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NUMERICAL MODELLING OF FIRE AND GASEOUS FIRE SUPPRESSION

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Abstract

This paper describes the CFD approach to the problem of design and optimisation of a gaseous suppressant injection system. Different ways of suppressant injection, applied for the same scenario of a real fire extinguishing experiment, were studied. The suppressant distribution effectiveness for three suppressant injection methods was studied with the use of specially constructed numerical parameter, which can be obtained from a CFD model. The analysis of the fire suppression and suppressant distribution proves that the most uniform suppressant distribution provides the most quick and reliable fire suppression. It is shown that the suppressant distribution doesn't differ significantly between the cases of isothermal and fire injection conditions. Hence, the practical design and optimisation of suppressant injection systems can be based on the numerical simulation of isothermal suppressant propagation without fire modelling.

Introduction

In the current time, the modelling of fire related phenomena becomes a significant part of fire safety engineering. It is especially important for design of new types of buildings and compartments, or not-standard facilities, where the implementation of performance-based fire regulation is needed.

Gaseous fire suppression systems are flexible for design, easy and cost-effective for maintenance. At the moment, the design of these systems is based on the traditional analytical model, which imposes the perfect isothermal suppressant mixing and the uniform suppressant distribution without regard to the construction of suppressant injection system [1].

The results of Computational Fluid Dynamics (CFD) modelling of a gaseous fire suppression [2] shows that the conditions of gaseous suppressant injection and propagation are far from the assumptions of the analytical model and fire can continue much longer than it can be expected from the analytical solution.

For the CFD approach to the gaseous fire suppression, the extinguishing model is necessary. An experimentally based extinguishing model, reported in [3], was used for the fire suppression with a dry aerosol. The model uses the flame extinguishing concentration of suppressant as the criterion of fire extinguishing. The flame extinguishing concentration for a considered suppressant and a fire load can be easily obtained from literature or experiment with high precision[2].

In this research, the fire suppression effectiveness is studied for different suppressant injection systems. The method of evaluation a suppressant distribution effectiveness is developed and demonstrated.

The Problem Formulation

At the moment, we assume that an effective gaseous fire suppression must provide uniform suppressant distribution. The real, non-uniform suppressant distribution can be obtained from a CFD solution, though it is difficult to evaluate the uniformity of a suppressant distribution from three-dimensional raw data.

For this propose, the use of some characteristic parameter, which reflects the suppressant distribution uniformity as one, single value, must be the most profitable.

The mentioned above parameter can be considered as follows [4]:

$$I = \frac{1}{M_{cmp}} \int_{V_{cmp}} \left(1 - \left|Y_{spr} - Y_{spr,u}\right|\right) \rho \, dV . \qquad (1)$$

The worst case of suppressant distribution, when suppressant is not distributed at all, is shown schematically in Figure 1; the whole suppressant amount is concentrated in one part of compartment, $Y_{spr} = 1.0$, while the other part is empty, $Y_{spr} = 0$. The following expression for the proposed parameter I can be obtained in this case:

$$I_* = \left(1 - Y_{spr,u}\right)^2 + Y_{spr,u}^2 . \qquad (2)$$

We can normalise the proposed parameter, using the value I_*,

$$I_m = \frac{I - I_*}{1 - I_*} . \qquad (3)$$

The normalised parameter I_m changes its' value between zero (in the worst case of non-distributed suppressant) and unity (for this ideal case of uniformly distributed suppressant). Now, the uniformity of any suppressant distribution can be represented as a one, single value of the parameter I_m, which has clear physical meaning.

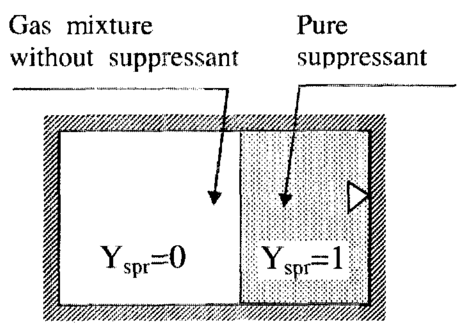

Figure 1. Calculation scheme of non-distributed suppressant

Modelling of Fire and Fire suppression

Calculation Domain and Fire Extinguishing Scenario

The fire scenario of the real fire extinguishing experiment in a garage compartment, which was held by the Science University of Tokyo, was used in this research. The description of fire modelling will be skipped in this paper and the attention will be paid only for the modelling of fire extinguishing.

