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Experimental verification of methane local concertations formation in a confined space

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Abstract. The paper describes the experimental measurements concerning the formation of critical concentrations of methane in a closed space. Measurements were carried out in order to monitor the formation, propagation and distribution of methane-air mixture in a confined space. Experimental data are also used for verification of numerical simulations of methane distribution and formation of its local critical concentrations in a closed space. Within experiments, the spaces with low velocities of flow of flammable gas were primarily watching and the measurements provided information about local changes of methane concentration in time. During experiments more points could be monitored at the same time so compact description of flammable gas propagation through given space was obtained. Gained results will be used for choice of suitable mathematical model for numerical simulations.

1 Introduction

Leakages of hazardous gases or vapours of hazardous liquids occur increasingly today. In case of determination of an ignition source, which may cause inflammation of the formed gas mixture, it is necessary to perform more detailed analyses. One of the possibilities consists in the use of CFD numerical simulations [1][2] describing the propagation of the flammable gas through the investigated space and the formation of local critical concentrations depending on time.

However, mathematical models used in numerical simulations must be after their completion filled with sufficiently precise input data (determined often experimentally), and simulation results must be verified by experimental measurements. Verification of calculations and experiments helps to choose the appropriate mathematical model, which can accurately simulate the actual cases of leakages and propagation of flammable gases.

2 Experimental part – Modification of physical model

For verification of numerical simulations, physical measurements were taken on complex geometry of the building. Measurements were performed with use of a measuring set, which imitated the circulating area of common block of flats, in which a leakage of gas from the main gas valve located in the basement can occur. The measuring set consisted of a staircase area and a part of the basement. Special paper [8] concerned with detailed description of the measuring set. Due to certain problems and inaccuracies observing at verification of mathematical model, physical measurements should also be put more exactly. Previous measurements involved several insufficiencies, mainly due to specificity of the experiment. Therefore some significant modifications were made before following measurements. The first change compared to previous measurements consisted in replacement of the source of leaking gas. Instead of Transit natural gas (98.39 vol. % of methane [3][4]), only pure gas was used (concentration 99.95 vol. % of methane). Pressure tank was used as a source of methane (natural gas) which provided methane flow under constant pressure of 75 kPa using defined reducing valve. For previous measurement, public gas distribution system was used; however pressure oscillated during the day due to various consumption of natural gas. Intensity of leaking methane was controlled by regulation of flow rating which was setting in constant value $Q = 0{,}871\ dm^3/s$. Value of flow was chosen in relation to dimensions of the model and used gas detectors.

The second and the most significant improvement of physical measurement was to specify the detection of local methane concentrations in investigated confined space.

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2.1 Measurement of local methane concentrations

In previous measurements five two-stage detectors GC20-CH4 and five three-stage detectors GI30-CH4 calibrated to methane CH_4 (Figure 1) were inserted into external walls of the measuring kit. Detectors signalled occurrence of 0.5, 1 and 2.5 % of the methane volume fraction at the monitored points [7].

Figure 1 Detector GC20-CH4 (left) and the detector GI30-CH4 (right)

Detectors were equipped with non-selective hot-semiconductor sensors, which react to the presence of oxidizing or reducing gases. It concerns surface absorption detection where exchange of electrons proceed between conduction and valence band.

New detectors were developed and calibrated to improve the quality of experimental measurements of dynamic behaviour of local methane concentrations. Semiconductor sensors were used no longer after literature search (study of advantages and disadvantages of various sensors) and attention was paid to detectors with sensors on principle of catalytic combustion of flammable gases (detection proceeds through comparison of electric resistances of measuring spiral). Sensor MI-02 (Figure 2) by Hankook Gas kiki comp. was chosen from available sensors.

Newly developed detecting system enabled to obtain more detailed course of formation of local concentrations and immediate measured concentration was recorded in seconds intervals. The aim was to develop the detector for recognition of gas concentration within the range of lower than 1 vol. % to 5 vol. % (lower explosive limit of methane).

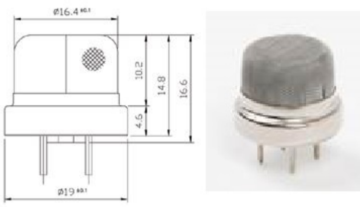

Figure 2 Catalytic sensor MI-02

Parameters of sensor MI-02:
Power supply 2.3 VDC ± 10 %; current lower than 210 mA ± 10 %; output loss 0,46 W ± 10 %; time of primary stabilization 30 s ± 10 %; speed of response 10 s ± 10 %; temperature at catalytic reaction 425 °C ± 10 %.

Newly developed detectors were constructed with the help of printed circuit (Figure 3). Total of a ten measuring circuits were made.

