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Abstract

In a hypothetical core melt severe accident in nuclear power plants, a large amount of burnable gas, such as hydrogen and carbon monoxide, with certain amount of oxygen is released into the containment. In case of high containment pressure a filtered venting is designed as a mitigation measure. After aerosols and condensable portions of the gas mixture from the containment are purged, the remaining burnable gases flows into a chamber connected to horizontal venting pipes and further to a vertical stack, which is open to free atmosphere at the top. 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 dynamic computer simulations.

Based on the calculations with different boundary conditions for different scenarios, it is concluded that the venting system has no risk of flame acceleration and detonation if the power supply of the ventilation fans can be maintained. In case of station blackout, the whole system has no risk of detonation if the scrubber – purging water pool – can get boiling in 10 minutes, owing to the heating effect resulted from the latent heat of the condensable gases into the water pool. It is because the injected steam from the boiling scrubber inerts the mixture of hydrogen, carbon monoxide plus oxygen, effectively and significantly. In this case, a gas mixture only in a very local region in the stack, as small as about 0.16 cubic meter, is in a risk of flame acceleration. It is in principle ignorable owing to the tiny volume and thus only a small amount of hydrogen and carbon monoxide.

Kurzfassung

In einem hypothetischen, schweren kernzerstörenden Reaktorunfall können große Mengen an brennbaren Gasen, insbesondere Wasserstoff und Kohlenmonoxid, in das Schutz-Containment freigesetzt werden. Dadurch und durch das generelle Aufwärmen kann ein hoher Druck im Containment entstehen, welcher durch ein Abblasen über entsprechende Filter begrenzt werden kann. Nach dem Filtern in Nassabscheidern (Pool-Scrubber) und Metallfilterkassetten, welche die Aerosole und ggf. kondensierbare Anteile wie Wasserdampf der Containmentatmosphäre entziehen, verbleiben unter Umständen brennbare Gasmischungen, die in der betrachteten Anlage über ein Ventilationsraum und über horizontale Rohre in den vertikalen Abblasekamin geführt werden. Ziel der Untersuchungen ist es, die Reaktivität, Brennbarkeit, sowie Potenziale für Flammenbeschleunigung und Detonationsumschlag der Gasmischungen über der Zeit mit Hilfe von detaillierten 3d CFD Simulationen zu ermitteln.

Die Rechenergebnisse für unterschiedliche Szenarien und Randbedingungen zeigen, dass es keine Gefährdung hinsichtlich Flammenbeschleunigung oder Detonationsumschlag besteht, so lange die aktive Ventilierung im Betrieb bleibt. Beim Ausfall der Stromversorgung tritt im gesamten Abblasesystem ebenfalls keine Gefährdung durch Detonationsumschlag auf, falls der Nassabscheider innerhalb von 10 Minuten auf Siedetemperatur kommt. Der dann dort erzeugte Dampf wirkt ausreichend inertisierend auf die abzuführenden Wasserstoff-Kohlenmonoxid-Sauerstoff-Mischungen. In solch einem Fall würde jedoch kurzfristig in einem Gasvolumen von etwa 0,16 m3 ein Gefährdungspotenzial bezüglich Flammenbeschleunigung auftreten. Dies ist jedoch aufgrund des geringen beteiligten Inventars vernachlässigbar.

Contents

Introduction

A filtered venting system is designed for the nuclear containment of the Emsland Nuclear Power Plant (NPP). In accidental scenarios with a core melt down, a large amount of burnable gases, such as hydrogen and carbon monoxide, with certain amount of oxygen is released into the containment. In case of high containment pressure, the severe accident measure “filtered venting” is foreseen. The gas mixtures from the containment is guided through an inerted piping system. At the end of the filter system the gas mixture flows into the filter room, and from there through two horizontal ventilation pipes and a high vertical stack to the free atmosphere. A 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 apply the computational fluid dynamics (CFD) computer code - GASFLOW, to analyze the distribution of the H_2 and CO in the ventilation system, and to find how sensitive the mixture is to detonation in different scenarios.

This report is composed of the following contents: a brief introduction of the containment filtered venting system and its geometrical model and numerical mesh for the GASFLOW 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 four defined accidental scenarios, including cases with power supply to the ventilation fans or blackout, with or without steam injection into the filter room, with or without modeling of the silencer structure in the filter room.

1. GASFLOW geometrical model and numerical mesh

1.1 Containment venting system

In a Konvoi type of nuclear power plant like Emsland NPP, 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, CO, CO_2 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 will boil in about 10 minutes. Afterwards steam is released into the filter room, too. The schematic plot about the ventilation system is summarized in Figure 1.1.

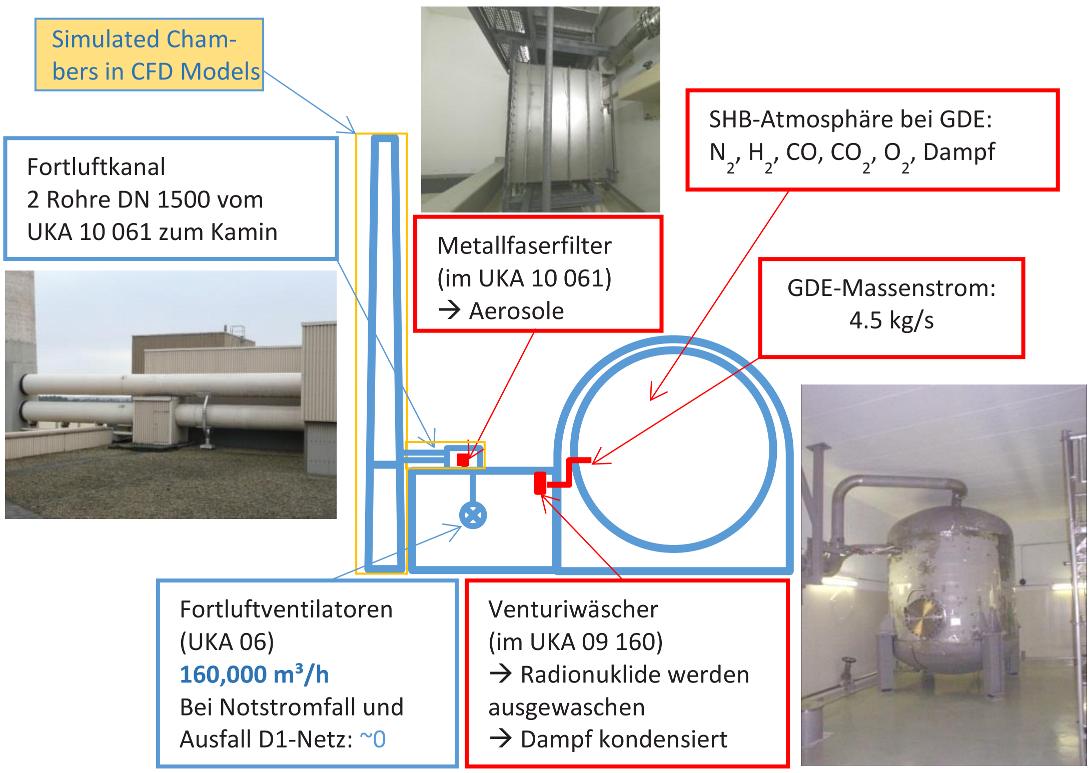

Figure 1.1 Containment filtered venting system

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 (B x T x H: 5.7 x 9.9 x 5.6 m^3) with internal structures, the two horizontally positioned ventilation pipes (about 30 m long and 1.5 m inner diameter each) and a stack with a height of about 163 m and a diameter of about 11 m on the ground level.

1.2 Source terms from MELCOR calculations

In order to conduct the CFD calculations, the injection source has to be specified as a boundary condition. According to the design of the filtered venting system, *the exhaust mass flow rate is 4.5 kg/s.*

Meanwhile, a lumped parameter computer code – MELCOR – has been applied to calculate the compositions of the exhaust gas mixture. The compositions in the mixtures are listed in Table 1.1, depending on different cases.

Table 1.1 Source terms obtained by MELCOR calculations

Reference code	H_2O [vol. %]	O_2 [vol. %]	N_2 [vol. %]	H_2 [vol. %]	CO [vol. %]	CO_2 [vol. %]
Q1[(1)]	76.03	0.39	14.13	3.87	3.72	1.86
Q2[(2)]	72.88	0.18	15.77	9.42	1.18	0.57

[(1)]Q1 – Case of station blackout scenario with fast pressurization of containment to 7 bar at 48 h
[(2)] Q2 – Case of a LOCA scenario with pressurization of containment to 7 bar at 88 h

For the case of Q2, the venting system (the ventilation fan) is assumed to be in operation. The flow rate of the ventilation air is 160,000 m^3/h in standard condition, i.e., *the ventilation air mass flow rate is 57.333 kg/s.*

1.3 Geometrical model and mesh

These extremely long or high chambers pose a big challenge to general CFD codes to model and to simulate. Fortunately, the GASFLOW code has a multi-block function, which enables the code to model the four connected chambers. According to such a multi-block function, the four chambers are modeled as three-dimensional (3D) domains, separately; the 3D domains are connected by a group of one-dimensional (1D) ducts in a way of cell-to-cell connection. Therefore the four separated domains are integrated by the 1D ducts.

Cartesian coordination system is chosen in GASFLOW modeling. The geometrical model and corresponding mesh information is presented in Figure 1.2 through Figure 1.4.

