Swedish PRISME project – Part 4 – Results of benchmark exercises at LTH

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Abstract

Fires in nuclear power plants can be an important hazard for the overall safety of the facility. One of the important aspects is the effect of ventilation on the fire and vice-versa. Research was with this aspect in mind performed in the PRISME project supported by OECD/NEA. As part of the project also a Swedish research project was initiated. This report is the part, which summarizes the validation work performed at Lund University within the benchmark group of the project and includes both the two benchmark simulations and a blind simulation of one of the Integral tests.

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Preface

This report, part 4, is one of the reports within the Swedish research project of the PRISME project. The different reports are:

- Swedish PRISME project – Part 1 -Overview and Summary of Tests and Results – Report 3154
- Swedish PRISME project – Part 2 - Use of test results from PRISME for practical applications in Sweden – Report 3155
- Swedish PRISME project – Part 3 – Results and use of overall benchmark exercises in PRISME – Report 3156
- Swedish PRISME project – Part 4 – Results of benchmark exercises at LTH – Report 3157
- Swedish PRISME project – Part 5 – Results of benchmark exercises from other partners in PRISME – Report 3158

Due to the OECD/NEA rules some of these reports can only be published 5 years after finishing of the contract and are as such confidential until January 1st 2015.

This report deals with an overview of all the validation activities, which were done by LTH in the benchmark group and as support to the benchmark exercises. It does not give the results of the overall benchmark exercise, which are given in Part 3.

This report would not have been possible without support from all partners in the OECD partners and especially IRSN who was willing to allow us to use pictures and photos from their publications.

The Swedish part of the PRISME project was possible thanks to financial support of Brandforsk (Swedish Board for Fire Research) and NBSG (National Fire Safety Group, with representation of Strålsäkerhetsmyndigheten SSM, Svenskt KärnBränsle SKB, Forsmark- Oskarshamn- Ringhals nuclear power plants). Also parts of the validation work were possible thanks to support of SSF (Strategic Research Fund).

Lund, 15 December 2011.

Patrick van Hees

Jonathan Wahlqvist

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REFERENCES

ACRONYMS

1. Introduction

1.1. Background

The PRISME project [1] is an OECD/NEA project with participation of the following countries:

- Belgium
- Canada
- Finland
- France
- Germany
- Japan
- Netherlands
- Republic of Korea
- Spain
- Sweden.
- United Kingdom
- United States

The budget of the project was 7 M€ and the project time of the project was from January 2006 to June 2011. The major PRISME project financed fire tests at IRSN (France). A project and management group was installed by means of the contract and had meetings at least twice a year. During the meetings the technical content and scope of the project was discussed.

The PRISME acronym is the French acronym for "**Pr**opagation de l'**I**ncendie lors de **S**cénarios **M**ulti-locaux **E**lémentaires" which is translated as "Fire Propagation in Elementary Multi-room Scenarios". The project mainly aims on studying smoke and hot gases propagation in full scale, well confined and mechanically ventilated fire compartments

The PRISME project consisted of a series of fire and smoke propagation tests in a dedicated facility at the French Institut de radioprotection et de sûreté nucléaire (IRSN) centre at Cadarache, France. The facility is used to investigate room-to-room heat and smoke propagation, the effect of network ventilation and the resulting thermal stresses to sensitive safety equipment of such room configurations. It is also planned to use data from the project to study multi-room fires and for validating fire computer codes and this will be part of another sub-report of this series (Part 3).

Several propagation modes were being studied: through a door; along a ventilation duct that crosses the room containing the fire and that ventilates an adjacent room; along a ventilation duct when flow is reversed within; and through leakages between several rooms.

Apart from the project, which incorporated the fire test, a separate project dealing with validation was conducted. This project was not covered by a contract but

conducted based on national resources. However it used only the test data from the OECD/NEA PRISME project

The motivation and need for benchmarking comes from the fact that use of CFD (computational fluid dynamics) software packages within fire performance based engineering and risk assessment is increasing substantially. An important part in the process is the quality assurance. This validation work is a part of a larger effort [7] to quantify comparisons between several computational results and measurements performed during a pool fire scenario in a well-confined compartment with forced ventilation. Fires in enclosures equipped with forced (or mechanical) ventilation remain one of the key issues for fire safety assessment in the nuclear industry. The ventilation system ensures confinement by setting an appropriate pressure cascade. The scenario of a fire in a confined and ventilated enclosure is a typical hazard during which the pressure may vary to an extent where it modifies the confinement levels and hence the safety of the installation. An understanding of the mechanisms leading to pressure variations during a fire scenario is of prime interest. Few validation efforts have been done up to now.

