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CFD Simulation of Spontaneous Ignition and Its Extinguishment in Biomass Fuel Storage

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PREFACE

A reliable advanced CFD simulation is a very powerful method for study of spontaneous ignition in biomass fuel storage and the extinguishment. In comparison with experimental measurement which can be very expensive, time consuming and sometimes also with big uncertainty, CFD simulation is much more efficient and economic. CFD simulation can also give much more detailed information.

Most recently, with many thanks to the financial support by Swedish Fire Research Board (Brandforsk in Swedish), Aarhus Karlshamn, Wood Pellets Association of Canada (WPAC), Värme- och Kraftföreningen, Lantmännen, Dong Energy, Öresundskraft samt Vattenfall-Danmark, a joint Brandforsk project 602-071 based on the continuation of a previous Brandforsk project no. 632-051 was performed to study the extinguish of spontaneous fire in wood pellets silo. In this joint project, a total budget of 550 KKr devoted to CFD simulation. Among this 550 KKr, 350 KKr was allocated to Lunds Tekniska Högskola for the CFD simulation work presented in this report. This budget of 350 KKr also covers the contribution by the author on providing some initial technical advices and help to SP Technical Research Institute of Sweden on the CFD simulations performed in SP.

This report presents the results from CFD simulations performed at Lunds Tekniska Högskola, which have been carried out to simulate spontaneous ignition fire propagation and its extinguishment in biomass fuel storage.

ABSTRACT

CFD computations have been performed to simulate the spontaneous ignition and its extinguishment by inert gas (nitrogen) discharge in cylindrical silos filled with wood pellets. Different cases were computed with different silo sizes, various discharge rates, inlet locations and inlet diameters. These CFD computations simulate how a spontaneous ignition fire can develop in a wood pellets storage silo and how the spontaneous ignition fire can be extinguished by inert gas discharge. Meanwhile, the computations also show the effect of silo size, discharge rates, inlet locations and inlet diameters on the inert gas distribution and the extinguishment process.

With these computations, important information about the extinguish gas distribution is revealed. This distribution information provides useful guideline for design of extinguish system for wood pellets storage silo.

THEORETICAL MODELS

The computation was carried out using a parallel finite volume CFD code *SIMTEC* (*Simulation of Thermal Engineering Complex*, previously also known as *SMAFS and FIRCOSIM*) [1]. It was based on numerical solution of a set of governing equations including the continuity equation, extended Darcy momentum equations, energy conservation equations for both gas and solid phases, and mass conservation equations for different chemical species [2, 3]. With consideration of a series of essential physical and chemical processes, including convection and diffusion in porous media, evaporation, condensation and heat generation which is mainly due to chemical oxidation, the computation simulated the temporal state evolution inside the biomass fuel storage.

The simulation is based on the porous media approach with turbulence ignored. The governing equations, including the continuity equation,

momentum equations, mass transport equations for chemical species and energy equations for both gas and solid phases, are listed below.

Continuity equation

$$\varphi \frac{\partial \rho_g}{\partial t} + \frac{\partial(\rho_g u_i)}{\partial x_i} = S_{gas} \quad (1)$$

Momentum equation

$$\varphi \frac{\partial(\rho_g u_i)}{\partial t} + \frac{\partial(\rho_g u_i u_j)}{\partial x_j} = \varphi^2 \left\{ \begin{array}{l} -\frac{\partial p}{\partial x_i} - \frac{\mu}{\kappa} u_i + \frac{\partial}{\partial x_j} \left[\mu \left(\frac{\partial u_i}{\partial x_j} \right) \right] \\ -\frac{C_F \rho_g}{\kappa^{0.5}} (u_i u_i)^{0.5} u_i + \rho_g a_{gi} \end{array} \right\} \quad (2)$$

Mass conservation equation for chemical species

$$\varphi \frac{\partial(\rho_g Y_i)}{\partial t} + \frac{\partial}{\partial x_j} (\rho_g Y_i u_j) = \varphi \frac{\partial}{\partial x_j} \left[\frac{\mu}{Sc} \frac{\partial Y_i}{\partial x_j} \right] + S_{Y_i} \quad (3)$$

Energy conservation equation for gas phase

$$\varphi \frac{\partial(\rho_g H_g)}{\partial t} + \frac{\partial}{\partial x_j} (\rho_g H_g u_j) = \varphi \frac{\partial}{\partial x_j} \left[\frac{\mu}{Pr} \frac{\partial H_g}{\partial x_j} \right] + S_{H_g} \quad (4)$$

Energy conservation equation for solid phase

$$\frac{\partial(\rho_s H_s)}{\partial t} = \frac{\partial}{\partial x_j} \left[\frac{\lambda_s}{C_p} \frac{\partial H_s}{\partial x_j} \right] + S_{H_s} \quad (5)$$

The moisture balance in solid

$$-\frac{\partial(\rho_s W)}{\partial t} = r_w \quad (6)$$

In the above equations, the source terms represent the contribution of sub-processes. A systematic description of these sources can be found in [2].

For simulation of spontaneous ignition and its extinguishment in biomass fuel storage, the most important sub-process is the chemical reaction. The chemical reaction converts chemical energy into heat which is responsible of temperature increase and fire. To have a detailed description of the chemical reaction, a detailed chemical reaction mechanism has to be formulated and high quality experimental measurement will be needed to provide the kinetic data for the chemistry.

In biomass fuel combustion, the detailed chemical reaction can be very complicated. At present, no detailed chemical reaction data is available. In this work, the description of chemical reaction is based on empirical formation with an overall single step reaction. The reaction kinetic data is derived in SP from a simple cross-point measurement.

Based on the experimental measurement, the heat release rate from chemical reaction is given by:

$$\dot{h} = A \exp\left(-\frac{E}{RT_s}\right) \quad (7)$$

where T_s represents the solid temperature, A is the pre-factor constant and E the activation energy, which respectively have values of $1.5 \times 10^9 J/(kg \cdot s)$ and $69.4 kJ/mol$. These values are unpublished data but were reported at project meeting. They are from the crossing-point measurement made in SP.

THE SIMULATION CASES

This simulation is a part of the work in a research project which aims to study the extinguish inert gas dispersion in a silo filled with biomass fuel such as wood pellets. This research includes both experimental test and numerical computation. For the numerical computation, a number of

simulations were performed with different silo sizes and injection conditions. All the *SIMTEC* simulations reported in this study are pre-experiment simulations where there was no experiment data at the time of performing simulation. As a result, there is no iterative adaptation made in the simulation to fit experiment.

In the simulations, the silo and pellets are assumed to have the same initial temperature as the ambient temperature of 300 K. In practice, the injected nitrogen gas usually comes from liquid nitrogen. With this consideration, in the simulations, the injected nitrogen gas is assumed to have temperature of 273 K at the inlet. The material properties are assumed to be similar as those in a previous study [2]:

Compact dry density	1190 kg/m ³
Specific heat	1700 J/kgK
Conductivity	0.17 W/mK
Bulk porosity	0.52
Bulk permeability	8.0E-08 (m ²)

In this report, three series of simulations are presented.

Simulation series 1

In this series of simulation, the simulated process is the gas injection in silo with 40 m in diameter and 30 m in height under condition of no spontaneous ignition fire. There was only one gas inlet at the bottom centre of the silo. Some more details of the scenario can be found in SP's document "Proposal for silo simulations-revised after telephone meeting 2007-11-20". As the intention is to achieve a comparison between the *COMSOL* and *SIMTEC* software, only simulations no. 1, 5 and 6 shown in Table 1 below were performed with *SIMTEC* [1].

Table 1 Simulation cases in series 1

Simulation no	Diameter / Height (m)	Injection rate (kg/h)	Inlet velocity (m/s)	Inlet diameter (mm)
1	40/30	6280	3	770
2	40/30	6280	30	243
3	40/30	1256	3	344
4	40/30	1256	30	109
5	40/30	628	3	243
6	40/30	628	30	77
7	40/30	251	3	154
8	40/30	251	30	49

Simulation series 2

In this series of simulation, pre-test simulations were made to simulate the cold silo experiments without spontaneous ignition fire which were to be performed in Ulricehamn. With the pre-test simulation, very useful guidance was provided for the planning and design of the experiment.

Figure 1 is a sketch of the test silo. The silo is 10.5 m high but only filled with wood pellets up to 9m. At the top, the cone of pellets is assumed to be even out so that the surface becomes flat (in the experiment, the top surface is also intended to be manually flatted).

Two different scenarios with two different inlet locations were simulated using *SIMTEC*. In the first scenario, there is one inlet located at the bottom centre. In the second scenario, there is one inlet at the side of the silo. The side inlet is located 0.5 m above the silo bottom as shown in the Fig. 1.

For each scenario, two different injection rates of 33.2 and 165.8 kg/h were considered. It is assumed that the inlet gas temperature is 0 C. This gives a volume flow rate of 26.5 and 132.7 m³/h. As the inlet has a diameter of 43 mm, these two injection rates respectively correspond to

injection velocity of 5 m/s and 25 m/s. In total, four simulations were performed in this series of simulation. Table 2 gives a summary of these four simulations.

Table 2 Simulation cases in series 2

Simulation	Diameter / Height (m)	Gas inlet	Injection rate (kg/h)	Comments
1	6.5/9	Centre	33.2	Axis-symmetric simulation
2	6.5/9	Centre	165.8	Axis-symmetric simulation
3	6.5/9	Side wall	33.2	3D-simulation
4	6.5/9	Side wall	165.8	3D-simulation

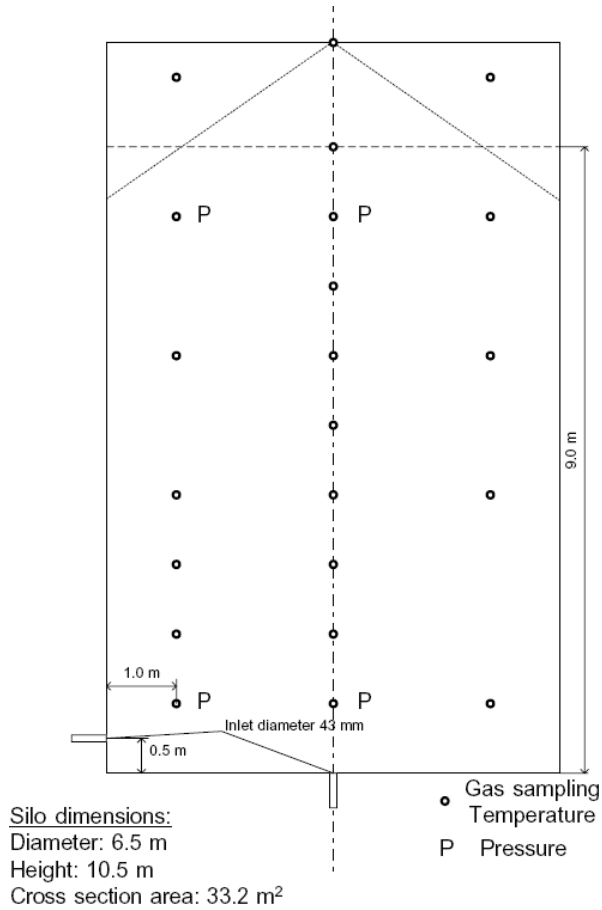


Figure 1 Sketch of the silo used in the Ulricehamn test

Simulation series 3

In this series of simulation, *SIMTEC* was used to simulation the nitrogen gas injection under a condition of spontaneous ignition fire. The simulations compute the spontaneous ignition fire development, gas injection process, gas dispersion and also the extinguishment of the fire by nitrogen. The sketch of the geometry for this series of simulations is shown in Fig. 2.

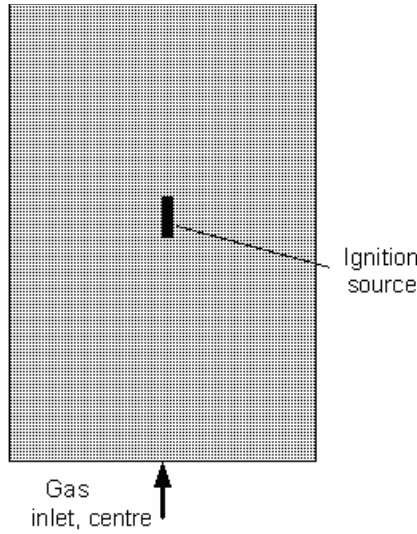


Figure 2 Sketch of the considered silo in simulation series 3

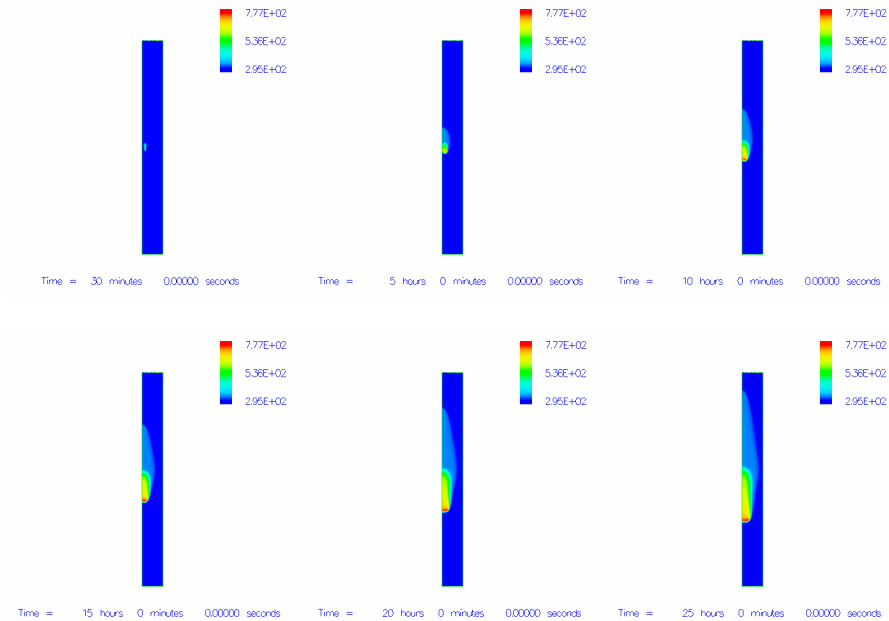


Figure 3 Pellets temperature development in the silo, *SIMTEC* simulation

It is well noted that the previous version of *SIMTEC* (known as *SMAFS* at that time) was successfully used in a blind simulation of an experiment

performed in SP about fire development and its extinguishment in a silo filled with wood pellets [4]. Since *SIMTEC* comes from its precursor *SMAFS* with substantially further development, in order to verify and validate *SIMTEC*'s performance in such simulations, before the simulation, *SIMTEC* was used to re-simulate the silo experiment [4]. As shown in Fig. 3, *SIMTEC* well predicts the downward fire propagation in the silo and successfully reproduces the silo experiment [4]. With this verification and validation, *SIMTEC* was applied with confidence to simulate all the cases in series 3 which are listed below in Table 3.