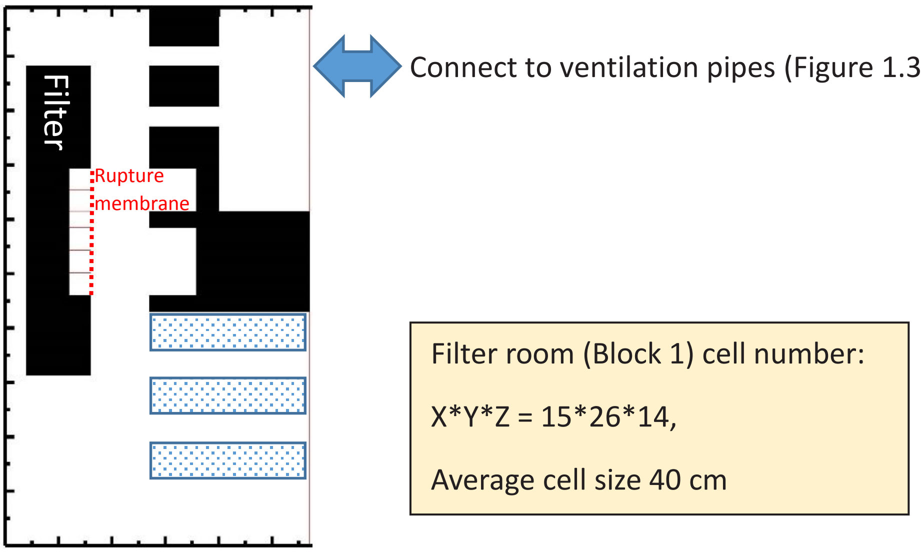

Figure 1.2 Geometrical model of filter room

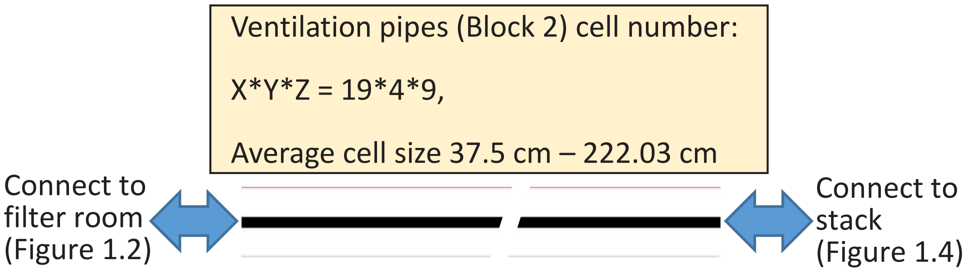

Figure 1.3 Geometrical model of ventilation pipes

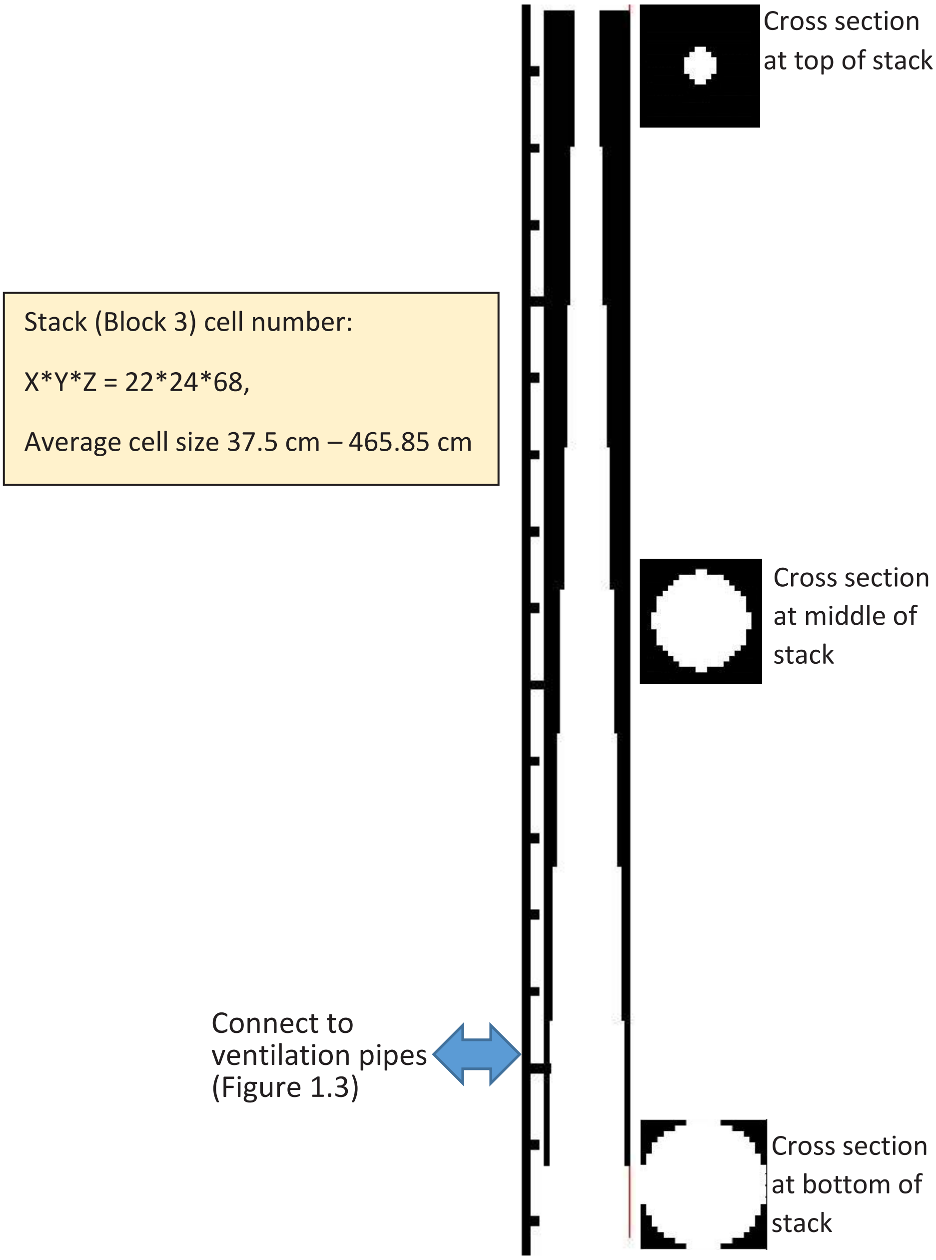

Figure 1.4 Geometrical model of stack

2. Theory of hydrogen risk criteria

2.1 Risk of flame acceleration – sigma criterion

The so-called “sigma cloud” means the hydrogen- oxygen mixture would potentially exhibit flame acceleration (FA) once being ignited. The “sigma” is a transformed expansion-ratio-related parameter; if it is bigger than unit, the mixture is in a risk of flame acceleration. The judgment is called sigma criterion. The sigma value is a function of the composition of the hydrogen mixture and its thermo-dynamic conditions, e.g., pressure and temperature.

2.2 Risk of detonation – lambda criterion

The prediction of deflagration to detonation transition (DDT) is still a challenging topic theoretically. Meanwhile DDT phenomena is somehow stochastic in laboratory for a given hydrogen mixture in a given control volume. A lambda criterion has been developed in KIT, 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. It says, the hydrogen mixture is in risk of detonation if the characteristic dimension of the confined volume, usually noted as D, is bigger than seven times of the detonation cell size, noted as 7*lambda, which depends on the property of the mixture, i.e., composition and thermo-dynamic condition.

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 modeling of the GASFLOW code.

3. 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.

To be conservative in GASFLOW simulations, as many rooms are defined as possible, to check the sensitivities of the gas mixtures.

At different stages of the work, three sets of room definitions have been defined at different times for different simulations.

3.1 Scheme of 13 rooms

Thirteen rooms are defined in the three blocks: the filter room without the silencer structures, the two horizontal pipes and the vertical stack. The explained scheme of room definitions in the following is used only in the case of running ventilation fan (reference number: Q2).

The definitions are listed as follows, and depicted in Figure 3.1.

Room 01: the whole gas volume of the filter room
Room 02: half of the filter room on the side of the ventilation grids (upstream)
Room 03: half of the filter room on the other side from the ventilation grids
Room 04: the small space close to the door in the middle of the filter room
Room 05: the narrow space behind the filter structures
Room 06: the corner formed by the filter walls and the filter room walls
Room 07: the volume between the rupture membrane and the facing wall structure of the room
Room 08: the source volume in GASFLOW model (it can be ignorable)
Room 09: the horizontally positioned pipe on the lower side
Room 10: the horizontally positioned pipe on the upper side

Room 11: the volume in the stack below the height of the connection between the upper ventilation pipe and the stack

Room 12: the volume in the stack above the height of the connection between the upper ventilation pipe and the stack

Room 13: the whole space in the stack

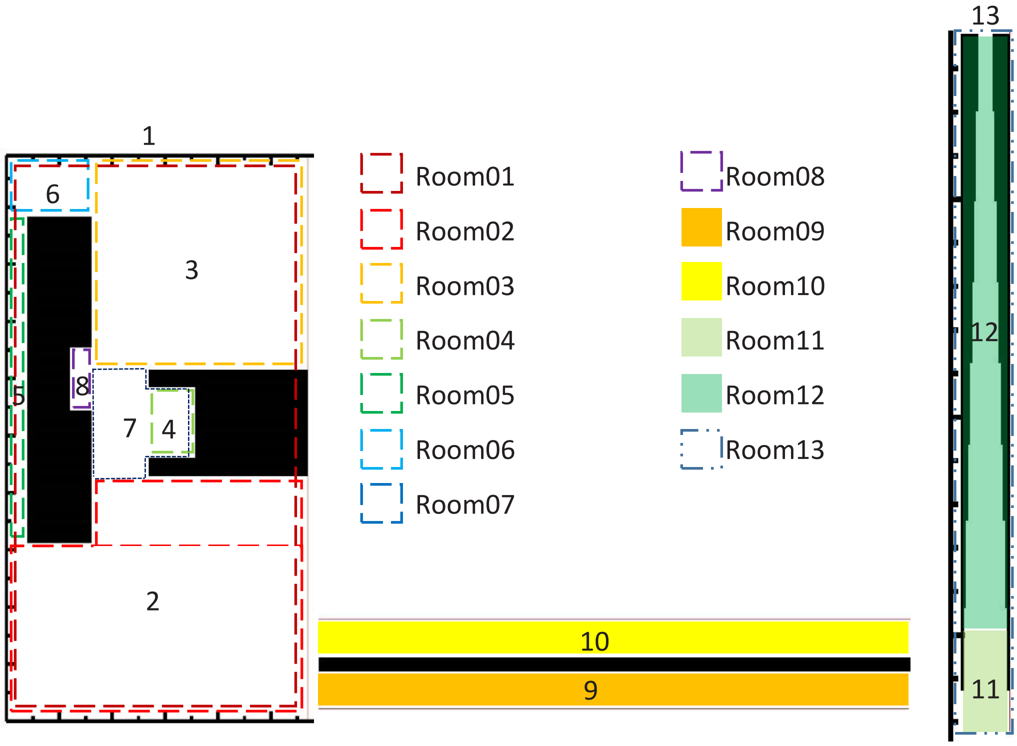

Figure 3.1 Scheme of 13 rooms: room definitions

3.2 Scheme of 43 rooms

Forty three rooms are defined in the three blocks, without modeling the silencers in the filter room. The scheme of room definitions is used in the case of blackout (reference number: Q1), without considering the silencers.

The definitions are listed as follows, and depicted in Figure 3.2.