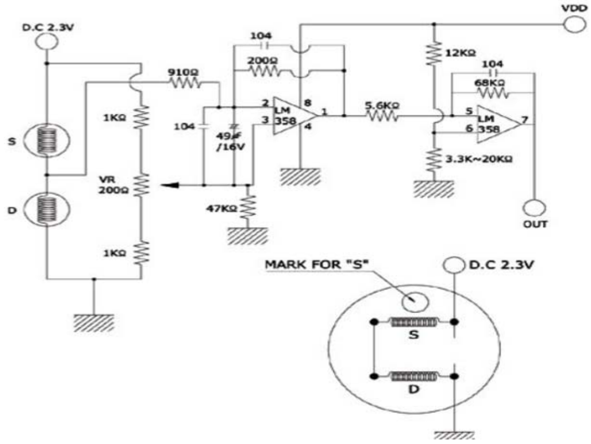

Figure 3 Circuit diagram

Testing of the prototype led to findings that temperature of a cooler does affect constructed measuring circuit and thus resulting measured voltage (measured concentration). Therefore more coolers were used and they were purposely placed farther from measuring circuits as it is seen in Figure 4. These changes (compares to the prototype) caused decrease of temperature and minimalization of influence on measuring circuits by ambient temperature.

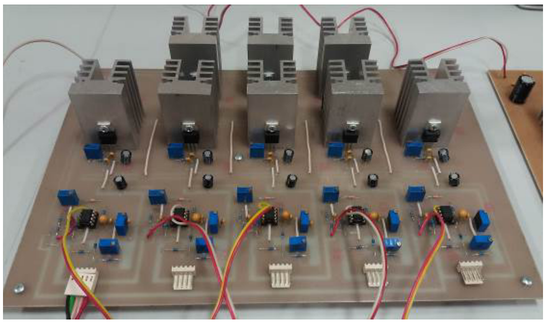

Figure 4 Five newly developed detectors

All used detectors were connected to the data loggers OMEGA RD8800 which afterwards recorded in second intervals changing voltage (Figure 5).

Figure 5 Data loggers of detectors

2.2 Calibration of detectors

Before measurement, newly made detectors were calibrated. The same gas (99.95 vol. % methane) was used both for calibration and physical model. The most available and exact method of calibration was to determine required methane concentration in the air using partial pressures in the explosive autoclave VA20 (Figure 6) in which homogeneous methane-air mixture was formed. Pressure sensor MSD100MRE was used for measurement of partial pressures. Measurements uncertainty of this sensor is ± 0,2 %.

Figure 6 Calibration of detectors

For calibration, mixtures were prepared one after another with 1 to 5 vol. % of methane with air. Measured voltages were inscribed in the graph (Figure 7).

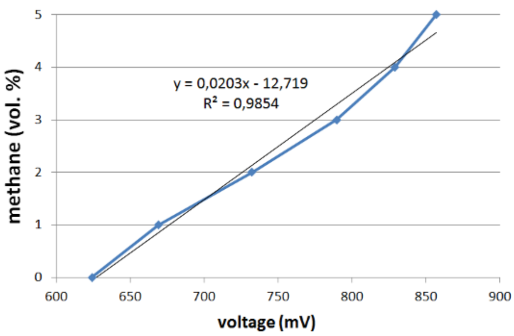

Figure 7 Calibration function for monitoring point 5

Measured points were interleaved with straight line using statistical methods. On the basis of this straight line, the function for conversion between measured voltage and methane concetration was generated. Graph of calibration function shows approximately linear course of voltage increase with concentration increase.

2.3 Process of measurement of local concentrations

Ten measurements of local concentration of methane were taken in confined space (Figure 9).

Figure 8 Location of new sensors

Current detectors were located at the same places as in previous measurements [8]. New detectors were added next to current detectors approximately to the same places (Figure 8).
Result of these measurements was to determine time between beginning of gas leakage and moment of occurrence of 5 % vol. methane concentration in all monitored points. The latest time to reach 5 % vol. methane concentration was in monitored points No. 2 and 5 located in the lowest and highest levels of the staircase area (Figure 10).

Figure 9 Measuring the formation of local concentrations of methane

3 Theoretical part – numerical model

The program ANSYS Fluent [1] was used for numerical modelling of physical measurements described above, as it is suitable especially for solution of the flows in the given space. The selected program uses for mathematical description of the ongoing physical processes following laws:

Navier-Stokes equations [5] express the conservation law of momentum and describe the flow as follows.

$$\frac{\partial \rho u}{\partial t}+\frac{\partial \rho uu}{\partial x}+\frac{\partial \rho uv}{\partial y}+\frac{\partial \rho uw}{\partial z}=\rho a_x-\frac{\partial p}{\partial x}+\nu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right)+S$$
$$\frac{\partial \rho v}{\partial t}+\frac{\partial \rho vu}{\partial x}+\frac{\partial \rho vv}{\partial y}+\frac{\partial \rho vw}{\partial z}=\rho a_y-\frac{\partial p}{\partial y}+\nu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)+S_y \quad (1)$$
$$\frac{\partial \rho w}{\partial t}+\frac{\partial \rho wu}{\partial x}+\frac{\partial \rho wv}{\partial y}+\frac{\partial \rho ww}{\partial z}=\rho a_z-\frac{\partial p}{\partial z}+\nu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)+$$

