An Influence of the Peculiarities of the Concentration Field of Gaseous Fire Extinguishing Substances with High Boiling Point on Their Fire Extinguishing Properties

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Abstract. Behaviour of fluoroketone CF₃CF₂C(O)CF(CF₃)₂ as gaseous fire suppressant in various volumes was studied computationally and experimentally. It was showed that non-uniformity of the concentration field of fire extinguishing agent having high boiling point influences strongly its effectiveness: extinguishing concentration of the fluoroketone rises from 3.5 % vol. in the smallest volume (1 m³) up to 4.5 % vol. in 100 m³. Relatively uniform extinguishing medium was found in 1 m³ only. In bigger volumes a torus-like inhomogeneity with a reduced concentration of fire suppressant in the middle part of the room is formed. To compensate this effect it is necessary to increase the average concentration of the agent. More complex geometry of the experimental premise may cause appearance of long-term existing non-uniformity of extinguishing environment which is difficult to overcome by increasing the average concentration of fire suppressant or by increasing the discharge time. To obtain practically effective test results it is necessary to increase standard test chamber to 100 m³ (or more).

1. Introduction

An effect of non-uniformity of distribution of fire extinguishing gaseous agents having high boiling point on their fire extinguishing effectiveness is known since 1960s when the agents containing C₂H₅Br, CH₂Br₂ and C₂F₄Br₂ began to be used [1,2]. Some modern fire suppressants like fluoroketone CF₃CF₂C(O)CF(CF₃)₂ or iodinated fluorocarbon C₃F₇I have similar physical properties: in particular, they are liquids at 20 °C, but can be effectively vaporized if the discharge
nozzle has correct characteristics. In the scientific literature we have not found works devoted to the study of the distribution of modern gaseous fire suppressants with high boiling point on their fire extinguishing properties. In this paper a behavior of fluoroketone CF3CF2C(O)CF(CF3)2 in various volumes was studied computationally and experimentally.

2. Experimental
A chamber of rectangular geometry with a volume of 1 m³ was used in the first series of the experiments. The experiments were conducted in the following order: homogeneous mixture of fire extinguishing agent with air was prepared directly in the chamber; after that a model fire source having a diameter of 30 mm and a volume of 20 cm³ filled with n-heptane was introduced into the chamber. By varying the concentration of fire suppressant its minimum extinguishing concentration was determined.

The second series of the experiments was carried out in the premises of rectangular geometry with a volume of 40, 74 and 100 m³ respectively. The experiments on determination of minimum fire extinguishing concentration were conducted in accordance with a procedure described in [3]. Four standard fire sources filled with n-heptane were used in the experiments. Fire extinguishing agent was discharged into the premise via one atomizer from a bottle with a volume of 50 dm³; discharge time was 10 sec. (it corresponds to discharge of 95 % of the agent mass), required extinguishing time was 60 sec.

Special series of the experiments was conducted in a premise imitating engine compartment of marine vessel to investigate an influence of obstacles inside of the volume on fire extinguishing concentration of CF3CF2C(O)CF(CF3)2. This premise with complex geometry has a volume of approximately 100 m³ with a model engine installed in the center of the premise (for more details refer to the description of relevant experimental results below).

All the experiments were conducted at temperature 20 °C.

3. CFD modelling
CFD modelling was conducted with the usage of ANSYS Systems Software with package: DESIGN MODELER, ANSYS MESHING, FLUENT and CFD-Post [4]. Domains were created with dimensions taken from the experimental set-up. The atomizer is installed in the center of the room at a distance of 200 mm from the ceiling. The investigated fluoroketone was injected into the air through several evenly distributed holes in the atomizer.

The geometry were created using ANSYS DESIGN MODELER. The meshes were created using ANSYS MESHING. A block-structured meshing approach was used to create meshes with only tetrahedral cells. Refinements were made in the vicinity of the nozzle to resolve the rapid changes in the flow occurring there. The smallest elements were created at the outlet of the nozzle to resolve boundary layers not less than 20 cells and the cell size increased by 10% in a radial direction. Trapezoidal cells were also created in several layers on all walls to model the boundary layer and the interaction of the phases with the wall surface.

Simulation settings: steady state simulation is much less time consuming than a transient simulation so from a time cost perspective it is better to run steady state simulations. However, multiphase flows often exhibit transient behavior and forcing a transient flow in to a steady state might produce an unphysical solution. A transient simulation was therefore run in each code, moreover, the premises are closed and there is no interaction with the external environment.

