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Simulation of fire development in a place of mass gathering

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Simulation of fire development in a place of mass gathering: *The complexity and variety of the observed phenomena which characterize fire dynamics precondition the necessity of using mathematical models in the process of study. Mathematical models give the opportunity of operational, less time and resource taking, appropriate and scientific prediction of fire spread. Therefore it is useful to work out mathematical models, which depending on the purpose - alone or relevantly grouped give the opportunity to solve actual or specific problems.*

Key words: *Fire, Mathematical Model, Simulation, Evacuation.*

SOME BENEFITS OF FIRE SIMULATION MODELING

Fire, as a process, might take different forms, each of which includes a chemical reaction between combustibles and oxygen in the air. if correctly used, this process is a source of energy and heat meeting our industrial and everyday needs but without control it might cause endless material damages and human sufferings.

In modern construction of buildings and facilities various polymer and easily igniting materials are used. Such materials are widely used for tiling, floor coverings, insulation, soundproofing, parts and structural elements, equipment and furniture. In the process of burning some of these materials release vast amounts of smoke and heat for a very short time. Combining such materials with errors or defects in the design and the exploitation of buildings results in highly dangerous situations when fire occurs.

Firefighters' general task is not to let people die or be injured in fire which leads to the conclusion that a basic part of preventive safeguarding activity in a building is to give answers to the following questions: where will the smoke go, is there a possibility to lead the smoke away so that the fire is prevented from spreading, how to keep the evacuation ways safe, could the smoke extracting be reduced, does leading way the heat help firefighting, etc [1, 2, 3].

When solving problems of fire safety the key issue is to have a precise and reliable method to estimate the heat and mass transfer. The complexity in working out such a model lies in the variety of factors and nonlinear solutions.

Fire development simulation is a combination of complex mathematical models, numerical methods, terms like "chemistry of fire", and "fire science" but it is not the solution of the problem itself.

A real fire, as non-controllable burning process, is a complex, nonstationary 3D, heat transfer physical process accompanied by changes in the chemical composition and changes of the gas environment parameters in the premises, which process is not fully studied yet.

In the focus of burning the turbulent, convective and eradicative heat and mass transfer is related to chemical reactions, heat transfer between burning gases and the side walls of the room. Existing openings and ventilation during firefighting lead to substantial differences in temperature, velocity and concentration regions of burning materials in the room, which complicates heat and mass transfer with the environment.

In the applicable technical regulations the design of systems (firefighting, smoke extraction and mechanical ventilation) is based on simplified methods for calculating heat and mass transfer during fire.

The present simulation is based on strict methods which give scientific prognosis of the dynamic of dangerous factors during fire and as a result provides the opportunity to optimize firefighting, smoke extracting and mechanical ventilation systems by taking into consideration the actual parameters during the occurrence, spread and evolution of fire, and also the thermo physical properties of the construction materials. Least but not last the present mathematical method helps the effective and efficient evacuation of people and valuable property.

In simulation with “PyroSim” there are different options for combustion modeling – from quite simple to complex enough. The simplest method is to design a fire source with predefined speed of heat emission.

Such a source is designed in three steps:

- ✓ Designing the reaction of combustion in gas medium;
- ✓ Designing a surface of type “Jet”;
- ✓ Designing an object in which to apply the surface.

One of the problems in the initial task is the lack of direct correspondence between the parameters which influence the intensity of fire, the parameters given in the reference data and the parameters built in “PyroSim”.

CHEMICAL REACTIONS IN GAS PHASE

This software supports two types of reactions in a gas phase – elementary stoichiometry (the fuel is composed only of atoms of carbon, hydrogen, oxygen and nitrogen) and complex stoichiometry (the fuel is composed of all possible kinds of atoms).

The present version of “PyroSim” supports only the reactions of elementary stoichiometry. Reactions with substances containing chlorine could be set but it is a comparatively difficult task.

