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Effect of the flow of large water droplets on the water mist sprays

László Beda[1] and Csaba Szikra[2]

[1]Institute of Disaster Management and Fire Protection Engineering, Szent István University, Ybl Miklós Faculty of Architecture and Civil Engineering, Budapest, Hungary
beda.laszlo@ybl.szie.hu

[2]BME Faculty of Architecture, Department of Building Energetics and Services
szikra@egt.bme.hu

Abstract: *The purpose of this study is to investigate the velocity field generated by water droplets with relatively large diameter that has great effect on the movement of several orders of magnitude smaller particles. A CFD model, Fire Dynamic Simulator (FDS) version 5.5.3 was used for the numerical simulation. The data obtained from the numerical studies are analysed.*

Keywords: *fire simulation, FDS, sprinkler spray, water mist spray, water spray dynamics*

1. INTRODUCTION

Water has favourable physical properties for fire suppression. Its high heat capacity and high latent heat of vaporization can absorb a significant quantity of heat from flames and fuels. Water also expands considerably when it evaporates to steam, which results in the dilution of the surrounding oxygen and fuel vapours. With the formation of fine droplets, the effectiveness of water in fire suppression is increased, due to the significant increase in the surface area of water that is available for heat absorption and evaporation [1].

In fixed fire extinguishing systems, water is used in sprinklers and water mist in fire suppression equipment. Between the two methods, primarily the rate of flow, the size of water droplets, and the droplet size distribution make the difference.

Standard sprinkler-sprays contain larger than 1 mm diameter droplets in high proportion. The water mist consists of fine droplets, where 99% of the droplets are less than 1mm in diameter as defined in NFPA 750 [2]. Due to the very fine dispersion, the water mist can exhibit gaseous-like behaviour and superior mixing characteristics

In regard to the quantitative characterization of sprays, four factors are needed to properly characterize a water spray for fire suppression purposes. These are: drop size distribution (diameter and range), spray flux density, spray angle, spray momentum.

The mentioned set of parameters has a direct connection to suppression mechanisms [3]. Droplet trajectory and evaporation rate are mainly governed by the interaction between the sprayed flow (droplets) and the surrounding fluid (momentum, mass and heat transfer). These phenomena are significantly affected by dynamics of the fluid flow, i.e. velocity and temperature, together with the fluid properties (i.e.: viscosity and density). Fire suppression is basically governed by these mentioned parameters.

The whole multiphase flow is made up by dispersed droplets, generated vapour, fire-induced air flow and spray-induced air flow. Multiphase fluid dynamics strongly affects fire-suppression performances and it may be described through the classic relations on mass, momentum and energy conservation for each phase [4, 5, 6]

Water mist systems work mainly by flame extinguishing, where the droplets evaporate and lower the flame temperature. The area of surface contact between water and the surrounding hot gases increases with decreasing droplet size. However, very small droplets decelerate rapidly, and may have difficulties in penetrating a flame zone. In other cases, a high percentage of small water droplets enter the fire plume or flames, rapidly evaporate and contribute to the extinction. Droplet size seems to be one of the determining parameters in judging the efficiency of fire suppression [3, 7, 8].

In dense spray, the drops can interact. Influence on each other is usually significant if the separations of droplets are smaller than 10 radii ($10d_p$).

The effect of neighbours will become important with increasing dispersed-phase volume fraction. In this respect, the flow can be divided into three sections [9].

- collision-free flow (dilute phase flow);
- collision-dominated flow medium (concentration flow);
- contact-dominated flow (dense phase flow).

Attempts can be found in the literature to describe the water droplets collisions. However, in the absence of conclusive data, the effect of neighbouring particles or droplets on interphase interactions has been difficult to quantify, these interactions are usually neglected for flows with dispersed-phase volume fraction less than 10% [10, 11, 12].

The rapid development in computer technology has permitted more sophisticated modelling of the dynamics of fires. In particular, it is now possible to include the effects of water sprays on the fire spread. For example, the Fire Dynamics Simulator (FDS) developed at the National Institute of Standards and Technology (NIST) is used to predict large-scale fire phenomena in a variety of fire scenarios. However, for including the effect of sprinkler droplets and water mists on the fire dynamics, it is necessary to provide characteristics of the water spray produced by the active system devices. In this paper, using numerical simulation, we investigate what influence the flow of larger (at least 1 mm) droplets has on the water mist (35.5μm mean diameter) distribution.

