary cell along the axis Oz [m].

Dimensions of the elementary cells in i-th compartment along the axis Ox, Oy and Oz can be determined using the following formulas:

$$x_k[i] = \frac{D[i]}{n_x[i]} \qquad y_k[i] = \frac{S[i]}{n_y[i]} \qquad z_k[i] = \frac{H[i]}{n_z[i]}. \qquad (2)$$

The schemes of mass and heat flows between the cell [j,k,l] of i-th compartment and adjacent cells, shown in the horizontal and vertical projections, are presented in Figs 3, 4.
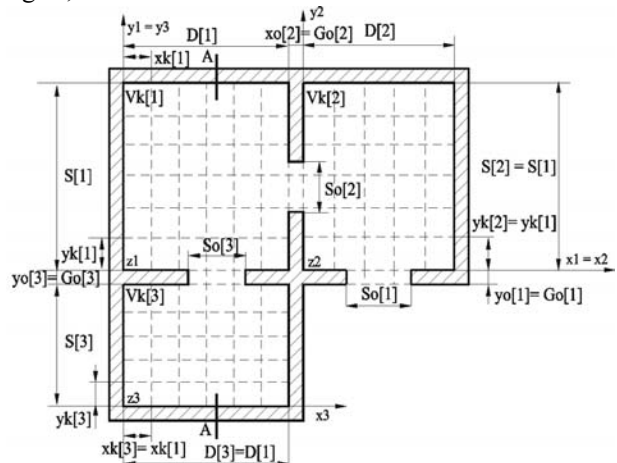
Fig. 1. The horizontal view of 3 adjacent compartments with the elementary cells
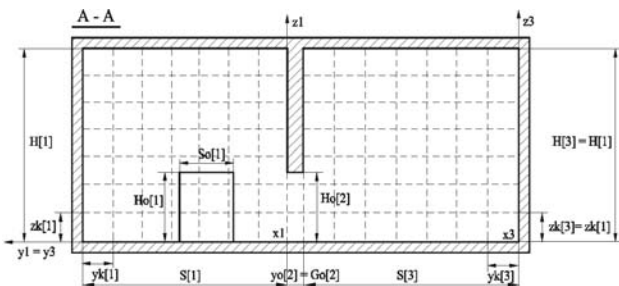
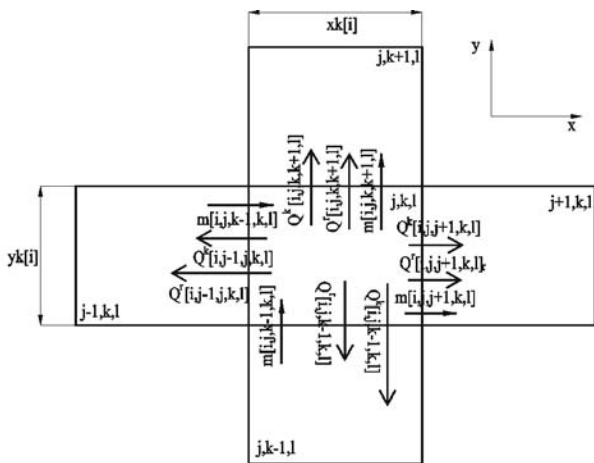**Fig. 2.** The vertical view of 3 adjacent compartments with the elementary cells

Fig. 3. A diagram of the horizontal mass and heat flow between [j,k,l] cell and adjacent cells
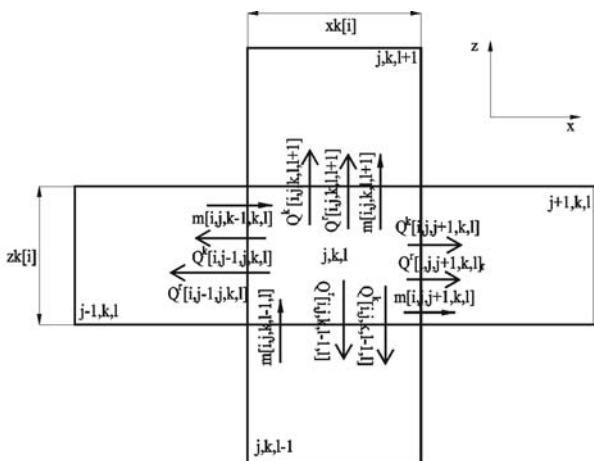

Fig. 4. A diagram of the vertical mass and heat flow between [j,k,l] cell and adjacent cells