The clear forced convection type of flow existed inside of garage during the period of suppressant discharge. It allowed the use of a small calculation domain, consisted only of garage compartment without free regions, to overcome the problem of unacceptable loss of computer resources. The calculation domain is shown in Figure 2. The garage itself and internal layout (car parking construction and two cars, installed in it) were modelled. The numerical grid consisted of 29, 33 and 46 grid nodes along width, length and height of garage correspondingly (44,022 grid nodes in total). At the preliminary stage of fire, the door and the window were opened. Before the discharge, all openings were shut and the gas mixture left the garage through the pressure release valve, installed near the door. In the numerical simulation, it was assumed that the kerosene pool fire served as a source of the whole Heat Release Rate (HRR). The fuel mass flow rate of kerosene was estimated as follows:

$$\tau \le 320\,\text{s} \quad \dot{m}_{fl} = 9.93\times10^{-7}\tau \ \text{kg/s}, \qquad \tau > 320\,\text{s} \quad \dot{m}_{fl} = 12.42\times10^{-6}(\tau - 294.4) \ \text{kg/s}.$$

The inert gaseous suppressant IG541 [5] was used in experiment. The suppressant was discharged in the period $520 < \tau < 624$ s. The suppressant mass amount was $M_{spr} = 128.5$ kg, which corresponds to the mean mass flow rate of suppressant $\dot{m}_{spr} = 1.23$ kg/s.

In the experiment, the suppressant was injected through the nozzle, which distributed suppressant in a radial direction. In the modelling, three different suppressant injection methods were used:

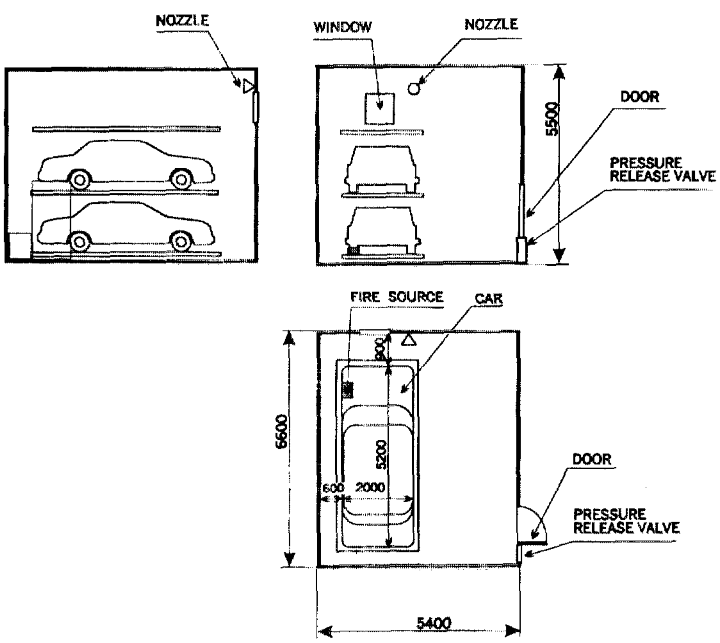

Figure 2. Calculation domain

1) the experiment case - a radial spreading flow, which distributed the suppressant along the wall and ceiling;
2) the one nozzle flow, forming a straight suppressant jet flow, directed at the opposite wall. The initial velocity of suppressant jet is $u = 55.7$ m/s;
3) the three nozzle flow, formed by three similar nozzles at different garage levels. The initial velocity of every jet flow is $u = 18.6$ m/s in this case.

All three methods of the suppressant injection are shown schematically in Figure 3 (a, b and c). The injection nozzles were positioned on the opposite wall in the second and third cases, to prevent an excessive leakage of suppressant jet to the pressure release valve.

Mathematical Model

The mathematical model, used for the fire and fire extinguishing simulation, was formed by the following three-dimensional governing equations:

- mass conservation equation,
- momentum conservation equations,
- energy conservation equation,
- conservation equations for species (Y_{ox}, Y_{fl}, Y_{spr}),
- equations for k-ε turbulence model of Launder-Spalding, adapted for naturally convected flows [6].

The combustion was modelled with Eddy Break-Up model [7]. Radiation heat transfer was taken into account as a heat sink term (the fraction of the total heat release rate, lost due to radiation, was taken as χ=0.3).

