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Validation of a CFD Study of Particle Distribution in Nuclear Workplace

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INTRODUCTION: In nuclear work environments where contaminated materials are handled there is always a possibility of accidental airborne releases of toxic or radioactive substances in form of aerosols and gases. Because of that, safety professionals and engineers are required to design effective warning systems and countermeasures to minimize a worker's risk. Understanding the air flows patterns and aerosol trajectories in ventilated rooms can provide key information for determining where to place early warning and monitoring instruments, and how to minimize hazardous materials in the worker's breathing zone. In particular, with the numerical simulations, they have been firstly evaluated the capabilities of the numerical model to reproduce the available experimental data and secondly the optimized positioning of continuous air monitoring to obtain a quickly and good sensitive response.

Figure 1. Glove-box example

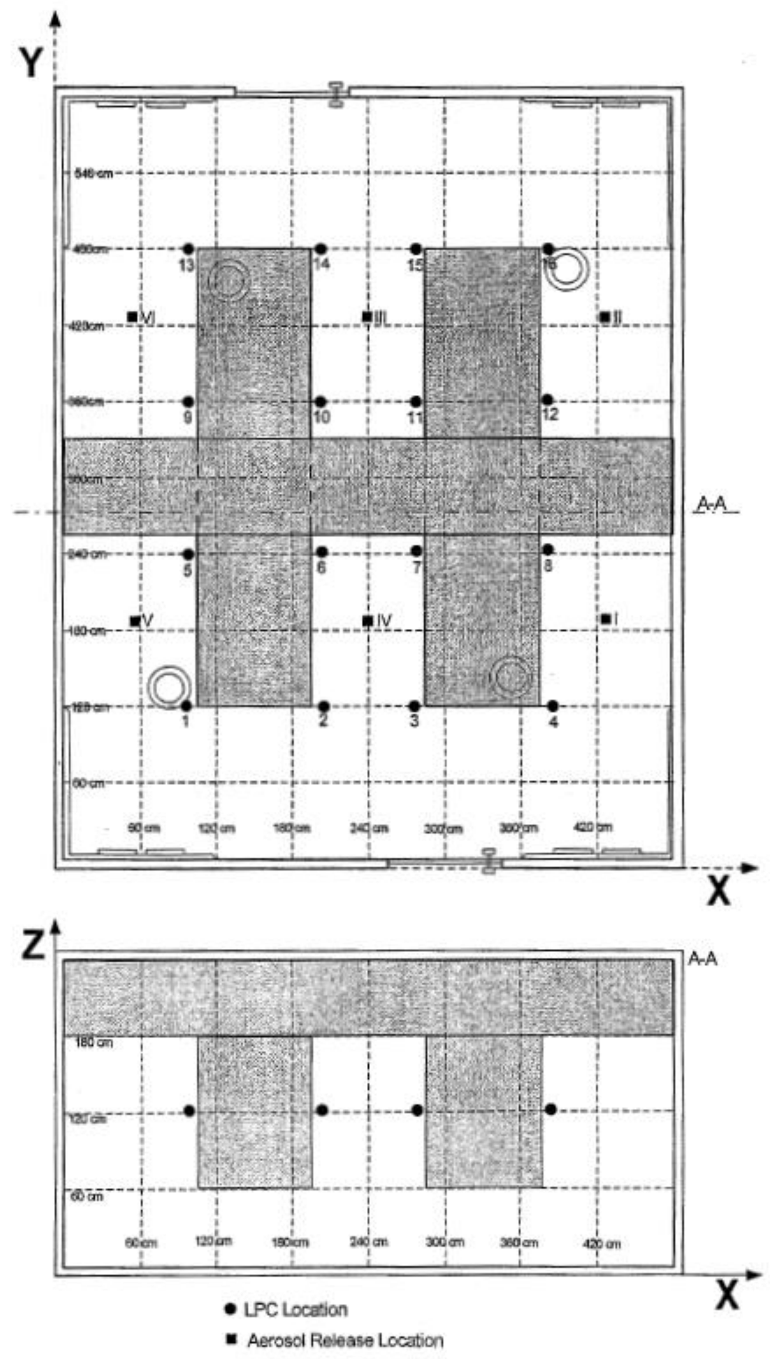

Figure 2. Experimental test facility

COMPUTATIONAL METHODS: The 3D simulations have been performed with COMSOL Multiphysics version 5.2, Heat Transfer and Particle Tracing Modules, and they are based on the following steps: 1) stationary fluid flow study (single phase incompressible and isothermal turbulent k-eps closure model); 2) time dependent particle transport study, using the air velocity field obtained in the first study.