1.2. Scope

1.2.1. PRISME OECD project

The project (citation from reference 1) aims to provide such critical information as the time that elapses before target equipment malfunctions and to qualify computer codes modelling heat and smoke propagation phenomena. The objective is to answer questions concerning smoke and heat propagation inside an installation, by means of experiments tailored for code validation purposes. In particular, the project aims to provide answers to the following questions:

- What is, for a given fire scenario, the failure time for equipment situated in the nearby rooms that communicate with the fire room by the ventilation network and/or by a door (which is open before the fire or opens during the fire)?
- Is it valid to assume that no propagation occurs beyond the second room from the fire room when the rooms communicate through doors, and beyond the first room when rooms communicate only by the ventilation network?
- What are the safety consequences of the damper or door failing to close, or of an intervention delay which is too long?
- What is the best way to operate the ventilation network in order to limit pressure-driven phenomena and releases to nearby rooms?
- Is it the admission damper closing following fire detection? Is it the extraction damper closing when the temperature threshold of filters has been reached or when the filters are plugged?

The results obtained will be used as a basis for qualifying fire codes (either simplified zone model codes or computerised fluid dynamics codes used in the fire safety analysis of nuclear installations and plants). After qualification, these codes could be applied for simulating other fire propagation scenarios in various room configurations with a good degree of confidence. The information will be useful for designers in order to select the best fire protection strategy. For the operators, this

data could be useful for establishing the suitable operation of the plant, such as the operation of the ventilation network (e.g. closing dampers to reduce the ventilation flow rate or to stop the ventilation) in case of a fire.

1.2.2. Swedish PRISME project

The main scope of the Swedish PRISME project was mainly to assess and determine the CFD tools used for fire safety evaluations in buildings and constructions where similar fire scenarios will occur as in the PRISME project.

The objectives were covering three parts:

1. Validation of CFD tools in the scenarios within the PRISME project (mainly FDS [2, 3] but possibly also other CFD tools e.g. Ansys-CFX [5]). This will be limited to the scenarios and exercises within the PRISME project. The results will give further input and improvement of the quality manual for fire safety evaluations.
2. Dissemination of the test results within the PRISME project to the Swedish fire community by reporting to the NBSG and presenting at the NBSG meetings.
3. Participate in the benchmark group meetings and other PRISME meetings.

The project consisted of three work packages:

1. Validation of CFD codes.
2. Dissemination of the results
3. Reporting

1.2.3. Scope of this project

The scope of the project is to report the validations performed within the Swedish part of the PRISME project. This report covers therefore item 1 of the scope of the Swedish PRISME project.

The purpose of this work was to compare the experimental data and the numerical results from the fire test with simulations done with FDS 5.5.3 (SVN 7170) [2, 3] and ANSYS-CFX version 13.0 using the SAS-SST turbulence model [5]. One specific goal was to predict the behaviour of the ventilation system, for example backflows, using the new HVAC capabilities in FDS [4]. The importance of room leakages was also studied as this greatly affects the pressure in the fire room, which in turn affects the ventilation system behaviour

1.3. Method

The experimental scenario (figure 1) was conducted at the French "Institut de Radioprotection et de Sûreté Nucléaire" (IRSN). The quantitative comparisons between measurements and numerical results obtained from "open" calculations concerned six important quantities from a safety viewpoint: gas temperature, oxygen concentration, wall temperature, total heat flux, compartment pressure and ventilation flow rate during the whole fire duration. The fire source [10] consisted of a 0.4 m^2 steel pan filled with hydrogenated tetra propylene (TPH), an isomer of n-dodecane. The walls, ceiling and floor of the room were 30 cm thick and made out of concrete. During the experiment, rock wool (THERMIPAN) with a thickness of 5 cm insulated the ceiling to prevent damage to the facility. The ventilation system in

the fire room included a blowing branch and an exhaust branch, the relative static pressures and volume flow rates was recorded before the fire was ignited and was later used as input data in FDS.