The control-volume based finite-difference method [8] was used to solve the described above mathematical model.

The extinguishing model [3] was applied for the fire suppression modelling. The model prescribes zero fuel consumption rate S_{fl}, when the local suppressant concentration Y_{spr} is higher than the flame extinguishing concentration of a suppressant Y^*_{spr}:

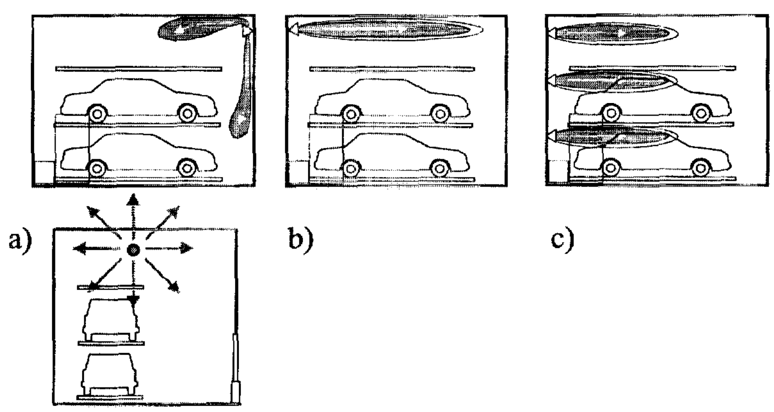

Figure 3. Different methods of the suppressant injection

$S_{fl} = 0$ when $Y_{spr} \geq Y_{spr}^*$.

In this research, the volume flame extinguishing concentration of IG541 for kerosene $v_{spr}^* = 0.31$ [9] was used for the fire suppression modelling since the flame extinguishing concentrations for car materials were unknown.

Boundary Conditions

The boundary conditions at inflow assumed the constant mass flow rate of suppressant over the whole period of injection ($Y_{spr} = 1.0$, $\dot{m}_{spr} = 1.23$ kg/s). The outflow boundary conditions were set for all variables at the pressure release valve, where the boundary velocities were obtained from the assumption of equal mass fluxes at inflow and outflow, $\dot{m}_{spr} = \dot{m}_{out}$. All obstacles were assumed adiabatic and impermeable. To solve the conservation equations of the k-ε turbulence model, the turbulence level of ambient atmosphere was set to 5% and an ambient atmosphere viscosity was $\mu_t = 10^{-4}$ Pa·s. The initial distributions of dependant variables for the time $\tau = 520$ s were taken from the solution of the previous stage of the fire ($0 < \tau \leq 520$ s).

Results of Fire Suppression Modelling

Heat Release Rate

The Heat Release Rate (HRR) behaviour with time must be the most interesting result of the fire extinguishing modelling. The HRR for all injection cases is shown in Figure 4.

It needs to notice that a HRR can not be helpful for evaluation of the fire extinguishing system. The HRR depends on the peculiar fire source position and it can possess a quite different behaviour for another position of fire source. Nevertheless, the comparison of different injection methods on the base of modelled HRR values can be voluble.

It is seen that the fire was suppressed in all three injection cases during simulation. It is also interesting, that the fire suppression process is time dependent, which is impossible to reproduce, using the analytical model.

Though the radial spreading flow shows the earliest time of extinguishing beginning, at $\tau = 575$ s, the fire suppression occupies the longest time and the extinguishing is very unstable. Otherwise, the decrease of HRR, delivered with the one-nozzle and three-nozzle flows, is very quick and sharp. Although for the three-nozzle flow, the extinguishing begins later, it finishes in the same time as for the one-nozzle flow. This fact of different HRR behaviour must have explanation in the terms of the suppressant distribution over the compartment.

Parameter I_m

The results for the proposed parameter I_m with time are shown on the Figure 5. Let us be reminded that the value $I_m = 1.0$ corresponds to the absolutely uniform suppressant distribution.

It is interesting to see that the all suppressant injection systems provided almost the uniform suppressant distribution at $\tau = 624$ s and the value of the parameter I_m, during the most part of injection, is different for all of them and the suppressant distribution is far from uniform.