Table 3 Simulation cases in series 3

Simulation	Diameter / Height (m)	Gas inlet	Injection rate (kg/h)	Inlet diameter (mm)	Comments
1	40/30	Centre	628	243	Axis-symmetric simulation
2	8/40	Centre	628	243	Axis-symmetric simulation

NUMERICAL ASPECTS AND SENSITIVITY ANALYSIS

The control volume method was employed with PLDS scheme. The computation was performed with convergence mass residual of about 10^{-6} .

The computations were performed with consideration of the axis-symmetry for all the cases in series 1, cases 1 and 2 in series 2 and all the cases in series 3. For other cases, the simulations were performed in three-dimensional using plane symmetry to consider half of the silo.

For the axi-symmetry case simulations, a mesh of 103×103 cells was used. For the three-dimensional simulation, a mesh of $53 \times 103 \times 53$ cells was used. To provide a fine spatial resolution at the inlet, the mesh was clustered at the inlet location. Figure 4 shows a representative grid system used in a computation.

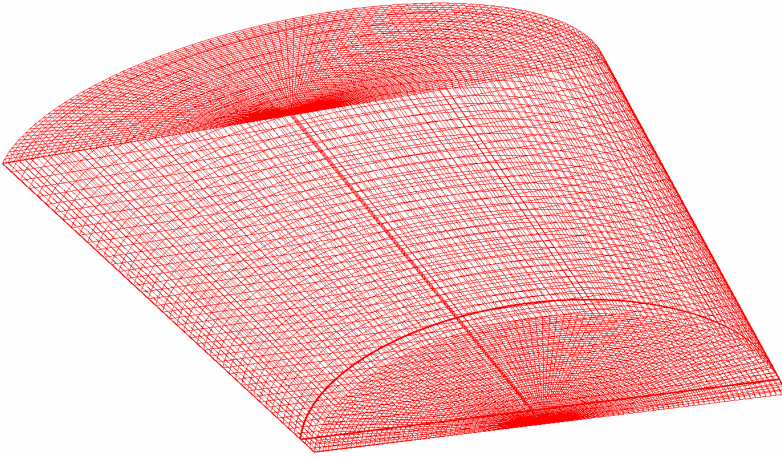


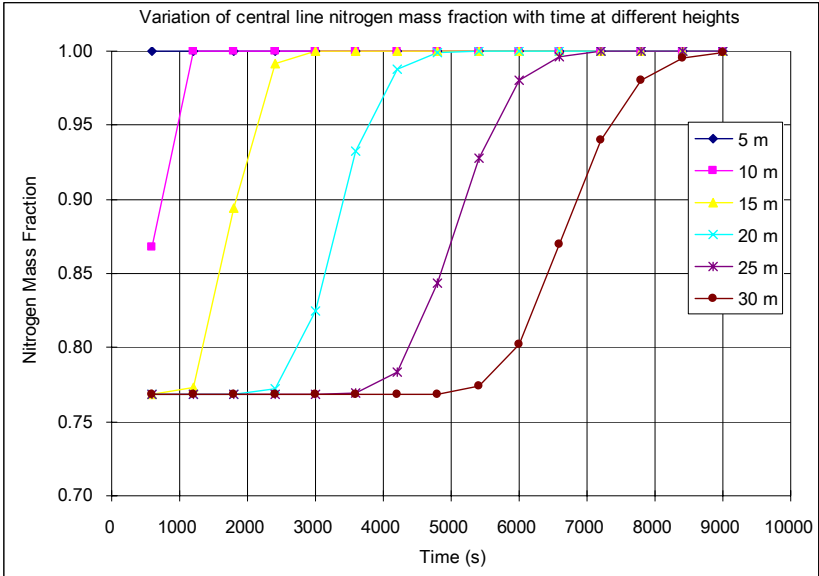
Figure 4 An example grid used in computation

Grid sensitivity study

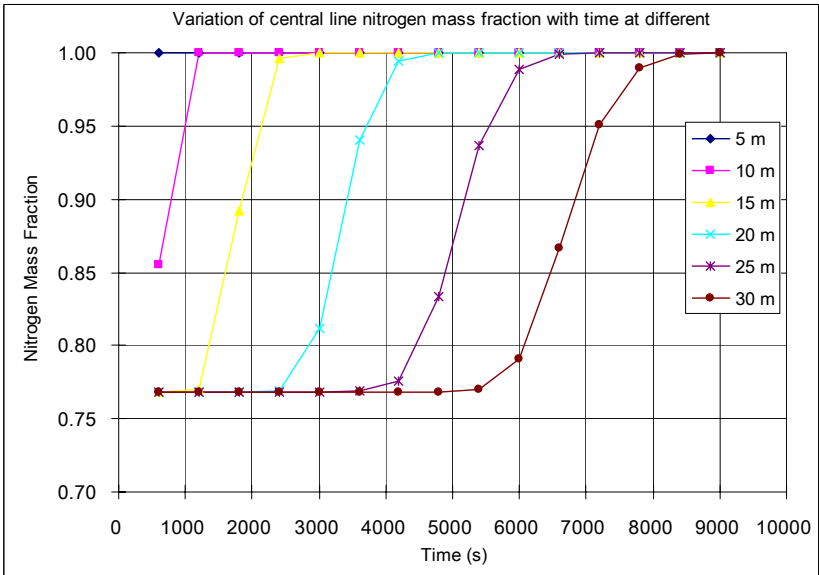
Before accepting the results from the CFD computations, grid sensitivity analysis was carried out to ensure that the grids used in the computation are fine enough so that the computation result is grid independent.

In the grid sensitivity study, a base grid is refined and the results from both base grid and refined grid are compared to check the result variation with grid refinement.

Figure 5 compares the results from both base grid of 103×103 and refined grid of 153×153 for the simulation of case 1, series 1. The comparison shows the results variation with grid refinement is negligible and the base grid is enough to be used in the computation.



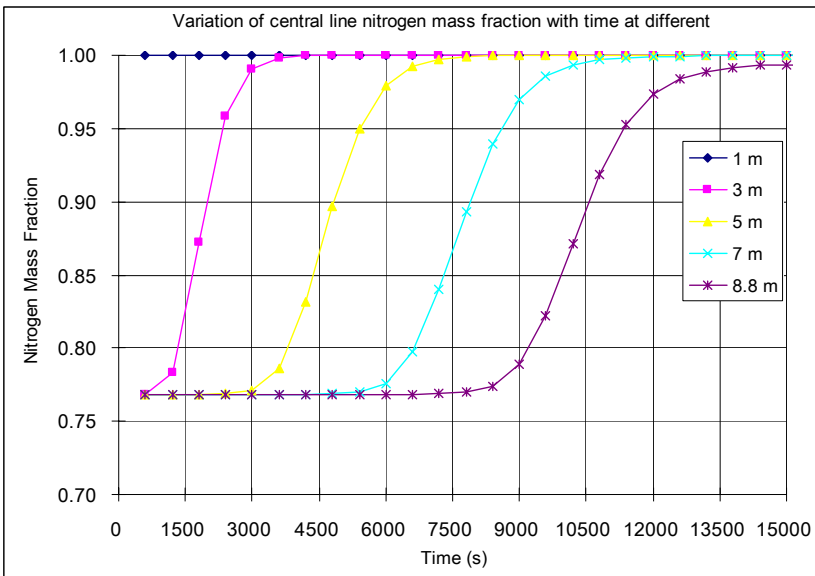
a) Base grid



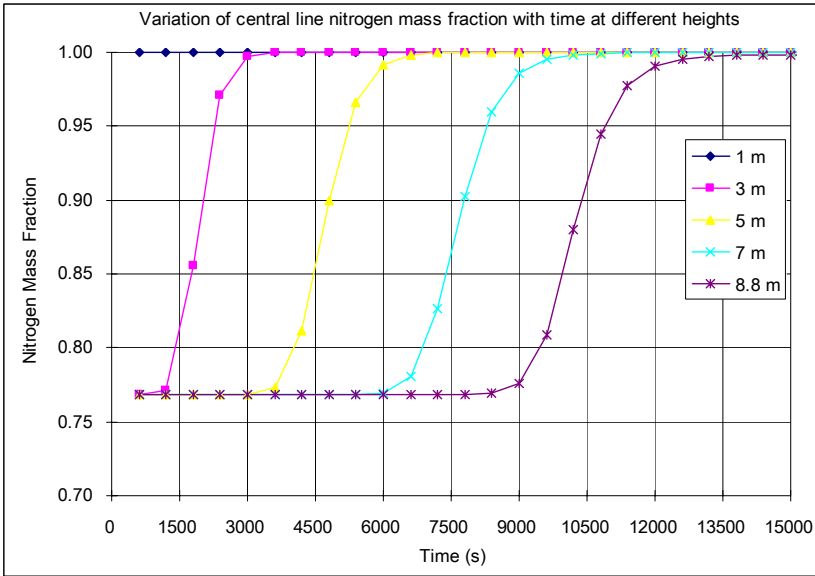
b) Refined grid

Figure 5 Time variations of nitrogen mass fraction at different heights along central line of silo for case 1, series 1

Figure 6 compares the results from both base grid of 53×53 and refined grid of 103×103 for the simulation of case 1, series 2. In the simulation for series 2, the silo of 9 m in height and 6.5 m in diameter is much smaller than the silo of 30 m in height and 40 m in diameter in simulation series 1. Therefore, a reduced number of grids were used in the computation. From the comparison, one can see that there is only minor grid effect on the result for the point at the height of 8.8 m and the results variation with grid refinement is negligible. As a result, one can conclude that the base grid is enough to be used in the computation. To be better secured, in the final computations, for the cases 1 and 2 of this series of simulation, the refined grid of 103×103 was used.



a) Base grid



b) Refined grid

Figure 6 Time variations of nitrogen mass fraction at different heights along central line of silo, for case 1, series 2

For the cases 3 and 4 of series 2, the simulation has to be performed in three dimensional. On the radial and vertical directions, from the two dimensional simulation for case 1 of series 2, grids of 53×53 can be sufficient. For the azimuth direction, a base grid of 103 cells and a refined grid of 153 cells were used in simulations to check effect of grid refinement. Figure 7 compares the simulation results from both base grid and refined grid for case 3 of series 2. As one can notice, the difference between two simulations is reasonably small and the thus base grid is assumed to be sufficient. Due to the long computation time in the three dimensional computation, the base grid was used in the final three dimensional simulation.

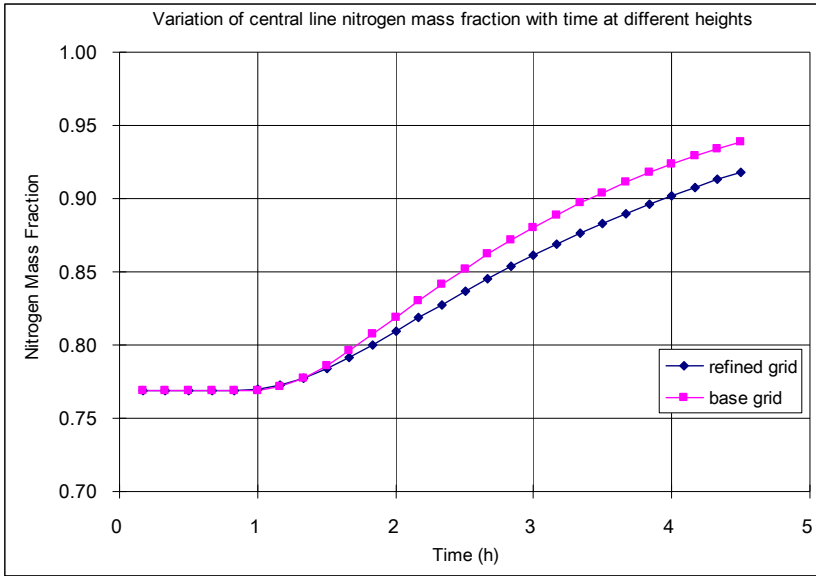


Figure 7 Time variations of nitrogen mass fraction, at 1 m above floor on central line of silo, for case 3, series 2

For the simulation in series 3, two cases were simulated. Since the first case has the same geometry as the case 1 of series 1, the base grid tested for series 1 is expected to be fine enough and was thus used in the computation. The second case in series 3 has a silo of 40 m in height and 8 meter in diameter. In this second case, the silo is about 30% higher than the silo in case 1 but much smaller in diameter. Therefore, the same grid number of 103×103 can be acceptable for the simulation.

The computation was performed on a Linux cluster using a parallel CFD code *SIMTEC* [1].

RESULTS AND DISCUSSIONS

CFD simulation provides detailed information including the time dependent nitrogen concentration distribution and temperature distribution, etc. In this report, only some representative results are presented to show the temporal variation of gas distribution and temperature profile which are the major concerns in the study.