To obtain for every cell the main fire parameters like: temperature, pressure, density, species concentrations, optical smoke density and so on, the equations of mass, energy and species balances applied to the zone model presented by Piórczyński *et al.* (1998) were used. As an example, the equations of mass conservation and relations for obtaining mass flow between adjacent cells were given below ($i=1..N$, $j=1..n_x[i]$, $k=1..n_y[i]$, $l=1..n_z[i]$):

$$\frac{dm[i,j,k,l]}{d\tau} = w[i,j-1,j,k,l]\cdot\overset{\bullet}{m}[i,j-1,j,k,l]+$$

$$+ w[i,j,j+1,k,l]\cdot\overset{\bullet}{m}[i,j,j+1,k,l]+w[i,j,k-1,k,l]\cdot$$

$$\overset{\bullet}{m}[i,j,k-1,k,l]+w[i,j,k,k+1,l]\cdot\overset{\bullet}{m}[i,j,k,k+1,l]+$$

$$w[i,j,k,l-1,l]\cdot\overset{\bullet}{m}[i,j,k,l-1,l]+w[i,j,k,l,l+1]\cdot$$

$$\overset{\bullet}{m}[i,j,k,l,l+1]+\sum_{im=1}^{lm[i]}w_m[im,i,j,k,l]\cdot\psi[im,i,j,k,l]+$$

$$+\sum_{iw=1}^{lw[i]}w_v[iw,i,j,k,l]\cdot\overset{\bullet}{m}_v[i,j,k,l], \qquad (3)$$

where: N – a number of the compartments,
$w[i,j-1,j,k,l]$, $w[i,j,j+1,k,l]$, ... – coefficients of mass flow between [j,k,l] cell and adjacent cells. They can only take 2 values: 1 if an adjacent cell exists or 0 if an adjacent cell does not exist (e.g. near wall, ceiling and floor),

$w_m[im,i,j,k,l]$ – coefficient of im-th flammable material corresponding to the cell [j,k,l] of i-th compartment. It can only take 2 values: 1, if i-th flammable material is present in the cell [j,k,l] and 0, if there is no i-th flammable material in the cell or it was burned out,

$\psi[im,i,j,k,l] = v_m[im]\cdot A_b[im,i,j,k,l]$ – mass flow output of the products generated during burning of im-th flammable material in [j,k,l] cell of i-th compartment ($v_m[im]$ – mass velocity of the combustion of im-th material obtained by experiment in m/s, $A_b[im,i,j,k,l]$ – combustion area of im-th material in [j,k,l] cell of i-th compartment in m²) [kg/s],

$w_v[iw,i,j,k,l]$ – coefficient of iw-th ventilation system corresponding to the cell [j,k,l] of i-th compartment. It can only take 2 values: 1, if outlet of iw-th ventilation system is fully or partly inside of [j,k,l] cell and 0, if there is no outlet of iw-th in the cell,

$$\overset{\bullet}{m}_v[i,j,k,l] = A_v[iw,i,j,k,l]\cdot v_v[iw]\cdot\rho_v[iw]$$ – mass flow output of the air produced by lw[i] ventilation systems, which outlets are fully or partly placed in [j,k,l] cell in kg/s ($A_v[iw,i,j,k,l]$ – outlet area of iw-th ventilation system being inside of [j,k,l] cell in m², $v_w[iw]$ – a mean value of the air velocity flowing out from iw-th outflow duct in m/s, $\rho_v[iw]$ – a mean value of air density of iw-th ventilation system in kg/m³).

Mass streams of gas flowing between the adjacent cells can be determined using Bernoulli equation. For example, 2 relations corresponding to the horizontal (between [j-1,k,l] and [j,k,l] cells) and vertical (between [j,k,l-1] and [j,k,l] cells) flows are given below:

$$\overset{\bullet}{m}[i,j-1,j,k,l]=\alpha\cdot z_k[i]\cdot y_k[i]\times$$

$$\times\sqrt{\frac{2\rho[i,j,k,l]|p[i,j-1,k,l]\rho[i,j,k,l]-p[i,j,k,l]\rho[i,j-1,k,l]|}{\rho[i,j-1,k,l]\cdot(1+f[i,j,k,l])}}\times \quad (4)$$

$$\times\text{sgn}\left(p[i,j-1,k,l]\cdot\rho[i,j,k,l]-p[i,j,k,l]\cdot\rho[i,j-1,k,l]\right)$$

$$\overset{\bullet}{m}[i,j,k,l-1,l]=\alpha\cdot x_k[i]\cdot y_k[i]\times$$

$$\times\sqrt{\frac{2\rho[i,j,k,l]\cdot\left|\begin{matrix}g\cdot\rho[i,j,k,l-1]\cdot\rho[i,j,k,l]\cdot z_k[i]+\\p[i,j-1,k,l]\cdot\rho[i,j,k,l]-p[i,j,k,l]\cdot\rho[i,j-1,k,l]\end{matrix}\right|}{\rho[i,j1,k,l]\cdot\left(1+f[i,j,k,l]\right)}}\times(5)$$

$$\times\text{sgn}\left(\begin{matrix}g\cdot\rho[i,j,k,l-1]\cdot\rho[i,j,k,l]\cdot z_k[i]+\\p[i,j-1,k,l]\cdot\rho[i,j,k,l]-p[i,j,k,l]\cdot\rho[i,j-1,k,l]\end{matrix}\right),$$

where:

α – mass flow coefficient assumed as a constant value for all cells,

$f[i,j,k,l]$ – coefficient of the linear loss of energy considering viscosity, kind of gas flow, friction etc,

$\rho[i,j-1,k,l]$, $\rho[i,j,k,l]$, ... – mean values of gas density in the cells $[j-1,k,l],[j,k,l]$ etc. of i-th compartment calculated from the following relation given as an example for the cell $[j,k,l]$:

$$\rho[i,j,k,l]=m[i,j,l,k]/V_k[i], \qquad (6)$$

$V_k=x_k[i]\cdot y_k[i]\cdot z_k[i]$ – volume of the elementary cell in i-th compartment,

$p[i,j-1,k,l]$, $p[i,j,k,l]$, ... – mean values of the pressure in the cells $[j-1,k,l]$, $[j,k,l]$ etc. of i-th compartment calculated from the following expression based on ideal gas law (for the cell $[j,k,l]$):

$$p[i,j,k,l]=\rho[i,j,k,l]\cdot R[i,j,k,l]\cdot T[i,j,k,l]. \qquad (7)$$

The expression for calculation mass gas constant $R[i,j,k,l]$ is as follows:

$$R[i,j,k,l]=B/M[i,j,k,l], \qquad (8)$$

where:

B – universal gas constant equal to 8314 J/(kmol K),

$M[i,j,k,l]$ – molar mass of the gas in the cell $[j,k,l]$ of i-th compartment which can be calculated using the following expression:

$$M[i,j,k,l]=Y[1,i,j,k,l]\cdot M_{O2}+Y[2,i,j,k,l]\cdot M_{CO}+$$
$$+Y[3,i,j,k,l]\cdot M_{CO2}+ \qquad (9)$$
$$+(1-Y[1,i,j,k,l]-Y[2,i,j,k,l]-Y[3,i,j,k,l])\cdot M_{N2},$$

$Y[1,i,j,k,l]$, $Y[2,i,j,k,l]$, $Y[3,i,j,k,l]$ – mass concentrations of oxygen, carbon monoxide and dioxide in the cell $[j,k,l]$ of i-th compartment obtained by use of (25). Mass concentrations of other air components were assumed to be 0.

M_{O2}, M_{CO}, M_{CO2}, M_{N2} – molar mass of oxygen, carbon monoxide, carbon dioxide and nitrogen.

   A sign of the value determined by the expressions of the form (4) or (5) indicates a direction of mass flow. If the value is positive, gas flows into the cell. When the value is negative, gas flows from the cell.

   An average value of temperature in the cell $[j,k,l]$ in i-th of compartment can be determined from the energy balance equation of the following form:

$$\frac{dT[i,j,k,l]}{dt}=\frac{T[i,j,k,l]}{c_p\rho_0 T_0 V_k[i]}\times$$

$$\times\left\{\begin{matrix}w[i,j-1,k,l]\cdot c_p\overset{\bullet}{m}[i,j-1,k,l]\cdot(T[i,j-1,k,l]-T[i,j,k,l])+\\[4pt]+w[i,j,j+1,k,l]\cdot c_p\overset{\bullet}{m}[i,j,j+1,k,l]\cdot(T[j+1,k,l]-T[i,j,k,l])+\\[4pt]+w[i,j,k-1,k,l]\cdot c_p\overset{\bullet}{m}[i,j,k-1,k,l]\cdot(T[i,j,k-1,l]-T[i,j,k,l])+\\[4pt]+w[i,j,k,k+1,l]\cdot c_p\overset{\bullet}{m}[i,j,k,k+1,l]\cdot(T[i,j,k+1,l]-T[i,j,k,l])+\\[4pt]+w[i,j,k,l-1,l]\cdot c_p\overset{\bullet}{m}[i,j,k,l-1,l]\cdot(T[i,j,k,l-1]-T[i,j,k,l])+\\[4pt]+w[i,j,k,l,l+1]\cdot c_p\overset{\bullet}{m}[i,j,k,l,l+1]\cdot(T[i,j,k,l+1]-T[i,j,k,l])+\\[4pt]+\sum\limits_{im=1}^{lm}w_m[im,i,j,k,l]\cdot\left(\overset{\bullet}{Q}_m[im,i,j,k,l]-c_pT[i,j,k,l]\cdot\psi[im,i,j,k,l]\right)+\\[4pt]+w_v[i,j,k,l]c_p\overset{\bullet}{m}_v[i,j,k,l]-\overset{\bullet}{Q}{}^{r}[i,j,k,l]-\overset{\bullet}{Q}{}^{k}[i,j,k,l]+\\[4pt]-w_g[i,j,k,l]\overset{\bullet}{Q}{}^{g}[i,j,k,l],\end{matrix}\right\}$$

$$(10)$$

where:

$c_p=f(T[i,j,k,l])$ – specific heat capacity at a constant pressure as a function of temperature,

ρ_0 – initial air density identical for all cells and compartments,

T_0 – initial air temperature identical for all cells and compartments,

$\overset{\bullet}{Q}{}^{r}[i,j,k,l]$ – radiation heat flux between $[j,k,l]$ cell of i-th compartment and adjacent cells or constructive surface like wall, ceiling or floor, which can be obtained using the following expression:

$$\overset{\bullet}{Q}{}^{r}[i,j,k,l]=\overset{\bullet}{Q}{}^{r}[i,j-1,j,k,l]+\overset{\bullet}{Q}{}^{r}[i,j,j+1,k,l]+\overset{\bullet}{Q}{}^{r}[i,j,k-1,k,l]+$$
$$+\overset{\bullet}{Q}{}^{r}[i,j,k,k+1,l]+\overset{\bullet}{Q}{}^{r}[i,j,k,l-1,l]+\overset{\bullet}{Q}{}^{r}[i,j,k,l,l+1],$$

$$(11)$$

$\overset{\bullet}{Q}{}^{k}[i,j,k,l]$ – convection heat flux between $[j,k,l]$ cell of i-th compartment and adjacent cells, which can be obtained using the following expression:

$$\overset{\bullet}{Q}{}^{k}[i,j,k,l]=\overset{\bullet}{Q}{}^{k}[i,j-1,j,k,l]+\overset{\bullet}{Q}{}^{k}[i,j,j+1,k,l]+\overset{\bullet}{Q}{}^{k}[i,j,k-1,k,l]+$$
$$+\overset{\bullet}{Q}{}^{k}[i,j,k,k+1,l]+\overset{\bullet}{Q}{}^{k}[i,j,k,l-1,l]+\overset{\bullet}{Q}{}^{k}[i,j,k,l,l+1],$$

$$(12)$$

$w_g[i,j,k,l]$ – extinguishing coefficients. It can take only 2 values 0 or 1. If water or other extinguishing medium flows through the cells, value is equal to 1. Otherwise, its value is equal to 0.

$\overset{\bullet}{Q}{}^{g}[i,j,k,l]$ – heat flux absorbed by sprayed stream of water or other extinguishing medium flowing through the cell $[j,k,l]$.

A determination of mathematical model of extinguishing process will be the main purpose of another work.

Radiation heat flux transferred through every wall of elementary cell [j,k,l] of i-th compartment can be calculated by standard Boltzmann equation for 2 parallel surfaces.

The equations for $\overset{\bullet}{Q}{}^{r}$ (radiation heat flux) given for 2 cases, first when coefficient of mass flow is w=1 (the adjacent cell exists) and second, when w=0 (the cell adjoins wall, ceiling or floor) are given below:

a) for w=1 (13)

$$\overset{\bullet}{Q}{}^{r}[i,j-1,j,k,l] = \frac{y_k \cdot z_k \cdot \sigma_0}{\frac{1}{\varepsilon[i,j,k,l]} + \frac{1}{\varepsilon[i,j-1,k,l]} - 1} \cdot \left(T^4[i,j,k,l] - T^4[i,j-1,k,l]\right);$$

(13)

b) for w=0 (14)

$$\overset{\bullet}{Q}{}^{r}[i,j-1,j,k,l] = \frac{y_k \cdot z_k \cdot \sigma_0}{\frac{1}{\varepsilon[i,j,k,l]} + \frac{1}{\varepsilon_k[i,j-1,k,l]} - 1} \cdot \left(T^4[i,j,k,l] - T_k^4[i,j-1,k,l]\right);$$

(14)

where:

$\sigma_0 = 5.67 \cdot 10^{-8}$ – Stefan-Boltzmann constant [W/m²K],

$\varepsilon[i,j,k,l]$, $\varepsilon[i,j-1,k,l]$, ... – emissivity of gas, being function of temperature, included in the appropriate cell,