2. FORMULATION AND METHOD

2.1 Droplets and air interaction

While moving with their own velocity in the test space, droplets influence the movement of the neighbouring air. Modelling this, we use force f_b generated by particles moving in the cell (14):

$$\boldsymbol{f}_b = \frac{1}{2}\frac{\sum \rho C_D \pi r_d^2 (\boldsymbol{u}_d - \boldsymbol{u})|\boldsymbol{u}_d - \boldsymbol{u}|}{\delta x \delta y \delta z} \quad (1)$$

Where C_D is the droplet's air resistance coefficient, r_d denotes droplet diameter, u_d droplet velocity vector, u is the velocity vector of the neighbouring air; dividing all this by cell volume, we obtain force for one cell. Calculations require droplet acceleration for which the following equation is used:

$$\frac{d}{dt}(m_d \boldsymbol{u}_d) = m_d \boldsymbol{g} - \frac{\rho}{2} C_D \pi r_d^2 (\boldsymbol{u}_d - \boldsymbol{u})|\boldsymbol{u}_d - \boldsymbol{u}| \quad (2)$$

where m_d is the droplet mass. Finding a model for droplet's air resistance coefficient is necessary for both equations. For this, we use the Reynolds number. Particle's Reynolds number can be calculated from the equation below:

$$Re_d = \frac{\rho |\boldsymbol{u}_d - \boldsymbol{u}| 2r_d}{\mu(T)} \quad (3)$$

where μ denotes the air viscosity depending on the cell temperature. It can be seen from the above equation that we calculate the local Reynolds (Re) number with the relative velocity of droplet. Knowing Re, equation of air resistance can be approximated by the following three equations:

$$C_D = \begin{cases} 24/Re_d & Re_d < 1 \\ 24\left(0.85 + 0.15 Re_d^{0.687}\right)/Re_d & 1 < Re_d < 1000 \\ 0.44 & 1000 < Re_d \end{cases} \quad (4)$$

For handling dynamic processes between particle and air, droplet size is needed.

2.2 Droplet distribution model

For diameter distribution of droplets, we can use a CVF (Cumulated Volume Fraction) model where droplet fraction depends on diameter rather than mass. Sprinklers can be modelled by combination of log-normal distribution and Rosin-Rammler distributions; integration of this model into droplet distribution modelling was proposed by Factory Mutual (FM) (14).

$$(d) = \begin{cases} \frac{1}{\sqrt{2\pi}} \int_0^d \frac{1}{\sigma d'} e^{-\frac{[ln(d'/d_m)]^2}{2\sigma^2}} dd' & d \le d_m \\ 1 - e^{-0.693\left(\frac{d}{d_m}\right)^\gamma} & d_m < d \end{cases} \quad (5)$$

Parameters of distribution equation are d_m mean droplet diameter, depending on sprinkler's opening size, pressure and design. γ=2.4 and σ=0.6 are empiric constants. Based on a research performed by FM, there is a relationship between mean droplet diameter (D) and sprinkler opening's size:

$$\frac{d_m}{D} \propto We^{-\frac{1}{3}} \quad (6)$$

where We is Weber number, expressing relationship between force of inertia and force coming from surficial stress:

$$We = \frac{\rho_d u_d^2 D}{\sigma_d} \quad (7)$$

where u_d is sprinkler efflux velocity and σ_d is water's superficial stress. Sprinkler efflux velocity can be calculated by the help of pressure together with mass flow computed based on head's hydraulic coefficient and free opening size. The model's drawback is that in the case of a real hydraulic topology, pressure in head depends also on number of open sprinklers. For standard sprinklers, above parameters are well described. Figure 1 shows the distribution function of a standard sprinkler with dm=1mm, γ=2.4, σ=0.6.

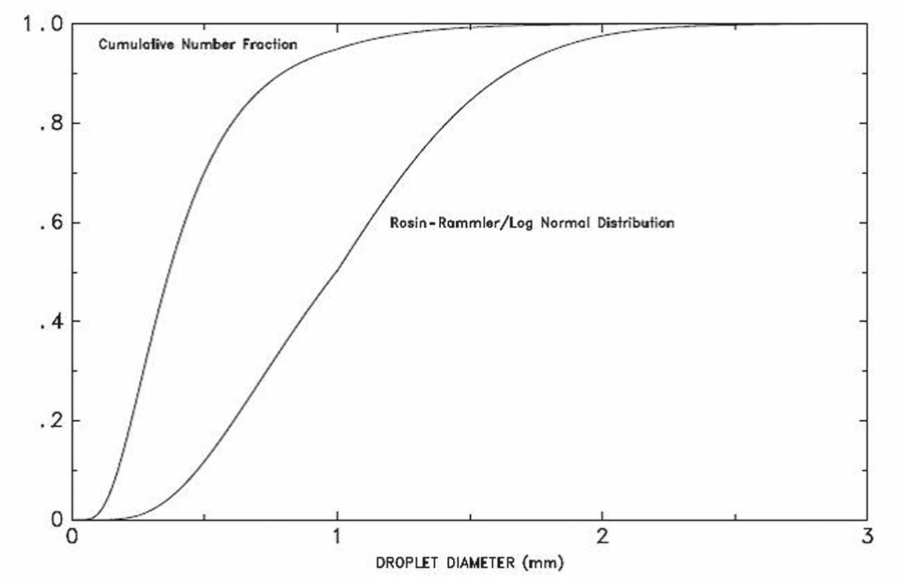
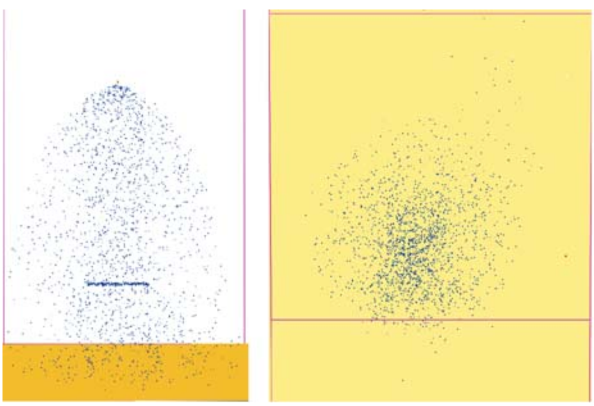


