NUMERICAL ANALYSIS OF FIRE RISK AT INDUSTRIAL GAS PIPELINES

Seleznev V., Skiteva I.
Computation Mechanics Technology Center, Russia

Abstract: This paper covers one of new procedures of direct numerical simulation of fire. This simulation is meant for parameters estimation of burning methane-air mixture plume; forecast and analysis of zones thermally effected by fires at industrial gas pipelines. The results of this procedure application can be used for generation of statistical database (obtained as a result of numerical experiments).

1. Introduction

High pressure gas pipeline ruptures that occur outdoor entail often intense fires. Extensive thermal damage areas are typical for such fires. For example, the passage diameter of thermal damage area, caused by fire occurred in 2001 in Slovakia at gas pipeline, exceed some hundreds of meters [1]. It makes the problem on forecast and analysis of thermal damage areas, caused by failures at gas pipeline networks under outdoor conditions, very topical. The paper describes one of the approaches to estimation of thermal damage areas caused by intense fires occurred while ruptures of gas pipelines transmitting natural gas.

2. Fire models at industrial gas pipelines

The first step for application of the developed method is simulation of elastic-plastic rupture of the pipeline segment. At this, the main problem is defining the geometry of the emission source of natural gas into the atmosphere [1]. This problem is reduced mathematically to numerical solution of the differential equations of deformable solid motion in 3D nonlinear statement using finite element method. Analysis of transmitted natural gas flow rate into the fire source is executed using computation fluid dynamic simulators of gas pipelines [1].

Diffusive turbulent plume parameters of methane-air mixture combustion are obtained as a result of numerical solution of Reynolds’s equation system adapted for transient
simulation of fires occurred at gas pipelines. \((k - \varepsilon)\) or \((k - \omega)\) turbulence models are used to complete the system of Reynolds’s equations [1].

In the first approximation all chemical reactions can be changed by one-stage irreversible gross reaction between fuel and the oxidizing agent:

\[
Y_{methane} + v_{air} \cdot Y_{air} \rightarrow (1 + v_{air}) \cdot Y_{prod},
\]

where \(v\) is the stoichiometric coefficient of the reactant (\(v_{mole}\) - is the mole stoichiometric coefficient of the reactant); \(Y_m = \rho_m / \rho\) is the relative mass fraction of the \(m\)-th component (\(\rho_m\) is the density of the \(m\)-th component of the mixture). Well known Arrhenius law is used for estimation of global chemical reaction rate. A mathematical model of outdoor diffusive methane-air mixture combustion including \((k - \varepsilon)-\)turbulence model and one-stage global exothermal reaction (1) can be presented as follows:

\[
\frac{D\rho}{Dt} + \rho \cdot (\vec{V} \cdot \nabla) = 0;
\]  

\[
\rho \cdot \frac{DY_{methane}}{Dt} = \vec{V} \cdot \left( \frac{\mu + \mu_T}{Sc} \cdot \vec{V} \cdot Y_{methane} \right) - \varepsilon_{methane} \cdot \omega;
\]  

\[
\rho \cdot \frac{DY_{air}}{Dt} = \vec{V} \cdot \left( \frac{\mu + \mu_T}{Sc} \cdot \vec{V} \cdot Y_{air} \right) - \varepsilon_{air} \cdot \omega;
\]  

\[
Y_{prod} = 1 - Y_{methane} - Y_{air};
\]  

\[
\omega = M_{methane} \cdot Z \cdot \exp \left( -\frac{E}{R \cdot T} \right) \cdot \left( \frac{\rho \cdot Y_{methane}}{M_{methane}} \cdot \frac{\rho \cdot Y_{air}}{M_{air}} \right) \cdot \left( \frac{\rho \cdot Y_{methane}}{M_{methane}} \right)^{\omega_{methane}} \cdot \left( \frac{\rho \cdot Y_{air}}{M_{air}} \right)^{\omega_{air}};
\]  

\[
\rho \cdot \frac{DV}{Dt} = (\rho - \rho_{atm}) \cdot \vec{g} - \vec{V} \cdot \left( \frac{\mu + \mu_T}{\mu} \cdot \tau \right) - \frac{2}{3} \cdot \vec{V} \cdot (\rho \cdot K); 
\]  