Room 01: the whole gas volume of the filter room

Room 02- 04: fractional volumes of Room 01 divided vertically, at the bottom, in the middle and at the top, respectively

Room 05: half of the filter room on the side of the ventilation grids

Room 06- 08: fractional volumes of Room 05 divided vertically, at the bottom, in the middle and at the top, respectively

Room 09: half of the filter room on the side of the ventilation pipes

Room 10-12:	fractional volumes of Room 09 divided vertically, at the bottom, in the middle and at the top, respectively
Room 13:	the small space close to the entrance in the middle of the filter room
Room 14-16:	fractional volumes of Room 13 divided vertically, at the bottom, in the middle and at the top, respectively
Room 17- 19:	fractional volumes behind the filter structure on the side of ventilation grids, divided vertically, at the bottom, in the middle and at the top, respectively
Room 20- 22:	fractional volumes behind the filter structure at the middle position, divided vertically, at the bottom, in the middle and at the top, respectively
Room 23- 25:	fractional volumes behind the filter structure on the side of ventilation pipes, divided vertically, at the bottom, in the middle and at the top, respectively
Room 26-28:	fractional volumes of the corner between the filter structure and the filter room walls, divided vertically, at the bottom, in the middle and at the top, respectively
Room 29-31:	fractional volumes between the rupture membrane and the entrance of the room, divided vertically, at the bottom, in the middle and at the top, respectively
Room 32-34:	fractional volumes in the lower ventilation pipe, at the side of filter room, in the middle, at the side of stack, respectively
Room 35-37:	fractional volumes in the upper ventilation pipe, at the side of filter room, in the middle, at the side of stack, respectively
Room 38:	fractional volume in the stack, on the bottom
Room 39:	fractional volume in the stack, right above the connection between the upper ventilation pipe and the stack
Room 40- 42:	fractional volumes in the stack between Room 39 and the exit of the stack, distributed vertically and uniformly
Room 43:	fractional volume right before the exit of the stack

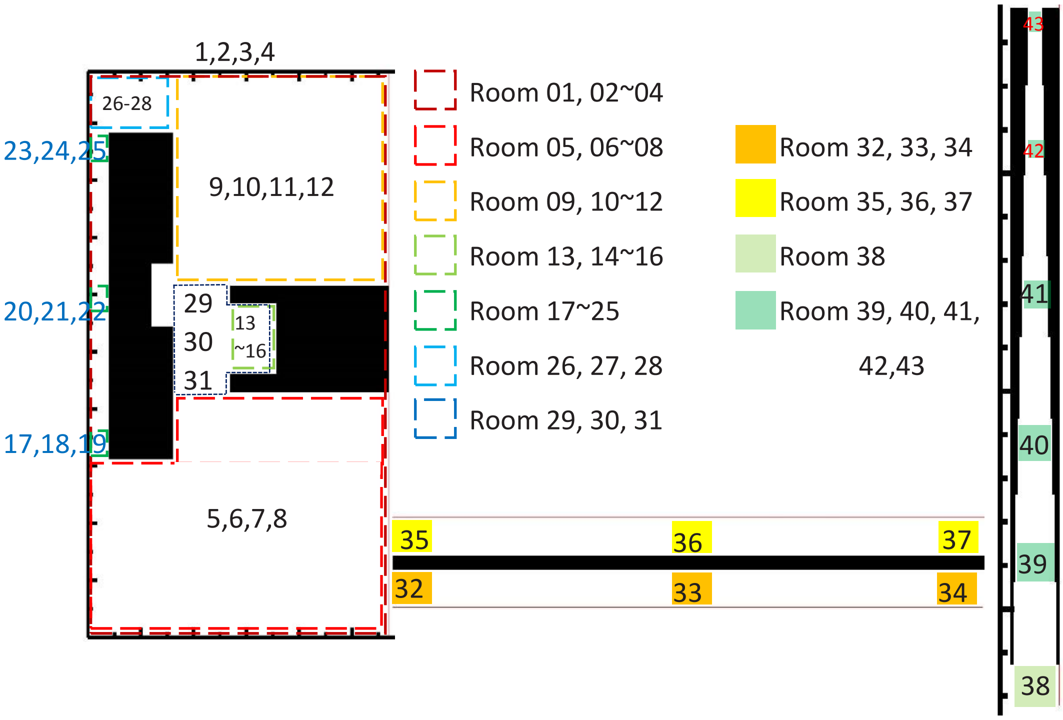

Figure 3.2 Scheme of 43 rooms: room definitions

3.3 Scheme of 46 rooms

Forty six rooms are defined in the three blocks, with modeling the silencers in the filter room. The scheme of room definitions is used in the case of blackout (reference number: Q1), with modeling the silencers.

The definitions are listed as follows, and depicted in Figure 3.3.

Room 01:	the whole gas volume of the filter room
Room 02-04:	fractional volumes of Room 01 divided vertically, at the bottom, in the middle and at the top, respectively
Room 05:	half of the filter room on the side of the ventilation grids
Room 06-08:	fractional volumes of Room 05 divided vertically, at the bottom, in the middle and at the top, respectively
Room 09:	a part of the filter room between silencers and the wall on the side of the ventilation pipes
Room 10-12:	fractional volumes of Room 09 divided vertically, at the bottom, in the middle and at the top, respectively
Room 13:	the small space close to the entrance in the middle of the filter room
Room 14-16:	fractional volumes of Room 13 divided vertically, at the bottom, in the middle and at the top, respectively

Room 17-19: fractional volumes behind the filter structure on the side of ventilation grids, divided vertically, at the bottom, in the middle and at the top, respectively

Room 20-22: fractional volumes behind the filter structure at the middle position, divided vertically, at the bottom, in the middle and at the top, respectively

Room 23-25: fractional volumes behind the filter structure on the side of ventilation pipes, divided vertically, at the bottom, in the middle and at the top, respectively

Room 26-28: fractional volumes of the corner between the filter structure and the filter room walls, divided vertically, at the bottom, in the middle and at the top, respectively

Room 29- 31: fractional volumes between the rupture membrane and the entrance of the room, divided vertically, at the bottom, in the middle and at the top, respectively

Room 32-34: fractional volumes in the lower ventilation pipe, at the side of filter room, in the middle, at the side of stack, respectively

Room 35-37: fractional volumes in the upper ventilation pipe, at the side of filter room, in the middle, at the side of stack, respectively

Room 38: fractional volume in the stack, on the bottom

Room 39: fractional volume in the stack, right above the connection between the upper ventilation pipe and the stack

Room 40-42: fractional volumes in the stack between Room 39 and the exit of the stack, distributed vertically and uniformly

Room 43: fractional volume right before the exit of the stack

Room 44-46: fractional volumes in between two of the silencers, divided vertically, at the bottom, in the middle and at the top, respectively

Figure 3.3 Scheme of 46 rooms: room definitions

4. Common considerations

4.1 Initial condition

In all simulations, all the three blocks and the connecting 1D ducts are initially filled with air at 1 atm. pressure and 293.15 K of temperature, namely, 1.013 bar and 20°C, at t = 0 s.

4.2 Model configurations

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

4.3 Treatment of component carbon monoxide

According to the input information supplied by the plant operator, the composition of the containment exhaust include both hydrogen and CO. Like hydrogen, CO is flammable and detonable, too. Unfortunately the component of CO is NOT considered while making judgments about flame acceleration risk (sigma criterion) and detonation risk (lambda criterion) in the current GASFLOW code. It can predict only the distribution of CO and the risk of CO is excluded if no any special treatment.

To solve the problem while both H_2 and CO are in the mixture, a compromise way is proposed that the fraction of CO in the source can be replaced by an additional hydrogen fraction. This is a conservative assumption, because hydrogen is more diffusive, owing to a smaller molecular weight, and more sensitive to burn and to detonate, than CO.

The component CO in the exhaust is replaced by hydrogen in an equivalent way that the extra volume fraction of hydrogen is assumed to be the same as that of the CO in the source. It means the substituting extra hydrogen has the same molar number as the CO, instead of the same mass.

Therefore, in the following discussion, the fraction of CO is always zero, and the hydrogen fraction is always corrected, by adding the extra fraction compensated by the substituted CO component in a sense of equal molar number.

5. Simulation results

Four cases are simulated and are summarized in Table 5.1.

Table 5.1 Summary of simulated cases

<table>
<tr><th rowspan="3"></th><th rowspan="3">Q2

• With ventilation
• No steam injection
• No silencer model</th><th colspan="3">Q1 (blackout, no ventilation)</th></tr>
<tr><th rowspan="2">• No steam
• No silencer model</th><th colspan="2">With steam injection</th></tr>
<tr><th>No silencer model</th><th>With silencer model</th></tr>
<tr><td>Case</td><td>Case 1</td><td>Case 2</td><td>Case 3</td><td>Case 4</td></tr>
</table>

Case 1: The ventilation fan is functioning. There is no steam injection in the source from the filter room. The silencer structures are not modeled.

Case 2: The ventilation fan does not run in case of the whole station blackout. There is no steam injection in the source from the filter room. The silencer structures are not modeled.

Case 3: The ventilation fan does not run in case of the whole station blackout. Steam injection starts in 10 minutes. The silencer structures are not modeled.

Case 4: The ventilation fan does not run in case of the whole station blackout. Steam injection starts in 10 minutes. The silencer structures are modeled.

5.1 Simulation results of Case 1 (with ventilation)

5.1.1 Boundary conditions

The injection source, the venting condition and the outflow boundary are defined as follows.

- Exhaust mass flow rate: 1209.725 g/s @ 1.2 bar and 20 °C
- Molar fraction of components in the exhaust:
  N_2: 0.58149, O_2: 0.006637, H_2: 0.390855, CO: 0.0, CO_2: 0.021018, no steam
- Correspondingly, the mass fraction of the components are,
  N_2: 0.89457, O_2: 0.011669, H_2: 0.04295, CO: 0.0, CO_2: 0.050811, no steam
- Ventilation air mass flow rate: 57333 g/s, air @ 1 atm. and 20 °C
- Outflow boundary condition at the exit of the stack:
  P = 0.98 atm. and T = 19 °C
- Horizontal wind speed at the exit of the stack: V=1 m/s

5.1.2 Simulation results

Computation indicates that no sigma cloud appears in the whole domain in Case 1. Hence there is no risk of flame acceleration. Neither is there a risk of detonation in any room. It proofs that the ventilation is very effective to avoid accumulation of hydrogen plus oxygen. The only plot shown here is the hydrogen mass in each room as a function of time. According to the plot, the flow field is developing till a steady state. The over-all H_2 mass in the stack is about 6.5 kg. However, owing to being highly diluted, it does not pose a risk of detonation.