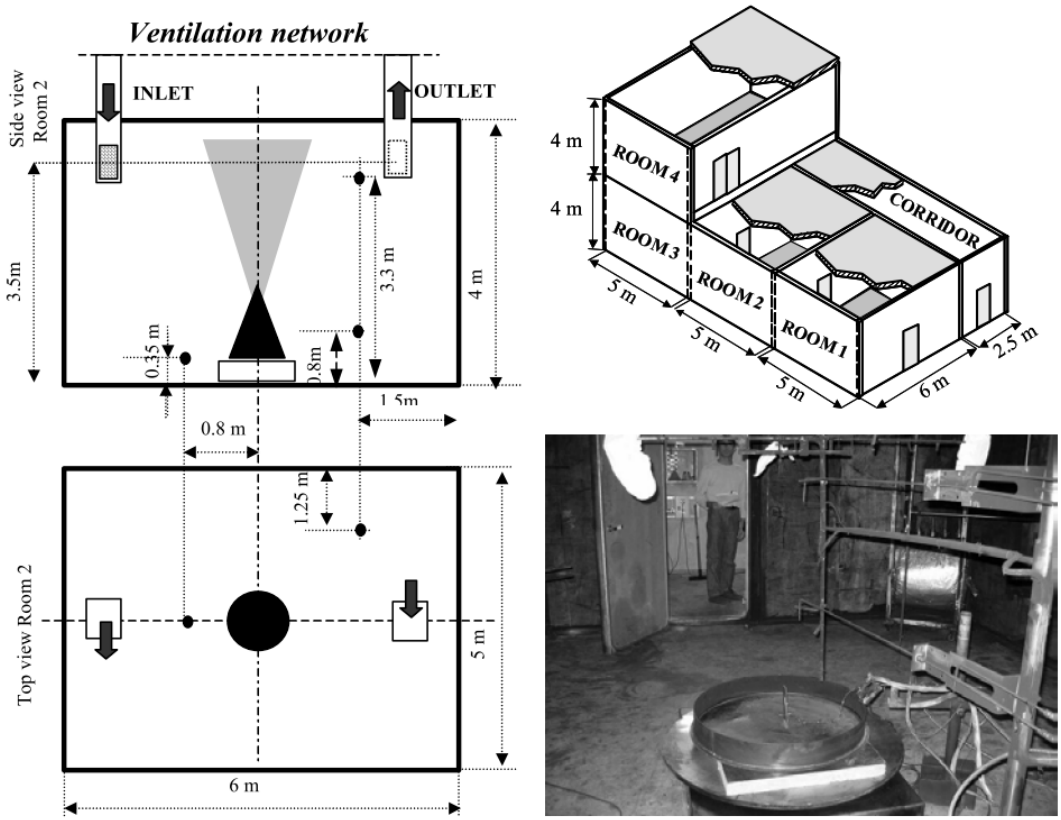

Figure 1 Overview of the experimental setup (courtesy of IRSN).

As calculation methods both FDS and ANSYS-CFX were used. For further information on these models the reader is referred to the manuals of these programmes.

2. Benchmark Exercises in the PRISME project

In total 3 benchmarks exercises were performed in the PRISME project. Information on the details of these benchmark exercises can be found in part 3 of the report series.

The benchmark exercises are summarised in the following paragraphs.

2.1. Benchmark 1

Benchmark 1 [6] focused on validation of the PRISME Source and Door tests.

Originally benchmark 1 would consist both of open and blind simulations:

- Open calculations on three PRISME Source tests,
- Blind calculations on two PRISME Door tests.

In a first step the blind simulations were abandoned. The open simulation would first contain both the simulation with the HRR from the open calorimeter and HRR from the tests but the final benchmark only contained open simulation of the PRISME SOURCE-D1 tests where HRR and ventilation conditions during the test could be used as boundaries. For the final paper in total 17 participants took part from 12 organisations. 8 numerical codes were used (3 CFD, 1 lumped code and 4 zone models). The different participations are given in Table 1.

	T_{mean}	X_{O_2}	T_w	P_{th}	Q_{adm}
CFD 1 [CSN, FDS]	o	o	o		
CFD 2 [JNES, FDS]	o	o	o		o
CFD 3 [IBMB, FDS]	o	o	o	o	o
CFD 4 [NRG, FDS]	o	o	o	o	o
CFD 5 [Trac., FDS]	o	o	o		
CFD 6 [Lund Uni., FDS]					
CFD 7 [VTT, FDS]	o	o	o		
CFD 8 [KINS, FDS]	o	o			
CFD 9 [DGA, SAFIR]					
CFD 10 [IRSN, ISIS]	o	o	o	o	o
LC 1 [GRS, COCOSYS]	o	o	o	o	o
ZC 1 [JNES, CFAST]	o	o	o	o	o
ZC 2 [BEL V, CFAST]	o	o	o	o	o
ZC 3 [NRG, CFAST]	o	o	o	o	o
ZC 4 [DGA, OEIL]	o	o	o	o	o
ZC 5 [EDF, MAGIC]	o	o	o	o	o
ZC 6 [IRSN, SYLVIA]	o	o	o	o	o

Table 1 Overview of participants in BE1

2.2. Benchmark 2

The second numerical exercise conducted by the OECD PRISME Benchmarking Group (PBG) aimed at studying the behaviour of some relevant responses given by fire models in function of input factors. A briefly description of the two benchmarks performed by the PRISME AWG is provided in [6] and a technical specification of

this exercise can be found in [9]. A complete description of the fire test experiment is available in [6] or [9]. In this second numerical exercise, a sensitivity analysis of fire models was performed, by using a fractional factorial design to generate numerical samples. The statistical tool SUNSET, developed at IRSN [8], was used to determine the regression coefficients of the linear regression. This exercise has involved 12 organizations and 6 fire models detailed in Table 2