Simulation series 1

As previously indicated, three cases were simulated in this series, with varied injection rates and/or inlet sizes. In this section, the *SIMTEC* simulation results will be presented for all these three cases. Afterwards, a brief general comparison with corresponding *COMSOL* simulations will be given.

Case 1

In this case, a high inject rate (see Table 1) is employed. Figure 8 plots the variation of nitrogen mass fraction at different heights along the central line of silo. As can be seen, the injected nitrogen comes to the top central point after about 5500 seconds, but it takes about 9000 seconds (2.5 hours) for nitrogen mass fraction at the top central point to reach 100%.

Figure 9 gives a spatial distribution of nitrogen mass fraction at the time of 3 hours after injection. As one can clearly see, the injected nitrogen has substantially stronger tendency to propagate upwards than laterally (the silo is 30 meters in height and 20 meters in radius). As indicated in Fig. 8, after about 9000 seconds (2.5 hours), the nitrogen mass fraction at the top central point reaches 100%. However, as shown in Fig. 9, it is rather difficult for nitrogen to fully reach the area close to the silo's side wall. After 3.0 hours, the nitrogen mass fraction in the area close to the silo's side wall still remains at its initial value (76.8% in air). The side wall effect can be one of the most important reasons for this.

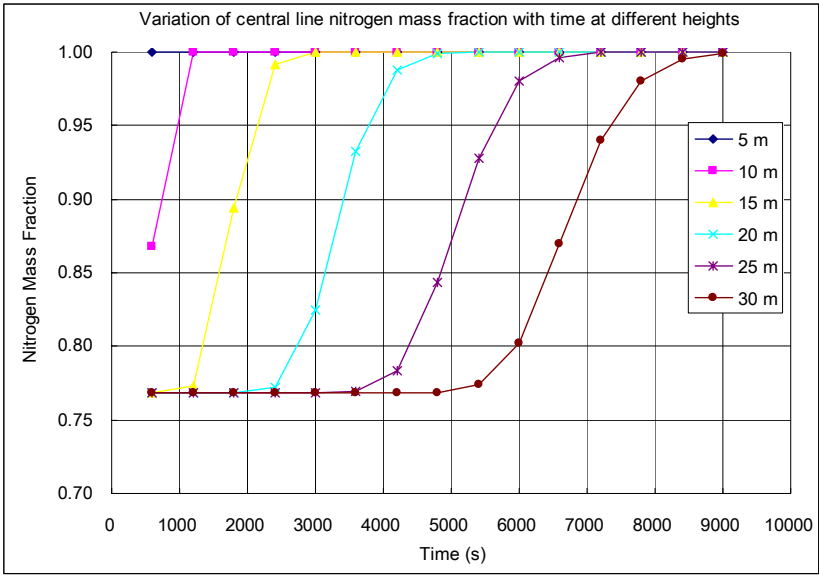
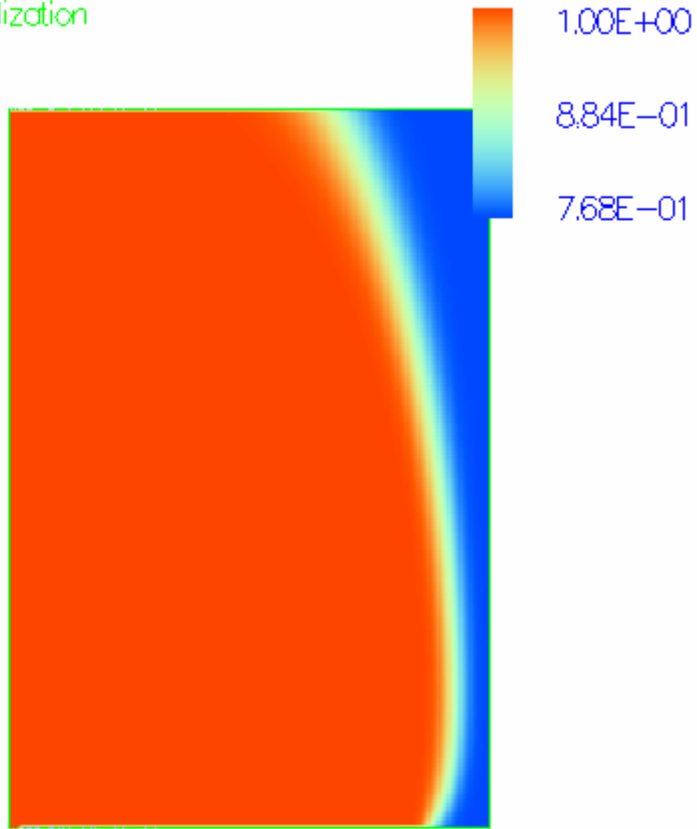


Figure 8 Time variations of nitrogen mass fraction at different heights along central line of silo for case 1, series 1

SMAFS Visualization



Time = 3 hours 0 minutes 0.00000 seconds
Nitrogen mass fraction distribution

Figure 9 Spatial distribution of nitrogen mass fraction at the time of 3 hours after injection for case 1, series 1

Case 5

In comparison with conditions in case 1, with a reduced inlet diameter, the injection rate in this case is reduced by a factor of 10 (see Table 1). In general, the result in this case has certain similarities with result in case 1. However, because of the substantially reduced inlet diameter (and consequently the injection rate), as shown in Fig. 10, it takes much longer time for the injected nitrogen comes to the top central point. Meanwhile, as one can see in Fig. 11, because of the reduced injection rate and inlet size, in this case, the upward propagation tendency is stronger than in case

1. After 18 hours, the injected nitrogen has fully contaminated the top central part of the silo, but with a large lateral part of silo untouched. Again, the side wall effect can be one of the most important reasons for this. This revealed phenomenon is important and should be carefully considered in a practical design of inert gas discharge for extinguishment of silo fires. It should be aware of that inert gas injected from a small inlet at the bottom center may not be able to directly reach a fire location if the fire is at the side part of silo. Of course, this indication is based on the current simulation where no fire is at place. When a fire is at place, due to the strong interaction between fire and nitrogen injection, the picture may be different. A simulation with a condition more close to real fire situation is needed. The simulation in series 3 will provide more information on this point.

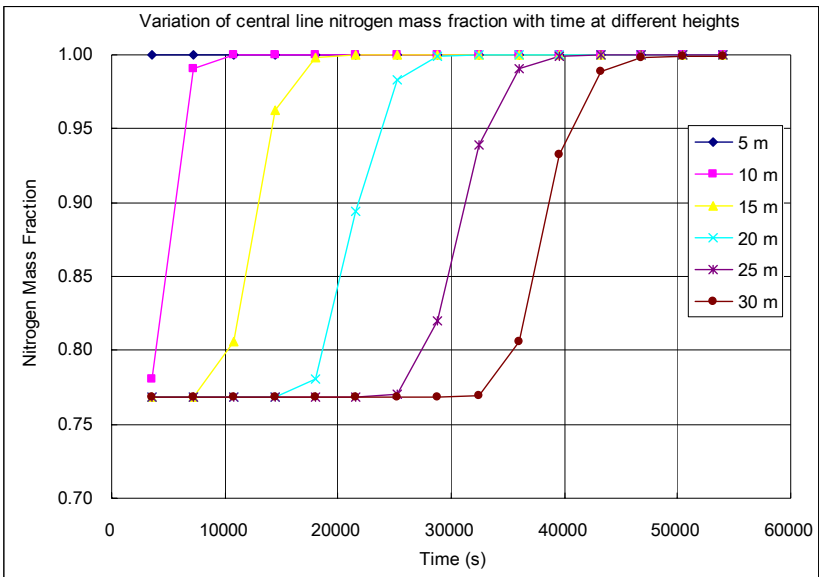


Figure 10 Time variations of nitrogen mass fraction at different heights along central line of silo for case 5, series 1

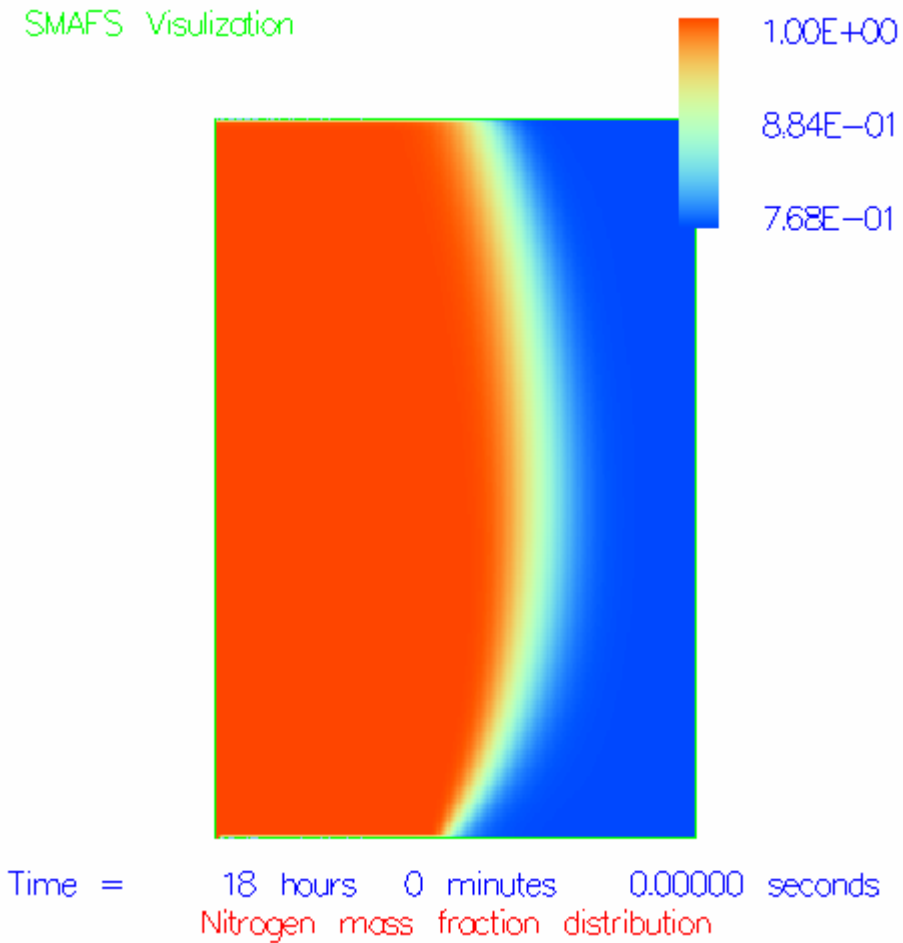


Figure 11 Spatial distribution of nitrogen mass fraction at the time of 18 hours after injection for case 5, series 1

Case 6

In comparison with conditions in case 5, in this case, the inlet is reduced in size but injection velocity is correspondingly increased to keep the same injection rate as in case 5 (see Table 1).

Because of the same injection rate, as shown in Fig. 12, the time variations of nitrogen mass fraction at different heights along central line of silo are similar as those in case 5. A spatial distribution of nitrogen mass fraction is shown in Fig. 13.

By comparing Figs. 11 and 13, one can see that the upward propagation tendency is also similar as that in case 5. By keeping the same low injection rate, in the simulation, the reduction of inlet diameter from 243 mm to 77 mm does not have important effect on the upward propagation tendency. However, one should be careful when interpreting this result. This can be case dependent.

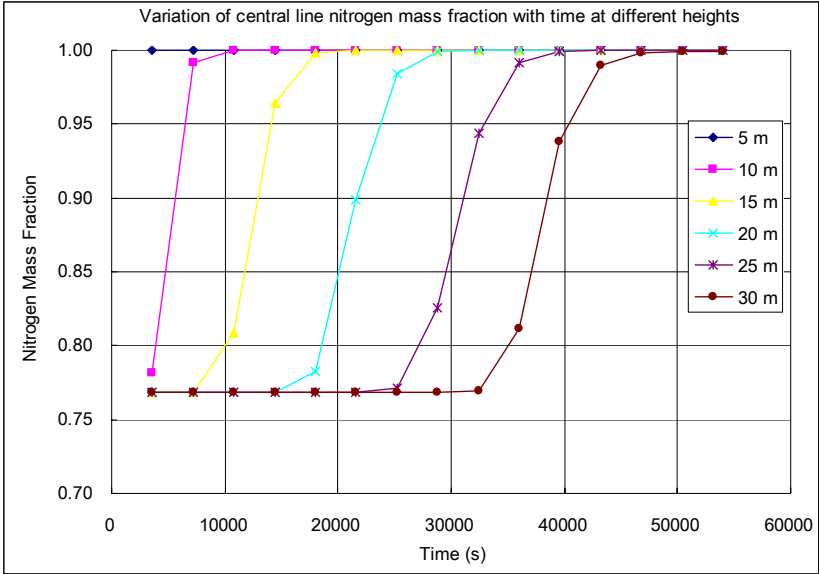


Figure 12 Time variations of nitrogen mass fraction at different heights along central line of silo for case 6, series 1