\[
\rho \cdot \frac{DH}{Dt} = \frac{\partial P}{\partial t} + Q_{burn} \cdot \omega - S_{pas} + \frac{\partial Q}{\partial t} + (\rho - \rho_{atm}) \cdot \vec{g} \cdot \vec{V} +
\left( \lambda + \lambda_T \right) \cdot \nabla T + \frac{\mu + \mu_T}{\mu} \cdot \vec{V} \cdot \varepsilon - \frac{2}{3} \cdot \rho \cdot K \cdot \vec{V} \right) +
\sum_{m=1}^{N} \nabla \cdot \left( C_v \right) \cdot T + \frac{\mu + \mu_T}{Sc} \cdot \vec{V} \cdot Y_m; 
\]
\[ \rho \frac{DK}{Dt} = \nabla \cdot \left[ \frac{\mu + \mu_T}{Pr} \nabla K \right] + G - \rho \cdot \epsilon - \frac{\mu_T}{\rho \cdot Pr} \left( \mathbf{g} \cdot \nabla \rho \right); \]

\[ \rho \frac{De}{Dt} = \nabla \cdot \left[ \frac{\mu + \mu_T}{Pr} \nabla e \right] + \frac{e}{K} \left( C_2 \cdot G - C_3 \cdot \rho \cdot e - C_1 \cdot \frac{\mu_T}{\rho \cdot Pr} \left( \mathbf{g} \cdot \nabla \rho \right) \right); \]

\[ S_{rad} = \sum_{j=1}^{L} \varphi_j \left( Y_j \right) \cdot \int_{\Theta} \nabla \cdot \mathbf{q}_{v,j} dV, \]

where \( \mathbf{q}_{v,j} = \chi_{v,j} \cdot \left( 4 \cdot \pi \cdot I_{vb} (T) - \int_{4\pi} I_{v,j} (s, \bar{\theta}, t) d\bar{\theta} \right); \)

\[ \ \]

\[ \frac{1}{c_{rad}} \frac{\partial I_{v,j} (s, \bar{\theta}, t)}{\partial t} + \left( \chi_{v,j} \cdot I_{vb} (T) + \frac{\beta_{v,j}}{4 \cdot \pi} \int_{4\pi} \chi_{v,j} \left( \bar{\theta}, \bar{\theta}' \right) \cdot I_{v,j} (s, \bar{\theta}, t) d\bar{\theta}' \right) = \]

\[ = \chi_{v,j} \cdot I_{vb} (T) + \frac{\beta_{v,j}}{4 \cdot \pi} \int_{4\pi} \chi_{v,j} \left( \bar{\theta}, \bar{\theta}' \right) \cdot I_{v,j} (s, \bar{\theta}, t) d\bar{\theta}', \quad j = 1, L; \]

\[ C_{soil} \cdot \rho_{soil} \cdot \frac{\partial T}{\partial t} = \nabla \cdot \left( \lambda_{soil} \cdot \nabla T \right); \]

\[ P = \rho \cdot R_0 \cdot T \cdot \sum_{m=1}^{N_v} \frac{Y_m}{M_n} + \rho_{am} \cdot g \cdot (x_3 - x_{3,0}); \]

\[ H = C_p \cdot T + \frac{\mathbf{V} \cdot \mathbf{V}}{2}; \quad \alpha_{mix} = \sum_{m=1}^{N_v} f_{a,m} (Y_m, \alpha_m), \quad \text{where} \ \alpha = \mu, \lambda, C_p, C_v; \]

\[ \mu = \left( \frac{T}{273.15} \right)^{3/2} \cdot \frac{273.15 + C_S}{T + C_S} \cdot \mu_0; \quad \mu_T = \frac{C_p \cdot \rho \cdot K^2}{\epsilon}; \quad \lambda_T = \frac{C_p \cdot \mu_T}{\rho \cdot \mu_T}; \]

\[ \tau_{i,j} = \mu \left[ \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \delta_{i,j} \cdot \frac{\partial u_k}{\partial x_k} \right]; \quad Sc = \frac{\mu}{\rho \cdot D}; \]