Organization	Code	version	Organization	Code	version
CSN	FDS	4.06	**BelV**	CFAST	6
iBMB	FDS	5	**JNES**	CFAST	6.1
JNES	FDS	4	**NRG**	CFAST	6
LUND U.	FDS	5.4.0	**EdF**	MAGIC	4.1.3
NRG	FDS	4	**Tractebel**	MAGIC	4.1.3
VTT	FDS	5.4.3	**IRSN**	SYLVIA	1.4
GRS	COCOSYS	2.4 beta 5	**DGA**	OEIL	1.5.1

Table 2 Overview of the participating members in BE2

2.3. Benchmark 3

The last benchmark exercises started only recently and cannot be reported. Results will only be discussed and reported in the PRISME 2 project.

3. Benchmark Exercise 1

3.1. Computer Resources at LTH

All simulations were run on clusters provided by Lunarc. Lunarc is a centre for scientific and technical computing for research at Lund University. The centre provides computational resources for academia in Sweden within all aspects of computational science. Lunarc has been in operation since 1986. As of 2003, the services are synchronized with five other centres within the Swedish National Infrastructure for Computing, SNIC, www.snic.vr.se. One of the major collaborations is Swegrid, see www.swegrid.se. The FDS programme was compiled on the cluster in order to obtain maximal efficiency.

3.2. Summary of work within BE 1

LTH jointed the project at the end of 2008 when this benchmark exercise was already ongoing and it took time to catch up the information of the project. In April 2009 a plan for the BE1 work and the Swedish part of PRISME was given in the PRG and PRB meetings. LTH started with the simulation as given in the first BE1 tasks that is using the HRR from the open pool fire and applying it on the Source D1 and D3 test. Then the simulations for the BE1 paper were made using the HRR and ventilation from the test. Finally the ventilation module in FDS was investigated in the project as well as a first try with ANSYS CFX.

3.3. Preliminary simulations within BE 1 with original plan

3.3.1. Information on the simulations

In these simulations the Source D1 and Source D3 was simulated on the Lunarc cluster with the FDS 5.2 December 2008 version. The conditions of these runs are the following:

- MPI version of FDS 5.2 compiled with Linux Intel v 10 compiler and MPI library
- Run on the LUNARC Milleotto cluster which has the following characteristics:
  - 252 nodes with 4 processors per node.
  - Each processor is an Intel Xeon 5160 with a clock frequency of 3.0 Ghz.
  - The memory is 4 GB per node
  - The system was started up in March 2007

The Information used from the background document of IRSN was used for boundary conditions, i.e. ventilation rate with the boundary condition volume flow rate and HRR from the open pool fire source.

- Coarse grid of 10 by 10 by 10 cm
- Renewal of ventilation as in document
- No interaction of ventilation i.e. the ventilation rate was fixed.
- No radiation calculation as well as adiabatic walls which was done in order to save time at that stage