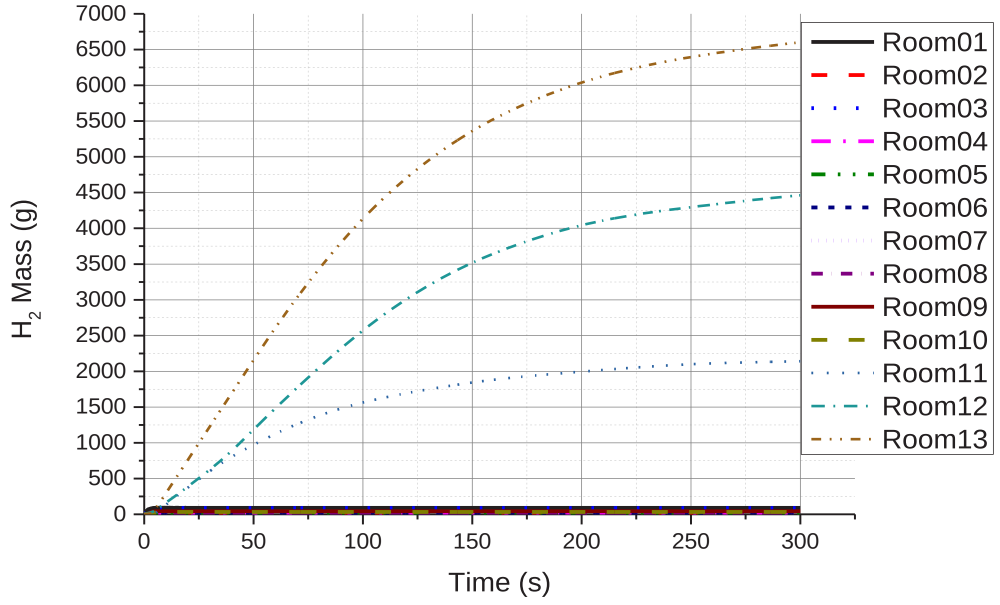

Figure 5.1.1 Hydrogen mass in rooms in Case 1 (Q2)

5.2 Simulation results of Case 2 (blackout, no steam injection)

Totally 7200 s of physical time has been simulated in this case.

5.2.1 Boundary conditions

The injection source, the venting condition and the outflow boundary are defined as follows.

- Exhaust mass flow rate: 1153.645 g/s @ 1.2 bar and 20°C
- Molar fraction of components in the exhaust:
  N_2: 0.58949, O_2: 0.01627, H_2: 0.31664, CO: 0.0, CO_2: 0.0776,
  no steam
- Correspondingly, the mass fraction of the components are,
  N_2: 0.783225, O_2: 0.024705, H_2: 0.03005, CO: 0.0, CO_2: 0.162019,
  no steam
- Ventilation air mass flow rate: 0 g/s
- Outflow boundary condition at the exit of the stack:
  P = 0.98 atm. and T = 19 °C
- Horizontal wind speed at the exit of the stack: V=1 m/s

5.2.2 Simulation results

For every gas mixture contained in all the defined rooms, the sigma value and the ratio of characteristic dimension of the room (D) to seven times detonation cell size (7*lambda) are shown in Figure 5.2.1 and Figure 5.2.2, respectively.

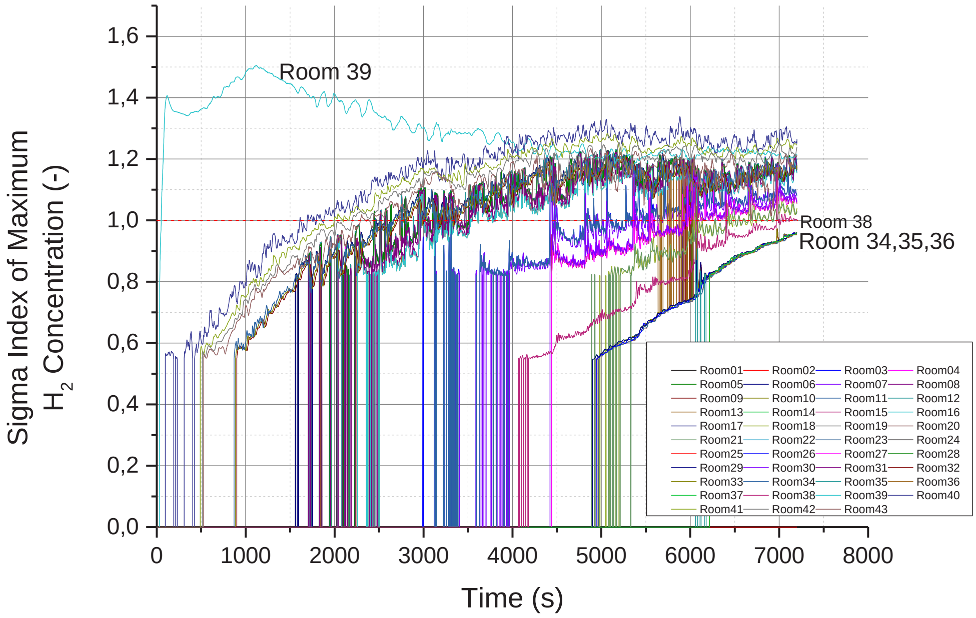

Figure 5.2.1 Sigma index of maximum H2 concentration in rooms in Case 2 (Q1, no steam, no silencer)

Figure 5.2.1 indicates that the gas mixtures in most defined rooms meet the sigma criterion, hence there is a risk of flame acceleration. Deflagration could in principle generate also destructive shock waves. Only in some local regions in the ventilation pipes (Room 34, 35, 36) the gas mixture is not in the regime of deflagration.

The figure also shows that in the Room 39, a fractional room in the stack right above the connection between the upper ventilation pipe and the stack, the mixture reaches the deflagration regime from the very beginning. Nevertheless in most rooms, the mixtures becomes risky of deflagration sooner or later between 1500 s and 3500 s. The bottom of the stack (Room 38) becomes sensitive at a very late time, about 7000 s. It is because major part of hydrogen is transported by convection upwards owing to buoyance.

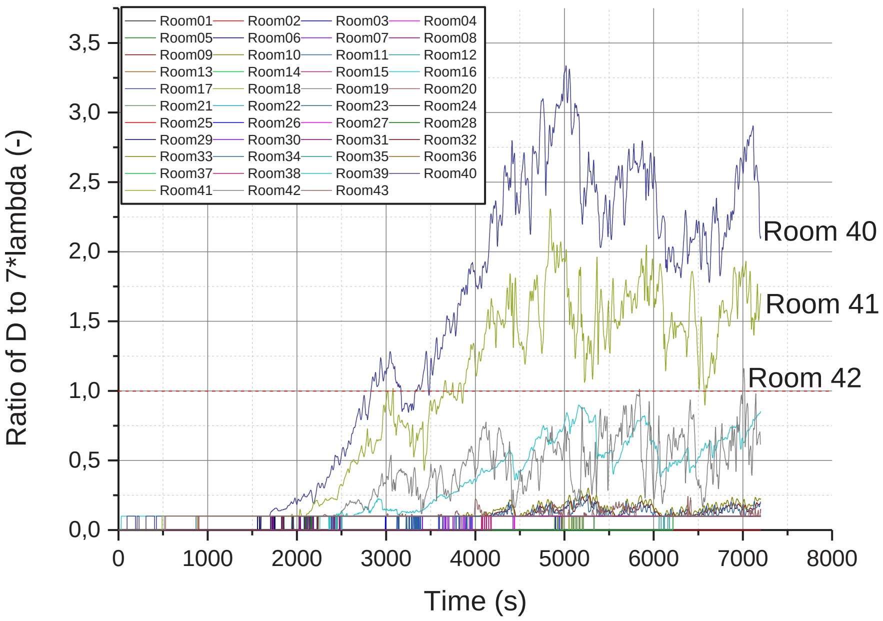

Figure 5.2.2 Ratio of D to 7*lambda in rooms in Case 2 (Q1, no steam, no silencer)

Figure 5.2.2 tells that the mixtures in the fractional volumes of the stack (Room 40, 41, 42) satisfy the lambda criterion after about 50 minutes, i.e., the ratio of the characteristic dimension, D, over 7 times detonation cell size, 7*lambda, is bigger than one, in those rooms. Namely, the hydrogen clouds in the rooms are in risk of detonation.

Only for information, the average hydrogen volume fractions in different rooms are shown in Figure 5.2.3. It indicates that all the clouds are flammable in all rooms. The hydrogen volume fraction ranges 4% up to 15%.

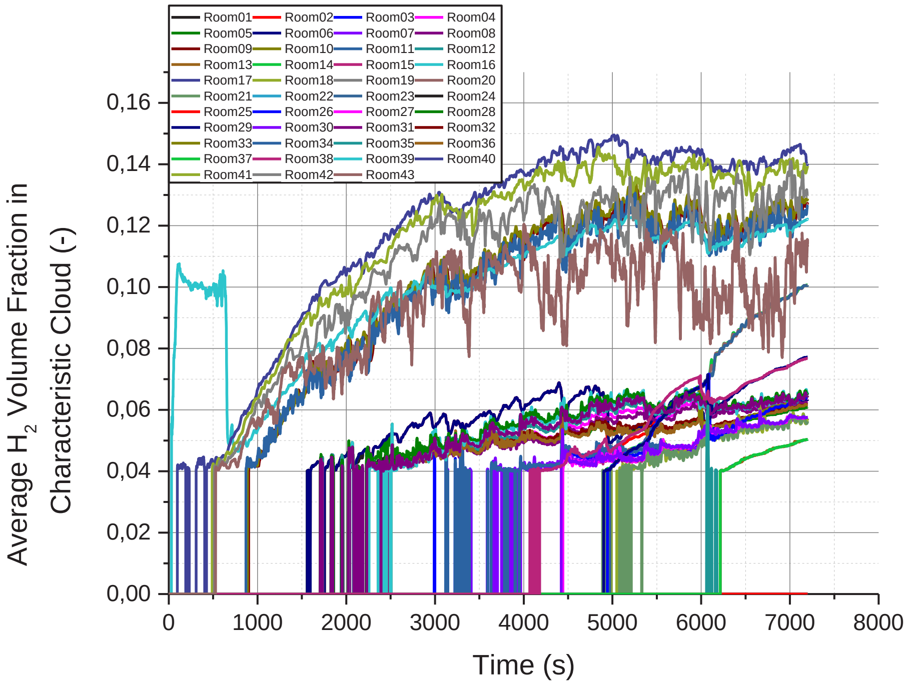

Figure 5.2.3 Average hydrogen volume fractions in rooms in Case 2 (Q1, no steam, no silencer)