\[ G = \mu_T \cdot \left\{ \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)^2 - \frac{2}{3} \left( \frac{\partial u_k}{\partial x_k} \right)^2 \right\} - \frac{2}{3} \cdot \rho \cdot K \cdot \frac{\partial u_k}{\partial x_k}, \]

where \( \rho \) – mixture density; \( P \) – piezometric pressure of mixture; \( T \) – mixture temperature; \( \mathbf{V} \) – velocity of mixture with the components \( u_1, u_2, u_3 \); \( \mathbf{g} \) – gravitational
acceleration; $t$ – time; $\omega$ – chemical reaction rate; $N^*$ – number of the components in mixture, in our case $N^* = 3$; $\frac{D(...)}{Dt}$ – substantial derivative from scalar function; $H$ – total enthalpy; $C_p$ – specific heat capacity under constant pressure; $C_v$ – specific heat capacity at constant volume; $(C_v)_m$ – specific heat capacity of $m$-th component at constant volume; $\lambda$ – thermal conductivity; $\lambda_T$ – turbulent conductivity; $\mu$ – dynamic viscosity; $C_S$ – Sutherland constant; $\mu_0$ – dynamic viscosity under the normal conditions; $\mu_T$ – turbulent viscosity; $x_1, x_2, x_3$ – Cartesian coordinates of the point; $x_{3,0}$ – fixed coordinate corresponding to the sea level; $\tau$ – viscous stress tensor with the components $\tau_{ij}$; $K$ – kinetic turbulence energy; $\varepsilon$ – turbulence dissipation rate; $C_J$, $C_i$, $i = \overline{1,4}$ – empirical constants; Pr – Prandtl number; inferior index $T$ means “turbulent”; $M_m$ – molar mass of $m$-th component; inferior index “atm” means that the parameter belongs to undisturbed atmosphere; $R_0$ – universal gas constant; $R$ – gas constant; $Sc$ – Schmidt number; $Q_{burn}$ – heat of fuel (methane) combustion; $S_{rad}$ – radiation source term; $Z = \mathbf{Z} \cdot T^\beta$ – preexponent ($\mathbf{Z}$, $\beta$ – assigned empirical coefficients); $E$ – activation energy; $c_{rad}$ – speed of light in medium; $\mathbf{\Theta}$ – direction of radiation spread; $S$ – path length (coordinate) measures along radiation spread $\mathbf{\Theta}$; $L$ – number of considered hot gases(for example, gaseous combustion products); $I_{\nu, j}$ – spectral radiation intensity of $j$-combustion product in the point with the coordinate $s$ ($j = \overline{1, L}$); $\chi_{\nu, j}$ – spectral coefficient of radiation absorption by $j$-gas; $\beta_{\nu, j}$ – spectral coefficient of radiation scattering by $j$-gas; $I_{sv}(T)$ – spectral radiation intensity of ideal black body under temperature $T$ in vacuum; $V$ – radiation frequency; $\gamma_{\nu, j}(\Theta, \Theta^\nu)$ – spectral in-scattering phase function; $\Theta^\nu$ – axial vector of the solid angle $d\Omega$; $\varphi_j(Y_j)$ – assigned weighting function; $G$ – dissipative function of turbulent fluid flow, expressing heat equivalent of mechanical power spending during deformation of gas mixture because of its viscosity; $f_\alpha(...)$ – known semiempirical functions; $C_{soil}$ – specific heat capacity of soil adjoining to the failure place; $\rho_{soil}$ – density of soil; $\lambda_{soil}$ – thermal conductivity of soil.
The method of control volumes is used for numerical analysis of Reynolds’s equations, equations of chemical kinetics; integro-differential radiative transfer equations and thermal conductivity equations for soil (see (2-17)). The method of control volumes is added by the following:

- Monte-Carlo statistical algorithms [2] and algorithms for numerical solution of the weighted sum of grey gases offered by G. Hottel and A. Sarofim [3];
- Modified differential approximation algorithm of mean radiation fluxes offered by N.N. Ponomarev and N.A. Rubtsov [4].