The geometry for these simulations can be seen in Figure 2

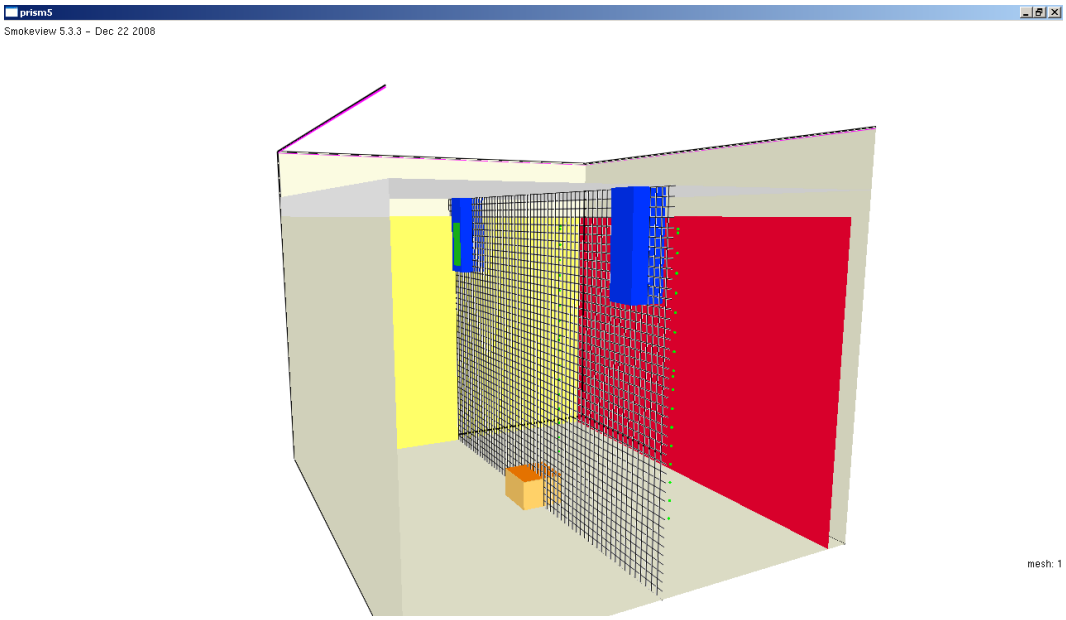

Figure 2 Geometry for the preliminary simulations

3.3.2. Results

In Figure 3 on the left the HRR can be see from the beginning of the test where the fire still has enough oxygen to burn. On the right the HRR is shown when the fire is ventilation controlled. In this case FDS gives only spots of flames and they are closer to the ventilation duct where the fresh air comes into the room.

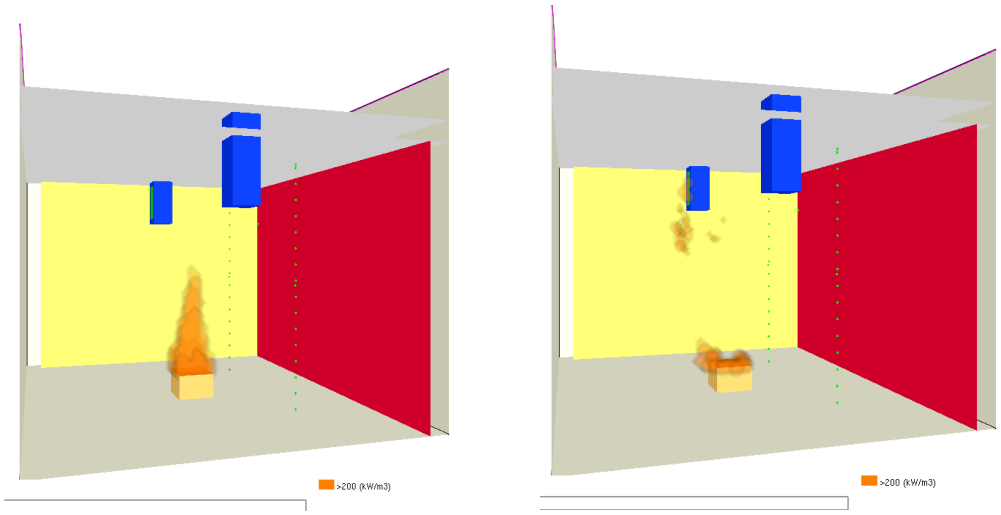

Figure 3 View of the HRR at the start of the test (left) and after the fire became ventilation controlled (HRR)

Figure 4 shows the difference between the HRR measured in the test and the HRR from the FDS simulation for test Source D1. As can be seen, FDS is reducing the HRR at a certain moment when conditions are becoming underventilated but the levels are somehow different.

Figure 5 shows the difference for the same test and the FDS simulation for the smoke layer. While in the test the smoke falls almost down to zero, FDS has still a

smoke layer of about 0.5m. Figure 6 shows the different in the hot layer temperature where the difference is around 100 degrees C.