$$\nabla \cdot \boldsymbol{U} = 0$$

$$\rho \frac{\partial \boldsymbol{U}}{\partial t} + \rho(\boldsymbol{U} \cdot \nabla)\boldsymbol{U} = \nabla \cdot [-p\boldsymbol{I} + \boldsymbol{\tau}]$$

$$\frac{d}{dt}(m_p \boldsymbol{v}) = \left(\frac{1}{\tau_p}\right) m_p(\boldsymbol{u} - \boldsymbol{v}) + m_p \boldsymbol{g} \frac{(\rho_p - \rho)}{\rho_p} + \boldsymbol{F}_{brow}$$

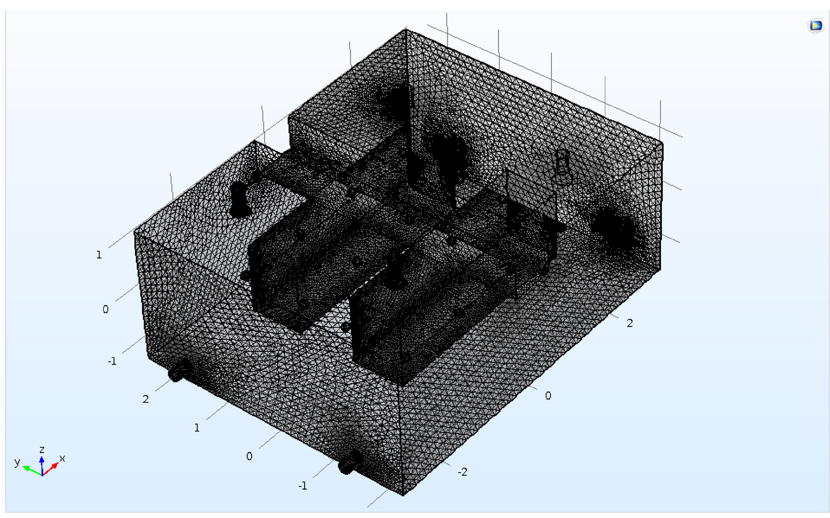

Figure 3. Mesh used for both steps

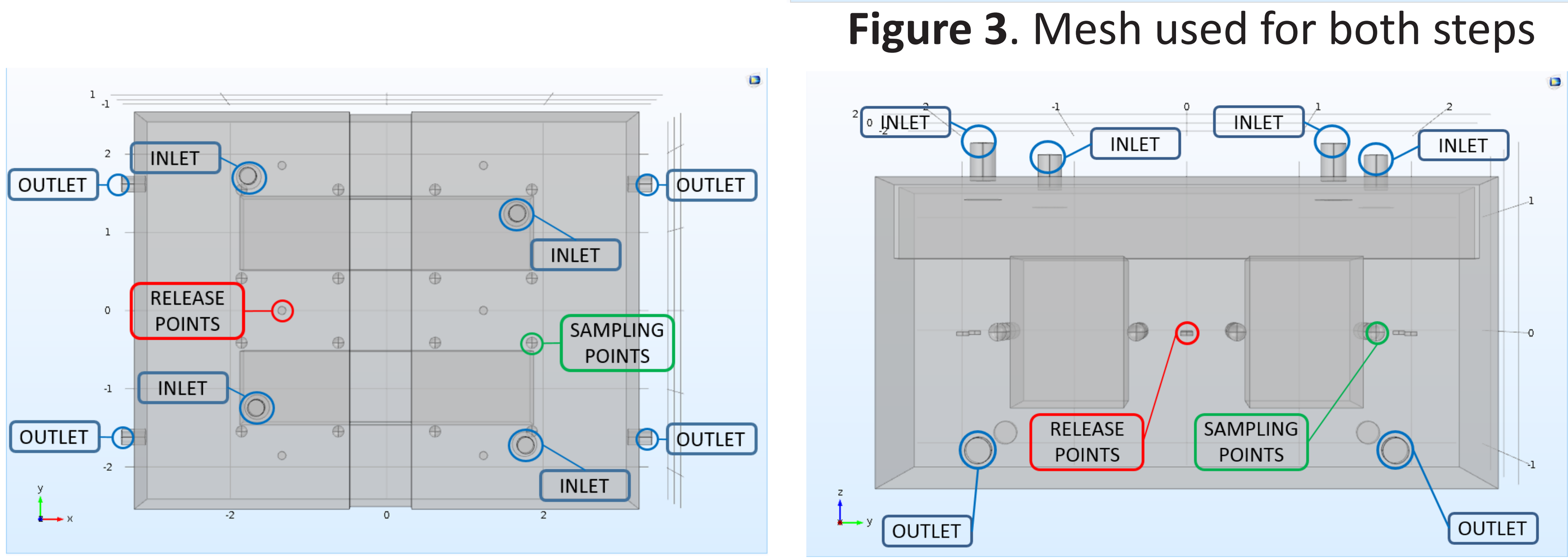

Figure 4. Boundary conditions details

RESULTS: With the numerical simulations, they have been firstly evaluated the capabilities of the numerical model to reproduce the available experimental data and secondly defined the optimized positioning of continuous air monitoring to obtain a quickly and good sensitive response. Computations are carried out for two nominal room air exchange, approximately 6 vol/h (low ventilation LV) and 12 vol/h (high ventilation HV) and for three different release locations. The particle aerodynamic equivalent diameter is set to 0.52 µm.