The results of numerical solution for the system (2-17) with $S_{rad} = 0$ and $\omega = 0$ are used as initial conditions. Boundary conditions on the lateral and upper surfaces of the computational domain are assigned either on the assumption that the atmosphere is undisturbed or in accordance with the specified field of the wind. Underlying surface at a depth of two meters beyond the emission area is considered isothermal with known temperature $T_{soil}$. Mass fluxes of all chemical species and the vertical component of velocity are assigned equaling to zero on underlying surface beyond ignition source. Plume ignition is simulated in accordance with the approach described in [1].

Coupled thermal and fluid dynamics problem, concerned with numerical simulation of thermal effect caused by diffusion plume, is solved for estimation of flame effect on the neighboring pipes in the pipeline network. At this transient temperature field of the pipeline walls is calculated. Then the structural analysis of the open gas pipeline segments under assigned transient temperature field of the pipe walls is executed.

While defining the temperature field of the pipeline walls undergoing thermal effect caused by fire, the mathematical model (2-17) is added by thermal conductivity equation for the pipe wall and by the condition of impermeable stationary pipe wall. Additional conjugation conditions connect radiant energy flux, heat flux in the pipe wall and convective heat transfer in near the wall layer under assigned emissivity of the outside pipe wall. Convection heat transfer boundary conditions are assigned on the inside surface of the pipe wall. Temperature of natural gas in the pipe is estimated using computation fluid dynamics simulator. Initial conditions are assigned as some known temperature field of the pipe wall and gas being inside this wall.

3. Estimation of thermal damage areas

To assess the maximum effect of thermal radiation on people, vegetation and adjacent structures, an approximation of an optically thin layer is used. This approach allows for the development of automated procedure for the analysis of thermal impact zones, which can be applied for the operative analysis of the consequences of fires at the gas transmission pipelines.
The main characteristic of thermal radiation is its intensity $I \ [W/m^2]$:

$$I = \varepsilon \cdot \sigma \cdot T^4,$$  \hspace{1cm} (18)

where $\varepsilon$ is the emissivity of the surface element, $\sigma$ is the Stefan-Boltzmann constant, and $T$ is the absolute temperature of surface element [K].

The thermal radiation energy $W$ emitted by the entire body in all directions is determined by the expression:

$$W = \sigma \cdot \int_A \varepsilon \cdot T^4 \, dA,$$  \hspace{1cm} (19)

where $A$ is the emitting surface of the body. In the case where the entire surface of the body is heated uniformly, and all its segments have the same emissivity, the expression (19) may be expressed as follows:

$$W = \varepsilon \cdot \sigma \cdot T^4 \cdot S,$$  \hspace{1cm} (20)

where $S$ is the area of the body emitting surface.

The equations (18-20) give the relationship between the hemispheric intensity of radiation of the surface element of the body and the thermal radiation energy emitted by the entire body into the surrounding space:

$$I = W / S.$$  \hspace{1cm} (21)

The hemispherical intensity of radiation coming from the surface of heated body $i$ on the element of the surface in an arbitrary point in space is related to the respective location of the heated surface and the elementary surface in space and is determined by the expression:

$$I_{da_i} = I \cdot F_{di},$$  \hspace{1cm} (22)

where $F_{di}$ is the diffusion angular coefficient (or radiation view factor). The view factor between surfaces $A_i$ and $A_j$ is determined as

$$F_{ij} = \frac{1}{A_i} \cdot \int_{A_i, A_j} \frac{\cos \theta_i \cdot \cos \theta_j}{\pi \cdot r^2} dA_i dA_j,$$  \hspace{1cm} (23)

where $r$ is the distance between element $dA_i$ on the heated surface and surface element in space $dA_j$; $\theta_i$ and $\theta_j$ are angles between the surface normal and the direction of the radiant heat flow for $dA_i$ and $dA_j$, correspondingly.

For a set of $N$ surfaces, values of the view factors may be united into a matrix containing $N^2$ members. To determine the amount of heat flow transferred from surface $i$ to surface $j$, taking into account their location in space, the Stefan-Boltzmann law looks as follows:
Finding an analytical solution of this equation for practical problems is very difficult when the view factors are to be determined. It is related to the fact that real-life problems of radiation heat exchange involve an ensemble of surfaces which have a complicated spatial shape (plume, local terrain, buildings and structures, etc.) and affect each other (wave reflection, shading of surfaces).

