HYDROGEN RISK ANALYSIS FOR A GENERIC NUCLEAR CONTAINMENT VENTILATION SYSTEM

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ABSTRACT

Hydrogen safety issue in a ventilation system of a generic nuclear containment is studied. In accidental scenarios, a large amount of burnable gas mixture of hydrogen with certain amount of oxygen is released into the containment. In case of high containment pressure, the combustible mixture is further ventilated into the chambers and the piping of the containment ventilation system. The burnable even potentially detonable gas mixture could pose a risk to the structures of the system once being ignited unexpectedly. Therefore the main goal of the study is to apply the computational fluid dynamics (CFD) computer code - GASFLOW, to analyze the distribution of the hydrogen in the ventilation system, and to find how sensitive the mixture is to detonation in different scenarios. The CFD simulations manifest that a ventilation fan with sustained power supply can extinguish the hydrogen risk effectively. However in case of station blackout with loss of power supply to the fan, hydrogen/ oxygen mixture could be accumulated in the ventilation system. A further study proves that steam injection could degrade the sensitivity of the hydrogen mixture significantly.

Key Words: nuclear containment; ventilation system; hydrogen safety; hydrogen distribution; hydrogen detonation.

1 INTRODUCTION

A filtered venting system is designed for a generic nuclear containment. In severe accidental scenarios with a core melt down, a large amount of burnable gases is released into the containment. A filtered ventilation is designed as a mitigation measure against a high containment pressure. After aerosols and condensable portions of the gas mixture from the containment are purged, the remaining burnable gases flow into a chamber connected to horizontal venting pipes and further to a vertical stack, which is open to free atmosphere at the top. The burnable or, even detonable gas mixture in these compartments could pose a risk to the structures of the system once being ignited unexpectedly. Therefore the main goal of the study is to investigate the chemical sensitivity of the burnable and potentially detonable gas mixture in the venting system by means of computational fluid dynamics (CFD) computer simulations.

This article is composed of the following contents: a brief introduction of the filtered containment venting system and its geometrical model and numerical mesh for the CFD simulations; theory of hydrogen risk criteria; room definitions in the simulations for deflagration-to-detonation transition (DDT) analysis; initial conditions, boundary conditions and simulation results in defined accidental scenarios, including cases with or without power supply to the ventilation fans and/ or, with or without steam injection into the filter room.

2 CONTAINMENT VENTING SYSTEM AND COMPUTATIONAL MODEL

2.1 Venting system

A filtered venting system is designed to ventilate the exhaust produced in the containment during a hypothetical core melt accident. In this case, the exhaust could be composed of gases of H_2, O_2, N_2, steam and radioactive aerosols and so on. The containment exhaust is guided by a piping system starting from an opening in the containment to a scrubber tank full of water, where aerosols and condensable portions of the gas mixture from the containment are purged in the scrubber and non-condensable gases are released into the filter room. However, owing to the limited amount of the water in the scrubber and the released latent heat of the injected hot steam, the pool begins to boil after a certain time then steam is released into the filter room, too. The schematic plot about the ventilation system is summarized in Figure 1 [1].