Fig. 1: Distribution of sprinkler droplets used in the model

For modelling droplets sprayed into air by sprinklers, the FDS program uses the Lagrange action principle. The algorithm selects the most probable droplet trajectory out of the possible trajectories based on the stationary effect rather than on accelerations generated by dynamic effects. Results of program run can be seen in Figure 2.



```
&PART ID='SPR_Droplet',
     WATER=.TRUE.,
     AGE=60.0,
     SAMPLING_FACTOR=5,
     SPECIFIC_HEAT=4.184,
     MELTING_TEMPERATURE=0.0,
     VAPORIZATION_TEMPERATURE=100.0,
     HEAT_OF_VAPORIZATION=2259.0/
&PROP ID='Water Spray',
     PART_ID='SPR_Droplet',
     FLOW_RATE=100.0,
     DROPLET_VELOCITY=5.0/
```

Fig. 2: Sprinkler FDS model

2.3 Smaller particles in space,

Droplets with relatively large diameter and kinetic energy interact with neighbouring air and increase kinetic energy of air. In this velocity space, we placed tracers with smaller diameters and, thus, smaller masses. We assigned also geometric material properties and thermal properties to tracer particles in order to make the model more realistic. Therefore, the tracer was water with a flow rate of 25 litres per minute. Droplet geometry has been described by Rosin-Rammler distribution. Mean diameter of tracer is 35.5μm while coefficients in distribution equation are $\gamma=2.4$, $\sigma=0.5$. Maximum diameter is 46.31μm, minimum diameter is 22.69μm.

2.4 Baseline data of the applied FDS model

Analysis was made by Fire Dynamics Simulator (FDS) software, version 5.5.3, Rev.: 2012.1.1221. FDS is based on results of CFD (Computational Fluid Dynamics) modelling. Program algorithms solve kinetic equations of a medium assumed to be continuous (Navier-Stokes equations). Turbulent movement of the test space can be described by Smagorinsky's LES (Large Eddy Simulation) model. The Euler-Lagrangian model is used in FDS. The Lagrangian particle tracking model in FDS does not include droplet collision or break-up of droplets.

As a special feature, FDS program allows definition of numerous grids. In simulation, a complex mesh was applied instead of one with homogeneous distribution, i.e. the test field was built from multiple grids of different decompositions (Figure 3). In the close neighbourhood of the test space, finer mesh, while farther, coarser mesh was applied. Use of multiple grids is necessary because the algorithm assigns each grid to a separate computer core. The grids applied in the model can be seen in Figure 3. The space is divided into 7 grids. Each grid has a different decomposition. Typically, cells of 20cm were applied in the field while, near to the test space, cells of 10cm and 5cm were used. Close to the sprinklers, cells are prism-shaped with a base of 10cmx10cm and height of 5cm. Thus, total number of cells in the whole field is about 400 000.