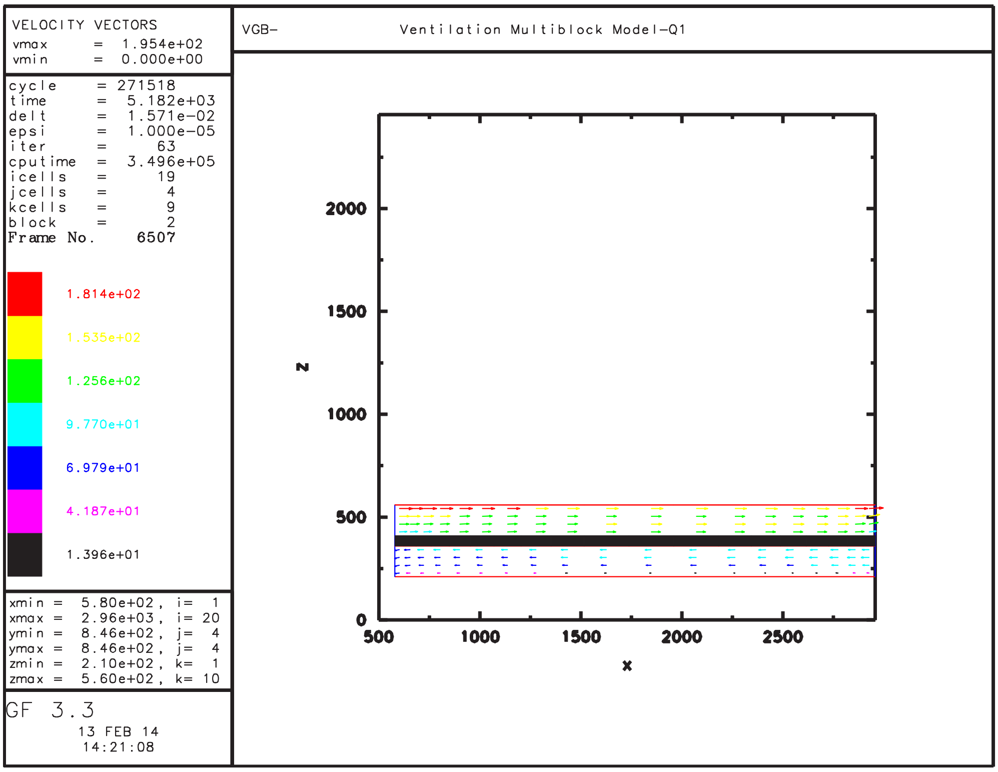

Figure 5.2.4 Flow direction in ventilation pipes

It is very interesting that, at about 40 s, a change of the flow direction in the lower ventilation pipe occurs. After 40 s, the flow direction has been changed from the stack backwards to the filter room, which is opposite to the major flow direction in the upper pipe, from the filter room towards the stack. Figure 5.2.4 shows a typical flow pattern in the two pipes at a time of 5182 s, which indicates the average velocity in the upper pipe, about 1.6 m/s, is two times faster than that in the lower pipe, about 0.8 m/s. The simulation predicts a minor circulation flow in between the two pipes connected at the filter room and the stack.

Summary: In the blackout scenario without steam release, hydrogen deflagration could occur in all chambers of the filter room and the stack. The mixture in the stack is even in a high risk of detonation.

5.3 Simulation results of Case 3 (blackout, with steam injection)

5.3.1 Boundary conditions

The injection source, the venting condition and the outflow boundaries are defined as follows.

t = 0 s – 600 s

- Exhaust mass flow rate: 1153.645 g/s @ 1.2 bar and 20°C
- Molar fraction of components in the exhaust:
  N_2: 0.58949, O_2: 0.01627, H_2: 0.31664, CO: 0.0, CO_2: 0.0776,
  no steam
- Correspondingly, the mass fraction of the components are,
  N_2: 0.783225, O_2: 0.024705, H_2: 0.03005, CO: 0.0, CO_2: 0.162019,
  no steam

t = 600 s – forever

- Exhaust mass flow rate: 3966.564 g/s @ 1.2 bar and 20°C
- Molar fraction of components in the exhaust:
  N_2: 0.152924, O_2: 0.004224, H_2: 0.082145, H_2O: 0.740577 CO: 0.0, CO_2: 0.02013
- Correspondingly, the mass fraction of the components are,
  N_2: 0.22779, O_2: 0.00719, H_2: 0.00874, H_2O: 0.70916 CO: 0.0, CO_2: 0.04712

t = 0 s – forever

- Ventilation air mass flow rate: 0 g/s
- Outflow boundary condition at the exit of the stack:
  P = 0.98 atm. and T = 19 °C
- Horizontal wind speed at the exit of the stack: V=1 m/s

5.3.2 Simulation results

The sigma indices in all rooms are shown in Figure 5.3.1. It shows the sigma indexes in all rooms but Room 39 are less than one. It means the hydrogen mixtures in most rooms are not sensitive to deflagration. Only in Room 39, the fractional volume in the stack adjacent to the connection to the upper ventilation pipe, the gas mixture is in the regime of deflagration during 52 s – 604 s. In other words, the Room 39 is in a risk of deflagration approximately in the first 10 minutes, i.e., before steam starts to be exhausted.

Meanwhile, the ratios of characteristic dimension over 7 times detonation cell size are shown in Figure 5.3.2. It shows the ratios are all less than one, actually, not greater than 0.1. It means the mixtures in all rooms are not sensitive to detonation.

Summary:

- Only Room 39, the second bottom part of the stack, is in danger of flame acceleration, and only during 52 s - 604 s.
- All rooms have no risk of DDT.
- Steam can dilute the mixture effectively. The dilution can reduce the mixture sensitivity significantly.

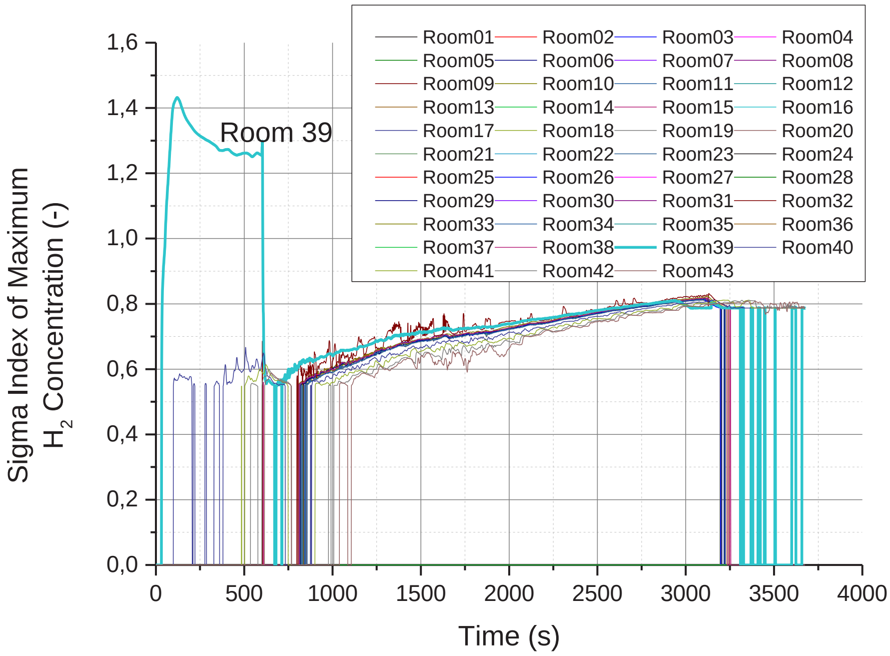

Figure 5.3.1 Sigma index of maximum H_2 concentration in rooms in Case 3 (Q1, with steam, no silencer)

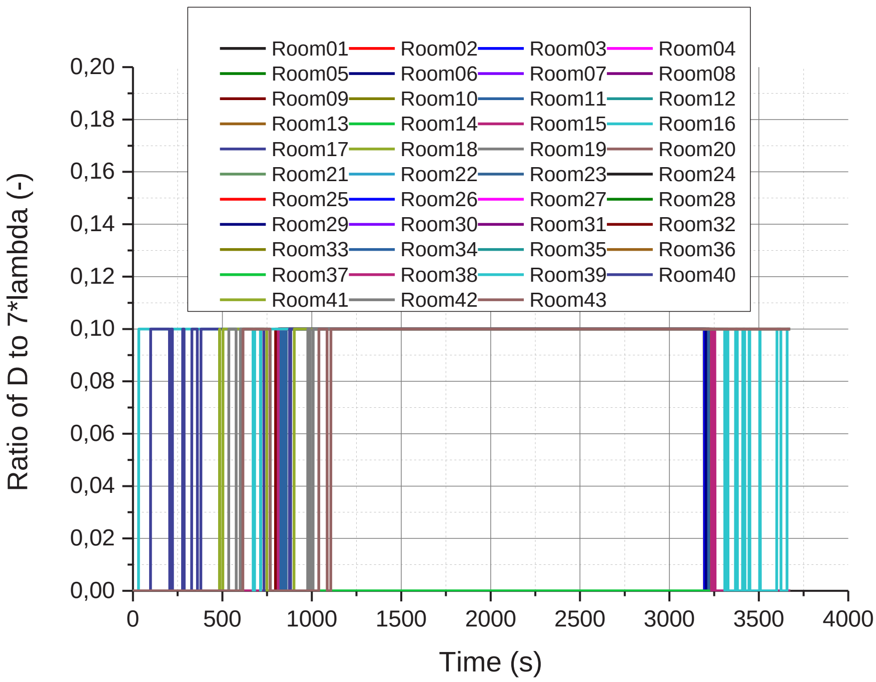

Figure 5.3.2 Ratio of D to 7*lambda in rooms in Case 3 (Q1, with steam, no silencer)

5.4 Simulation results of Case 4 (blackout, with steam injection, with silencers)

Remark: The boundary condition of Case 4 is identical to that of case 3. The only difference between Case 4 and Case 3 is that the silencers in the filter room is modeled in Case 4.