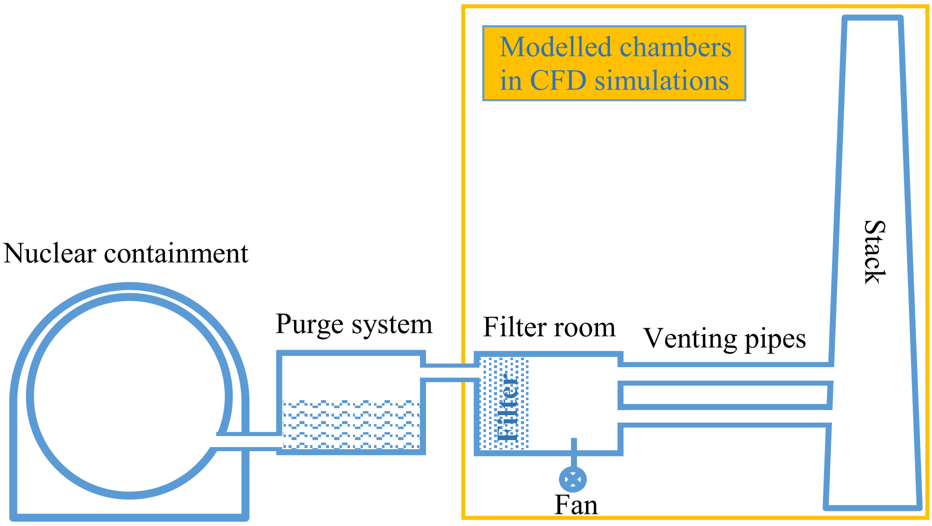

Figure 1. Schematic of filtered containment venting system

The model in the CFD study starts from the filter room. The upstream of the exhaust flow is ignored and treated as an injection source of the computational domain. Thus, the simulated chambers include simply the filter room with internal structures, the two horizontally positioned ventilation pipes and the stack.

2.2 Geometrical model and mesh

The extremely long venting pipes and the extremely high stack pose a big challenge to the CFD simulations. Fortunately, the GASFLOW code has a multi-block function [2], which enables the code to model the three blocks (the filter room, the venting pipes and the stack) in three dimensions (3D), separately. Then the three separated 3D domains are connected by a group of one-dimensional (1D) ducts in between the domains of filter room and the venting pipes, and between the domains of the venting pipes and the stack, in a way of cell-to-cell connection. Therefore the three separated blocks are integrated together by the 1D ducts.

Cartesian coordination system is chosen in the GASFLOW simulations and the scheme of the geometrical models and mesh information are shown in Figure 2. The cell size ranges from 0.4 m to 2 m and the total cell number is 42,048.

In the filter room model in Figure 2, the dot line stands for the rupture membrane, which is practically the injection location of the exhaust, while the three "venting inlets" are the venting air entrance [3].

3 THEORY OF HYDROGEN RISK CRITERIA

3.1 Risk of flame acceleration – sigma criterion

A hydrogen-air mixture would potentially exhibit flame acceleration (FA), if it satisfies,

$$\sigma > 1, \qquad (1)$$

where σ is determined by the composition of the mixture and its thermo-dynamic conditions, e.g., pressure and temperature [2]. The mixture in a risk of flame acceleration is called "sigma cloud" and the equation (1) is called "sigma criterion".