The continuity equation [5] is the fourth equation, which deals with conservation of mass flow.

$$\frac{\partial(\rho)}{\partial t}+\frac{\partial(\rho u_x)}{\partial x}+\frac{\partial(\rho u_y)}{\partial y}+\frac{\partial(\rho u_z)}{\partial z}=S_z. \quad (2)$$

Transfer of admixtures (mass fraction) is solved by the balance equation [5], which in a changing time computes with the values of mass fractions of admixture "Y_i" and with components of flow velocity of present gases "u_i". It takes into account the diffusion flux of the i^{th} component of " $J_{j,i}$ " mixture, the rate of production of admixtures resulting from chemical reaction " R_i " and the rate of formation of increments from the distributed admixtures "S_i". Distribution of admixtures varies in dependence on the diffusion flux [5].

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$$\frac{\partial}{\partial t}(\rho Y_i)+\frac{\partial}{\partial x_j}(\rho u_j Y_i)=-\frac{\partial}{\partial x_j}J_{i,j}+R_i+S_i \qquad (3)$$

Particular description of geometry and mesh is dealt in detail in different contribution [8]. The mesh was created in the program ANSYS Meshing and it consisted of **1 869 187 elements.** Parameter for **determination of quality of 3D element** (size of its deformation) was **0,899**.

Current monitoring points remained in ANSYS Fluent without changes. Then ten monitoring points were created in the model with use of the program ANSYS Fluent (Figure 10).

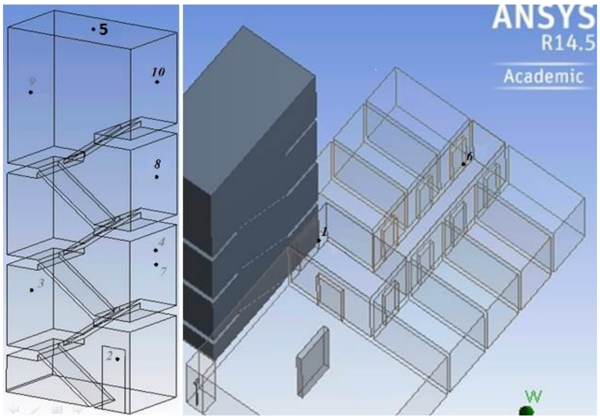

Figure 10 Placement of monitoring points

Location of monitoring points was identical with the placement of new detectors on the outer walls of the experimental model enclosing the space.

On the basis of these points the program ANSYS Fluent then made an evaluation of the dependence between the duration of leakage and the methane concentration in the air mixture.

4 Results

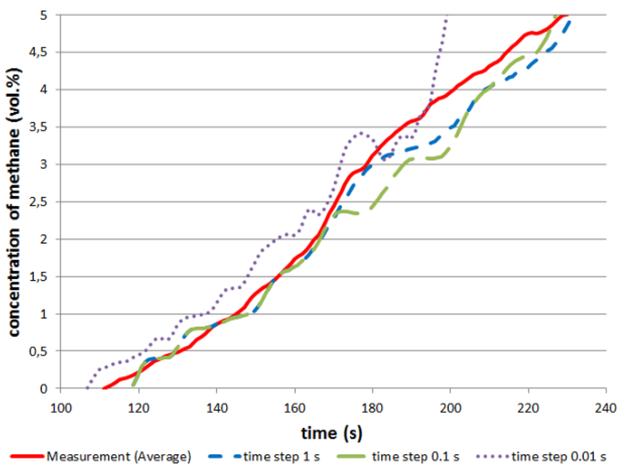

Figure 11 Comparison measurements with numerical simulation (model k-ε RNG) at the point 5

Comparison of measured and calculated values is presented in the graph (Figure 11). It describes describe the change of volume concentration of methane in monitoring point No. 5 in time.

The graph shows average values from ten measurements and values calculated in the program ANSYS Fluent (mathematical model k-ε RNG) at various time steps (1000; 100 and 10 ms).

5 Conclusions

Gradually five turbulence models (k-ε Standard, k-ε RNG, k-ε Realizable, k-ω Standard, k-ω SST) were tested. The best match with the results of experimental measurements was achieved by numerical simulations with mathematical models k-ε RNG.

In general, flammable gas first filled the spaces under the flight of stairs and stairs landings and only then the borders of the monitored concentrations decreased in the lower part of the staircase space, where they were detected by the sensor located in the monitoring point No. 2. This resulted in weak flow with low Reynolds number. After the last improvement of the quality of physical measurement using newly developed detectors for concentration, good agreement was achieved between results from experimental measurements and numerical simulations.

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