5.4.1 Boundary conditions

t = 0 s – 600 s

- Exhaust mass flow rate: 1153.645 g/s @ 1.2 bar and 20°C
- Molar fraction of components in the exhaust:
  N_2: 0.58949, O_2: 0.01627, H_2: 0.31664, CO: 0.0, CO_2: 0.0776,
  no steam
- Correspondingly, the mass fraction of the components are,
  N_2: 0.783225, O_2: 0.024705, H_2: 0.03005, CO: 0.0, CO_2: 0.162019,
  no steam

t = 600 s – forever

- Exhaust mass flow rate: 3966.564 g/s @ 1.2 bar and 20°C
- Molar fraction of components in the exhaust:
  N_2: 0.152924, O_2: 0.004224, H_2: 0.082145, H_2O: 0.740577 CO: 0.0, CO_2: 0.02013
- Correspondingly, the mass fraction of the components are,
  N_2: 0.22779, O_2: 0.00719, H_2: 0.00874, H_2O: 0.70916 CO: 0.0, CO_2: 0.04712

t = 0 s – forever

- Ventilation air mass flow rate: 0 g/s
- Outflow boundary condition at the exit of the stack:
  P = 0.98 atm. and T = 19 °C
- Horizontal wind speed at the exit of the stack: V=1 m/s

5.4.2 Simulation results

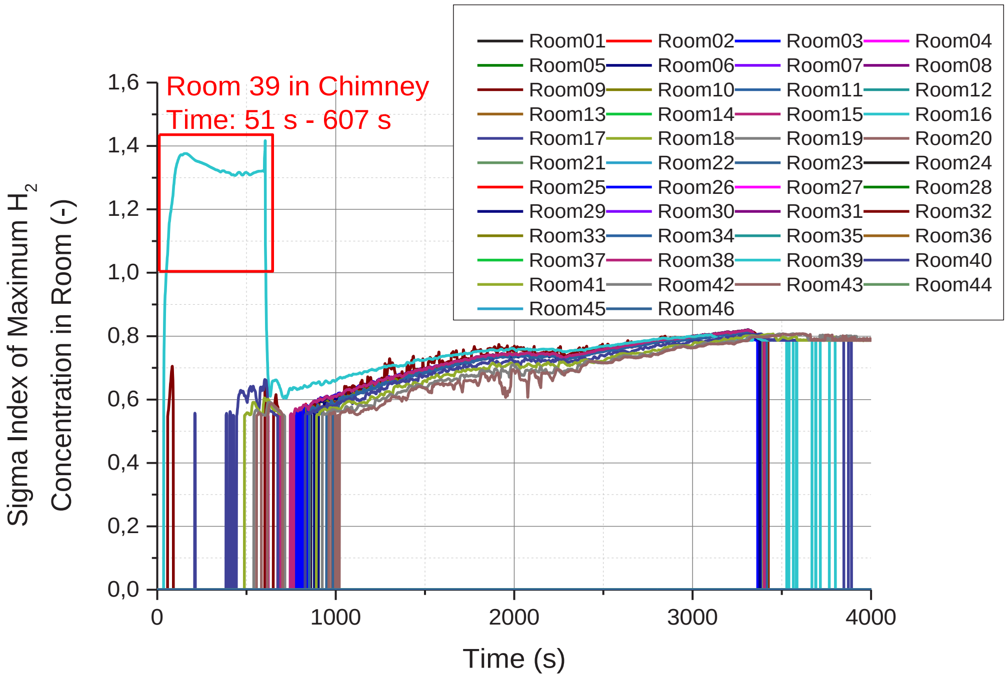

Figure 5.4.1 Sigma index of maximum H_2 concentration in rooms in Case 4 (Q1, with steam, with silencer)

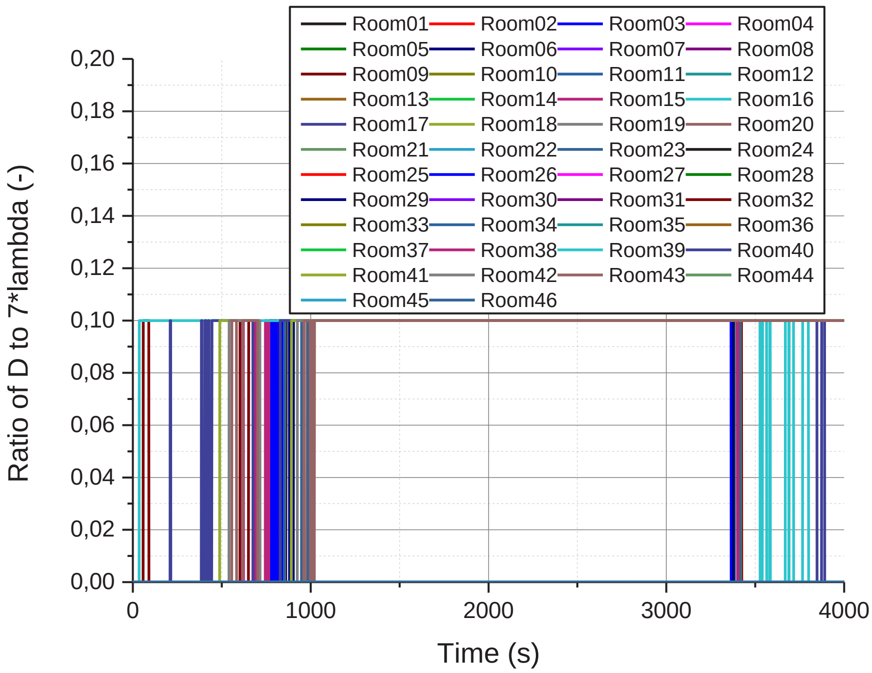

Figure 5.4.2 Ratio of D to 7*lambda in rooms in Case 4 (Q1, with steam, with silencer)

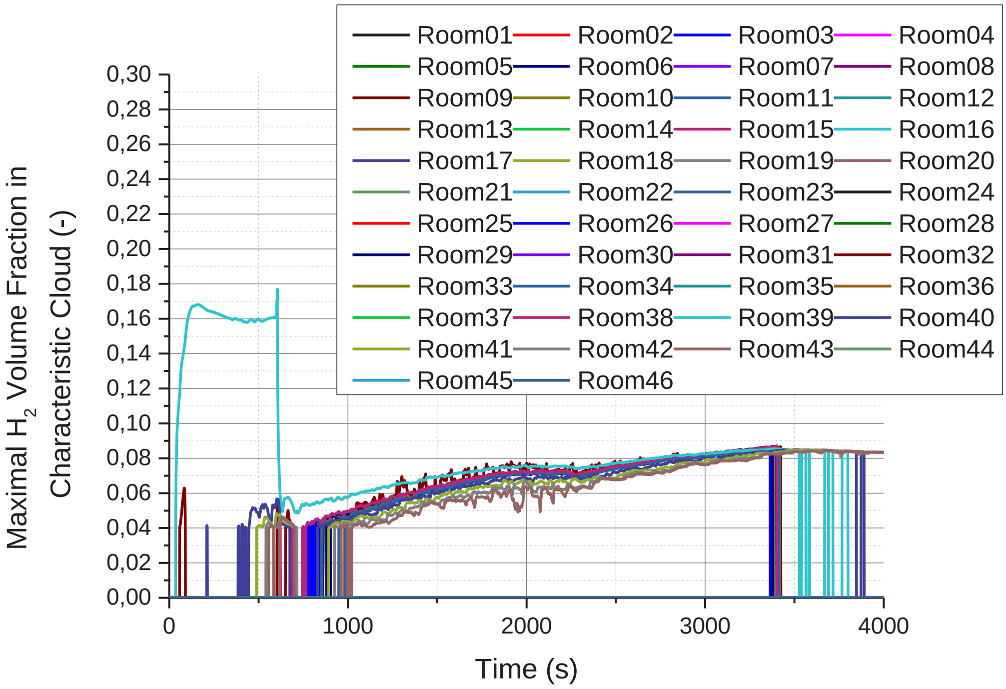

Figure 5.4.3 Maximum H_2 volume fractions in rooms in Case 4 (Q1, with steam, with silencer)

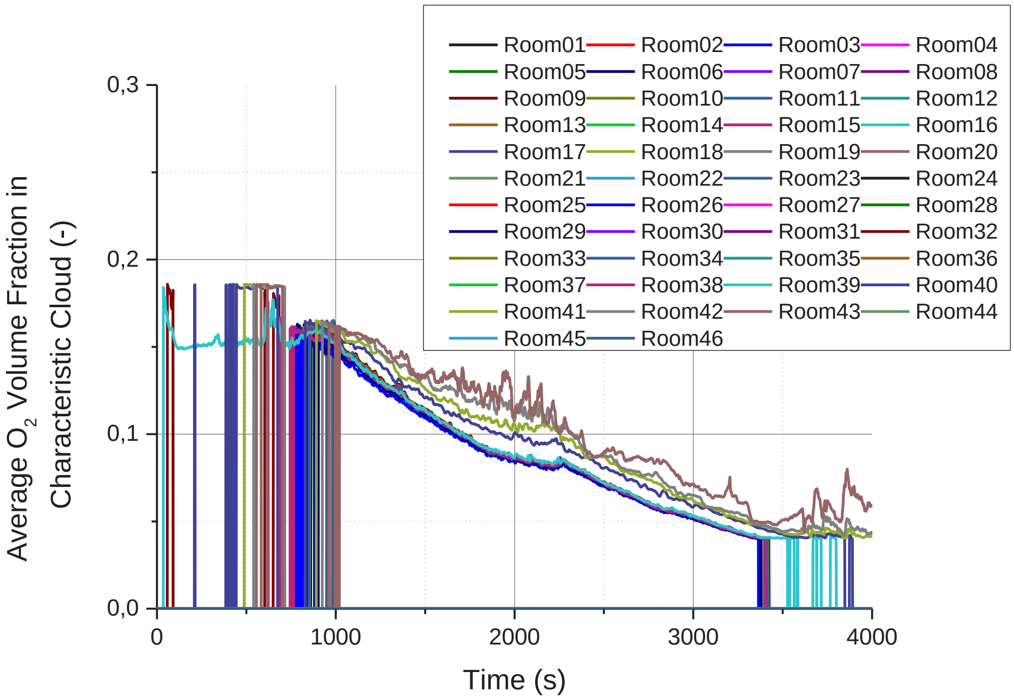

Figure 5.4.4 Average O_2 volume fractions in rooms in Case 4 (Q1, with steam, with silencer)

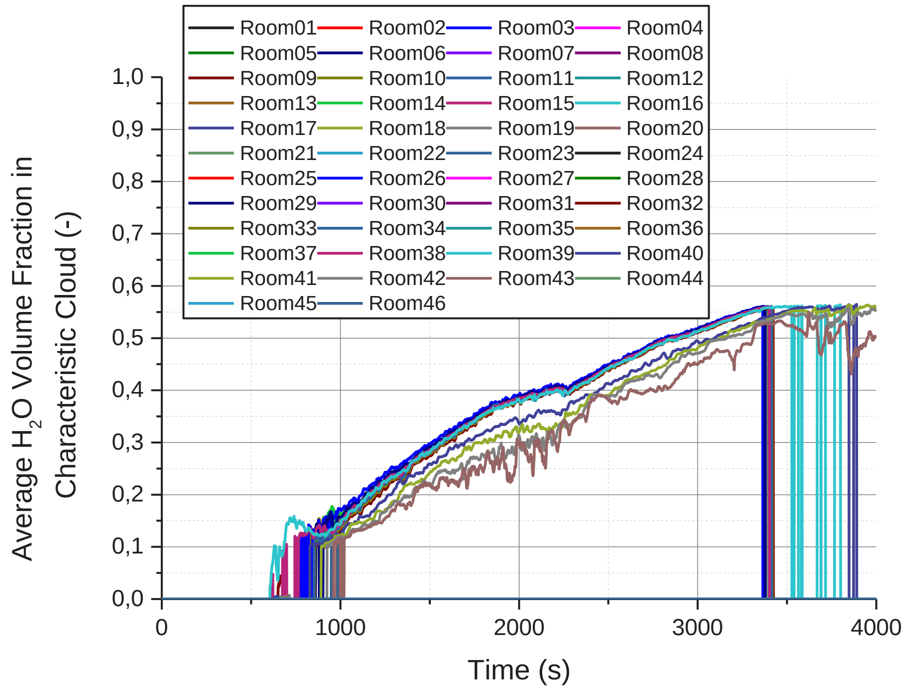

Figure 5.4.5 Average steam volume fractions in rooms in Case 4 (Q1, with steam, with silencer)

Figure 5.4.1 shows that all rooms have no risk of flame acceleration, except for Room 39, the second bottom part of the stack, is in danger of flame acceleration, and only during 51 s - 607 s. The observation is quite similar to that in Case 3 without the silencer model.