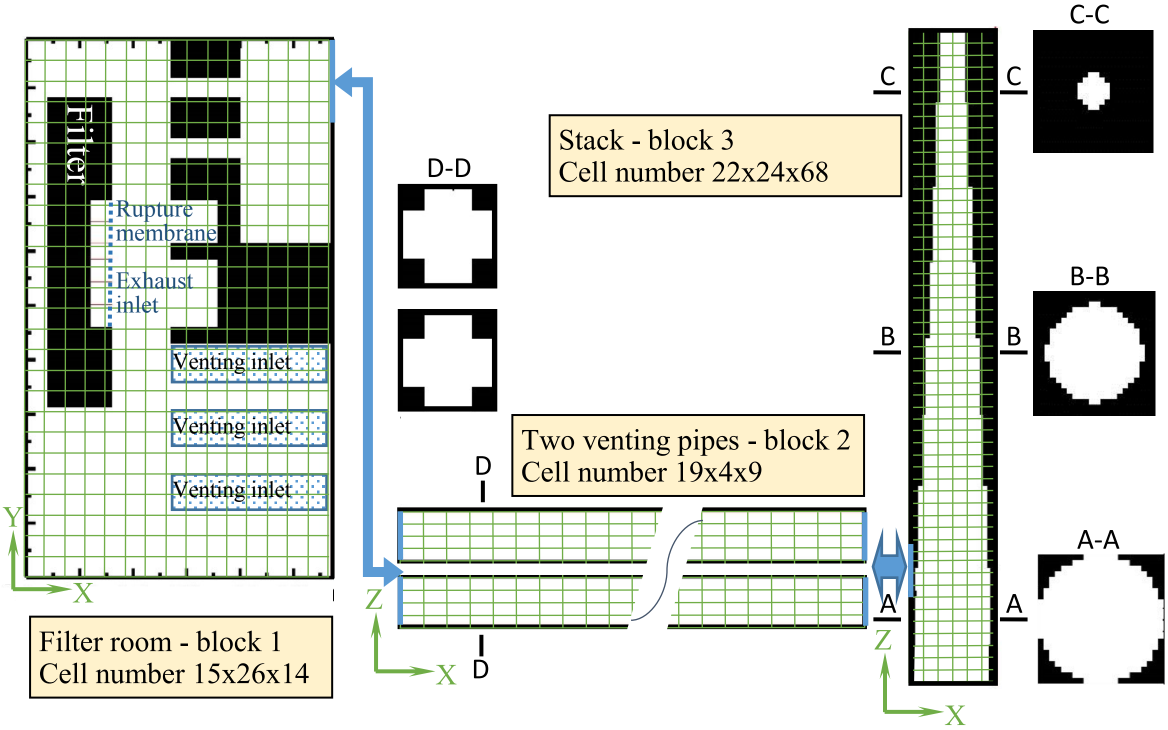

Figure 2. Schematic of geometrical models and mesh

3.2 Risk of detonation – lambda criterion

The prediction of DDT is still a challenging topic theoretically. Meanwhile DDT phenomena is somehow stochastic in laboratory for a given hydrogen-air mixture in a given control volume. A lambda criterion has been developed, based on a great amount of hydrogen explosion experiments in various confined or partially confined geometries in different length scales. The theory has been implemented into the GASFLOW code. The lambda criterion is formulated as,

$$D/(7\lambda)>1, \qquad (2)$$

where, D – the characteristic dimension of the confined volume, m; λ – the detonation cell size of the mixture, m, which depends on the property of the mixture, i.e., composition and thermo-dynamic condition [2].

The lambda criterion implies that the risk of detonation for a given hydrogen mixture is always associated to the characteristic dimension of the chamber containing the mixture, apart from the mixture properties. The chamber is called a "room" in the modelling of the GASFLOW simulations.

4 ROOM DEFINITIONS

Hydrogen detonation risk is always associated with the identification of certain confined or partially confined volumes, called "rooms". These rooms must have certain characteristic dimensions, which are important to judge whether the contained mixtures are detonable or not. Besides, of course, the composition of the gas mixture itself and its thermal-dynamic condition are also key factors to determine the sensitivity of the mixture. The room definitions in the GASFLOW simulations are shown in Figure 3.

In Figure 3, multiple numbers are denoted in the same square or region in the filter room, e.g. “Room 01, 02~04”, which means that “Room 01” stands for the room in a full height in gravitational (Z-) direction, “Room 02”, “Room 03” and “Room 04” for the sub-rooms in a fractional height on the bottom side, at the middle height and on the top side of “Room 01”, respectively. Sometimes only three numbers are denoted in the same location, e.g. “Room 44, 45, 46”, which means that the three rooms are all sub-rooms at the same region in a fractional height on the bottom, at the middle and on the top, respectively.