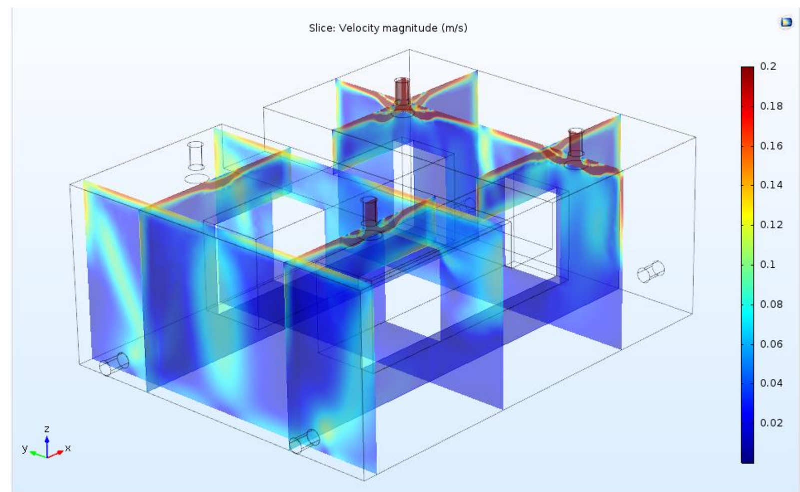

Figure 5. Slices of velocity magnitude for 6 vol/h

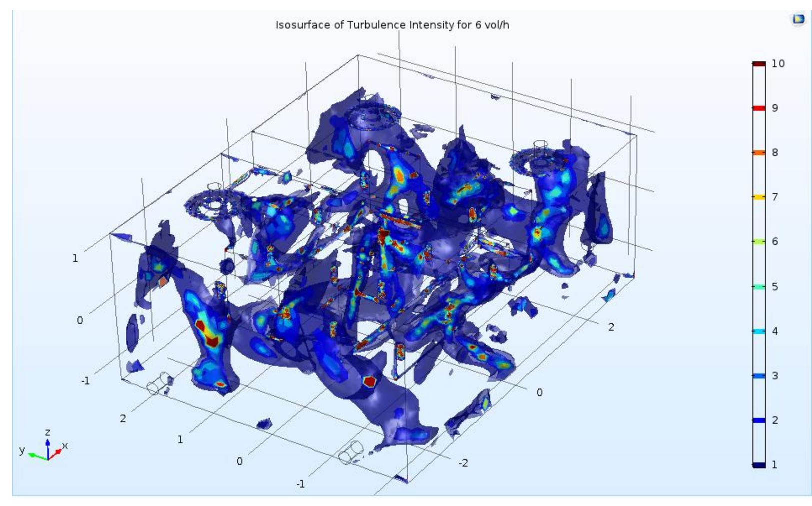

Figure 6. Turbulence intensity isosurface for 6 vol/h

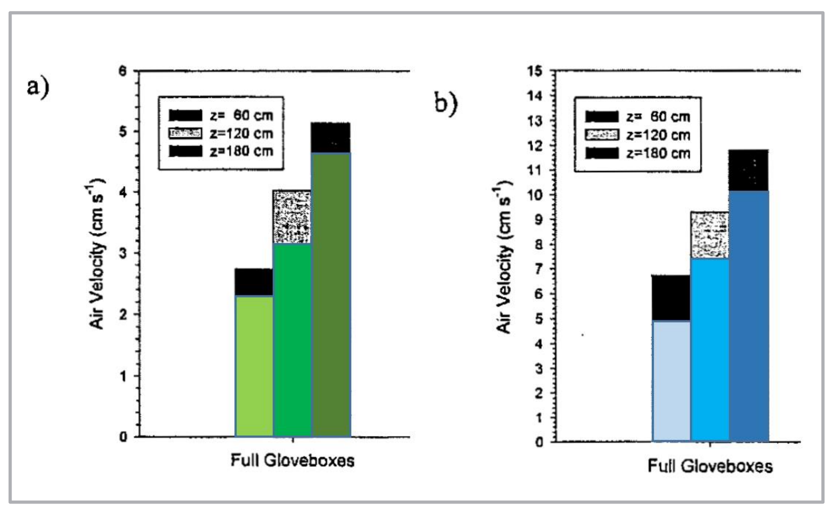

Figure 7. Comparison between experimental and numerical results: histogram graph

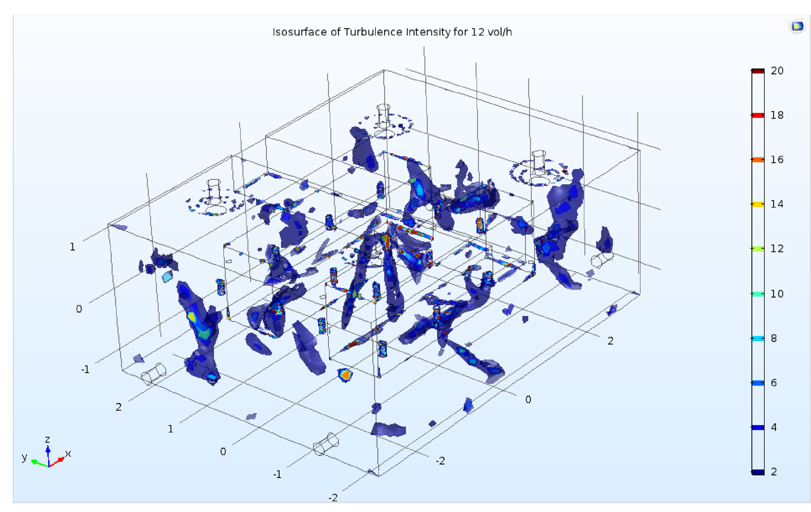

Figure 8. Turbulence intensity isosurface for 12 vol/h

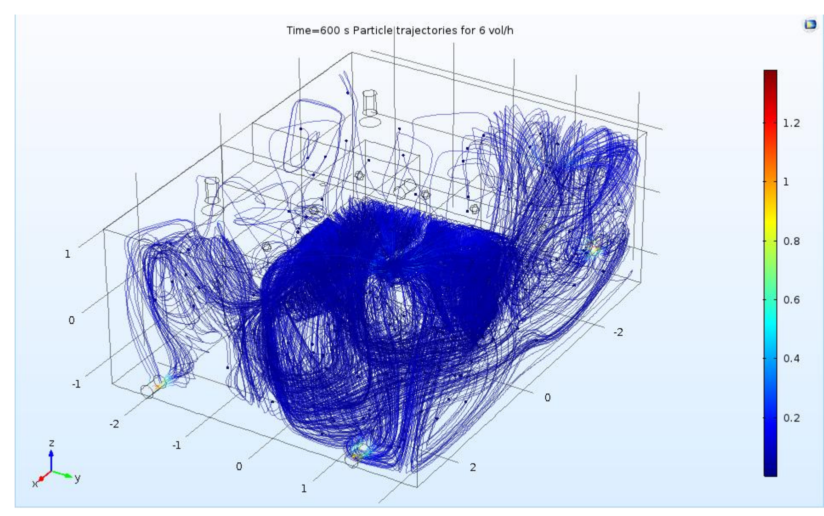

Figure 9. Particle trajectories for the release from station I and 6 vol/h ventilation exchange

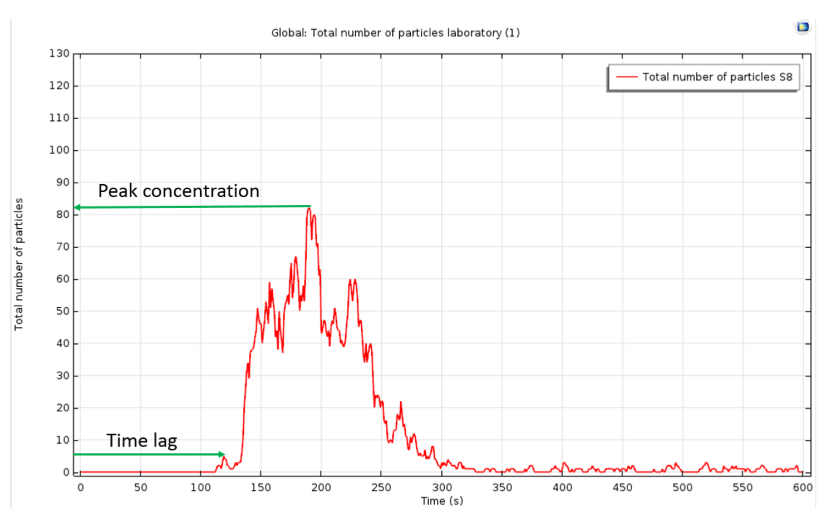

Figure 10. Concentration time history for LPC station 8, release station I and 6 vol/h exchange

Metric used for particle diffusion:

- time lag;