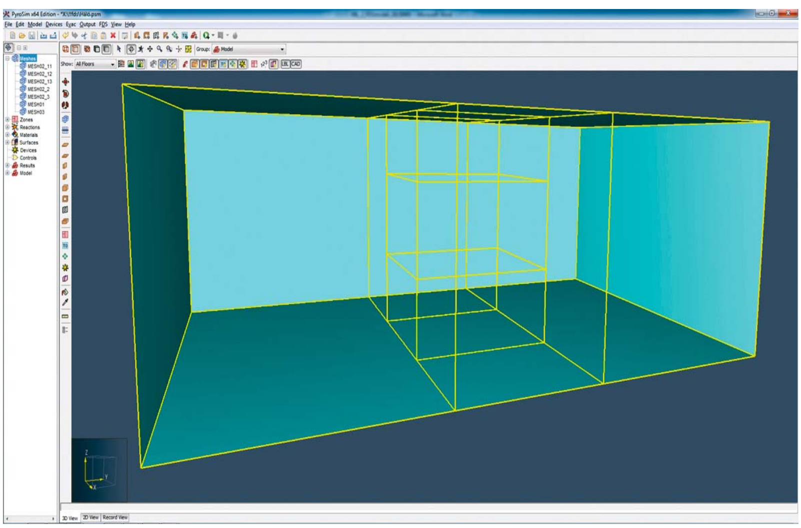


Fig. 3: Grids applied in the model

We built the 3D model of the building construction, with integrated load-carrying system, walls, floor and ceiling, doors and windows (Figure 4).

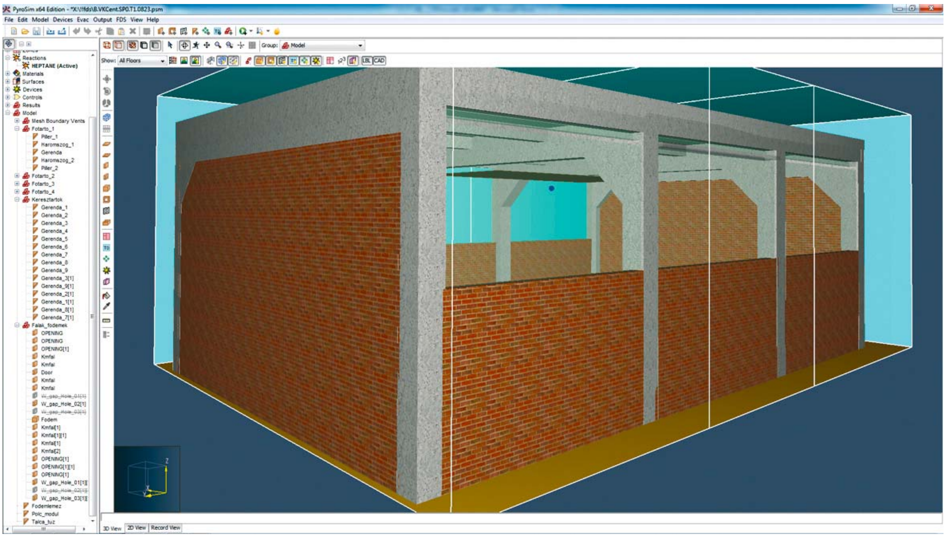


Fig. 4: The 3D model applied

Figure 5 contains the main geometric properties of the space modelled.

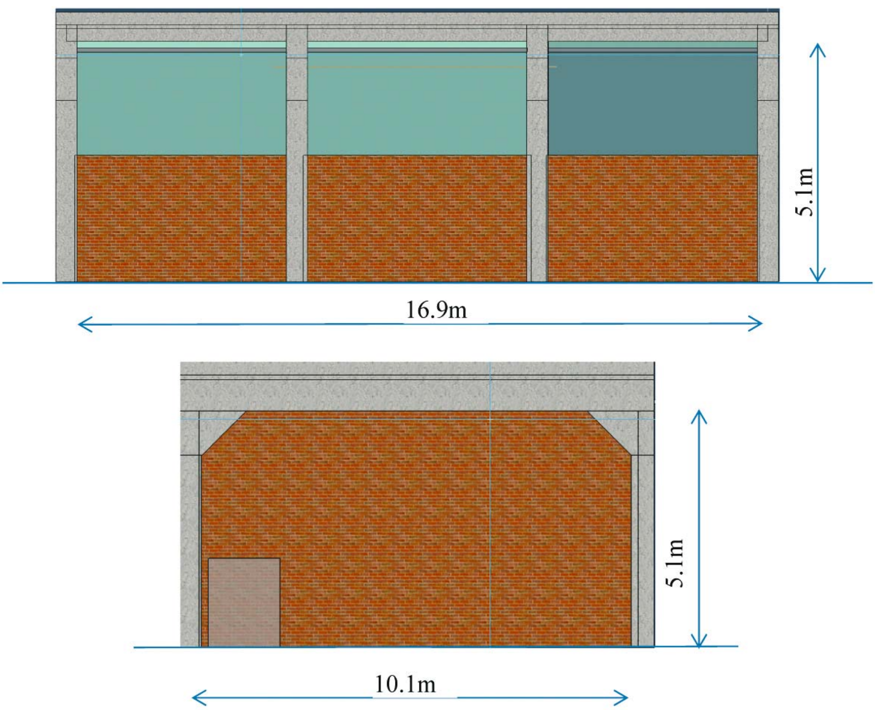


Fig. 5: Geometric properties of the model

In the test space, two sprinklers and two tracer sources were placed symmetrically below the ceiling, arranged at a distance of 3 m as shown in Figure 6.