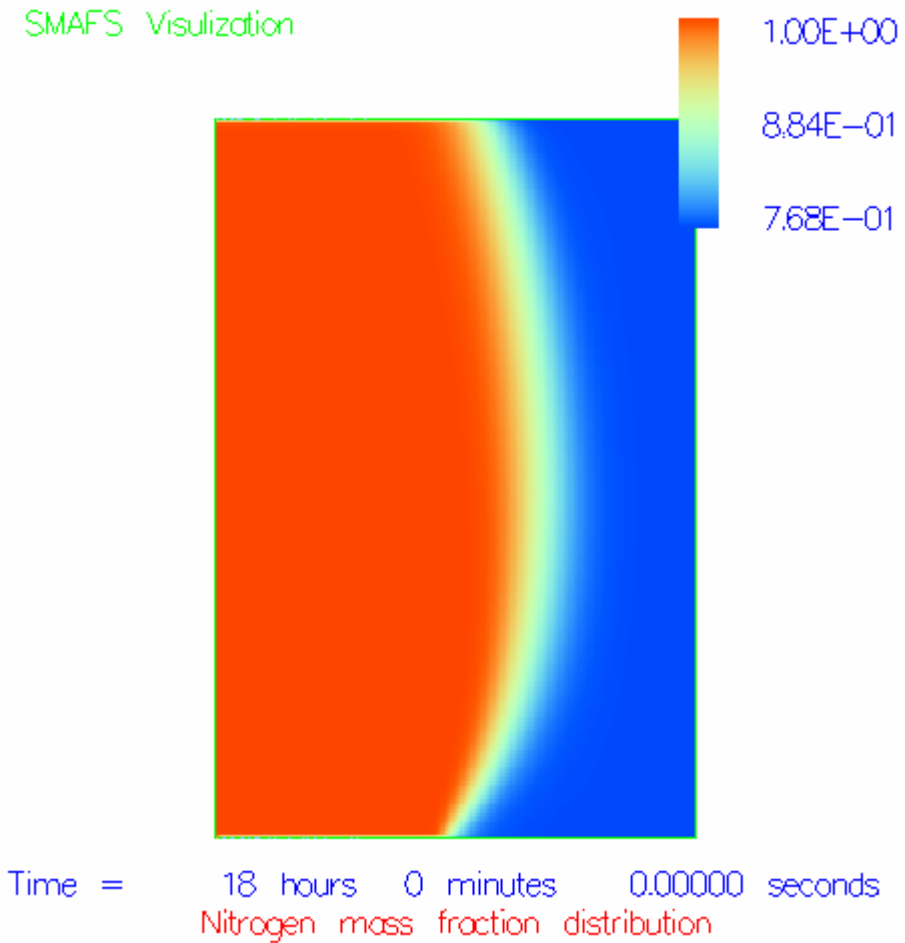


Figure 13 Spatial distribution of nitrogen mass fraction at the time of 18 hours after injection for case 6, series 1

Comparison with COMSOL simulations

The above simulated cases were also simulated using *COMSOL* by SP [5]. For a brief comparison between results from *SIMTEC* simulations and *COMSOL* simulations, Figs. 14 and 15 respectively present the spatial distribution of nitrogen concentration for case 5 and case 6 by *COMSOL* simulation. From Figs. 14 and 15, one can see that in *COMSOL* simulations, the injected nitrogen disperses radially at essentially equal speed. There is no apparent directional propagation tendency for nitrogen

dispersion. This is a very different picture from what is presented in *SIMTEC* simulations (see Figs. 11 and 13). The *SIMTEC* simulations on the contrary give obvious upward propagation tendency, which is well indicated by the experimental measurement for the cases in series 2.

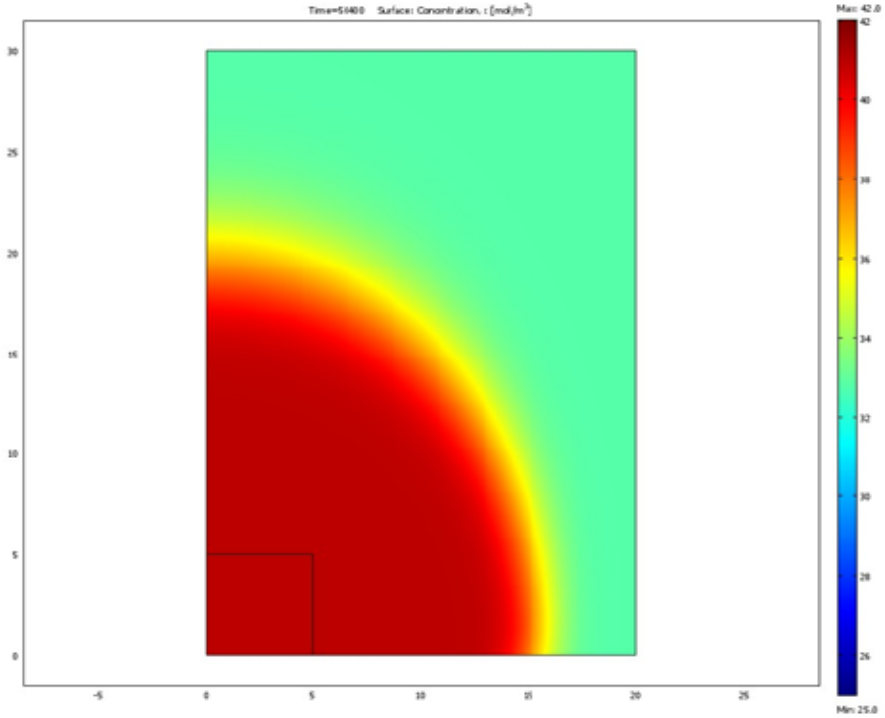


Figure 14 Spatial distribution of nitrogen concentration for case 5, series 1, *COMSOL*'s simulation, from [5]

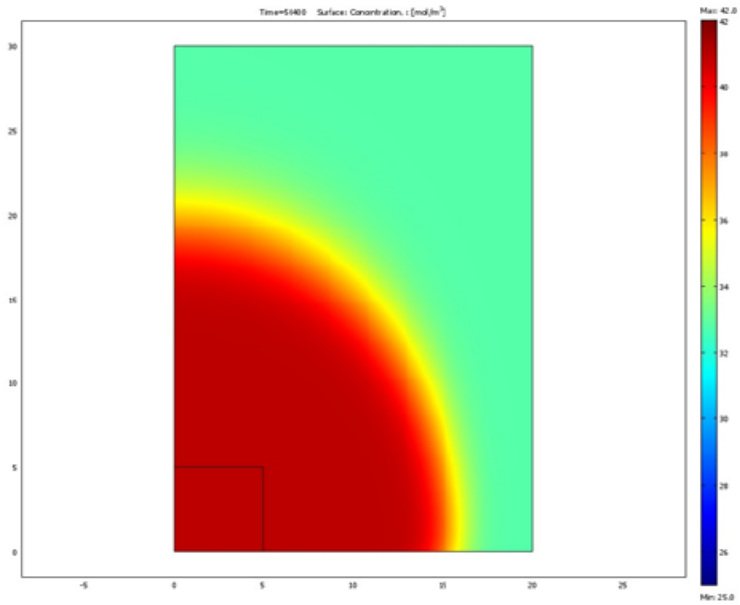


Figure 15 Spatial distribution of nitrogen concentration for case 6, series 1, *COMSOL*'s simulation, from [5]

Simulation series 2

In this series, four pre-test simulations were made to simulate the silo experiments which were to be performed in Ulricehamn to provide useful guidance for the planning and design of the experiment.

Case 1

In this case, nitrogen is injected from an inlet at the bottom center with an injection rate of a 33.2 kg/h (see Table 2).

Figure 16 plots the variation of nitrogen mass fraction at different heights along the central line of silo. As can be seen, the injected nitrogen comes to the top central point after about 9000 seconds, but it takes more than 12000 seconds for nitrogen mass fraction at the top central point to reach 100%.

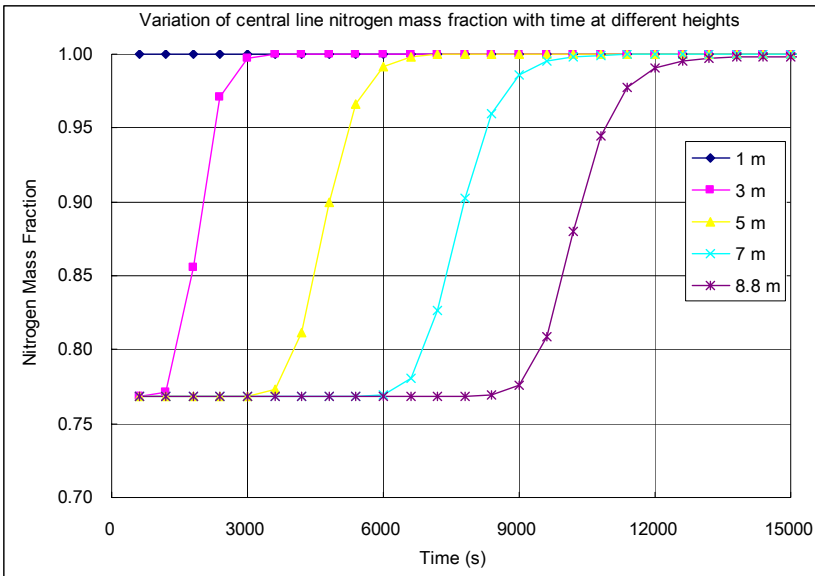


Figure 16 Time variations of nitrogen mass fraction at different heights along central line of silo, for case 1, series 2

Figures 17 and 18 give a spatial distribution of nitrogen mass fraction at the time of 1 and 5 hours respectively after injection. The upward propagation tendency observed in the simulations of series 1 can also be seen for this simulation.

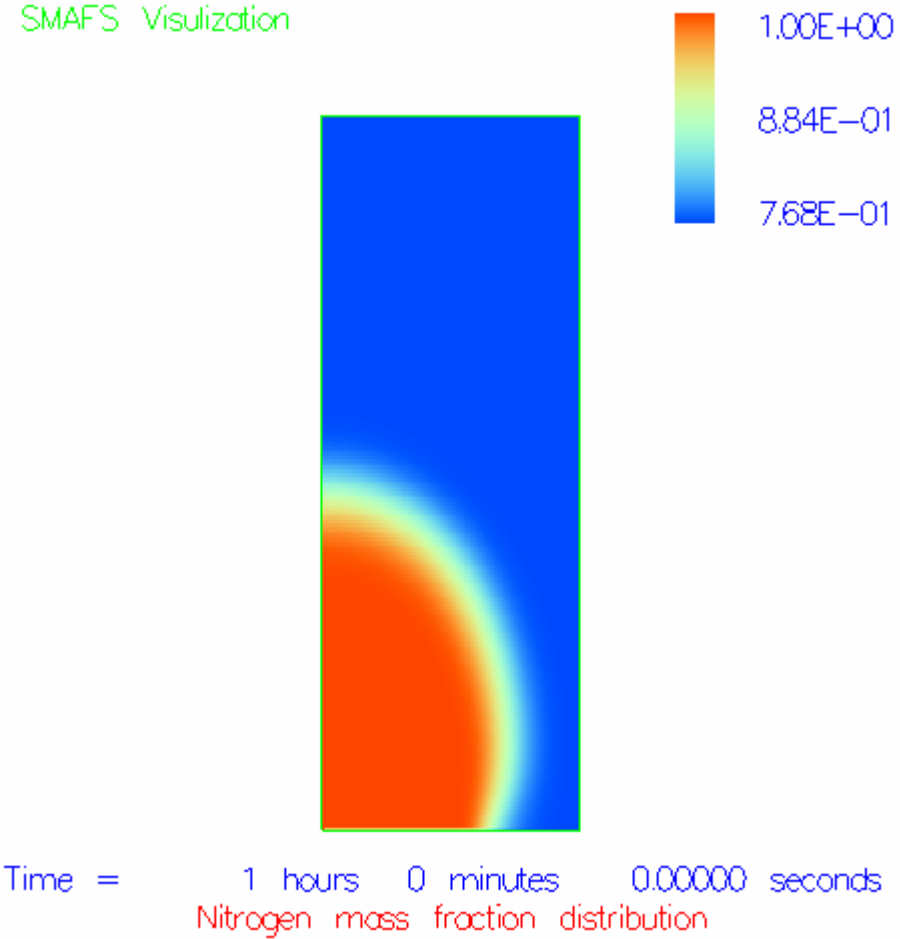
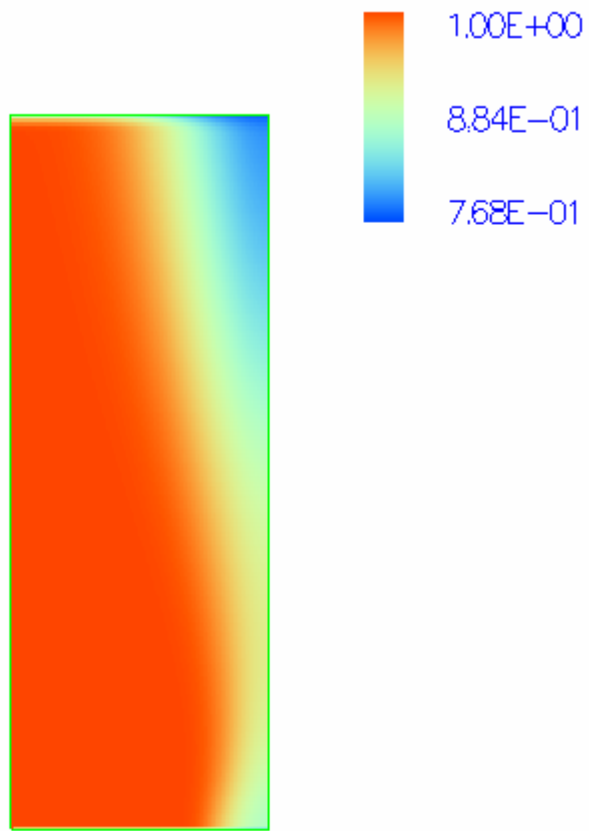


Figure 17 Spatial distribution of nitrogen mass fraction at the time of 1 hour after injection, for case 1, series 2

SMAFS Visualization



Time = 5 hours 0 minutes 0.00000 seconds
Nitrogen mass fraction distribution

Figure 18 Spatial distribution of nitrogen mass fraction at the time of 5 hours after injection, for case 1, series 2

Case 2

In this case, nitrogen is injected from an inlet at the bottom center with an injection rate of a 165.8 kg/h (see Table 2).