$\varepsilon_k[i,j-1,k,l]$ – emissivity of the wall (ceiling, floor) material dependent on temperature,

$T_k[i,j-1,k,l]$ – temperature of the wall sector adjacent to left side of the cell [j,k,l], calculated according to algorithm based on the theory of unsteady one-dimensional conductivity in [17],

The equations for $\overset{\bullet}{Q}{}^{k}$ (convective heat flux) given for 2 cases, first, when coefficient of mass flow is w=1 (the adjacent cell exists), and second, when w=0 (the cell adjoins wall, ceiling or floor) are given below:
a) for w=1

$$\overset{\bullet}{Q}{}^{k}[i,j-1,j,k,l] = \frac{y_k \cdot z_k \cdot \lambda[i,j-1,j,k,l] \cdot Nu[i,j-1,j,k,l]}{x_k[i]} \times$$
$$\times \left(T[i,j,k,l] - T[i,j-1,k,l]\right);$$

(15)

b) for w=0

$$\overset{\bullet}{Q}{}^{k}[i,j-1,j,k,l] = \frac{y_k \cdot z_k \cdot \lambda[i,j-1,j,k,l] \cdot Nu[i,j-1,j,k,l]}{0.5 x_k[i]} \times$$
$$\times \left(T[i,j,k,l] - T_k[i,j-1,k,l]\right),$$

(16)

where:
$\lambda[i,j-1,j,k,l]$, ... – mean values of thermal conductivity of gas during heat transfer between adjacent cells. They can be calculated approximately using the following expressions, given for 2 cases, when w = 1 or w = 0:

a) for w = 1

$$\lambda[i,j-1,j,k,l] = 6.5 \cdot 10^{-8} \cdot \left(\frac{T[i,j,k,l] + T[i,j-1,k,l]}{2}\right)^{4/5};$$

(17)

b) for w = 0

$$\lambda[i,j-1,j,k,l] = 6.5 \cdot 10^{-8} \cdot \left(\frac{T[i,j,k,l] + T_k[i,0,k,l]}{2}\right)^{4/5},$$

(18)

$Nu[i,j-1,j,k,l]$, ... – Nusselt numbers for gas flowing between adjacent cells (w = 1) or the cell and wall, ceiling or floor (w = 0), which can be obtained using the following set of relations:

a) for w = 1

$$Nu[i,j-1,j,k,l] = \begin{cases} 0.054\left(Gr[i,j-1,j,k,l]\Pr\right)^{0..38} \\ \text{for } T[i,j,k,l] > T[i,j-1,k,l] \\ 0.003 \cdot \left(Gr[i,j-1,j,k,l]\Pr\right)^{0.38} \\ \text{for } T[i,j,k,l] < T[i,j-1,k,l] \end{cases}$$

$$Gr[i,j-1,j,k,l] = \frac{g \cdot \left(x_k[i]\right)^3 \cdot \left(T[i,j,k,l] - T[i,j-1,k,l]\right)}{273\left(v[i,j-1,j,k,l]\right)^2}$$

$$v[i,j-1,j,k,l] = 7.18 \cdot 10^{-10}\left(\frac{T[i,j,k,l] + T[i,j-1,k,l]}{2}\right)^{7/4};$$

(19)

b) for w=0

$$Nu[i,j-1,j,k,l] = \begin{cases} 0.054\left(Gr[i,j-1,j,k,l]\Pr\right)^{0..38} \\ \text{for } T[i,j,k,l] > T_k[i,j-1,k,l] \\ 0.003 \cdot \left(Gr[i,j-1,j,k,l]\Pr\right)^{0.38} \\ \text{for } T[i,j,k,l] < T_k[i,j-1,k,l] \end{cases}$$

$$Gr[i,j-1,j,k,l] = \frac{g \cdot \left(x_k[i]\right)^3 \cdot \left(T[i,j,k,l] - T_k[i,j-1,k,l]\right)}{273\left(v[i,j-1,j,k,l]\right)^2}$$

$$v[i,j-1,j,k,l] = 7.18 \cdot 10^{-10}\left(\frac{T[i,j,k,l] + T_k[i,j-1,k,l]}{2}\right)^{7/4},$$

(20)

Pr – Prandtl number assumed to be an approximate value 0.72.

The possibility of existence of one independent combustion zone in each of the compartment was assumed. A heat flux emitted during combustion of im-th flammable material can be determined by the set of the following expressions. It takes into consideration 2 different cases of combustion: controlled by fuel, when oxygen is enough for complete combustion and controlled by air, when oxygen is not enough (incomplete combustion).

