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Numerical two-phase simulations of the propagation of an evaporating extinguishing agent for optimal fire suppression

Waldemar Stapel* and Michael Breuer

Micro Abstract
Fire suppression systems operate with extinguishing agents released from a reservoir and atomized into droplets. Flow predictions are separated into the release process and the propagation of the extinguishing agent. For the latter an Euler-Lagrange approach is used to model the two-phase flow. Data of the first simulation are used for the droplet initialization. The transformation of parcels into the gaseous state is treated by an evaporation model. The propagation of the agent is investigated.

Professur für Strömungsmechanik, Helmut Schmidt University, Hamburg, Germany
***Corresponding author**: waldemar.stapel@hsu-hh.de

Introduction

Fire suppression systems are used for the protection of occupied compartments of vehicles. They operate with a gaseous non-flammble extinguishing agent, which is released from a storage bottle. Nitrogen is added as a propellant agent to yield high pressures. Before release into the environment the extinguishing agent passes through a nozzle system, where it is atomized into droplets. Recently, 1,1,1,3,3,3-Hexafluoropropane (HFC-236fa) was introduced as a new extinguishing agent for fire suppression systems to meet the requirements of the Montreal Protocol [1] prohibiting the application of chemicals with ozone-depleting impact. However, HFC-236fa is a less effective fire suppressant than the formerly used Bromotrifluoromethane (Halon-1301). Low agent concentrations will fail to deliver any extinguishing effect, while too high concentrations show adverse health effects. This necessitates a more detailed understanding of the agent propagation behavior and a regulation of effective agent concentration ranges. A complete release of the storage bottle content needs to occur within a time frame of several hundred milliseconds. Therefore, the extinguishing agent is stored in liquidized state within a container at a pressure of about 52 bar. When released to the compartment, the extinguishing agent is present as a superheated liquid. The non-equilibrium thermodynamic state leads to a rapid evaporation by boiling. Additionally, the liquid jet at the nozzle outlet is disintegrated into a spray of small droplets. Further downstream droplets are subject to atomization by aerodynamic forces and evaporation until a complete gaseous state is reached.

The whole process is investigated by numerical flow predictions based on the open-source code OpenFOAM. The release process from the storage bottle and the propagation of the extinguishing agent in the compartment are treated separately. The first simulation investigates an incompressible, isothermal flow inside the agent storage bottle and the nozzle release system. The second simulation deals with the flow outside the storage bottle in the compartment. An Euler-Lagrange approach is used to model the two-phase flow behavior of the second stage.

1 Simulation of the nozzle release system

Prior to the propagation within the compartment the pressurized liquid extinguishing agent has to pass through a nozzle release system comprised of 46 outlet exits. The design of the nozzle release system is mainly of cylindrical shape, where the outlets are distributed along two separate planes of the cylinder height and at its bottom. Each plane consists of a distinct distribution of outlets in circumferential direction. Furthermore, the outlets vary in shape and size. Due to the complicated design of the nozzle a separate flow simulation of the nozzle release system is carried out to obtain detailed information on the outflow.

For further simplification a pressure control algorithm is introduced. In the real application a gaseous propellant agent at high pressure induces the outflow of the liquid extinguishing agent. In the flow calculation only the liquid phase of the extinguishing agent is taken into account. The expansion of the propellant agent is modeled by an adiabic expansion of an ideal gas. The volumetric output of the nozzle release system is coupled to the adiabatic expansion of the propellant agent in an time-resolved procedure. The respective pressure decrease due to expansion is set as a boundary condition. The pressure control algorithm is validated against a VOF two-phase flow prediction [2] of a simplified test case and shows a nearly perfect agreement.

The computational model consists of the storage bottle, the nozzle release system and an additional bounding box, which represents a small part of the outside space. During the mesh generation of the computational domain special attention is paid to the resolution of the boundary layers within the outlet channels of the nozzle release system. These regions and the vicinity are resolved by wall-refined, structured hexahedral cells. All other parts of the computational domain consist of unstructured tetrahedral cells. In total the computational grid is composed of 43.5 million control volumes. The flow solver is incompressible and isothermal. The computation is carried out in parallel with 560 processors on an HPC cluster.