Figure 19 plots the variation of nitrogen mass fraction at different heights along the central line of silo. As can be seen, in this case, because of increased injection rate, the injected nitrogen comes to the top central point after about 2300 seconds, but it takes more than 3300 seconds for nitrogen mass fraction at the top central point to reach 100%.

Figures 20 and 21 give a spatial distribution of nitrogen mass fraction at the time of 12 and 60 minutes respectively after injection. The injected nitrogen reaches the region close to side wall. But as in previous cases, the injected nitrogen propagates upwards substantially faster.

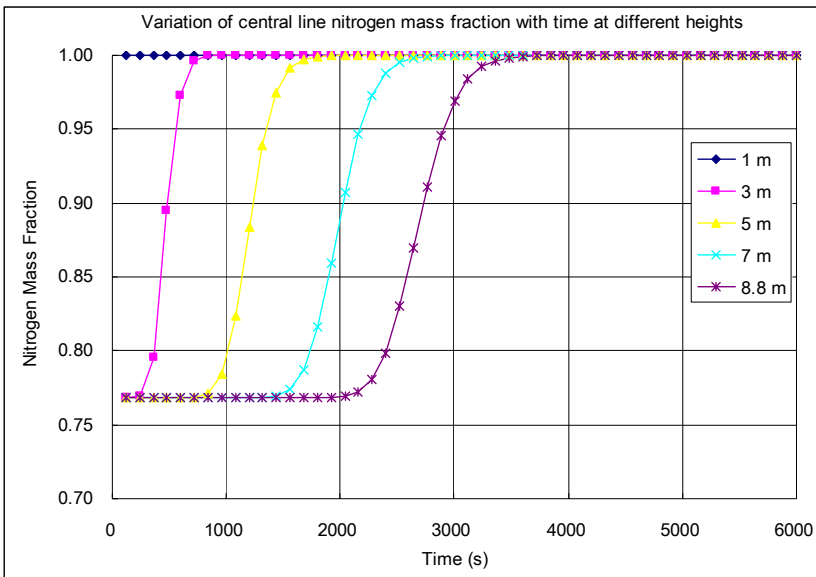
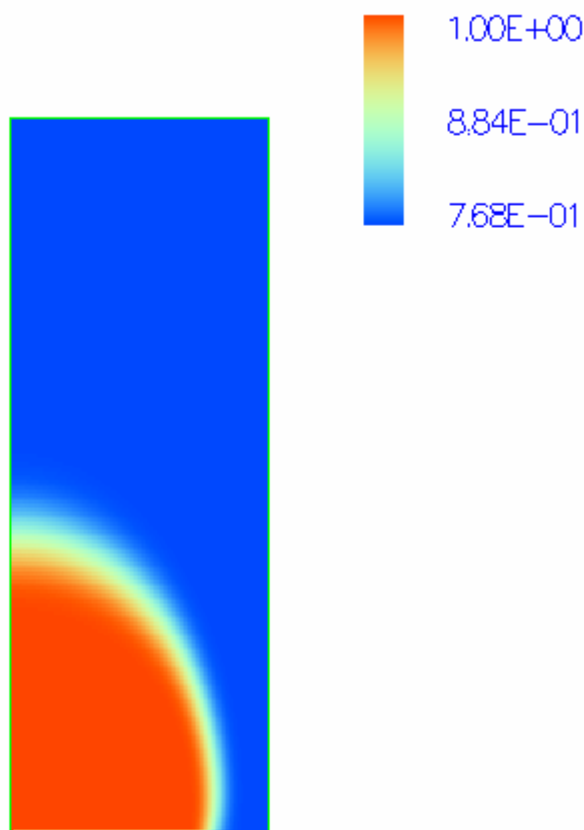


Figure 19 Time variations of nitrogen mass fraction at different heights along central line of silo, for case 2, series 2

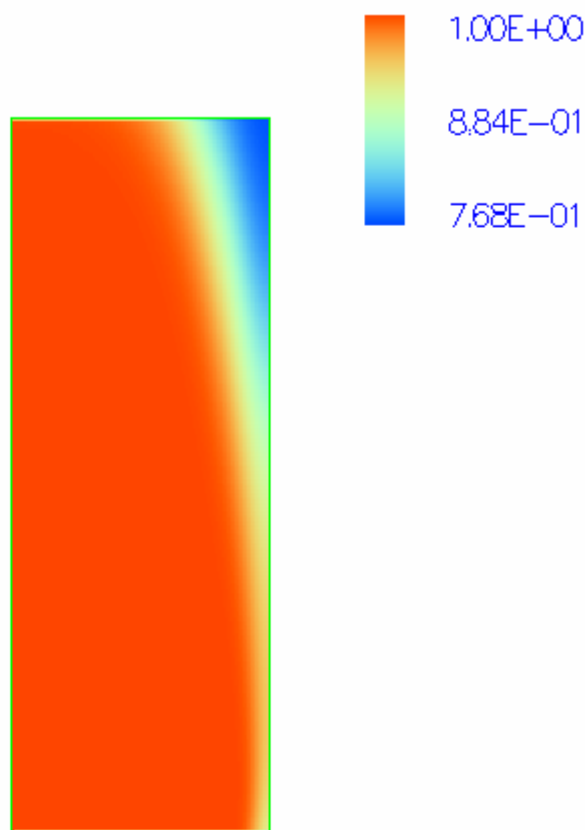
SMAFS Visualization



Time = 12 minutes 0.00000 seconds
Nitrogen mass fraction distribution

Figure 20 Spatial distribution of nitrogen mass fraction at the time of 12 minutes after injection, for case 2, series 2

SMAFS Visualization



Time = 1 hours 0 minutes 0.00000 seconds
Nitrogen mass fraction distribution

Figure 21 Spatial distribution of nitrogen mass fraction at the time of 1 hour after injection, for case 2, series 2

Case 3

In this case, nitrogen is injected from an inlet at the side wall of silo with an injection rate of a 33.2 kg/h (see Table 2). Since the inlet is at the side wall, axis-symmetric condition does not apply and the simulation has to be performed in 3-D where half of the silo is simulated.

Figure 22 plots the variation of nitrogen mass fraction at different heights along the central line of silo. As can be seen, in this case, because the inlet is at the side wall, the shape of the chart is quite different from the chart shape for case 1 of series 2. Meanwhile, the injected nitrogen comes to the top central point after about 4 hours and it takes about more than 10 hours for nitrogen mass fraction at the top central point to reach 100%. In comparison with the results in case 1 of series 2, it takes substantially longer time for injected nitrogen to propagate to the top center.

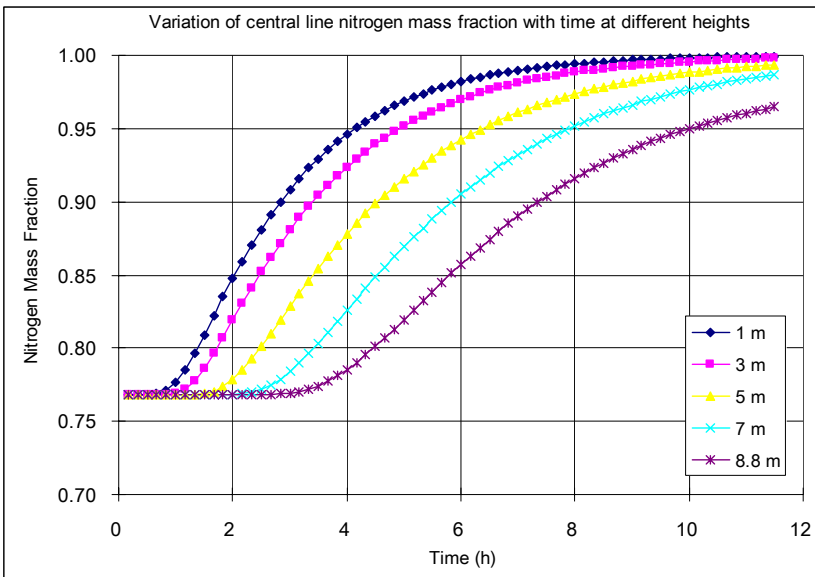


Figure 22 Time variations of nitrogen mass fraction at different heights along central line of silo, for case 3, series 2

Figures 23-25 give iso-plots of nitrogen mass fraction 83% at the time of 1, 6 and 10 hours respectively after injection. These iso-plots show the three dimensional nitrogen distributions. The injected nitrogen reaches the

region close to opposite side wall. But as in previous cases, the injected nitrogen propagates upwards substantially faster.

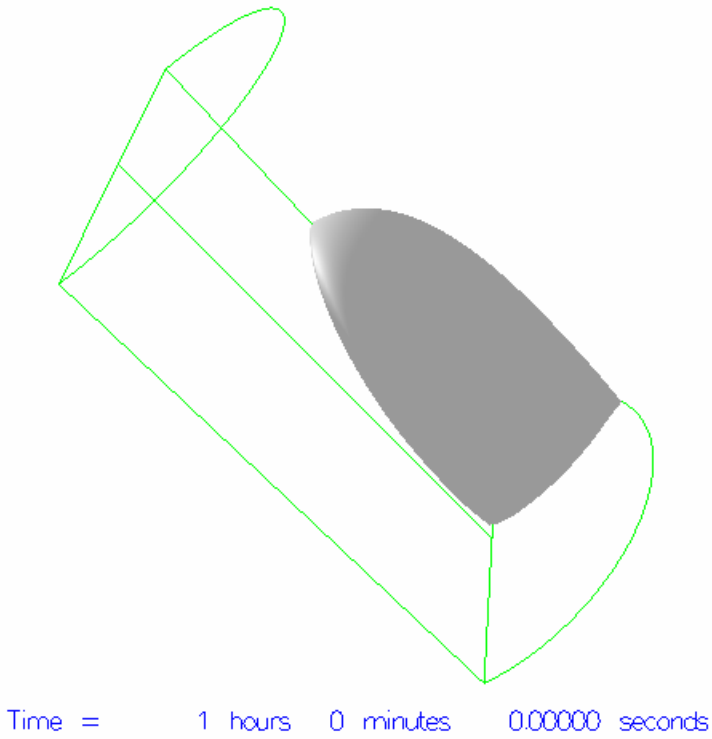


Figure 23 Iso-plot of nitrogen mass fraction at 83% after 1.0 hour of injection

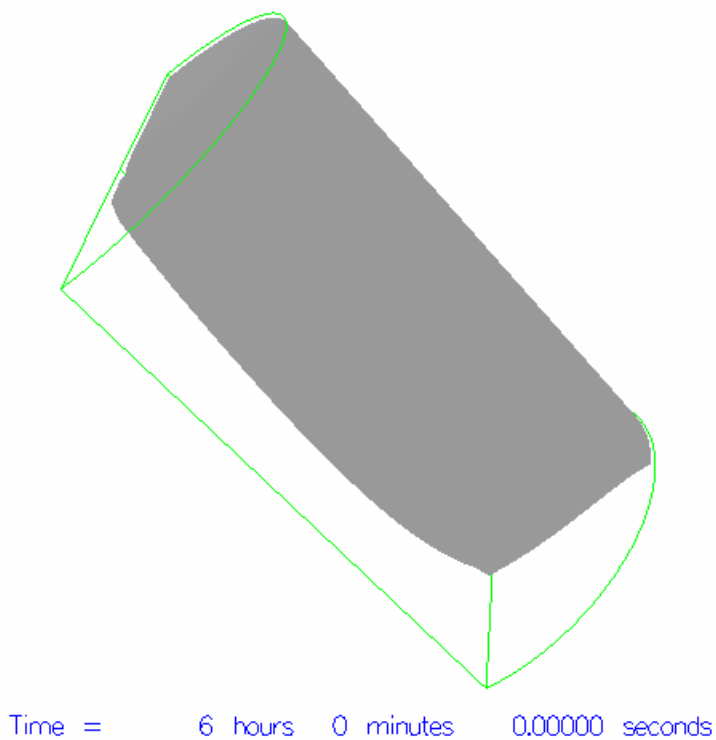
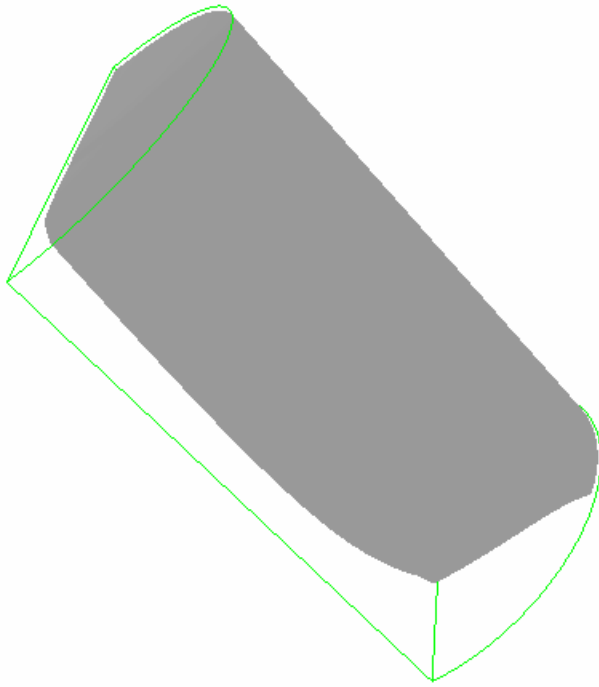


Figure 24 Iso-plot of nitrogen mass fraction at 83% after 6.0 hour of injection



Time = 10 hours 0 minutes 0.00000 seconds

Figure 25 Iso-plot of nitrogen mass fraction at 83% after 10.0 hour of injection

Case 4

In this case, nitrogen is injected from an inlet at the side wall of silo with an injection rate of a 165.8 kg/h (see Table 2). As for the previous case, since the inlet is at the side wall, axis-symmetric condition does not apply and the simulation has to be performed in 3-D where half of the silo is simulated.