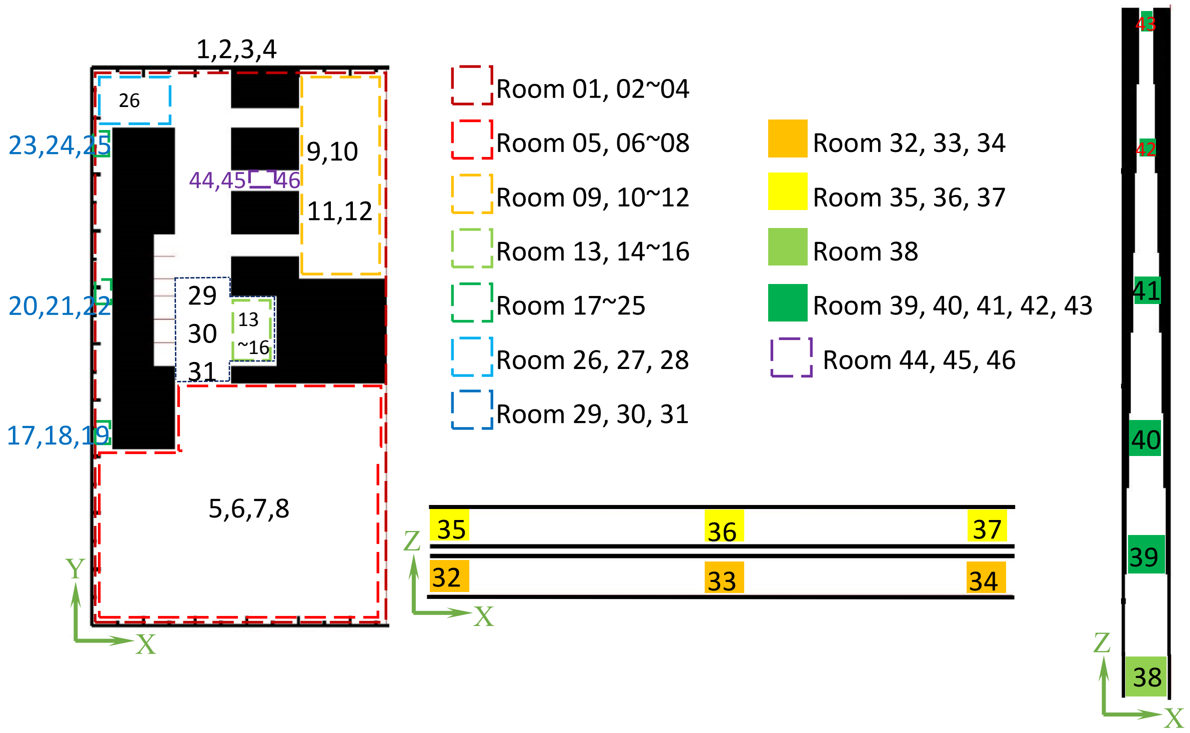

Figure 3. Schematic of defined rooms for judgement of deflagration to detonation transition (DDT)

5 COMMON CONSIDERATIONS

5.1 Initial condition

In all simulations, all the three blocks and the connecting 1D ducts are initially filled with air at 1.013×10^5 Pa of pressure and 293.15 K of temperature, at t = 0 s.

5.2 General boundary condition at stack exit

The outflow boundary condition at the exit of the stack is defined as a pressure of 9.927×10^4 Pa and 292.15 K of temperature. The atmospheric pressure at the exit is adapted from a normal atmospheric pressure by considering the extraordinary height of the stack.

A horizontal wind speed of 1 m/s is assumed at the exit of the stack.

5.3 Model configurations

In all simulations, no-slip and adiabatic wall boundary conditions are adopted, and a standard k-epsilon two-equation turbulence model is chosen.

6 SIMULATION RESULTS

6.1 Available venting

6.1.1 Boundary condition

If the power supply of the venting fan is available in certain scenarios, the ventilation functions. The venting air mass flow rate is 57.3 kg/s at a pressure of 1.013×10^5 Pa and a temperature of 293.15 K [1].

The exhaust mass flow rate is determined as 1.21 kg/s at a pressure of 1.2×10^5 Pa and a temperature of 293.15 K, with molar fractions of components as,

N_2: 0.58149, O_2: 0.006637, H_2: 0.390855, CO_2: 0.021018 [1].

6.1.2 Simulation results

The simulation indicates that no mixture satisfies the sigma criterion in the whole domain if the venting is available. No mixture satisfies the lambda criterion either. Hence there is no risk of flame acceleration and DDT in the whole venting system. It proves numerically that the ventilation can avoid effectively accumulation of hydrogen mixture.

6.2 Unavailable venting without steam injection

6.2.1 Boundary condition

In some scenario as station blackout, the ventilation is unavailable owing to loss of power supply to the fans. Thus there is no venting air flow at all. In the case, the exhaust mass flow rate is defined as 1.15 kg/s at a pressure of 1.2×10^5 Pa and a temperature of 293.15 K. The components molar fractions in the exhaust are,

N_2: 0.58949, O_2: 0.01627, H_2: 0.31664, CO_2: 0.0776 [1].