Reactions In Elementary Stoichiometry

Types of reactions

In elementary stoichiometry, the formula of combustion is:

$$C_xH_yO_zN_N + \nu_{O_2}O_2 = \nu_{CO_2}CO_2 + \nu_{CO}CO + \nu_C C + \nu_{H_2O}H_2O + \nu_{N_2}N_2 \;, \tag{1}$$

where: X, Y, Z, N are the numbers of the atoms of the relevant composing element; $\nu_{O_2}, \nu_{CO_2}, \nu_{CO}, \nu_C, \nu_{H_2O}, \nu_{N_2}$ are the moles of the relevant element/compound in the composition of the fuel.

In “PyroSim” it is necessary to input the values of X, Y, Z, N, as well as the values of Yco and Ys which are secondary combustion products – carbon oxide and soot, respectively.

Note: Please, have in mind that in reactions in elementary stoichiometry chlorine is not taken into consideration.

Data transformation

We assume that smoke, to a great extent, consists of carbon. Most of the reference sources do not contain information (data) of emissions of nitrogen or its derivatives. That is why we assume that the content of nitrogen in fuel is equal to zero, N = 0.

The value Yco – portion of the fuel, respectively the suffocative gas is essentially analogous to the value Lco: $Yco = Lco$.

The value Ys is obtained from the smoke forming ability of the burning material

$$Ys = \frac{Dm}{Km} = Lc \,, \tag{2}$$

where $Km = 8700 m^2 / kg$ is the light absorption coefficient.

In the equations of reactions X, Y, Z values acquire the following expressions:

According to the law of conservation of mass:

$$L_{H_2O} = 1 + L_{O_2} - L_{CO_2} - L_{CO} - L_C \quad (3)$$

$$X = \nu_{CO_2} + \nu_{CO} + \nu_C =$$
$$= \left[\frac{L_{CO_2}}{M_{CO_2}} + \frac{L_{CO}}{M_{CO}} + \frac{L_C}{M_C} \right] M_f = \left[\frac{L_{CO_2}}{M_{CO_2}} + \frac{L_{CO}}{M_{CO}} + \frac{D_M}{K_m M_C} \right] M_f \quad (4)$$

$$Y = 2\nu_{H_2O} = 2\frac{(1+ L_{O_2} - L_{CO_2} - L_{CO} - L_C)M_f}{M_{H_2O}} \quad (5)$$

$$Z = 2\nu_{CO_2} + \nu_{H_2O} + \nu_{CO} - 2\nu_{O_2} =$$
$$= \left[2\frac{L_{CO_2}}{M_{CO_2}} + \frac{L_{CO}}{M_{CO}} + \frac{(1+ L_{O_2} - L_{CO_2} - L_{CO} - L_C)}{M_{H_2O}} - 2\frac{L_{O_2}}{M_{O_2}} \right] M_f \quad (6)$$

There is only one unknown variable in the formulas above – the molecular mass of the fuel, Mf. The reference books give information about complex fuel mixtures which makes the unique determination of the molecular mass impossible. Therefore, in the equations we will use the known, “basic” molecular masses of the compounds typical for the concrete fuel.

For most of the materials one of the two “basic” compounds are used:

- ✓ wood ($C_{3.4}H_{6.2}O_{2.5}$, $M_f = 87 g/mol$) – for materials based on wood, pulp and different natural fabrics;
- ✓ styrene ($C_6H_5 - CH = CH_2$, $M_f = 104 g/mol$) – for materials containing plastic, rubber and other artificial materials.

Reactions in Complex Stoichiometry

Types of reactions

In complex stoichiometry, the formula of combustion is:

$$C_xH_yO_zCl_{Cl} + \nu_{O_2}O_2 = \nu_{CO_2}CO_2 + \nu_{CO}CO + \nu_C C + \nu_{H_2O}H_2O + \nu_{Cl}HCl, \quad (7)$$

where: X, Y, Z, Cl are the numbers of the atoms of the relevant composing element; $\nu_{O_2}, \nu_{CO_2}, \nu_{CO}, \nu_C, \nu_{H_2O}, \nu_{Cl}$ are the moles of the relevant element/compound in the composition of the fuel.