Figure 26 plots the variation of nitrogen mass fraction at different heights along the central line of silo. In comparison with results for case 3, the general development of nitrogen mass fraction is similar. Due to higher injection rate, the filling process is correspondingly faster.

Figures 27 and 28 show iso-plots of nitrogen mass fraction at the time of 10 and 50 minutes respectively after injection. These iso-plots show the three dimensional nitrogen distributions. Similarly, the simulation shows that the injected nitrogen is able to reach the whole volume. But as in previous cases, the injected nitrogen propagates upwards substantially faster.

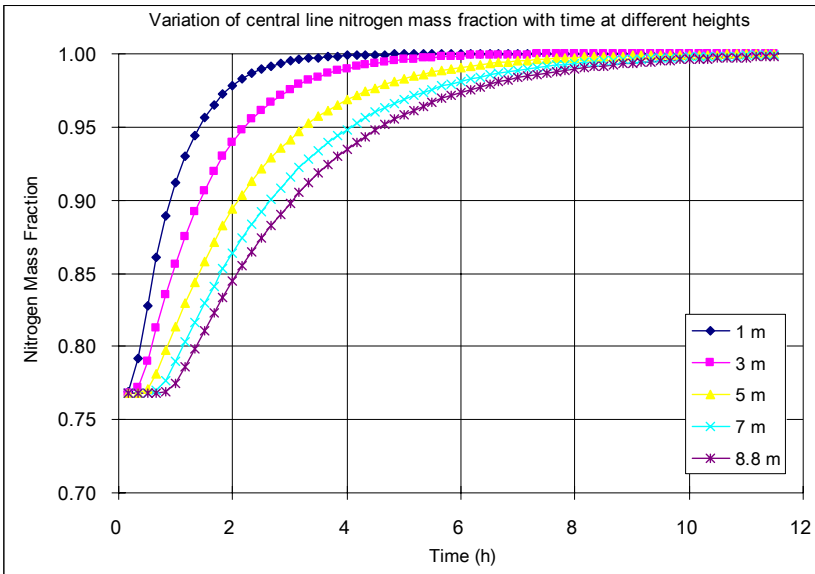
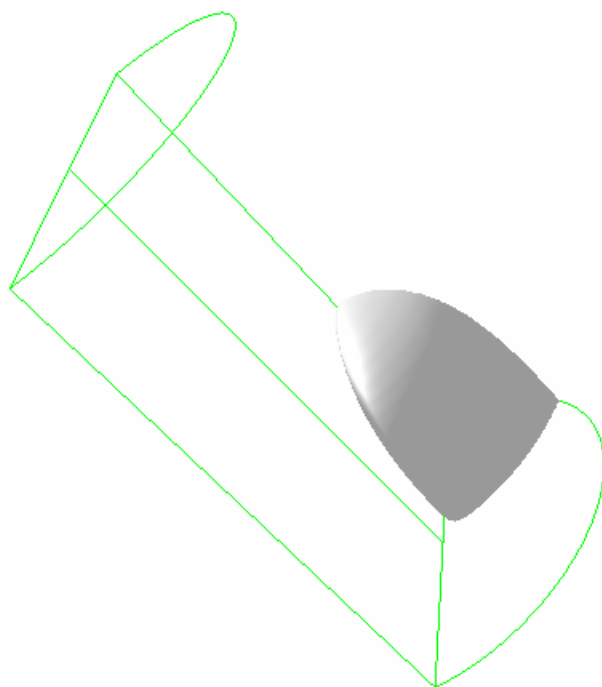


Figure 26 Time variations of nitrogen mass fraction at different heights along central line of silo, for case 4, series 2



Time = 10 minutes 0.00000 seconds

Figure 27 Iso-plot of nitrogen mass fraction at 99.8% after 10 minutes of injection

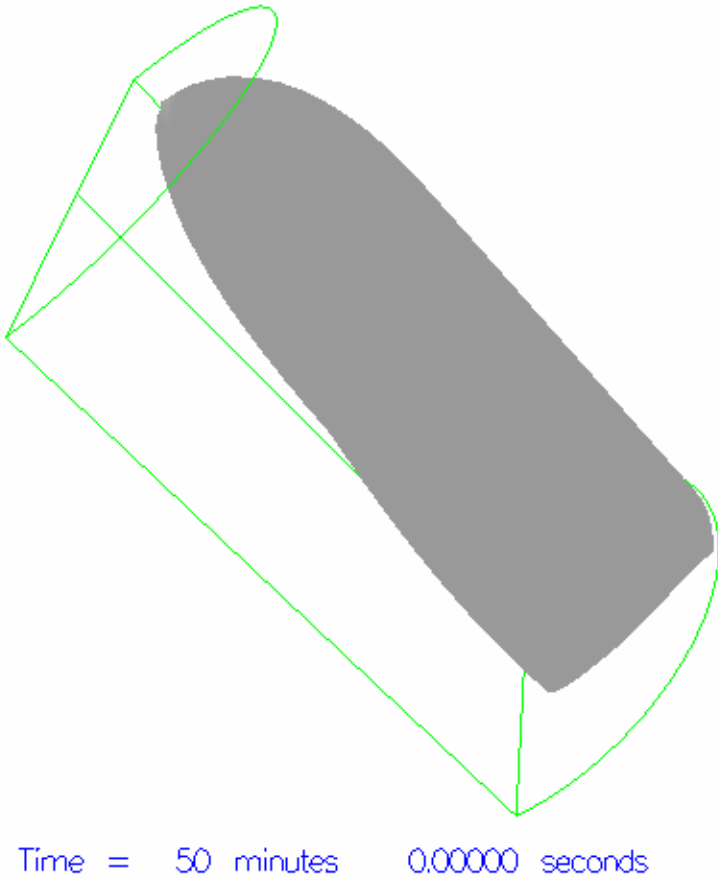


Figure 28 Iso-plot of nitrogen mass fraction at 99.8% after 50 minutes of injection

Comparison with COMSOL simulations and measurement

In this series of simulations, case 1 and 2 were also simulated using *COMSOL* by SP [6]. As for simulations in series 1, a brief comparison is presented below between simulations from *SIMTEC* and *COMSOL* (SP had difficulty to simulate the three-dimensional cases using *COMSOL* and therefore comparison for cases 3 and 4 cannot be available). Figs. 29 and 30 respectively present the spatial distribution of nitrogen concentration for case 1 and case 2 in this series of *COMSOL* simulation. From Figs. 29

and 30, once again, one can see that in *COMSOL* simulations, the injected nitrogen disperses radially at essentially equal speed. There is no apparent directional propagation tendency for nitrogen dispersion. This is a very different picture from what is presented in *SIMTEC* simulations (see Figs. 17, 18, 20 and 21). The *SIMTEC* simulations on the contrary give obvious upward propagation tendency.

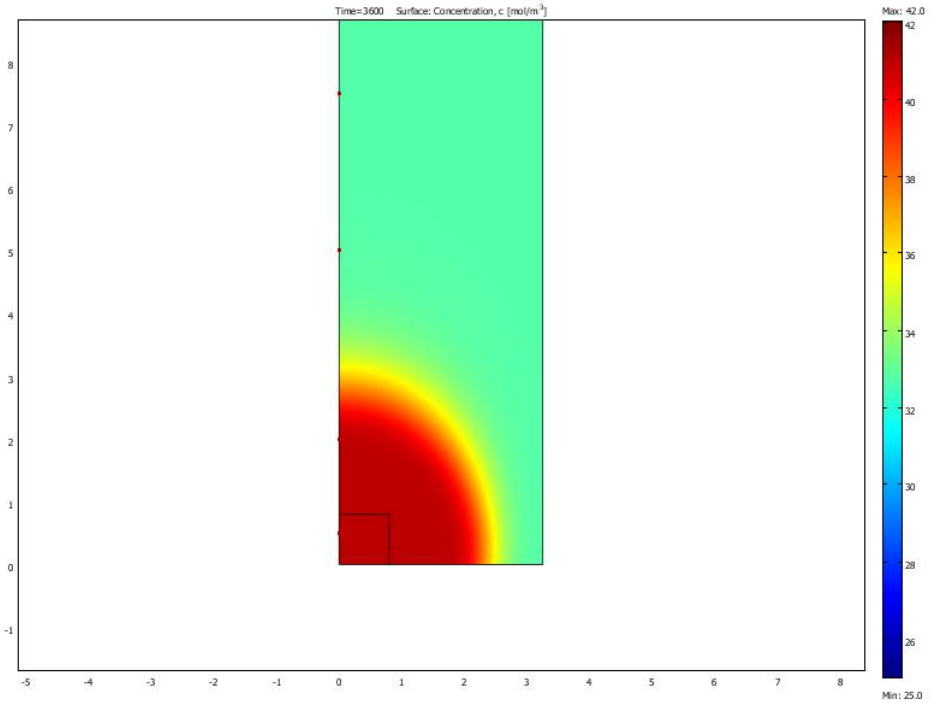


Figure 29 Spatial distribution of nitrogen concentration at time of 1 hour after injection, for case 1, series 2, *COMSOL*'s simulation, from [6]

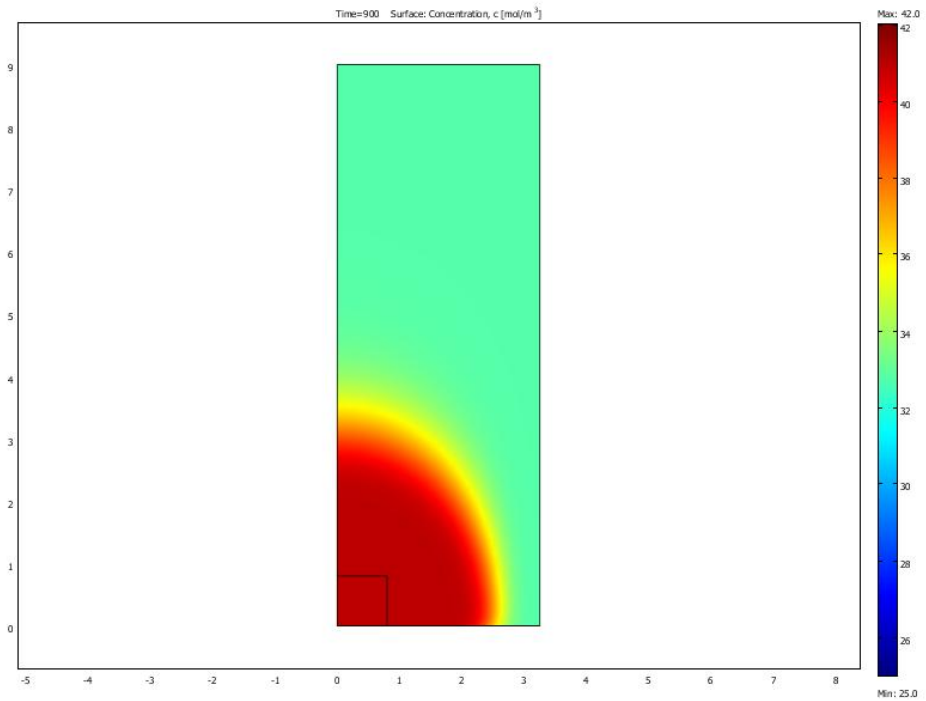


Figure 30 Spatial distribution of nitrogen concentration at time of 15 minutes after injection, for case 2, series 2, *COMSOL*'s simulation, from [6]

While making this brief comparison which reveals a big difference, it may be necessary to examine the simulation using experimental measurement data. After these simulations, experimental tests were performed in Ulricehamn by SP to measure the dispersion of injected nitrogen. At the time of writing this report, the author did not have access to the measurement data. However, the SP colleagues have indicated that the measurement did show the upward propagation tendency for the injected nitrogen. This measurement gives a very good support to *SIMTEC* simulation. More detailed assessment can be made when the experimental data is accessible.

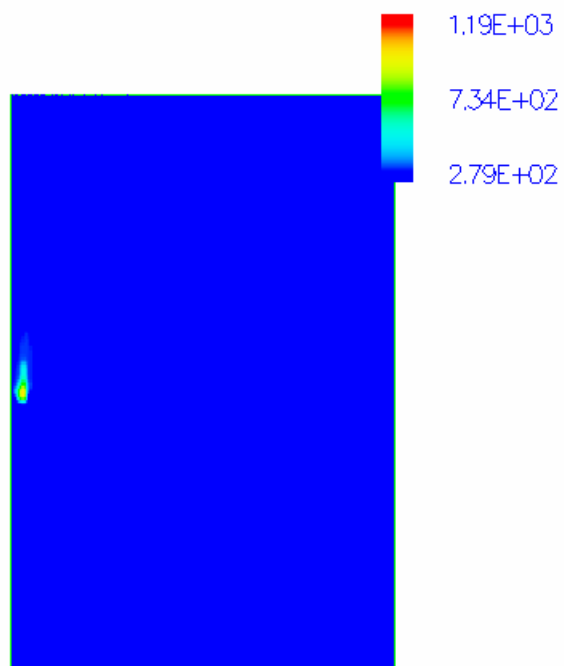
Simulation series 3

In this series, two simulations were made to simulate the nitrogen gas injection under a condition of spontaneous ignition fire. The simulations compute the gas injection process, gas dispersion and also the extinguishment of the fire by the nitrogen. In this series of simulation, in comparison with simulations in series 1 and 2, many more complex processes including the strong interaction between chemical reaction and nitrogen dispersion have to be considered.