6.2.2 Simulation results

A total physical time of 7200 s is simulated since the starting point of the exhaust injection into the filter room. The sigma indices of hydrogen mixture are computed according to the peak values of hydrogen concentrations in all defined rooms. The sigma index time-history plot is shown in Figure 4. According to the sigma criterion, the mixture is in a risk of flame acceleration (FA) if the index is greater than one. Figure 4 obviously shows that the mixtures in most rooms are in risk of FA at the end of the simulation time.

Meanwhile the lambda criterion is judged for every room at every time. The value of $D/(7\lambda)$ of the contained mixture is evaluated and is shown in Figure 5. The ratios in the 40^{th}, 41^{st} and 42^{nd} room are greater than 1 at certain time. According to the lambda criterion DDT can potentially occur in the three rooms.

In view of hydrogen safety the venting system is in risk of hydrogen deflagration and detonation if venting is unavailable and no steam is injected.

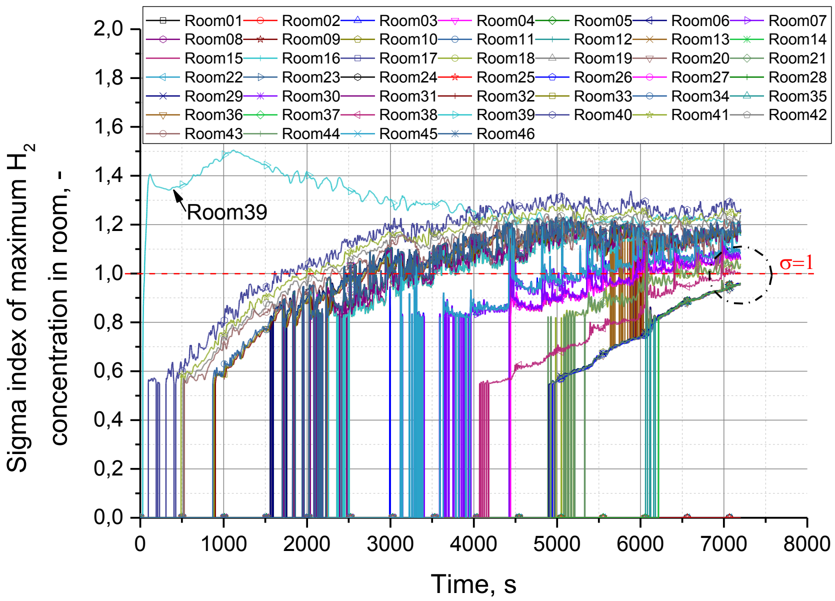

Figure 4. Sigma index of maximum H_2 concentration in rooms (no venting, no steam)

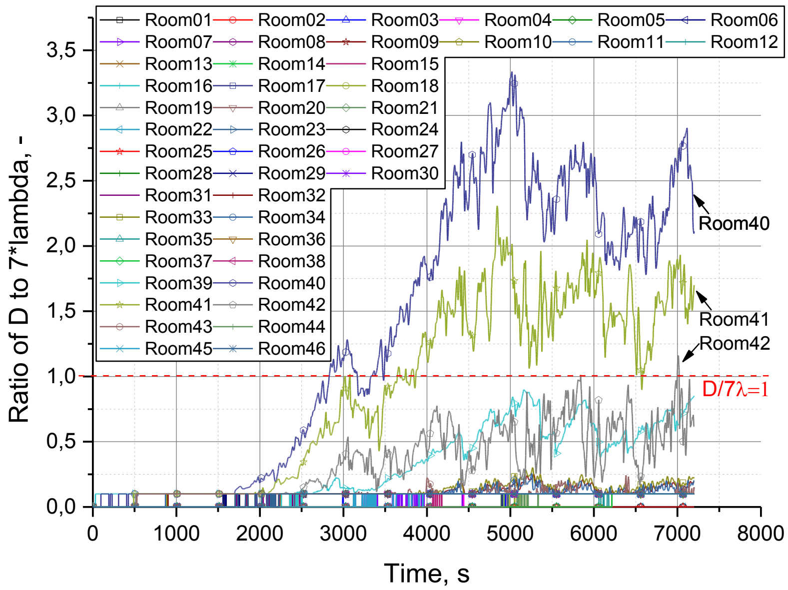

Figure 5. Ratio of D to 7*lambda in rooms (no venting, no steam)