Figure 5.4.2 indicates that all defined rooms have no risk of DDT. The conclusion is the same as that in Case 3 without the silencer model.

The above two results manifest that the silencer structure does not affect in principle the chemical sensitivities of the burnable mixture in the system. This result is plausible because the structure changes mainly the flow fields in the filter room with more turbulence in the gas flow as a side product.

Figure 5.4.3 shows the maximum H_2 volume fractions in the rooms. According to the figure, the H_2 volume fraction is no more than 8% in most rooms except Room 39, where the H_2 volume fraction is over 16% during 51 s - 607 s. This is the direct reason leading the mixture sensitive to fast combustion, as shown in Figure 5.4.1.

Figure 5.4.4 presents the average O_2 volume fractions in the rooms. The figure tells that, as time goes by, the initially resident oxygen in the system is evacuated gradually by the exhaust injection. The volume fraction becomes from initial value of 15 - 18% to a final value of about 5 - 8% at about 3300 s. At this time stage the mixture is in an oxygen starving state.

Figure 5.4.5 records the average steam volume fractions in the rooms. Initially there is no steam in the system. About 10 minutes later, steam injection starts and certainly the steam fraction in the rooms start to increase. At about 3300 s, the steam repository in the system gets steady and the average steam volume fraction reaches about 55%, which becomes the dominant component in the mixture. The great amount of steam injection is the direct reason to make the sensitive hydrogen mixture inert.

It can be concluded that steam can dilute the mixture effectively. The dilution can reduce the mixture sensitivity significantly.

5.5 Gas distribution analysis in Room 39 in Case 4

Based on the simulation in Case 4 formulated in the last section, the only risk in the system is in Room 39 during the time window of 51 s – 607 s.

5.5.1 Definition of Room 39

Room 39 is a compartment in the stack, connecting to the ventilation pipes, by referring to Figure 3.3. If the ground level of the stack is counted as 0 m, then Room 39 is the fractional volume of the stack between the heights of 23.95 m – 29.18 m.

In the GASFLOW model, Room 39 is located in the third block, and is bounded in the following mesh number:

- in X- direction, between mesh I = 02 and I = 22;
- in Y- direction, between mesh J = 02 and J = 24; and,
- in Z- direction, between mesh K = 09 and K= 24, respectively.

K = 09 is corresponding to the height of 23.95 m, and K = 24 to 29.18 m. A horizontal cut of Room 39 at K = 16 is shown in Figure 5.5.1.

As shown in Figure 5.5.1, the opening at the west side (left-hand side) is connected to the ventilation pipe.

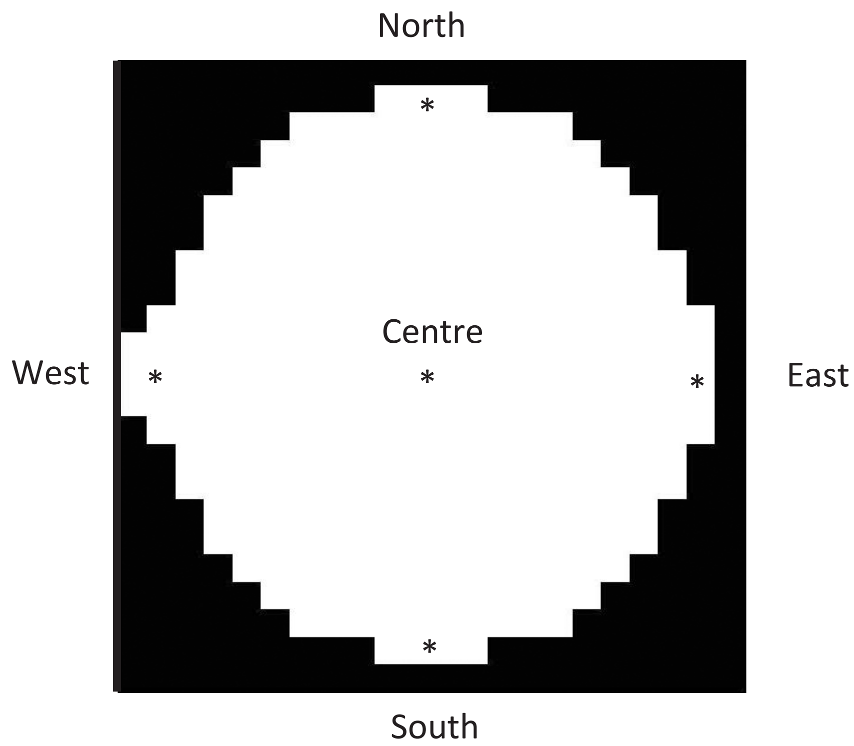

Figure 5.5.1 Horizontal cross section of Room 39 at K =16

5.5.2 Simulation results

The simulation was rerun from the time of 0 s to 607 s. The detailed gas species distributions in the region are recoded intensively.

At each corner/ location (west, east, north, south and center) in Room 39, as shown in Figure 5.5.1, the time histories of species volume fraction are recorded at bottom (K = 09) and at top (K =24), respectively. The time history plots about H_2, O_2 and H_2O volume fractions are shown in Figure 5.5.2, Figure 5.5.3 and Figure 5.5.4, respectively.

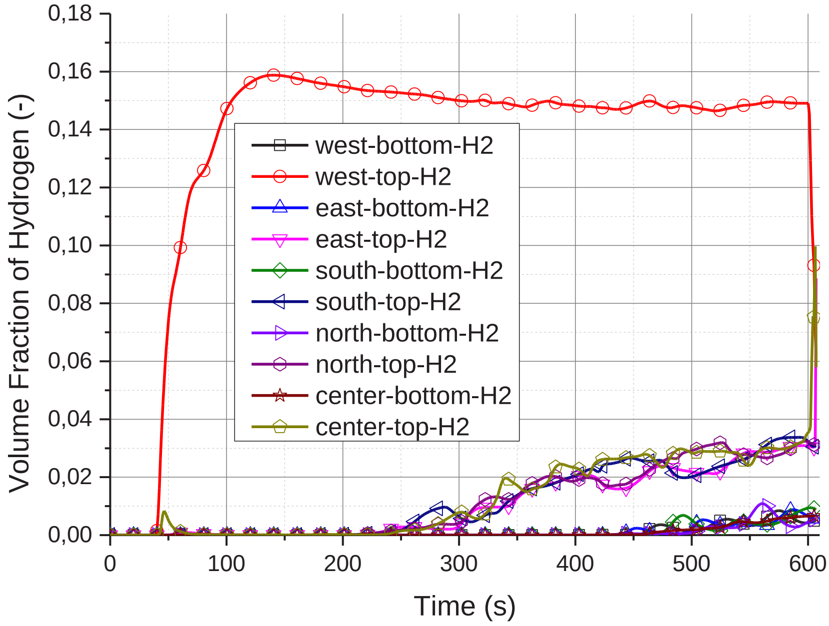

Figure 5.5.2 Volume fraction time history of H_2 in Room 39

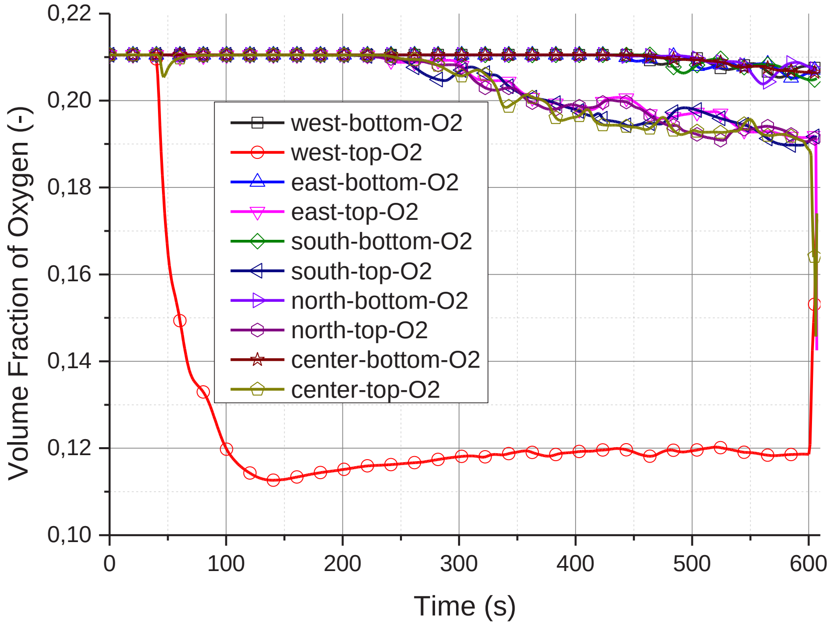

Figure 5.5.3 Volume fraction time history of O_2 in Room 39

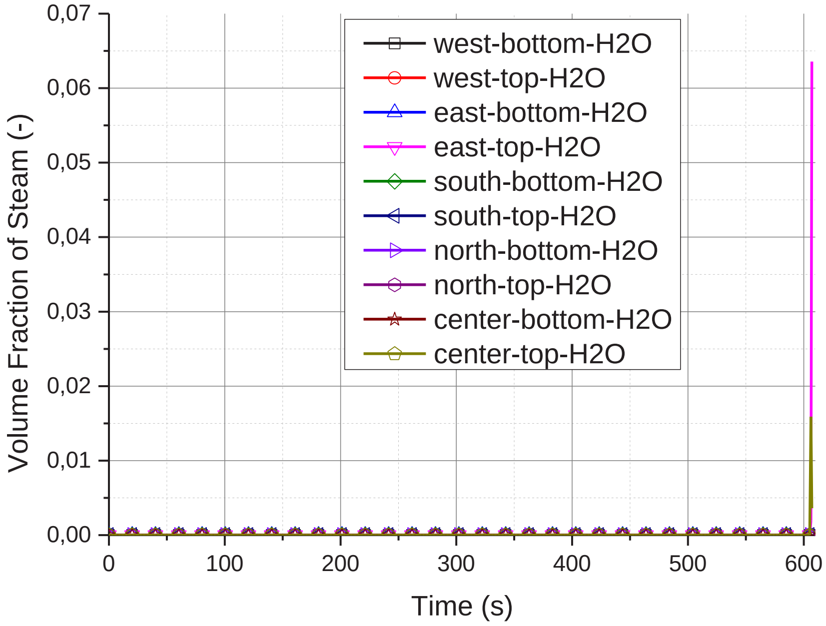

Figure 5.5.4 Volume fraction time history of H_2O in Room 39

Figure 5.5.2 shows that, the high hydrogen concentration appears at **the top corner of western side of Room 39**, with a fraction of 15%. Figure 5.5.3 indicates that the oxygen fraction at the same corner is about 11 - 12%. Figure 5.5.4 manifests there is little influence of steam to the gas mixture in almost the whole time window.