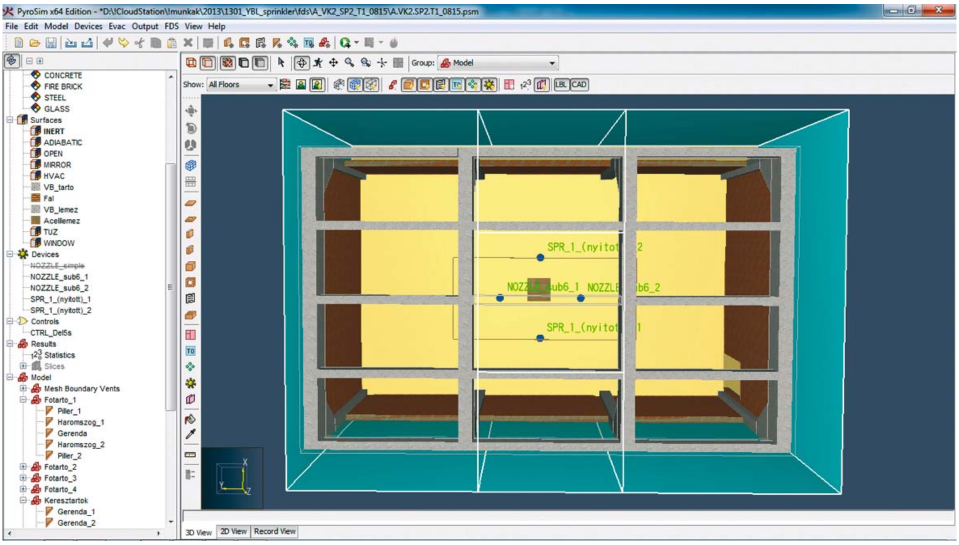


Fig. 6: Test arrangement

3. RESULTS AND DISCUSSION

For evaluation of the simulation results, test planes were defined in 3D space. Test planes were taken in axis of sprinklers and in axis of tracer sources being vertical to them. We studied the amount and direction of velocity and the trajectory of droplets and tracer. Results were displayed by the smoke view software.

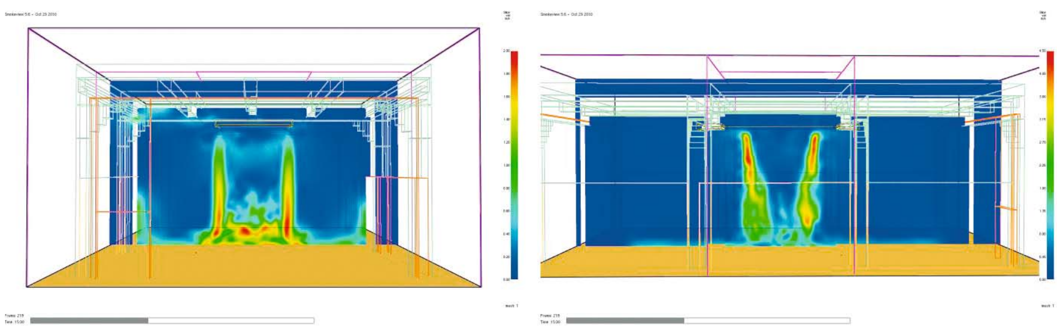


Fig. 7: Velocity field taken in the axis of sprinklers (left) and in the axis of tracer source (right) at a sprinkler droplet efflux velocity of 1m/s

Varying the efflux velocity of droplets escaping from sprinklers, we studied its effect on the tracer. Figures 7-12 display velocity fields taken in axis of sprinklers and tracer source as well as particle trajectories in the case of sprinkler flow efflux velocities of 1, 2, and 5m/s.

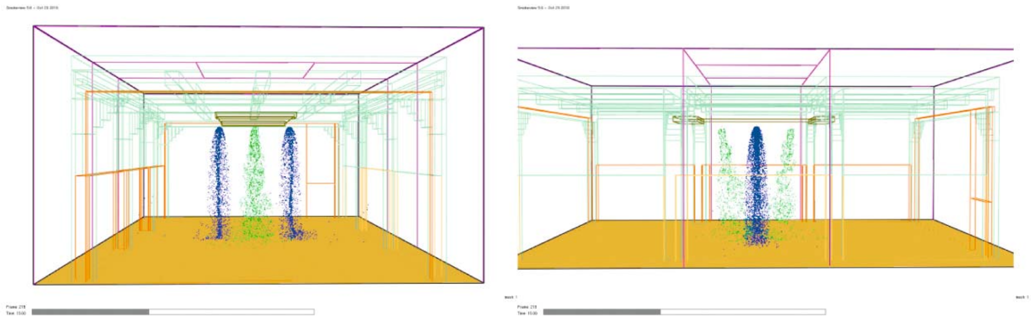


Fig. 8: Trajectory of particles in the space in axis of sprinklers and tracer source at a sprinkler droplet efflux velocity of 1m/s