6.3 Unavailable venting with steam injection

6.3.1 Boundary condition

The venting system would have potential hydrogen safety issue based on the discussion in last section if no steam were injected into the filter room. Fortunately the real scenario is not the case. By referring to Figure 1, the water temperature in the purge pool increases until the water boils in about 10 minutes after the starting point of the containment exhaust release. Since then a large amount of steam is released into the filter room owing to the saturation state of the tank water. The major energy to boil the tank water is the released latent heat of condensate of the hot steam entrained by the upstream exhaust flow continuously from the containment to the purge pool.

Therefore the exhaust mass flow rate and the corresponding component fractions are defined in two different stages in the case.

During the first 10 minutes, the exhaust is only non-condensable, which mass flow rate is determined as 1.15 kg/s at a pressure of 1.2×10^5 Pa and a temperature of 293.15 K, with molar fractions of components as,

N_2: 0.58949, O_2: 0.01627, H_2: 0.31664, CO_2: 0.0776, H_2O: 0.0 [1].

After the 10 minutes, steam injection starts and the overall exhaust mass flow rate increases to 3.97 kg/s. The mixture is supposed to be at the same pressure and the same temperature as the beginning stage. The components molar fractions are changed accordingly to:

N_2: 0.152924, O_2: 0.004224, H_2: 0.082145, CO_2: 0.02013, H_2O: 0.740577 [1].

Certainly it is assumed no venting air flow in all time in the case.

6.3.2 Simulation results

The gas dynamics in the venting system is simulated for 4000 s with the defined injection source. The sigma value and the value of $D/(7\lambda)$ are evaluated for the hydrogen mixtures in all the room defined, and are shown in Figure 6 and Figure 7, respectively.

The simulation results explicitly show that all the mixtures in the sub-chambers are significantly deactivated chemically by the steam component after 607 s. Figure 6 indicates that almost all the rooms are safe from the risk of FA because the sigma indices are less than the critical value in most case. The only exception is, that the mixture in the 39^{th} room is in a risk of FA but only during the time window between 51 s to 607 s.

On the other hand, Figure 7 manifests that the whole venting system has no risk of DDT in all time because the values of $D/(7\lambda)$ in all defined rooms are far less than unit. The simulation proves numerically that the dominant component – steam in the flow deactivates the hydrogen mixture and eliminates the sensitivity of detonation efficiently.

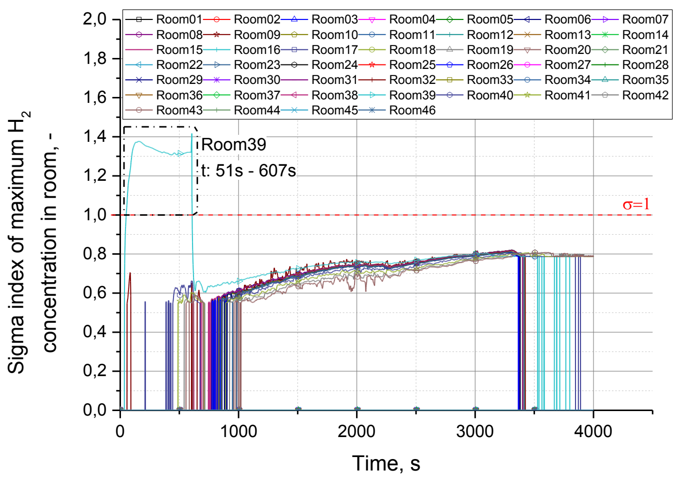

Figure 6. Sigma index of maximum H_2 concentration in rooms (no venting, with steam)