Computer simulation of the fluoroketone behavior was carried out in the ANSYS FLUENT software. For the simulations ran the pressure-based coupled solver was used with gravity enabled. For model turbulence, the k-ω SST model was selected. For computer modeling in FLUENT, a multi-phase Euler-Euler model was used.

This model is the most complex among multiphase flow models. The substance in each phase is assumed to be a continuous medium, and the motion of the substance of each phase is modeled by the intrinsic system of Navier-Stokes (Reynolds) equations as well as equations of continuity and energy.
According to this model, the equations of motion recorded for each phase are solved jointly. The interaction of the phases is taken into account through the pressure and the coefficients of interphase exchange.

The fluoroketone is assumed as incompressible fluid and a dispersed phase; air is a continuous phase.

At the entrance to the pipe, a pressure of 30 atm is given in front of the atomizer. For the pipe walls a no slip condition was implemented.

To simulate the distribution of fire suppressant in the room volume, a time step of 0.01 second was taken. For the initial stage of the sprayer operation, different time steps were also used. To calculate the filling of the nebulizer with the fluoroketone, the time step was 100 times less. From the beginning of the discharge of the agent from the nozzle to the steady work of the nebulizer, the time step was 50 times less.

4. Obtained results
The results of CFD modeling show that a relatively uniform extinguishing medium is formed in the smallest volume only. In bigger volumes a torus-like inhomogeneity with a reduced concentration of fire suppressant at the middle part of the room and in the area above the discharge zone of the extinguishing agent is formed (figures 1-3). Changes in concentration field of fire suppressant are shown in figures 2,3 for the middle section (see figure 1).

Figure 1. Common view of inhomogeneity in the room of 100 m3 during discharge of fire suppressant.
Figure 2. Inhomogeneity of the environment in the room of 100 m³ in 1 sec (a), 4 sec (b), 10 sec (c), 60 sec (d), 80 sec (e) after the beginning of the agent release.
Figure 3. Inhomogeneity of the environment in the room of 40 m³ in 10 sec after the beginning of the agent release.

The time of existence of such non-uniformity increase with increase in the volume of the premise. Starting from the volume of 40 m³, the time to achieve relative uniformity of the concentration field of the extinguishing agent exceeds 60 sec. To compensate this effect it becomes necessary to increase the average concentration of the agent to achieve extinguishing in the required time.

More complex geometry of the experimental premise may cause appearance of long-term existing non-uniformity of extinguishing environment which is difficult to overcome by increasing the average concentration of the extinguishing agent or by increasing the discharge time (see figure 4: crosses indicate zones where suppression of model fire sources [3] were not achieved in the experiments for required time of 60 sec.).

Figure 4. Formation of long-term existing non-uniformity of extinguishing environment in model engine compartment.
The obtained results of mathematical modeling were fully confirmed by the experiments. In particular, it was obtained that minimum extinguishing concentration of the investigated fluoroketone is equal to 3.5 % vol. in the smallest volume (1 m³) while it is 4.2 % vol. in 40 m³, 4.4 % vol. in 74 m³ and 4.5 % vol. in 100 m³ respectively.

5. Conclusions

It was showed both mathematical modeling and experimentally that non-uniformity of the concentration field of gaseous fire extinguishing agent having high boiling point influences strongly the effectiveness of the agent.

The structure of non-uniformity of the concentration field was determined and its behavior was investigated under various conditions. It was obtained that relatively uniform extinguishing medium is formed in the smallest volume only. In bigger volumes a torus-like inhomogeneity with a reduced concentration of fire suppressant at the middle part of the room and in the area above the discharge zone of the extinguishing agent is formed.

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More complex geometry of the experimental premise may cause appearance of long-term existing non-uniformity of extinguishing environment which is difficult to overcome by increasing the average concentration of the extinguishing agent or by increasing the discharge time.

The results of mathematical modeling were fully confirmed by the experiments: it was obtained that minimum extinguishing concentration of the investigated fluoroketone is equal to 3.5 % vol. in the cylindrical vessel while it is 4.2 % vol. in 40 m³, 4.4 % vol. in 74 m³ and 4.5 % vol. in 100 m³ respectively.

To obtain practically effective test results it is necessary to increase test chamber in standard [3, 5] to 100 m³ (or more).

6. References

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