For combustion controlled by fuel we have (21):

$$\overset{\bullet}{Q}_m[im,i,j,k,l] = \chi \cdot \psi[im,i,j,k,l] \cdot Q_s[im] + \overset{\bullet}{Q}_z[im,i,j,k,l],$$

while for combustion controlled by air we have (22):

$$\dot{Q}_m[im,i,j,k,l] = \dot{m}[i,j,k,l] \cdot Y[1,i,j,k,l] \cdot C_{LOL}[im,i,j,k,l] \cdot E +$$
$$+ \dot{Q}_z[im,i,j,k,l],$$

where:

χ – coefficient of combustion effectiveness,

$Q_s[im]$ – heat of combustion of im-th flammable material [J/kg],

$\dot{Q}_z[im,i,j,k,l]$ – additional heat flux connected with feedback thermal effect, which can be approximately obtained by the following formula (23):

$$\dot{Q}_z[im,i,j,k,l] = \chi \frac{Q_s[im]}{Q_g[im]} \cdot q_z[i,j,k,l] \cdot F_s[im,i,j,k,l],$$

$Q_g[im]$ – heat of gasification of im-th flammable material [J/kg],

$\dot{m}[i,j,k,l]$ – mass flow rate entrained into the cell [j,k,l] [kg/s],

$C_{LOL}[im,i,j,k,l]$ – lower oxygen limit coefficient corresponds to a fraction of the available fuel, which can be burned with the available oxygen. It varies from 0 at the limit to 1 above the limit. According to [12], the following functional form determined empirically was used to obtain C_{LOL} (24):

$$C_{LOL}[im,i,j,k,l] = 0.5$$
$$\left\{ \tanh \left[\frac{800 \cdot (Y[1,i,j,k,l] - Y_{LOL}[im,i,j,k,l])}{-4} \right] + 1 \right\},$$

E – heat release per mass unit of oxygen consumed. For typical fuels like polymer materials $1.31 \cdot 10^7$ J/kg is taken as a representative value of E,

$q_z[i,j,k,l]$ – total heat flux density entrained into the cell [j,k,l] of i-th compartment [W/m^2],

$Y_{LOL}[i,j,k,l]$ – lower oxygen limit for oxygen constrained burning in the cell [j,k,l] [kg/kg].

Mass concentrations of oxygen and species like carbon monoxide and dioxide, hydrogen chloride or hydrogen cyanide and soot can be determined using the following expression (25):

$$\frac{dY[is,i,j,k,l]}{dt} = \frac{T[i,j,k,l]}{c_p \rho_0 T_0 V_k[i]} \times$$

$$\times \left\{ \begin{array}{l} w[i,j-1,k,l]\dot{m}[i,j-1,k,l](Y[is,i,j-1,k,l] - Y[is,i,j,k,l]) + \\ + w[i,j,j+1,k,l]\dot{m}[i,j,j+1,k,l](Y[is,i,j+1,k,l] - Y[is,i,j,k,l]) + \\ + w[i,j,k-1,l]\dot{m}[i,j,k-1,l](Y[is,i,j,k-1,l] - Y[is,i,j,k,l]) + \\ + w[i,j,k,k+1,l]\dot{m}[i,j,k,k+1,l](Y[is,i,j,k+1,l] - Y[is,i,,j,k,l]) + \\ + w[i,j,k,l-1,l]\dot{m}[i,j,k,l-1,l](Y[is,i,j,k,l-1] - Y[is,i,j,k,l]) + \\ + w[i,j,k,l,l+1]\dot{m}[i,j,k,l,l+1](Y[is,i,j,k,l+1] - Y[is,i,j,k,l]) + \\ + w_m[i,j,k,l] \cdot \left(\sum_{im=1}^{lm} \psi[im,i,j,k,l](y[is,im] - Y[is,i,j,k,l]) \right) + \\ + w_v[i,j,k,l]\dot{m}_v[i,j,k,l] \cdot (Y_v[is,i,j,k,l] - Y[is,i,j,k,l]) \end{array} \right\}$$

where:

$Y[is,i,j,k,l]$, $Y[is,i,j-1,k,l]$... – mean mass concentrations of oxygen (is = 1), carbon monoxide (is = 2), carbon dioxide (is = 3), hydrogen chloride or hydrogen cyanide (is = 4) and soot (is = 5) in the cells [j,k,l], [j-1,k,l] etc. of i-th compartment [kg/kg],

$Y_v[is,i,j,k,l]$ – mean mass concentration of is-th gas component in the air supplied by ventilation system [kg/kg],

$y[is,im]$ – coefficient production yield for is-th species obtained from im-th flammable material (coefficient of reduction for oxygen), which can be calculated from the following formula (if equation of combustion reaction is known):

$$y[is,im] = \left(\frac{n[is,im]}{n[im]} \right) \cdot \left(\frac{M[is,im]}{M[im]} \right), \qquad (26)$$

where:

$n[is,im]$ – molar ratio of is-th species for a stoichiometric balance of the combustion reaction of im-th flammable material as a fuel,

$n[im]$ – molar ratio of the fuel (im-th flammable material),

$M[is,im]$ – particle mass of is-th product obtained during combustion reaction of im-th flammable material as a fuel,

$M[im]$ – particle mass of the fuel (im-th flammable material).