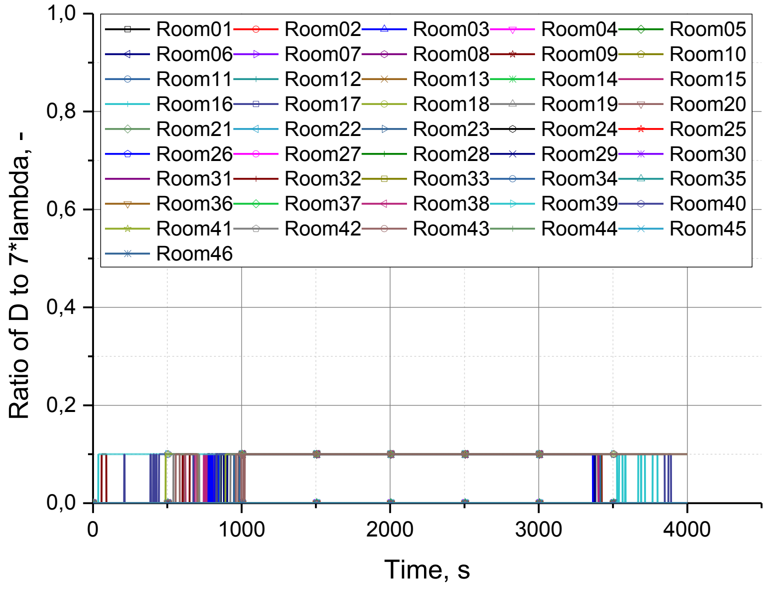

Figure 7. Ratio of D to 7*lambda in rooms (no venting, with steam)

6.3.3 Detailed analysis of sub-chamber

The discussion in the subtitle focuses on the detailed analysis for the questionable 39th room, which is a compartment in the stack, connecting to the two horizontal venting pipes. It has to be emphasized that the sigma index in Figure 6 is computed depending on the maximal hydrogen concentration in the concerned chamber in order to be conservative. Therefore it is good to know whether the risk of FA in Room39 is a local effect. For such a purpose Figure 8 compares the sigma value computed on the average hydrogen concentration to that on the peak value in the Room39. The plot indicates that the sigma value on the average concentration is less than the critical value of one. It proves that the risk is a local effect.

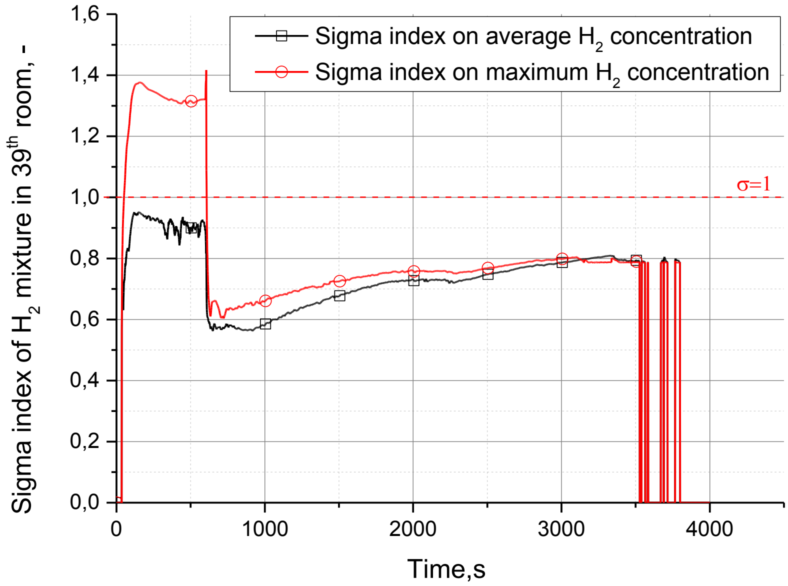

Figure 8. Sigma index on average H_2 concentration in Room39 (no venting, with steam)