Case 1

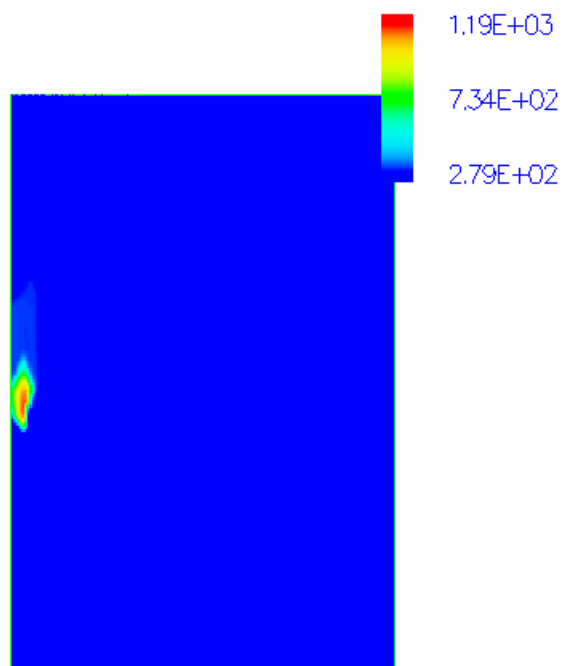
In this case, CFD simulation was then performed to simulate a spontaneous ignition fire and its extinguishment in a large scale wood pellets silo which is 30 m high and 40 m in diameter. There was only one gas inlet at the bottom centre of the silo. This simulated case is similar to the case 5 of simulation series 1 (see Table 1).

Since spontaneous ignition usually has a long initial developing period, to speedup the initial fire process, in the simulation, the fire was started using an external ring shaped heat source of 226.1 kW. Figures 31-34 shows the temporal temperature development. From these figures, one can clearly see downward fire propagation in silo. This downward fire propagation is in a big contrast to upward fire propagation which people may expect and usually see in a conventional fire scenario, but was confirmed by a small scale experiment [4].



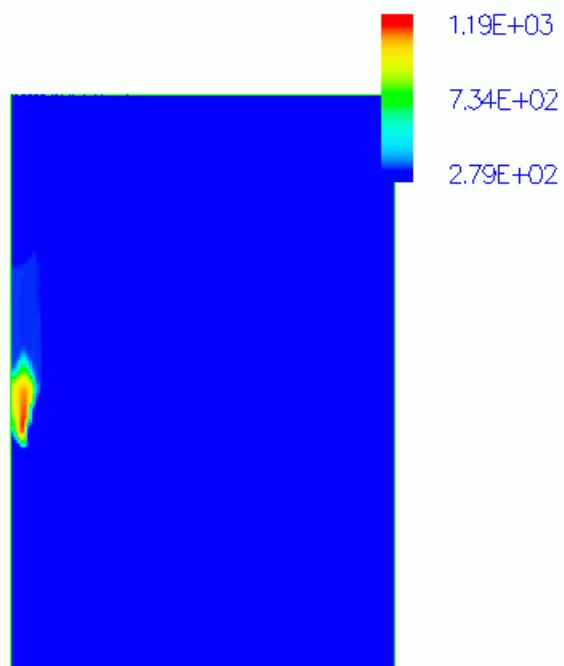
Time = 19 hours 0 minutes 0.00000 seconds

Figure 31 Pellets temperature profile in the silo at 19 hours



Time = 50 hours 0 minutes 0.00000 seconds

Figure 32 Pellets temperature profile in the silo at 50 hours



Time = 69 hours 0 minutes 0.00000 seconds

Figure 33 Pellets temperature profile in the silo at 69 hours

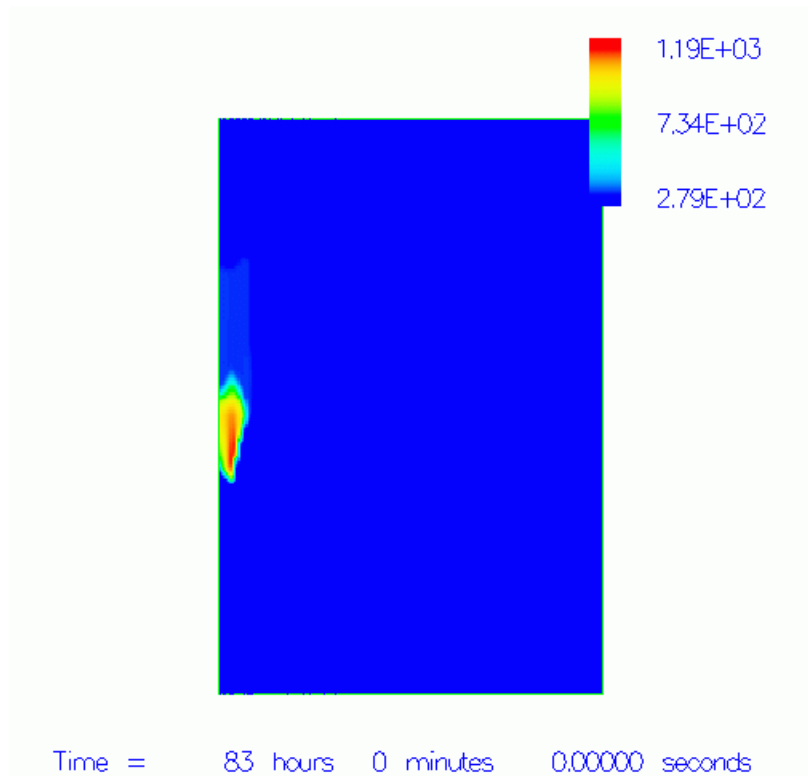
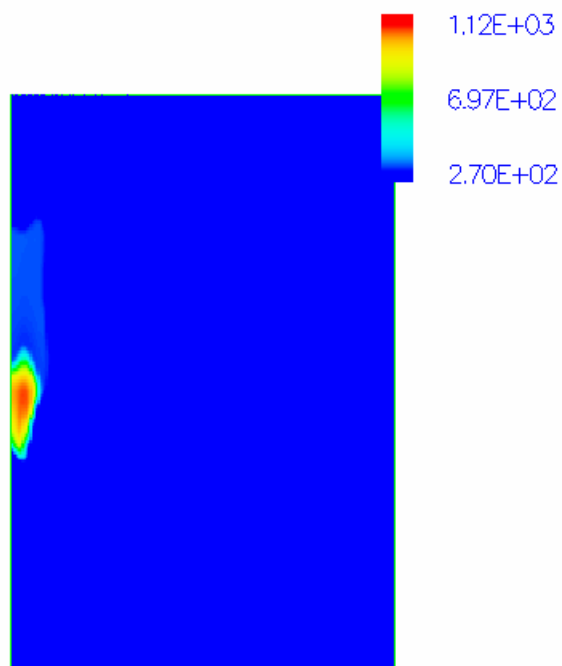


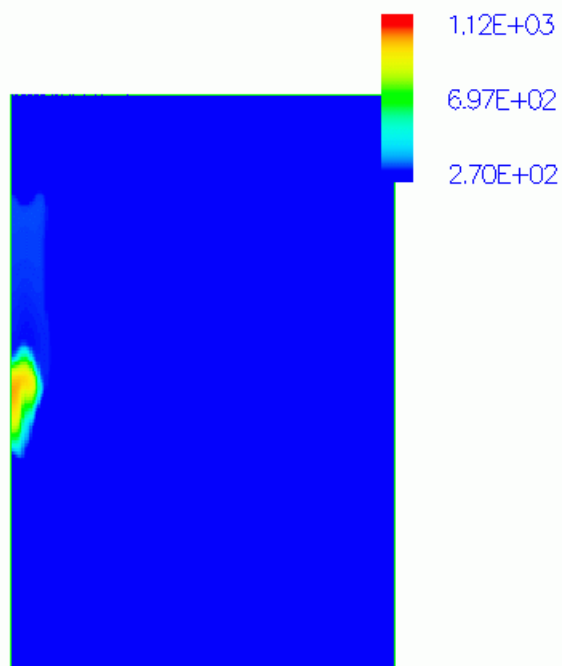
Figure 34 Pellets temperature profile in the silo at 83 hours

After the spontaneous ignition fire development, nitrogen is discharged to extinguish the fire at time of about 83 hours. Figures 35-37 shows the fire extinguishment after nitrogen discharge, where the temperature drops due to suppression of combustion.



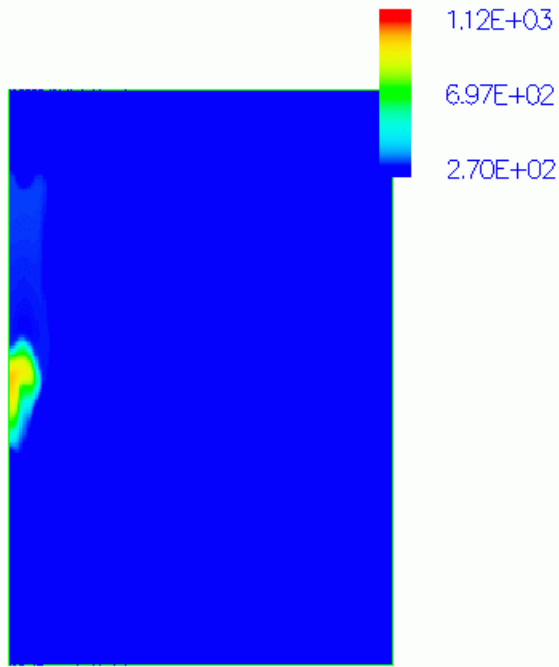
Time = 90 hours 0 minutes 0.00000 seconds

Figure 35 Pellets temperature profile in the silo at 90 hours



Time = 109 hours 0 minutes 0.00000 seconds

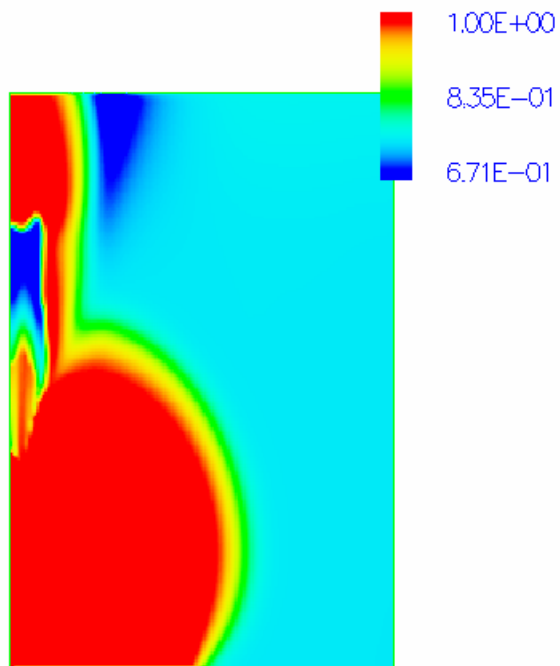
Figure 36 Pellets temperature profile in the silo at 109 hours



Time = 123 hours 0 minutes 0.00000 seconds

Figure 37 Pellets temperature profile in the silo at 123 hours

The drop of temperature is due to discharge of nitrogen which inhibits the combustion. The suppression of combustion is highly affected by the distribution of injected nitrogen in the silo. Figures 38 and 39 show the distribution of injected nitrogen in the silo at different times. As can be seen, with spontaneous ignition fire, due to important effect of the fire, the distribution of injected nitrogen can be very different from the distribution of injected nitrogen at the case without fire.



Time = 90 hours 0 minutes 0.00000 seconds

Figure 38 Nitrogen mass fraction profile in the silo at 90 hours

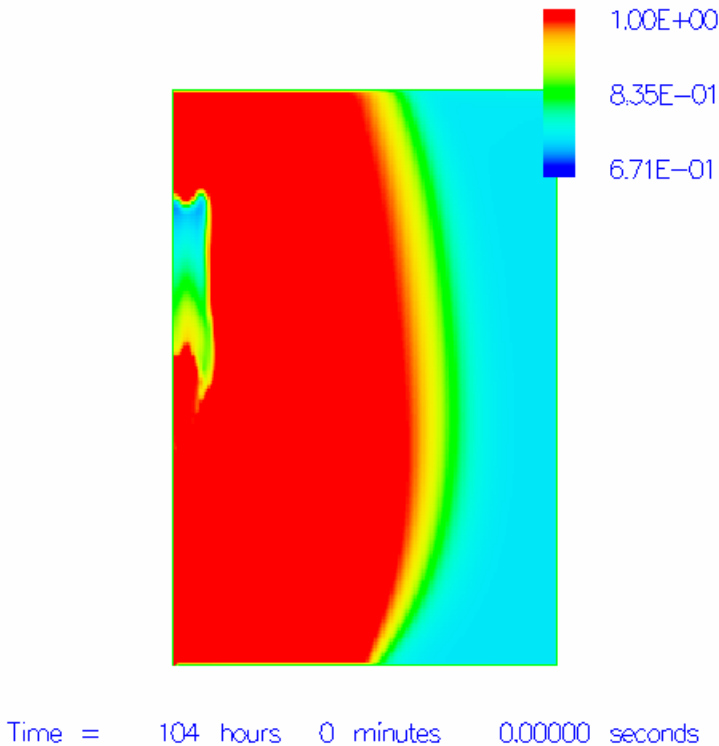


Figure 39 Nitrogen mass fraction profile in the silo at 104 hours

Case 2

In this case, CFD simulation was then performed to simulate a spontaneous ignition fire and its extinguishment in a tower-shaped wood pellets silo which is 40 m high and 8 m in diameter. As in case 1, there was only one gas inlet at the bottom centre of the silo.

The overall simulation is similar to that in case 1. First, to speedup the initial fire process, in the simulation, the fire was started using an external ring shaped heat source of 226.1 kW. After the fire development, nitrogen is injected to extinguish the fire. These processes were computed in the simulation to investigate how the fire would develop and how it would be extinguished by the injected nitrogen.

Figures 40-42 shows the temporal temperature development. From these figures, as for case 1, one can clearly see downward fire propagation in silo.