The complete release of 2.7 kg of the extinguishing agent takes place within a time span of $t_{inj} = 0.052\,\mathrm{s}$. Examples of the flow-rates for different outlets are shown in Figure 1. As visible the flow accelerates within about 2-3 ms. Afterwards, the flow-rates slowly decrease due to the decreasing pressure inside the bottle. The flow within the nozzle release system is strongly influenced by vortical structures. In general high fluctuations occur which need to be considered in subsequent calculations of the external flow. In some outlets nearly harmonically oscillating outflow patterns can be observed. Other outlets show irregularly fluctuating flow-rates with high amplitudes. During the simulation of the nozzle release system, velocity fields at the mesh resolution applied and the flow-rate data for every nozzle exit are stored at a time resolution of $5 \cdot 10^{-6}\,\mathrm{s}$. Overall a database of 144 GByte in OpenFOAM file format is generated for the nozzle release system. It will be accessed in the simulation of the propagation of the extinguishing agent in the compartment.

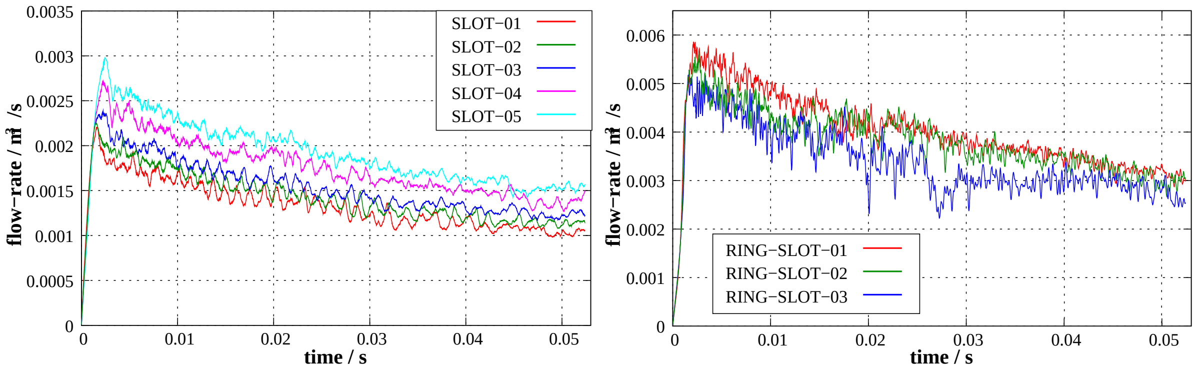

Figure 1. Exemplary flow-rates at some outlets of the nozzle release system.

2 Simulation of the extinguishing agent propagation within the compartment

The flow prediction outside the nozzle release system is concerned with the propagation behavior of the extinguishing agent. The extinguishing agent is released into a closed compartment with a square base area of 3.41 m x 3.41 m and a height of 1.8 m. A complete discharge leads to a 10% concentration assuming a perfectly equal distribution of the gaseous extinguishing agent. The multiphase character of the flow is modeled by an Euler-Lagrange approach, where the motion of liquid droplets and the gaseous phase is described within the Lagrangian and the Eulerian framework, respectively.

When the liquid extinguishing agent is ejected out of the nozzle release system, it disintegrates into droplets of various size (primary break-up). The droplet diameter distribution is described by the *log-normal* probability density function. The resulting droplet diameters are estimated by relying on experimental data of the surrogate agent R-134a [3, 6] which shows comparable physical characteristics. The secondary break-up of droplets and droplet collisions are not taken into account. To achieve computational feasibility, a parcel approach is utilized. A parcel represents a gathering of droplets with uniform properties. By following the Lagrangian motion of the reduced number of parcels, the computational effort can be limited to an acceptable amount. Parcels are generated at predefined areas equal to the exit cross-sections of the nozzle release system. The mass flow-rate data taken from the database of the nozzle release system determines how many parcels are generated within each simulation time step at each nozzle outlet. The injection position of a parcel within a nozzle outlet is defined by a random number generator. For each injection position at a given time a corresponding velocity vector can be assigned to the parcels using the nozzle release system database.

When released into the compartment, the liquid extinguishing agent droplets are in a superheated thermodynamic state. They evaporate into gaseous state by boiling and heat transfer. The transition from the liquid to the gaseous phase is incorporated by an evaporation model [4] and a heat transfer model [5].