The contour plots about species volume fraction in horizontal cuts at top (K = 24) at different times, 185 s, 365 s and 607 s, are shown in Figure 5.5.5 through Figure 5.5.7, respectively. The corresponding contour plots at lower heights (bottom K = 09 and middle K = 16) are not shown here, because they show lower concentration of hydrogen than that at top.

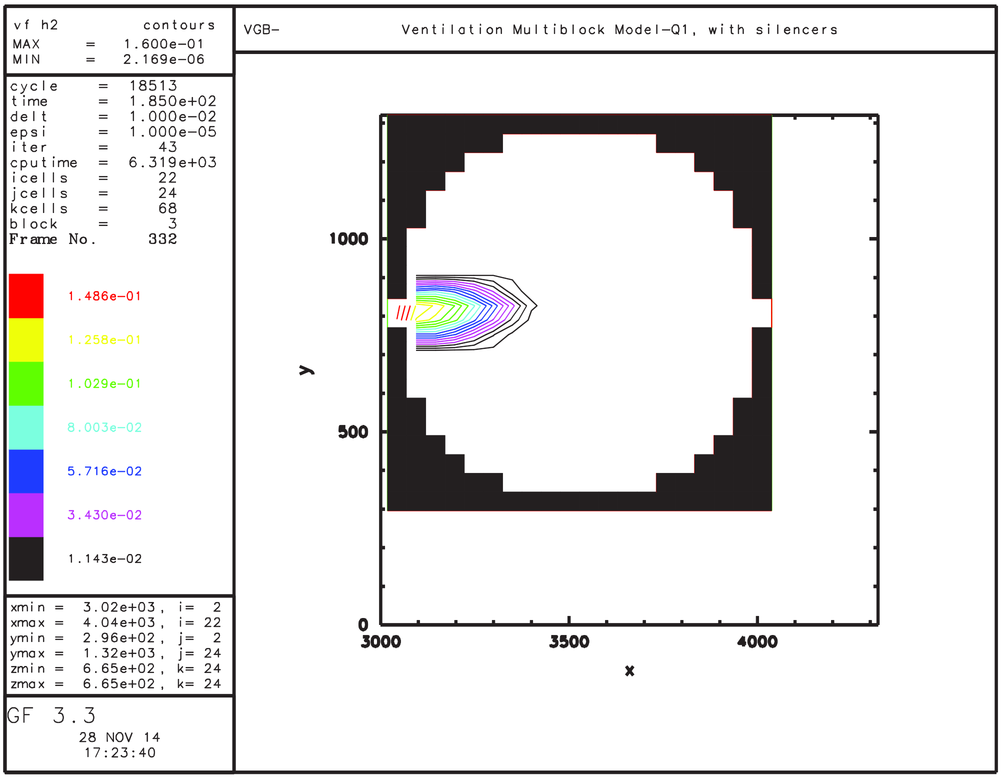

Figure 5.5.5 Volume fraction of H_2 in horizontal cut in Room 39 at 185 s

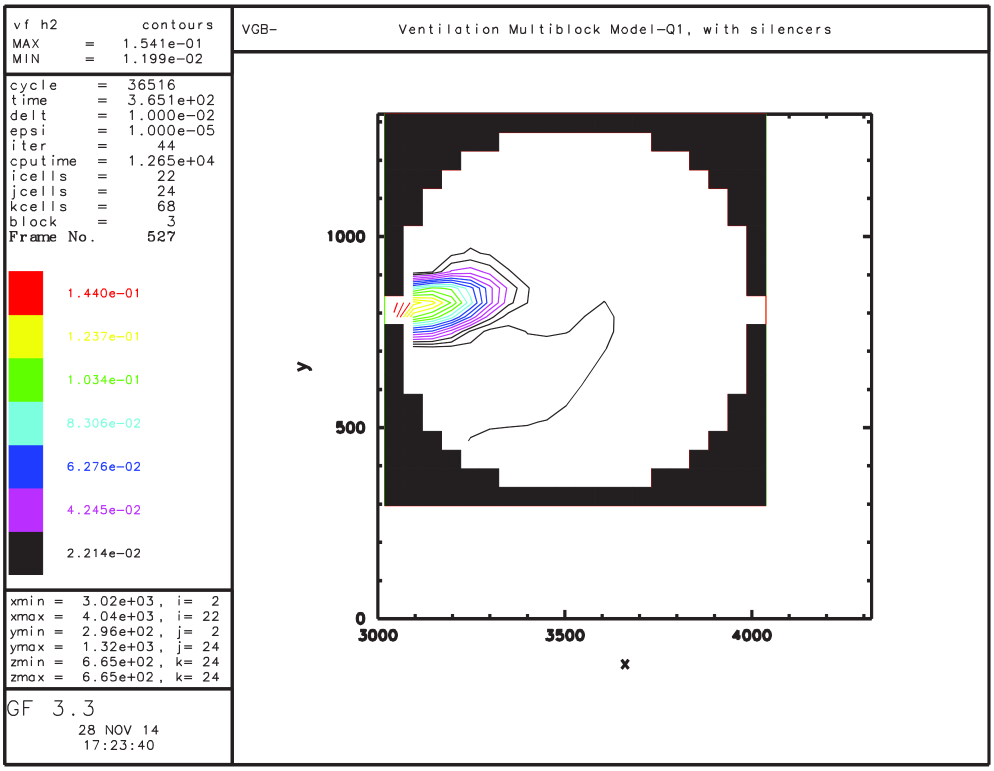

Figure 5.5.6 Volume fraction of H_2 in horizontal cut in Room 39 at 365 s

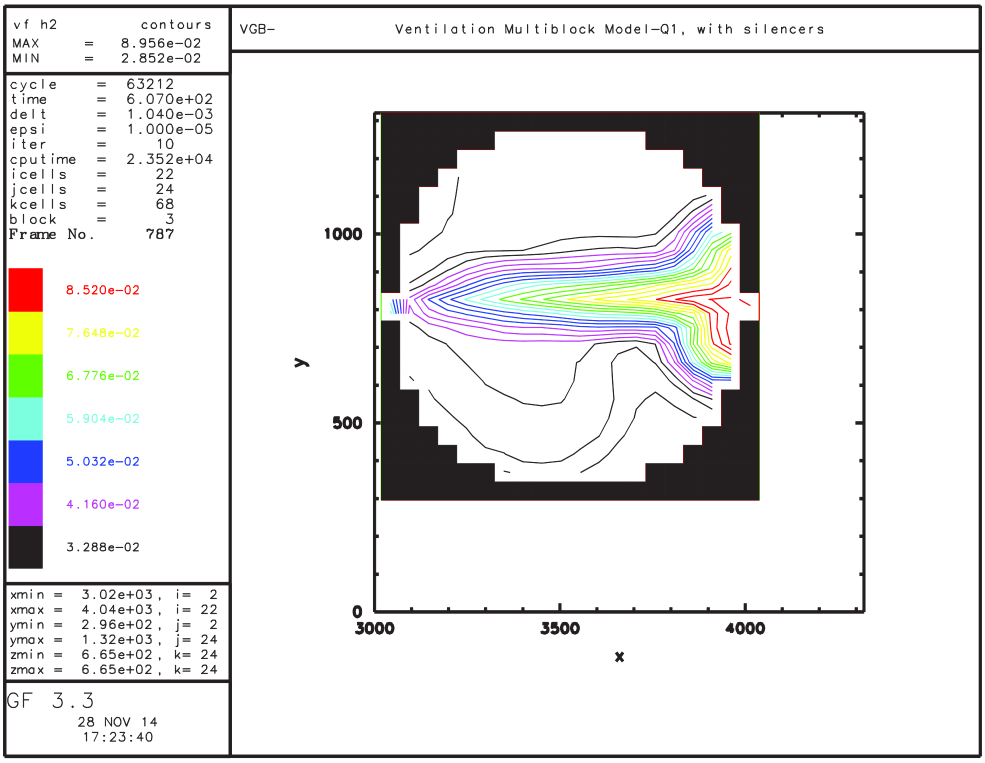

Figure 5.5.7 Volume fraction of H_2 in horizontal cut in Room 39 at 607 s

Both Figure 5.5.5 and Figure 5.5.6 show that the very local region with a high fraction of hydrogen (14 - 15%) is a small volume in Room 39, which is in the stack and on the side of the ventilation pipes. The two figures also tell the peak hydrogen concentration appears on the top-west corner. The claim is consistent to that observed in the time history plots Figure 5.5.2.

At the end of the time window, 607 s, the hydrogen distribution prints change owing to the injection of steam, as shown in Figure 5.5.7.

Summary: The region with a hydrogen volume fraction of 14 - 15% in Room 39 during 51 s - 607 s is a small volume, namely, around the cell at I = 2 - 3, J = 12 - 13, K = 23 - 24, which is a 50 x 37.5 x 86.8 cm^3 (about 0.16 m^3) rectangular.

6. Conclusions

The work done in the project is concluded as following points.

- If the ventilation fan works, there is no any risk of hydrogen flame acceleration and detonation in the ventilation system.
- In case of station blackout, if the water in the scrubber can get boiling in 10 minutes, there is no risk of detonation, and almost all the chambers have no risk of flame acceleration, except the compartment (Room 39) between the ventilation pipe and the stack only during the first 10 minutes of the accident.
- A detailed study has found that the region with a high volume fraction (14-15%) of hydrogen in Room 39 is limited in a small volume like 0.16 cubic meter. It is assumed not to pose a big risk to the system.
- The steam from the boiling scrubber inerts the hydrogen mixture effectively and significantly.
- The silencer does not affect the sensitivity of the mixture. It changes mainly the flow filed in the filter room, and mixes the gases.

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