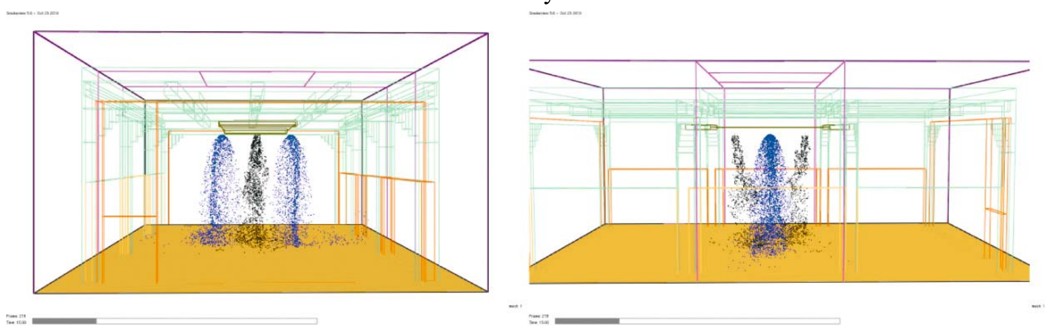


Fig. 9: Velocity field taken in axis of sprinklers and tracer source at a sprinkler droplet efflux velocity of 2m/s

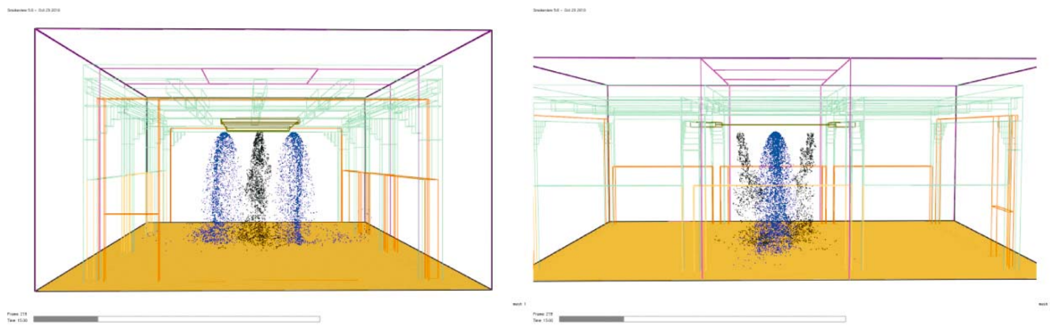


Fig. 10: Trajectory of particles in axis of sprinklers and tracer source in the space at a sprinkler droplet efflux velocity of 2m/s

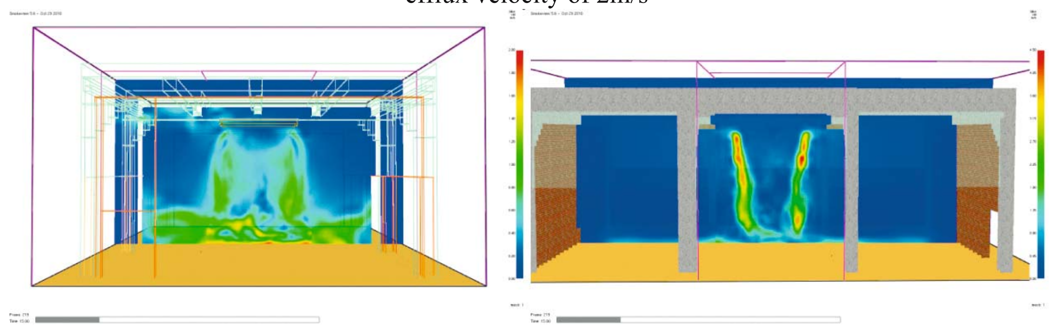


Fig. 11: Velocity field taken in axis of sprinklers and tracer source at a sprinkler droplet efflux velocity of 5m/s