Instead of chlorine, one or more elements except for nitrogen could be included in the reaction, i.e. contrary to the simple stoichiometry the complex one is universal.

In “PyroSim” it is necessary to input the value of M_f, which depends on the composition of fuel, as well as the values of $\nu_{O_2}, \nu_{CO_2}, \nu_{CO}, \nu_C, \nu_{H_2O}, \nu_{Cl}$.

Reference books give data about other parameters, too:

$$L_{O_2}(kg/kg); L_{CO_2}(kg/kg);$$
$$L_{CO}(kg/kg); L_{HCl}(kg/kg); Dm(m^2/kg), \quad (8)$$

where L_{XX} - the mass of the relevant element/compound necessary to burn out one kilogram of the combustive material.

Data transformation

We assume that smoke, to a great extent, consists of carbon. Most of the reference sources do not contain information (data) of emissions of nitrogen or its derivatives. That is why we assume that the content of nitrogen in fuel is equal to zero: $N = 0$.

The value Ys is obtained from the smoke forming ability of the burning material:

$$Ys = \frac{Dm}{Km} = Lc\,, \tag{9}$$

where $Km = 8700 m^2 / kg$ is the light absorption coefficient.

Consequently for the gas α:

$$L_\alpha = \frac{\nu_\alpha M_\alpha}{M_f} \Rightarrow \nu_\alpha = \frac{L_\alpha M_f}{M_\alpha} \tag{10}$$

Correspondingly for each gas is true that:

$$\begin{gathered} \nu_{O_2} = \frac{L_{O_2} M_f}{M_{O_2}}; \nu_{CO_2} = \frac{L_{CO_2} M_f}{M_{CO_2}}; \nu_{CO} = \frac{L_{CO} M_f}{M_{CO}}; \\ \nu_C = \frac{L_C M_f}{M_C} = \frac{D_m M_f}{K_m M_C}; \nu_{HCl} = \frac{L_{HCl} M_f}{M_{HCl}} \end{gathered} \tag{11}$$

Hence following the law of conservation of mass:

$$L_{H_2O} = 1 + L_{O_2} - L_{CO_2} - L_{CO} - L_C - L_{HCl} \tag{12}$$

$$\nu_{H_2O} = \frac{(1 + L_{O_2} - L_{CO_2} - L_{CO} - L_C - L_{HCl}) M_f}{M_{H_2O}} \tag{13}$$

There is only one unknown variable left in the equations above – the molecular mass of the fuel, Mf. The reference books give information about complex fuel mixtures which makes the unique determination of the molecular mass impossible. Therefore, in the equations we will use the known, “basic” molecular masses of the compounds typical for the concrete fuel.

COMBUSTIVE SURFACES

Combustion frequently starts with certain intensity (fire load) in a single point and therefore it spreads from that point uniformly in all directions until the whole surface is in flames.

If the length and the width of the fire load are of equal sizes then a circular spread of flames will occurs.

The velocity of heat loss in a case like this is described by the following formula:

$$Q = H_f.\Psi_d.S(t) = H_f.\Psi_d.\pi.\nu^2.t \tag{14}$$

where: H_f – the lowest combustion temperature mDj / kg; Ψ_d – individual material burning velocity, $kg / m^2 s$; $S(t)$ – surface of burning at the current moment, m^2, ν – linear velocity of flame spread, m / s.

In the formula $HRRPUA = H_f \Psi_d$ – the highest of individual velocities of heat transfer necessary to input for “Jet” type surface.

There are two variants to set the development of heat loss velocity from zero to its maximum value:

- ✓ To set the linear velocity of flame spread in the vents;
- ✓ To set the time necessary for the heat transfer to reach its maximum velocity in

the vents and to set the obstacles for its diffusion.