If we extend the Stefan-Boltzmann law for a system of $N$ grey enclosures, we obtain [1]:

$$\sum_{j=1}^{N}\left(\frac{\delta_{ij}}{\varepsilon_j + 1} - F_{ij} \cdot \frac{1}{\varepsilon_j}ight) \cdot \frac{1}{A_j} \cdot Q_j = \sum_{j=1}^{N}(\delta_{ij} - F_{ij}) \cdot \sigma \cdot T_j^4.$$  

(25)

The expression (25) may be used for the construction of a row in the following matrix equation

$$[\mathbf{C}] \cdot \{\mathbf{Q}\} = [\mathbf{D}] \cdot \{\mathbf{T}^4\},$$  

(26)

in such a way that $\left[\varepsilon_j\right] = \left(\frac{\delta_{ij}}{\varepsilon_j + 1} - F_{ij} \cdot \frac{1}{\varepsilon_j}\right) \cdot \frac{1}{A_j}$ and $\left[\delta_{ij} - F_{ij}\right] \cdot \sigma$, $j = 1, N$, where $\{\mathbf{T}^4\} = \{T_1^4, T_2^4, \ldots, T_N^4\}^T$, $\{\mathbf{Q}\} = [\mathbf{C}]^{-1} \cdot [\mathbf{D}] \cdot \{\mathbf{T}^4\} = [\mathbf{K}^{\mathcal{S}}] \cdot \{\mathbf{T}^4\}$, where $[\mathbf{K}^{\mathcal{S}}]$ is the radiation matrix. It is not difficult to solve equation for a thermal problem, given the initial and boundary conditions (generally, these are Type I conditions) are set.

Solving a problem of the spatial propagation of radiation from the burning methane-air mixture comprises of the following main stages: setting the geometry of surfaces involved in radiation heat exchange; setting the problems dimensionality (the axisymmetric or 3-D statement of the problem); creating an FE-model, which comprises of a computational mesh generation, the material properties definition and assignment of boundary conditions on the emitting and absorptive surfaces; the generation of the radiation matrix $[\mathbf{K}^{\mathcal{S}}]$, the application of the radiation matrix $[\mathbf{K}^{\mathcal{S}}]$ in thermal analysis; the visualization of the results obtained; the interpretation of the results obtained.

One of the main conditions for obtaining correct results from mathematical simulations of the problems of radiant heat transfer is an accurate description of the geometry of the emitting and absorptive surfaces. To make a mathematical model for the analysis of thermal radiation from a burning methane-air mixture, the required input data are the coordinates of the points describing the local terrain and the surface of the plume combustion front.

The main source of input data for the description of local terrain are geographic and topographic maps specifying the height above sea level in the form of fixed points and/or
contours, i.e., the data from electronic geographic information systems. To have a more detailed description of the terrain adjacent to the gas pipeline, with altitudes of natural and artificial obstacles indicated, it is necessary to take accurate measurements by means of advanced digital laser or optical elevation meters.

To determine the geometry of the flame front surface of the plume participated in radiation heat exchange, numerical simulation technology of methane-air mixture combustion is used (see "Fire Models at Industrial Gas Pipelines").

4. Results

Fig. 1 presents simulation of actual fire caused by gas pipeline rupture. This simulation is executed in 3D statement under conditions of undisturbed atmosphere using the state earlier approach.

![Fig. 1. The example of the unsteady diffusion combustion of methane-air mixture in turbulent plume mode: (a) actual fire at gas pipeline; (b) simulation results as the methane mass fraction (10% CH₄) field in the combustion zone](image)

Fig. 2 presents the example of problem solution results concerned with analysis of fire safety at power plants (PP) while failures at technological gas pipelines of HPP gas control points.
5. Concluding remarks

The paper presents the method for forecast and analysis of thermal damage areas behavior caused by outdoor fires while ruptures of industrial pipelines transmitted natural gas. The method is meant for solution of the industrial problems concerned with enhancing fire safety at the facilities of gas industry.

References