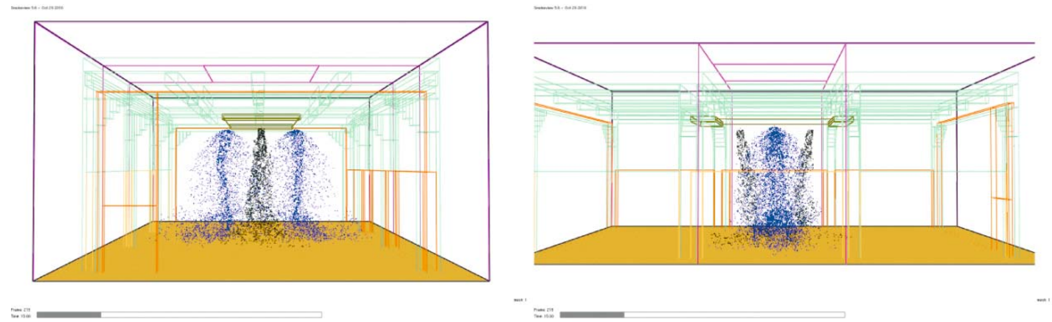


Fig. 12: Trajectory of particles in axis of sprinklers and tracer source in the space at a sprinkler droplet efflux velocity of 5m/s

Program run results show that sprinkler droplets generate free jet-like down-flow. Free jet is characterized by lower pressure inside. Thus, the modified pressure field influences the trajectory of water droplets smaller by several orders of magnitude and is able to divert them from their original path. Based on droplet distribution shown in Figures 8, 10 and 12, this effect is the largest at the sprinkler efflux flow of 5m/s.

Based on the results, we extended the velocity range of droplets escaping from sprinkler heads. We investigated the effect of initial velocity of sprinkler droplets on the extent of trajectory change. In additional program runs we varied the sprinkler droplets velocity between 0.25m/s and 10m/s. In this investigation, we used the velocity field taken in the axis of tracer source and the velocity vectors. Results are shown in Figures 13, 14 and 15. It can be seen that there are no changes in the tracer distribution above 5m/s sprinkler velocity.

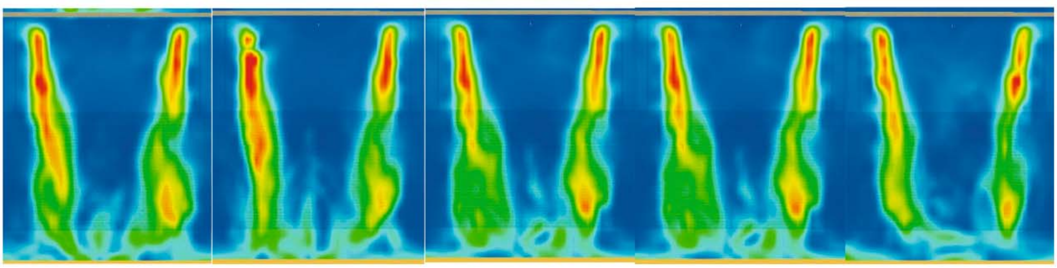


Fig. 13: Velocity field in the axis of the tracer source: trajectory change of tracer source against sprinkler droplets efflux velocity (for efflux velocities of 0.25m/s, 0.5m/s, 1m/s, 5m/s. 10m/s)

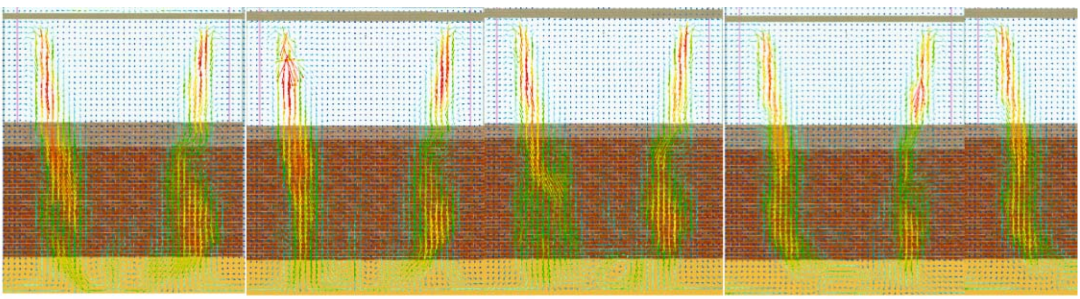


Fig. 14: Velocity vectors in the axis of the tracer source: trajectory change of tracer source against sprinkler droplets efflux velocity (for efflux velocities of 0.25m/s, 0.5m/s, 1m/s, 5m/s. 10m/s)