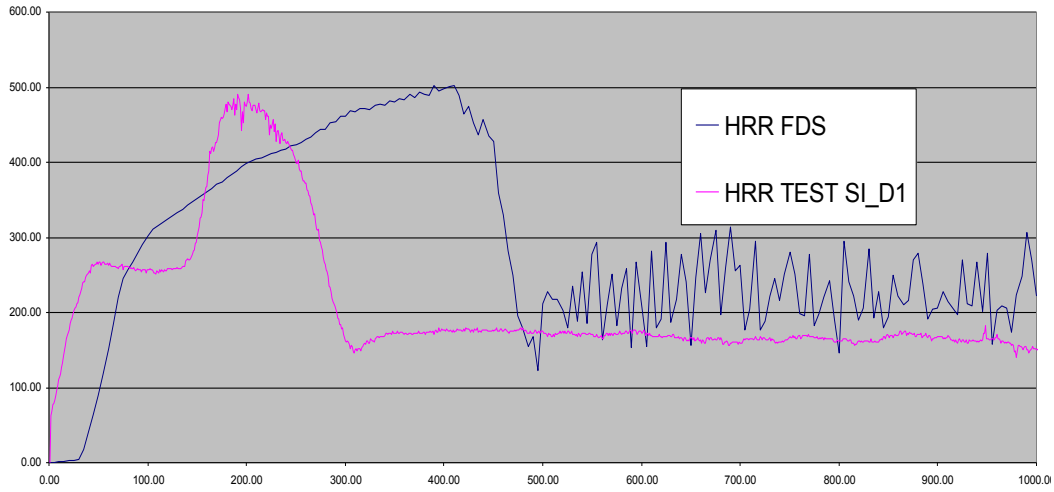

Figure 4 Comparison of HRR between Source D1 test and FDS simulation

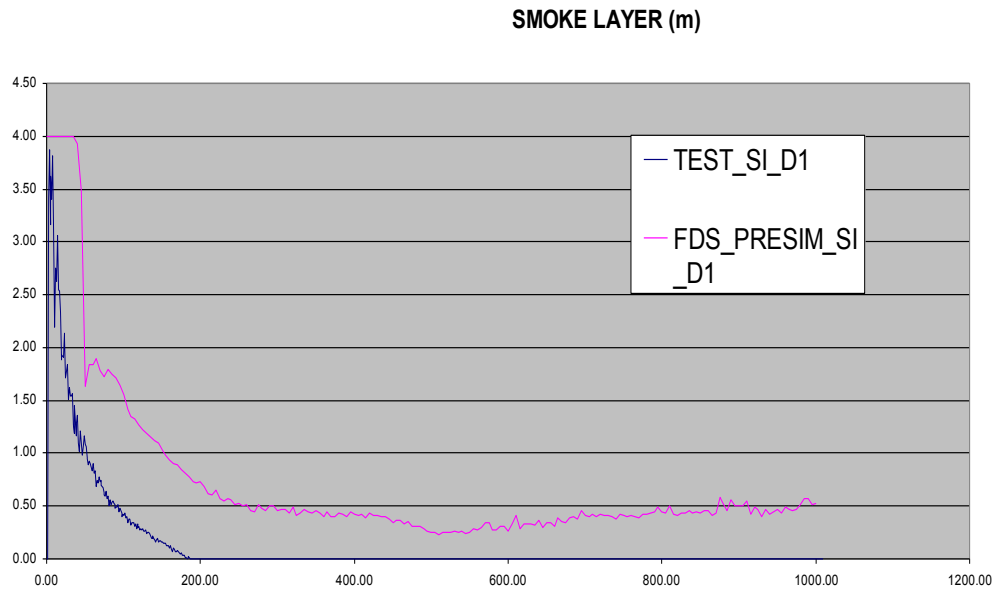

Figure 5 Comparison of smoke layer height between Source D1 test and FDS simulation

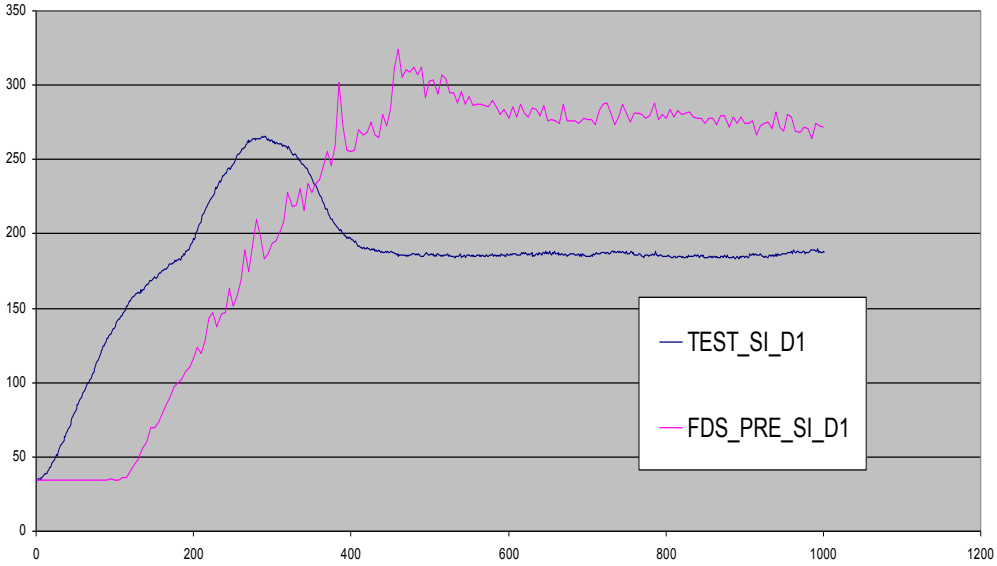

Figure 6 Comparison of hot layer temperature between Source D1 test and FDS simulation

Figure 7 shows the difference between the HRR measured in the test and the HRR from the FDS simulation for test Source D3. As can be seen, FDS is reducing the HRR at a certain moment when conditions are becoming underventilated but the levels are somehow different. In fact in the test the HRR is almost zero while FDS still has a value of around 50 kW.