For proposed model the following initial conditions are taken:

1. Air density in all elementary cells of the compartment is of the same initial value equal to $\rho_0[i]$. Hence, for example, the initial mass of gas in the cell [j,k,l] can be simply calculated by means of the following formula: $m_0[i,j,k,l] = \rho_0[i] \cdot V_k[i]$.

2. The same value of initial temperature $T_0[i]$ in all elementary cells of i-th compartment is assumed.

3. The same values of mass concentration of oxygen $Y_0[1,i]$, carbon monoxide $Y_0[2,i]$ and carbon dioxide $Y_0[3,i]$ in all elementary cells of i-th compartment are assumed. Mass concentrations of other considered products are assumed to be zero ($Y_0[4,i] = Y_0[5,i] = 0$).

4. The same values of initial temperature of the ceiling, floor and the walls in i-th compartment $T_{k0}[i]$ are assumed.

3. Computer program and database structure

In this part structure of the computer program based on the hybrid model of the fire, described in the previous section, is presented. The input data were: flammable and constructive material features, compartments geometry, initial conditions and simulation parameters. Extension of the program is relatively simple due to its modular structure. A general block diagram of the program is presented in Fig. 5. A proposed relational database associated with the program consists of the following tables:

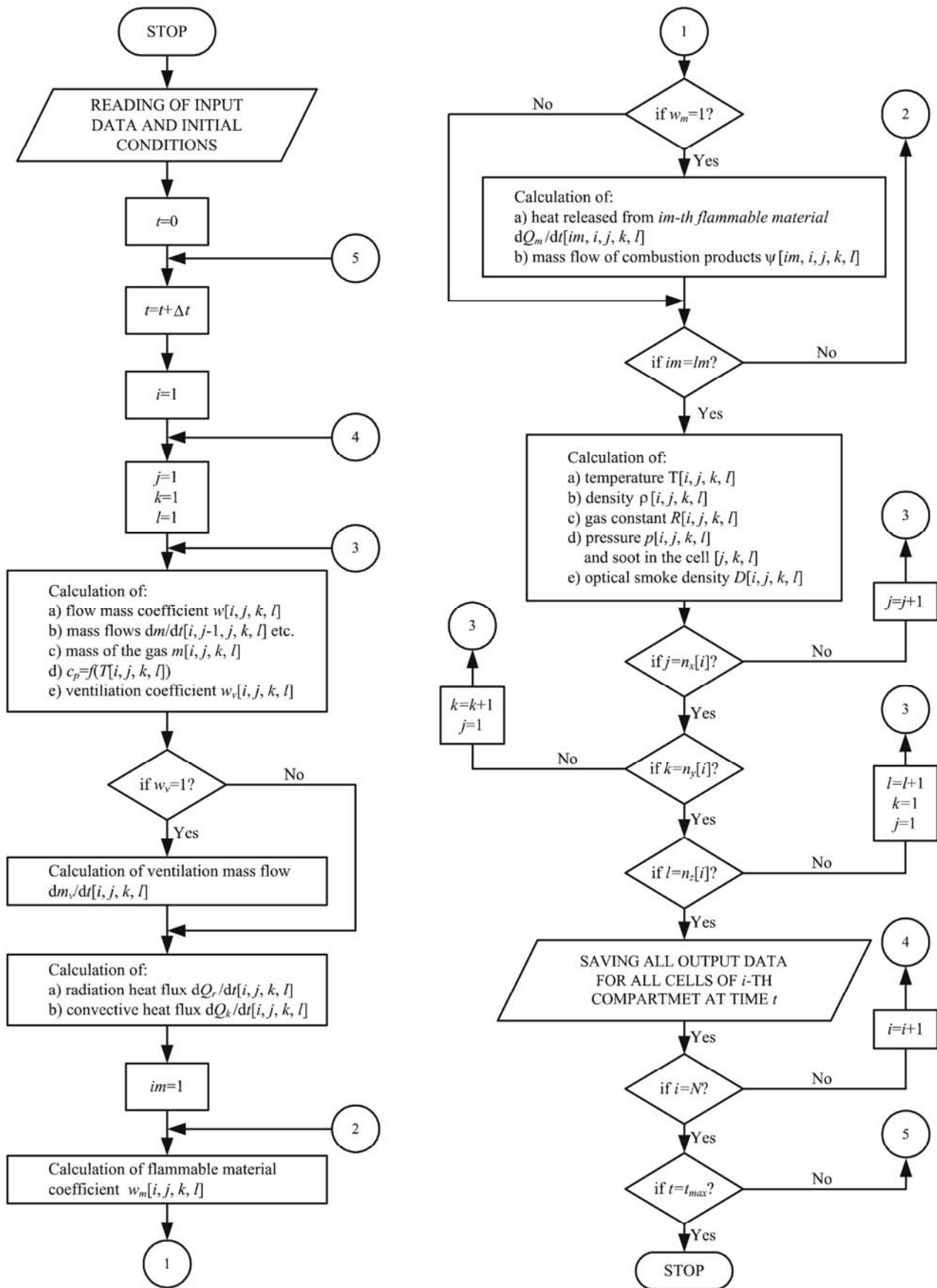a) COMPARTMENT – includes data on i-th compartment (e.g. length, width, height),