The Room39 is approximately a sectional cylinder of the stack. It is connected to the venting pipes on the west side (left hand side). The first plot of Figure 9 shows the volumetric fraction distribution of hydrogen in the vertical cut of the Room39 at t=365.1 s for an example. It presents that the high concentration appears only in the top corner, which is a typical distribution of a buoyancy driven flow. The second part of Figure 9 shows further the detailed hydrogen volumetric fraction distribution in the horizontal cut at the top level of the Room39 at the same time moment. It manifests that the high concentration zone of hydrogen is very limited on the west side. It is calculated that the hydrogen cloud in the Room39, which makes the sigma value greater than one during [51s, 607s], is limited in a small volume of 0.160 m^3 with a hydrogen mass of about 1.9 gram. The small amount of hydrogen does not pose a big risk to the venting system.

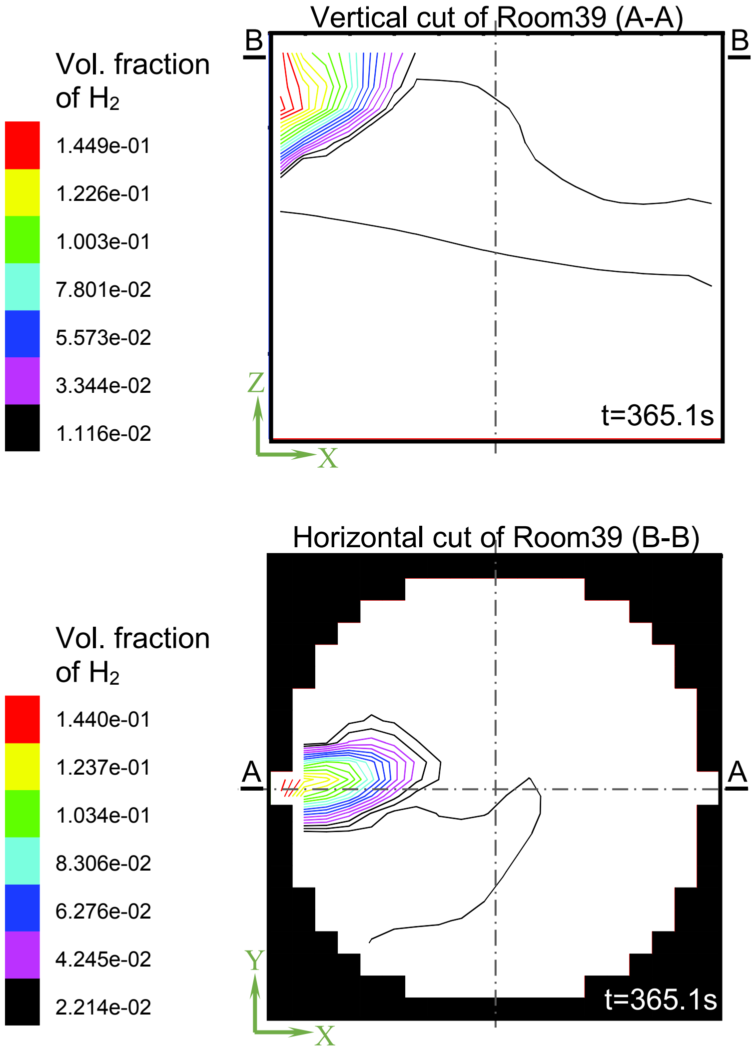

Figure 9. Detailed H_2 concentration distributions in Rom39 (no venting, with steam)

7 CONCLUSIONS

The hydrogen distribution in a generic nuclear containment venting system has been analysed for different accidental scenarios by using CFD code. The hydrogen clouds in the venting system are evaluated against the risk criteria of flame acceleration (FA) and deflagration to detonation transition (DDT). Numerical simulations manifest that the venting system is free of hydrogen issue if the venting fan functions well. In case of station blackout without power supply to the fan, i.e., without forced ventilation, the steam injection owing to the phase change of the water in the purge system can deactivate the hydrogen mixture in the venting system effectively and significantly, therefore, makes the system free of risk of DDT in all rooms and free of risk of FA in all rooms except a local tiny volume containing an ignorable amount of hydrogen, as found in a specific simulation.

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