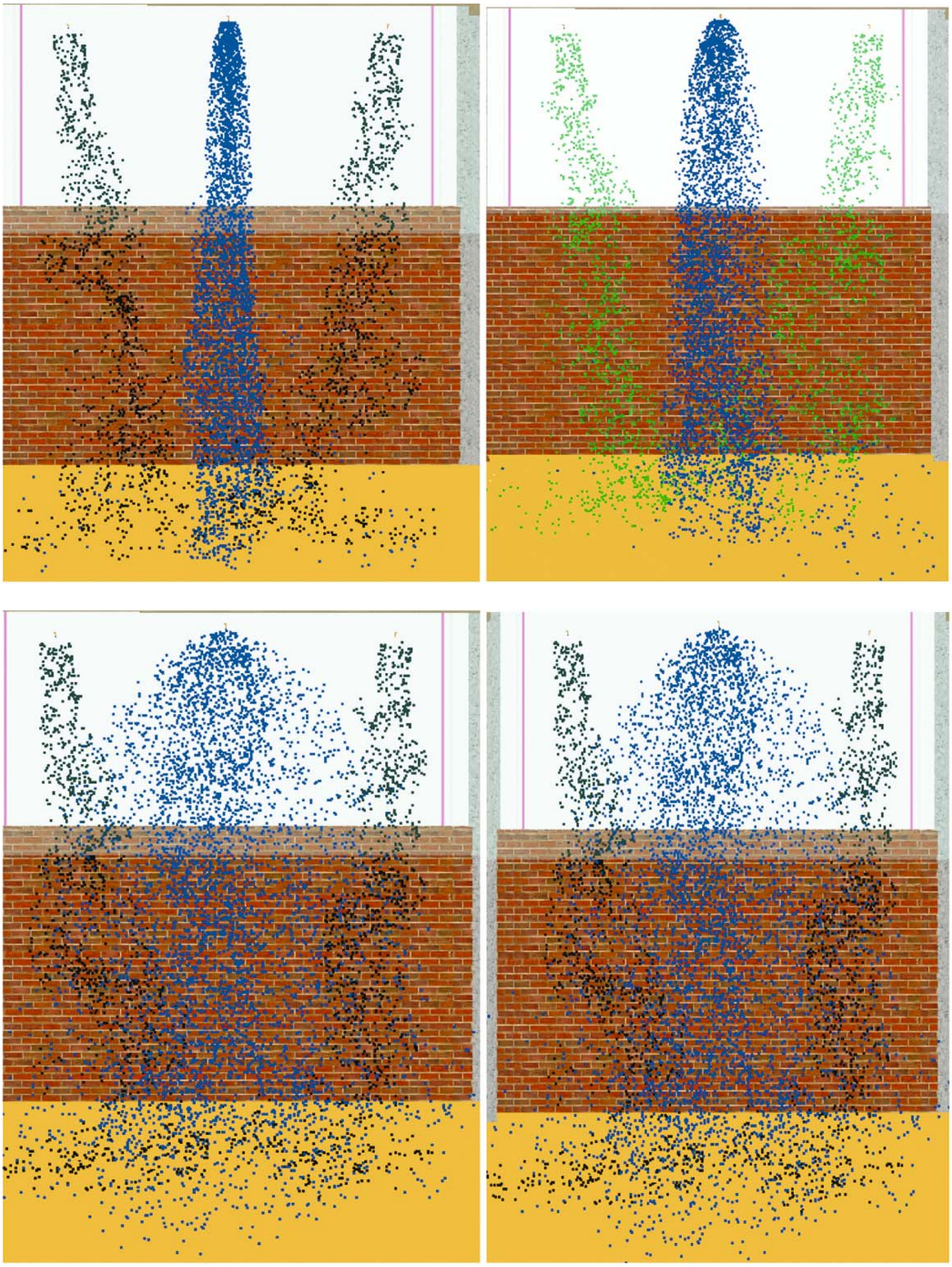


Fig. 15: Trajectory of particles in axis of tracer source at a sprinkler droplet efflux velocity of 0.5m/s, 1m/s, 5m/s, 10m/s.

4. CONCLUSION

As sprinklers are placed in symmetry axis of the tracer source, they generate intensive down-flow, driven mainly by inertia of sprinkler droplets being large in relation to their neighbourhood. Air flow generated by sprinkler spray droplets of 500μm creates a field like free jet. Pressure is inside the field lower, therefore, the field flowing down generates a horizontal inflow from the neighbourhood to the jet axis. Droplets of average diameters of 30μm applied as tracers react sensitively to the velocity of air flow in their neighbourhood, therefore, their trajectory changes. Due to the symmetric arrangement, lower pressure inside the jet flowing down diverts tracers from their trajectories to the centre.

Results of our investigations are in good agreement with the test results of Andersson, P. and Holmstedt, G. (17). According to their investigations, impulse force of fire plume may change the trajectory of droplets larger than 20μm to an extent significantly influencing efficiency of extinguishment. The field generated by sprinklers interacts with the field created by the high-velocity gas up-flow in the plume, decreases its influence, thus, smaller droplets may become able to come close to the fire. This implies that additional investigations are necessary concerning combined effect of sprinkler and fire plume on the trajectory of the tracer source.

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