Fig. 5. Block diagram of the computer program

b) FLAMMABLE_MATERIAL – includes data on flammable materials (e.g. heat of combustion, mass speed of combustion, density),

c) CONSTRUCTIVE_MATERIAL – includes data on constructive materials of the walls, ceilings and floors (e.g. density, specific heat capacity, emissivity),

d) FLAMMABLE_OBJECT – includes data on flammable objects (e.g. dimensions)

e) OBJECT_MATERIAL – includes data which assign flammable material (s) to the selected object,

f) FIRE – includes data on fire scenarios (e.g. number, name, ignition power, outside conditions),

g) FIRE_COMPARTMENT – includes data which assign compartments to the selected fire scenarios,

h) COMPARTMENT_OBJECT – includes data which assign objects to the selected compartment,

i) VENT – includes data on the vents such as doors, windows (e.g. dimensions of the opening),

j) VENTILATION – includes data on mechanical ventilation systems (e.g. air mass flow speed, dimensions of ventilation duct),

k) COMPARTMENT_VENTILATION – includes data which assign ventilation systems to the selected compartment,

l) FIRE_DETECTOR – includes data on the fire detector (e.g. type, threshold value),

m) COMPARTMENT_DETECTOR – includes data which assign fire detectors to the selected compartment,

n) EXTINGUISHMENT – includes data on the extinguishing systems (e.g. type, distribution of the droplets, extinguishing effectiveness),

o) COMPARTMENT_EXTINGUISHMENT – includes data which assign extinguishing system to the selected compartment,

p) SIMULATION – includes data on simulation process (e.g. number, name, time of simulation, sampling time),

q) RESULTS – includes data on simulation results (e.g. temperature, pressure, species concentrations).

4. Final remarks

A model of the fire in the complex of compartments based on the hybrid modelling concept was proposed. It combines simplified mathematical equations applied in the zone model and division of the compartment into control volumes used in the field model. It was concluded that the presented hybrid model enables to obtain all significant fire parameters with higher precision than with zone model at lower costs and shorter time than with field model. Additionally, it was suggested that a mathematical description of the model taking into account its future development was sufficient for fire safety purposes. Further investigations should focus on determination of extinguishing and combustion sub-models and development

of the computer program project. A computer program, consisting of a separate module, which structure was shown in this paper, can be simply extended with additional modules such as: evacuation, turbulence, optimization of fire-fighting action, post-fire analysis etc. It was concluded that some further improvements of the model, such as introduction of the different volume of the cells in the same compartment could be done. Furthermore application of the special graphical module in computer program is to be performed for the thorough analysis of different fire scenarios.

The completion of the first version of the computer program is foreseen for the end of 2009. Large number of simulation processes for different fire scenarios is to be conducted to verify the new hybrid model of the fire. Furthermore, to validate the model simulation results will be compared with the parameters obtained during the real fire.

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GAISRO HIBRIDINIO MODELIAVIMO PATALPOSE BENDROJI KONCEPCIJA

J. Gałaj

S a n t r a u k a

Aprašyta gaisro hibridinio modeliavimo bendroji koncepcija. Gaisro hibridinis modelis susieja zonų ir laukų modelių privalumus. Pateiktos fizikiniame modelyje naudojamos prielaidos, aprašyta matematinė modelio dalis. Aptarti kai kurie taikymo ir tobulinimo, kaip ir rezultatų patikrinimo ir patvirtinimo, ypatumai.

Reikšminiai žodžiai: gaisro modeliavimas, kompiuterinė simuliacija, laukų gaisro modelis, hibridinis gaisro modelis, degimas.

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