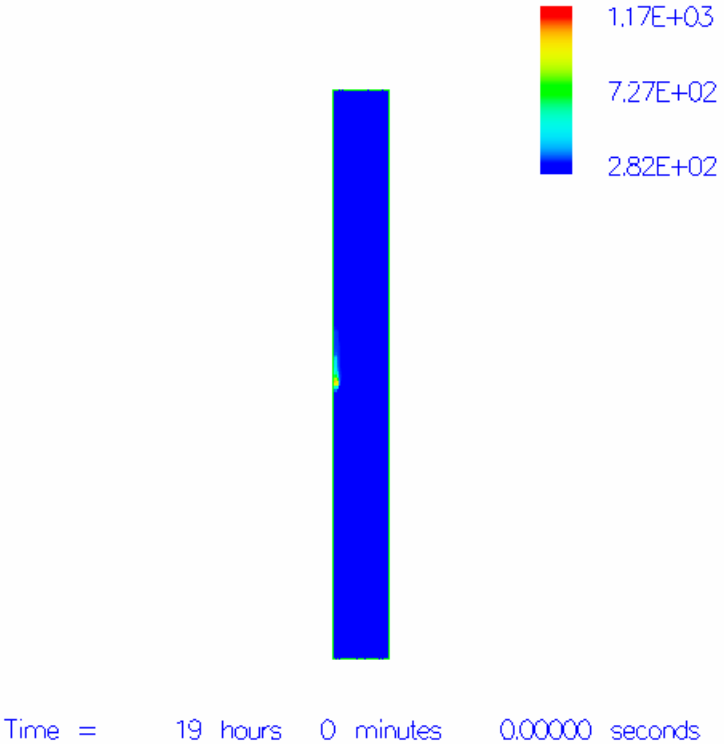


Figure 40 Pellets temperature profile in the silo at 19 hours

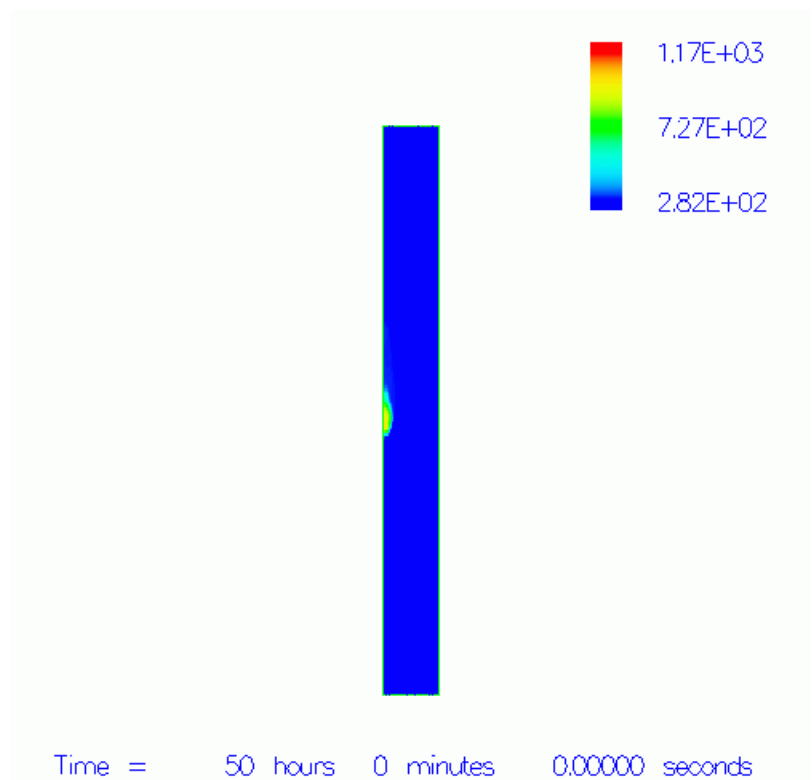


Figure 41 Pellets temperature profile in the silo at 50 hours

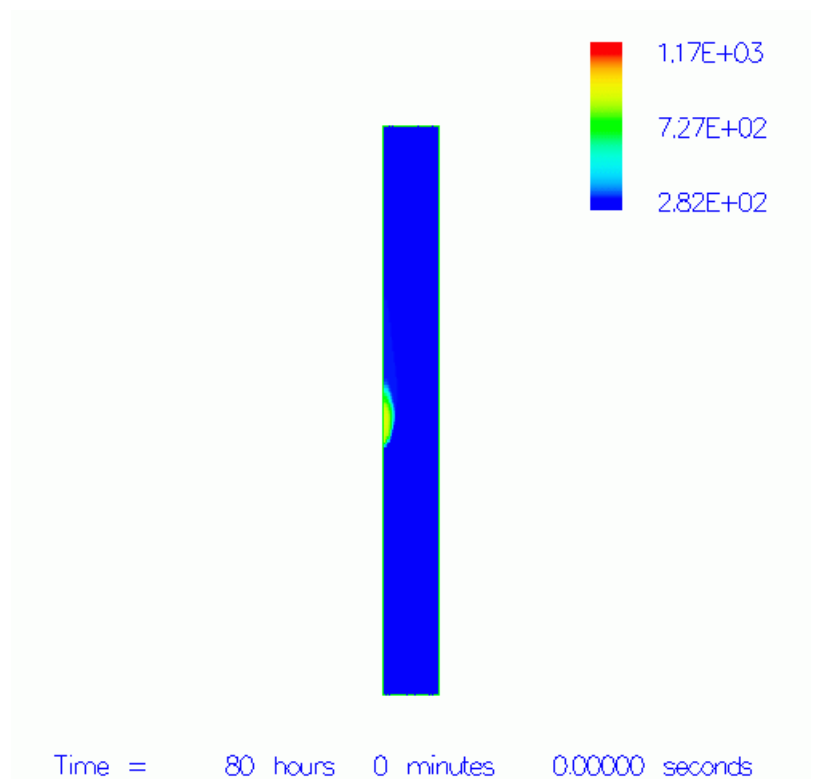


Figure 42 Pellets temperature profile in the silo at 80 hours

As for case 1, after the spontaneous ignition fire development, nitrogen is discharged to extinguish the fire at time of about 83 hours. Figures 43 and 44 shows the fire extinguishment after nitrogen discharge, where the temperature drops due to suppression of combustion.

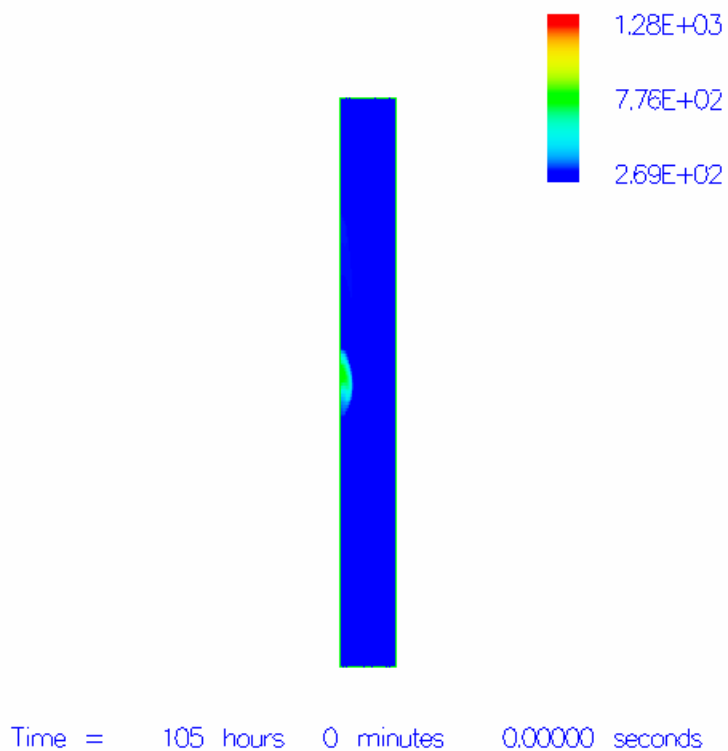


Figure 43 Pellets temperature profile in the silo at 105 hours

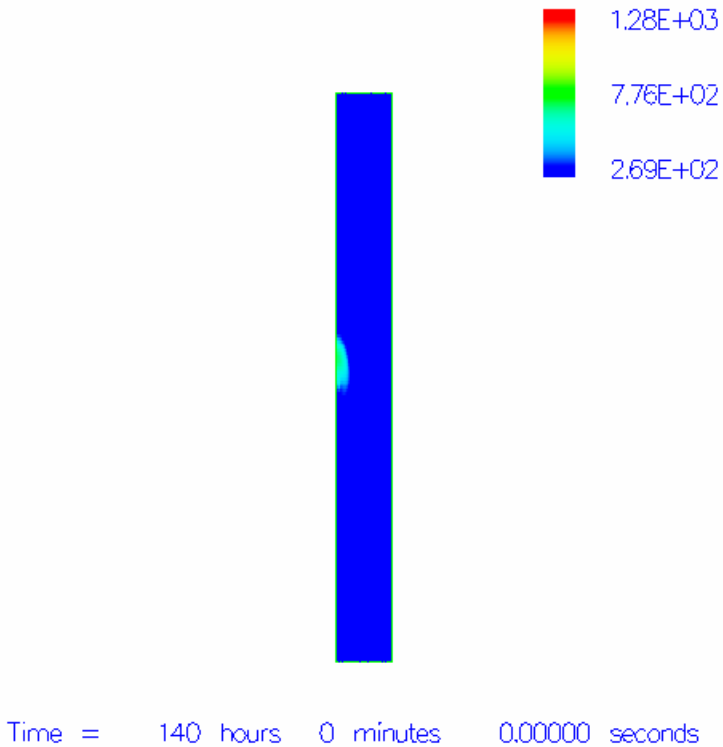
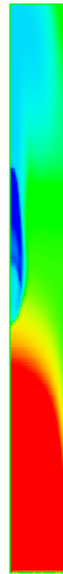
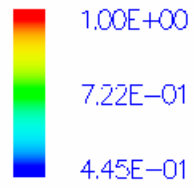


Figure 44 Pellets temperature profile in the silo at 140 hours

In order to characterize the fire extinguish process by the injected nitrogen, the distribution of injected nitrogen in the silo at different times are plotted and shown in Figs. 45 and 46.



Time = 84 hours 0 minutes 0.00000 seconds

Figure 45 Nitrogen mass fraction profile in the silo at 84 hours

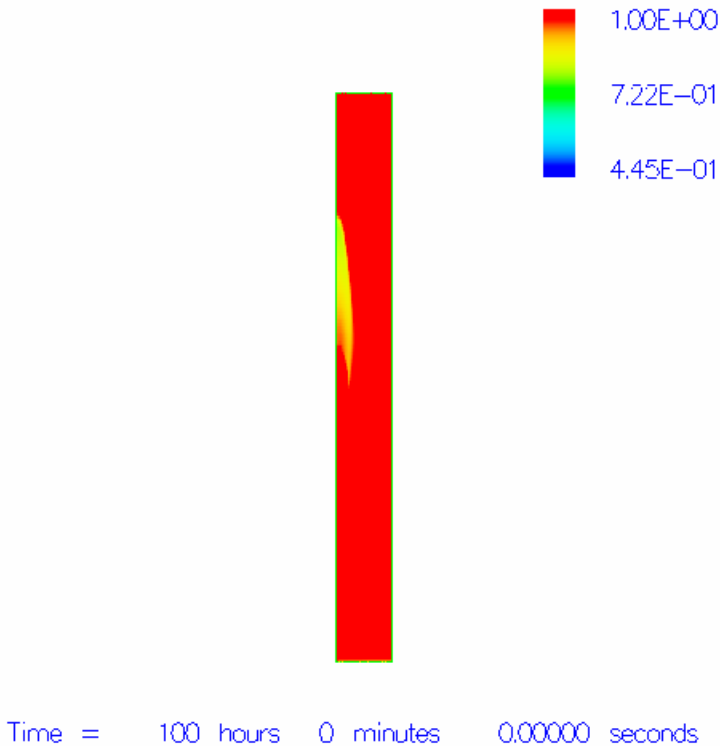


Figure 46 Nitrogen mass fraction profile in the silo at 100 hours

Comparison with COMSOL simulations

No such simulation using *COMSOL* is available. As a result, no comparison can be made between simulations using *SIMTEC* and *COMSOL*. Meanwhile, for this series of simulations, no experimental data is available either. Therefore, the *SIMTEC* simulations can not be compared with measurement. However, before performing this series of simulations, as presented earlier in this report, *SIMTEC* was validated using a smaller scale experiment with similar conditions.

CONCLUSIONS

A series of CFD simulations were carried out using *SIMTEC* [1] to study the spontaneous ignition fire and its extinguishment. Different cases were computed with and without spontaneous ignition fire. In general, the spontaneous ignition fire propagation, the extinguish gas discharge and the extinguishment of the spontaneous ignition fire by the discharged extinguish gas were all well computed in the simulation.

For the cases with spontaneous ignition fire, the simulation predicted downward fire propagation and the gradual extinguishment of the fire by injected inert gas. This predicted phenomenon was confirmed in a small scale experiment. Meanwhile, simulation also reveals that the injected inert gas distribution can drastically be changed by the spontaneous ignition fire, particularly around the important fire zone.

For the cases without spontaneous ignition fire, the simulation shows important effects of gas discharge rate and inlet location on the extinguish gas distribution. As expected, with higher injection rate, the inert gas filling in the silo becomes faster. The injected gas can have very different distribution patterns when injected from silo side and bottom. The simulations presented in this report also show that when injected at the bottom center of silo, the lateral propagation of injected nitrogen towards silo side can seriously be limited by the side wall and it can be difficult for the injected nitrogen to reach the far side in the silo. Instead, the injected nitrogen can have strong upward propagation tendency. This predicted extinguish gas distribution pattern is in consistence with the available experimental measurement which was performed after simulation.

ACKNOWLEDGEMENT

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