Figure 8 shows the difference for the same test and the FDS simulation for the smoke layer. While in the test the smoke falls almost down to zero, FDS has still a smoke layer of about 0.5m and the time scale is different. Figure 9 shows the different in the hot layer temperature where the difference is around 100 degrees C.

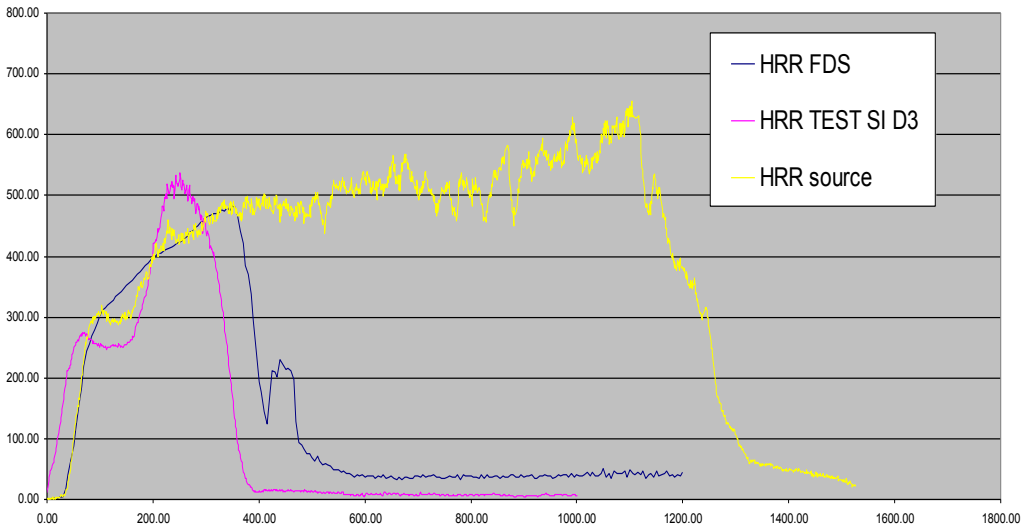

Figure 7 Comparison of HRR for the Source D3 test

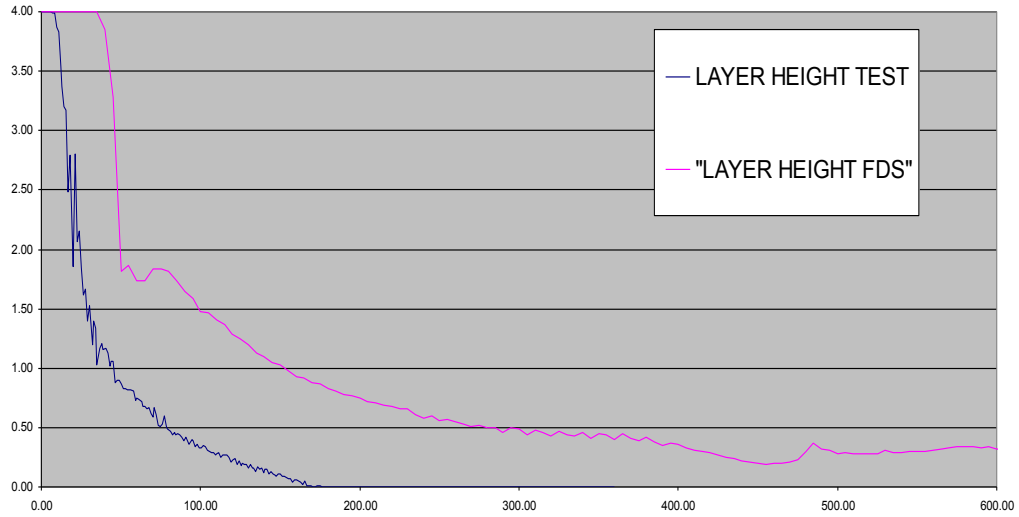

Figure 8 Comparison of smoke layer height between Source D3 test and FDS simulation