The one-nozzle flow demonstrates the most uniform suppressant distribution during the whole period of injection. The three-nozzle flow provides the value of I_m, which is very close to the same in the one-nozzle case. It means that for the both injection methods, the suppressant distribution uniformity doesn't differ significantly. This must be the reason for the same early moment of fire extinguishing for these methods. The radial injection demonstrates the least uniform suppressant distribution, and it is clearly reflected in the characteristic behaviour of the fire extinguishing, which goes very long time and unstable at some period.

Hence, we can conclude, the proposed parameter really reflects the effectiveness of the fire suppression system and can be used in practice for the design optimisation of the injection system or an objective comparison of different injection methods.

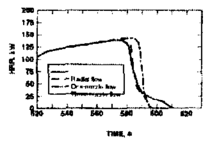

Figure 4. Heat Release Rate

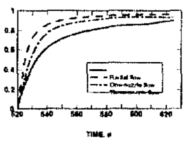

Figure 5. Distribution parameter I_m

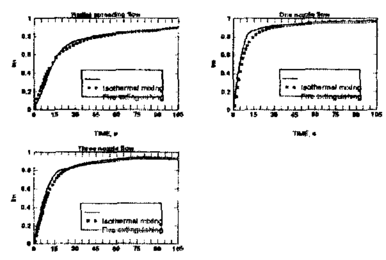

Figure 6. Comparison of suppressant injection under the isothermal and fire conditions

The amount of the suppressant, provided by all injection systems, are almost the same (95.4, 97.1 and 94.9 kg for radial spreading, one-nozzle and three-nozzle flows respectively). So, in this research the mass of suppressant, which is left in the compartment after extinguishing, can be eliminated from the analysis of the fire suppression effectiveness.

Results of Isothermal Injection Modelling

It is evidently, that the same distribution parameter I_m can be easily obtained for the isothermal injection conditions, without fire modelling. The mathematical model for this problem formulation is much simpler, because the less number of equations need to be solved now and the absence of temperature distribution provides a faster convergence in a numerical simulation.

For the modelling of the suppressant injection under isothermal conditions, the initial velocity was equal to zero all over the compartment and the compartment was assumed filled with air. The results of the isothermal injection modelling, in comparison with the modelling of the fire suppression, are presented in Figure 6 a, b, c for the radial spreading, one-nozzle and three nozzle flows respectively.

From these comparison it is clearly seen that generally there is no significant difference between suppressant distributions in the case of fire, where the initial temperature and velocity fields existed inside of compartment, and for the case of isothermal conditions. Some discrepancy in the suppressant distribution occurs during the early period of the suppressant injection. After the initial stage of injection, this difference disappears as the flow inside of compartment is controlled by the strong, forced-convected flow of suppressant.

Conclusion

In this research the investigation of the gaseous suppressant distribution effectiveness was made with the help of the CFD technique.

The results of the suppressant injection and the fire modelling demonstrated that the effectiveness of fire suppression is closely linked with the effectiveness of suppressant distribution.

The parameter I_m for the evaluation of suppressant distribution uniformity was proposed.

The analysis for the Heat Release Rate and the parameter I_m proves that the most effective and uniform suppressant distribution provides the most effective fire suppression. From this we conclude that the proposed parameter I_m can be used as the tool for design and optimisation of gaseous extinguishing systems.

The comparison of the suppressant discharge under fire conditions and for isothermal case shows that the initial naturally convected flow field and the initial temperature distribution don't play significant role for the suppressant distribution in the case of fire.

Hence, the evaluation of the gaseous fire suppression system effectiveness can be obtained from the reasonably simplified convection-diffusion CFD simulation without fire model, which makes the usage of the proposed evaluation method very simple and available for practical applications.

Nomenclature

I	Parameter for suppressant distribution uniformity (--)
I_m	Normalised parameter for suppressant distribution uniformity (--)
I_*	Parameter for non-distributed suppressant (--)
M	Mass (kg)
$\dot{m}$	Mass flow rate (kg/s)
S_{fl}	Fuel mass consumption rate (kg/m^3/s)
V	Volume (m^3)
Y	Mass concentration (--)
ν	Volume concentration (--)
μ_t	Turbulent viscosity (Pa·s)
ρ	Density (kg/m^3)
τ	Time (s)
Superscript	
•	flame extinguishing
Subscript	
cmp	compartment
fl	fuel
ox	oxygen
out	at outflow from calculation domain

spr	suppressant
u	uniform

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