The following Fig.1 shows the case when the flame is influenced by the preset location of ventilation thus it spreads on the burning surface gradually. The relative velocity of heat loss is always the same and the full velocity of heat loss depends on the area taken in the flame.

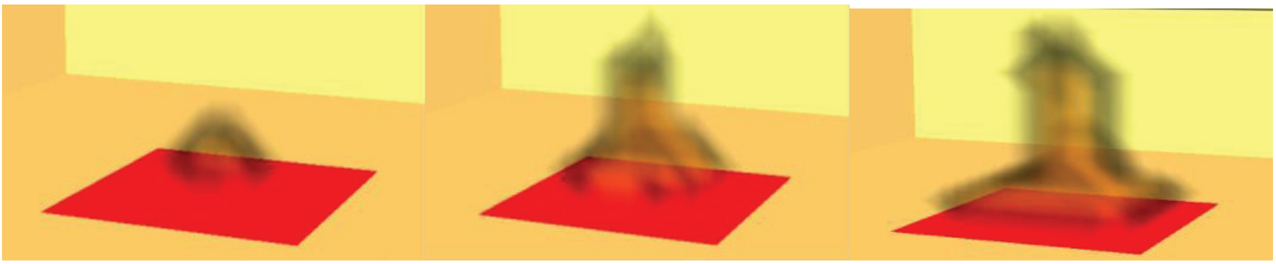

Fig.1

The following Fig.2 shows the case when the combustion is provoked all over the surface at the same time, then the relevant heat loss velocity is low at the beginning and then increases until its maximum values are reached. The area of the burning surface is always the same and the full heat loss velocity depends on the relevant power /vigour/ at the current moment.

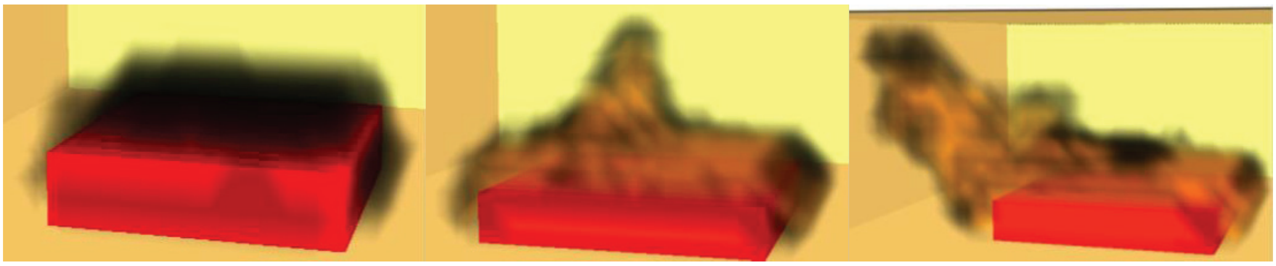

Fig.2

CONCLUSIONS

Simulations of fire development in places of mass gathering could be used in designing and constructing companies, as well as by the fire safety authorities with the purpose of optimization of firefighting systems, smoke extraction and mechanical ventilation in buildings, including garages and all of this orientated towards safe evacuation of people and property.

References

[1]. V.M.Astapenko, J.A.Koshmarov, I.S.Moldochanski, A.N. Shevliakov “Fire thermos gas dynamics in premises” M., Stroiizdat, 1986.

[2]. J.A.Koshmarov Prediction of fire hazards in premises”, textbook, M. Academy GPS MVD Rosia, 2000.

[3]. Ritchie, S.J., Steckler, K.D., Hamins, A., Cleary, T.G., Yang, J.C. and Kashiwagi, T., 1997. The Effect Of Sample Size On The Heat Release Rate Of Charring Materials. Fire Safety Science 5: 177-188. DOI: 10.3801/IAFSS.FSS.5-177 http://www.iafss.org/publications/fss/5/177/view

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