- concentration ratio $CR(i)_{20min}$ defined as as the ratio of the largest mean peak concentration $C_{20min(largest)}$ measured in the room divided by each of the mean peak concentrations measured at the other sampling locations $C(i)_{peak}$ during 20 min after the release as shown in the following equation:

$$CR(i)_{20min} = \frac{C_{20\min(largest)}}{C(i)_{20min}}$$

FB-LV

Release location	Lag time mean (s) ± SEM		Mean $CR_{20\text{-}min}$ ± SEM		Mean CR_{peak} ± SEM
I	223 ± 24	215	27 ± 8	23	69 ± 21
II	135 ± 20	195	13 ± 4	10	14 ± 4
III	159 ± 24	218	26 ± 9	26	66 ± 26
IV	83 ± 10		4 ± 1		20 ± 5
V	123 ± 20		11 ± 3		42 ± 13
VI	187 ± 28		33 ± 10		85 ± 26
Avg:	152		19		49
SD	49		11		29

FB-HV

Release location	Lag time mean (s) ± SEM		Mean $CR_{20\text{-}min}$ ± SEM		Mean CR_{peak} ± SEM
I	71 ± 10	105	6 ± 1	4.5	18 ± 5
II	63 ± 8	80	3 ± 0.4	3.5	10 ± 2
III	71 ± 9	100	4 ± 1	6	16 ± 4
IV	88 ± 11		9 ± 2		52 ± 15
V	79 ± 10		8 ± 2		22 ± 7
VI	78 ± 10		9 ± 2		22 ± 6
Avg:	75		7		23
SD	9		3		15

Figure 11. Comparison of experimental and numerical results for particle tracing study. The upper table refers to low ventilation scenario, the lower to the high ventilation.

CONCLUSIONS: Computed and measured ventilation fluidynamical characteristics and aerosol concentrations time history data are compared and show general agreement. A CAM placement strategy is defined in order to select the best locations that are generally "downwind" of the release points.

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