Various studies are performed to identify the influence on the propagation of the gaseous extinguishing agent and the resulting fire suppression performance. Firstly, the position of the storage bottle within the compartment is varied. Three predictions are performed, where the storage bottle is placed at the compartment center, near a wall and within a compartment corner. Secondly, intermediate walls are build into the compartment to perturb the extinguishing agent flow behavior. Thirdly, droplet diameters resulting from the primary break-up are varied. The transient propagation process is tracked by visualizing concentration iso-surfaces and 5% concentration intervals. Fire suppression performance is evaluated by the time intervals at a location within the compartment needed to attain a target concentration of 10%. The risk of an overconcentration is estimated by the cumulative times of an extinguishing agent concentration above 15% at every location within the compartment.

Results and Conclusions

The results of the two-phase flow predictions show that the extinguishing agent propagation can be divided into an initial rapid expansion and a subsequent mixing phase. The initial expansion phase occurs with high velocities ($\approx 80\,\mathrm{m/s}$) during the first 200 ms after release from the storage bottle. As an example Figure 2 shows the extinguishing agent propagation pattern during the initial expansion phase for two different storage bottle placements. The mixing phase takes place at a slower pace when the concentrations slowly converge towards the target concentration of 10%. The study of varying storage bottle placements shows a significant impact of bounding walls on the propagation behavior of the extinguishing agent. On the one hand, walls tend to redirect the extinguishing agent to different locations compared with the initial propagation direction and help to spread it within the compartment. On the other hand, this process is combined with a velocity reduction. Overconcentrations of the extinguishing agent are usually

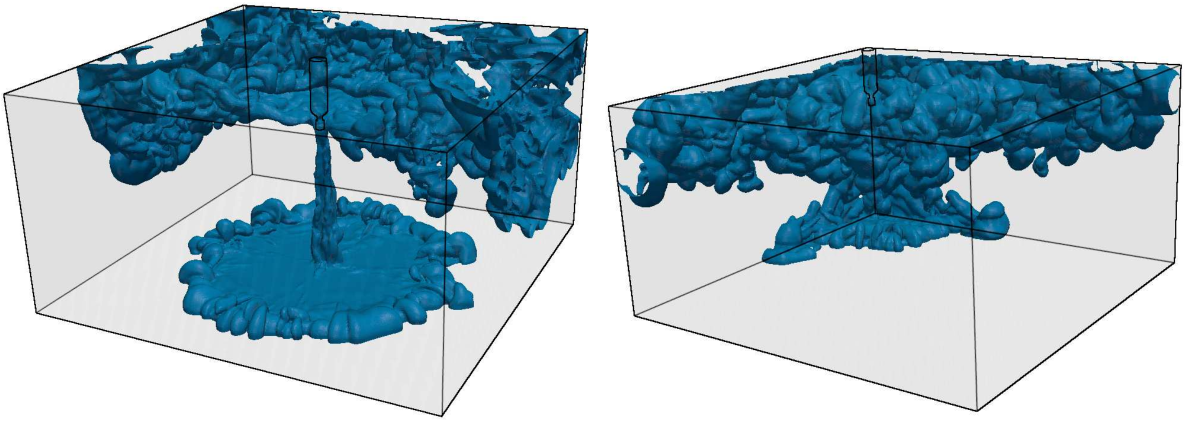

Figure 2. Visualization of the propagation by isosurfaces of a 10% gaseous concentration of HFC-236fa at $t = 0.080\,\mathrm{s}$: (left) centrally placed storage bottle, (right) storage bottle placed at a corner.

observed in near-wall regions.

Intermediate walls have a negative impact on the fire suppression in general. The effect is highly disadvantageous if the intermediate wall is placed normal to the main propagation direction and is being reached by the extinguishing agent during the initial expansion phase. In this case an extended region of overconcentration can be observed in front of the wall, whereas an extended region at the rear side is hardly reached by the extinguishing agent. The effect is far less significant if the intermediate wall is reached within the mixing phase or is oriented in the main flow direction.

Independent of the relative placement of the storage bottle, the initial expansion of the extinguishing agent is mainly governed by the outflow pattern of the nozzle release system. In this regard the design is evaluated as far from being optimal since the spreading of the liquid extinguishing agent happens only in a narrow plane area of the compartment. It is assumed that an extended spreading of the extinguishing agent by the nozzle release system would significantly improve the fire suppression performance.

The study of varying droplet diameters by primary break-up showed no significant influence on the propagation behavior. This is attributed to the rapid evaporation of the liquid droplets. Furthermore, the evaporation model shows a nearly drop size independent evaporation rate for the case of superheated boiling. This assumption needs to be further investigated in the future.

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