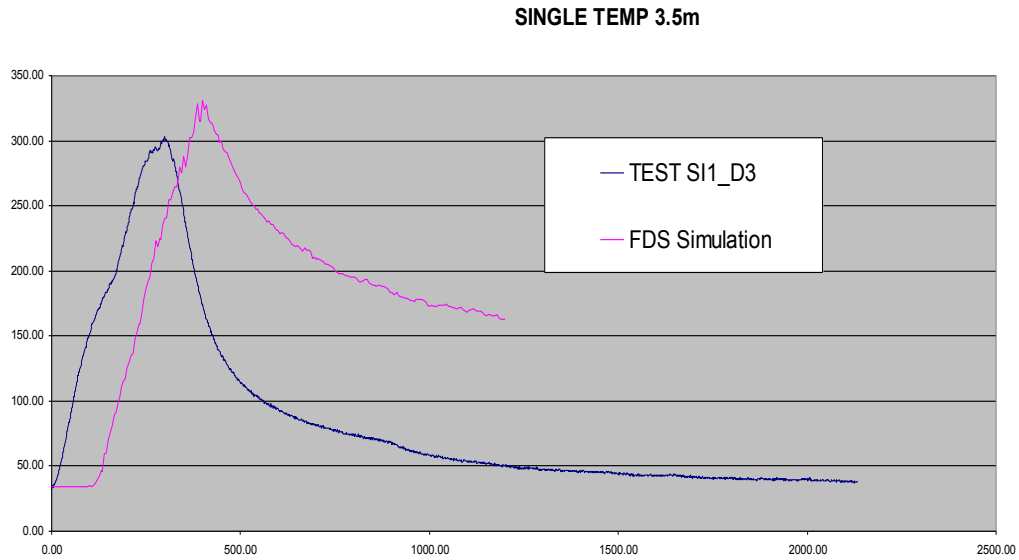

Figure 9 Comparison of hot layer temperature between Source D3 test and FDS simulation

3.3.3. Discussion

From the first simulations it was clear that the positive conclusion of the simulations was that FDS reduced the HRR from the open source test (a test in an open configuration without influence of the room). However the levels of HRR in underventilated condition does not match and as such all related fire parameters such as temperature, smoke layer, heat fluxes etc. were not correct. This confirms the results from previous studies [11], where it also has been pointed out that if the HRR is not correct temperatures etc. are also deviating.

It is clear also from this test that the ventilation influences the HRR and that in order to predict the HRR correctly you need to have the correct ventilation during the test.

Also the ventilation is affected by the HRR and fire since the pressure in the room is depending on a number of parameters of which the HRR is one through the fact that the temperature in the room is influenced by the HRR.

In these preliminary tests both ventilation boundaries were so called "volume flow boundaries" and no additional leakages or pressure reliefs were included. This of course results in incorrect pressure prediction. Since both boundary conditions were fixed these simulation could also not predict the back flow, which occurred in the tests.

3.4. Simulations as input at BE1

3.4.1. Information on the simulations

For the next step it was chosen to allow at least one ventilation boundary to be an open boundary (outflow) and to fix the inlet boundary similar to the test conditions that is with the backflow but with no interaction between the pressure in the room and the ventilation system. Instead of volume flow as boundary condition, mass flow was chosen as this was the input data given in the BE 1 exercise. Also the HRR from the test was given as input for the simulation and not the HRR from the open pool fire. Furthermore, the work was limited to PRISME source D1 test. The grid was extended outside the room and 4 grids were chosen in order to reduce the calculation time. The information from the simulations can be summarised as follows:

- Parallel FDS 5.4 dated June 2009
- 10 cm grid was used with radiation and heat losses.
- More output parameters as requested in BE1
- HRR from the test
- Inlet ventilation from the test, defined as mass flow
- Outlet as open boundary
- Suppression false
- Geometry extended above the room to allow the open outlet boundary to work properly, see Figure 10.

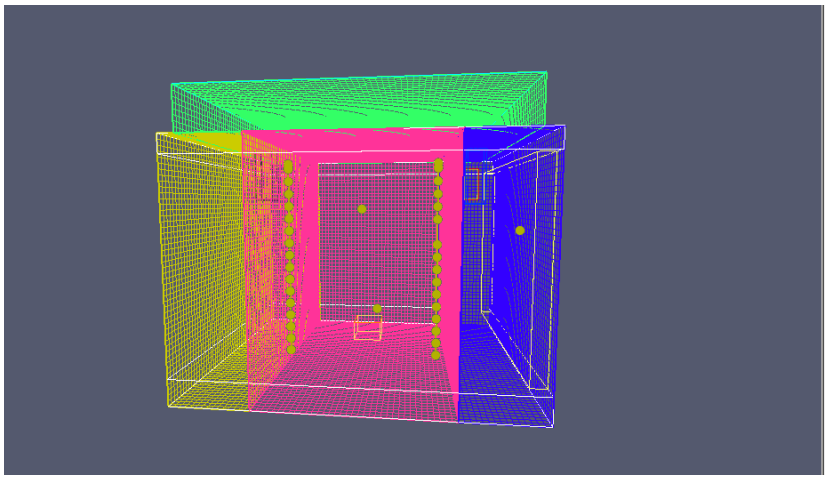

Figure 10 Geometry for the 4 grid system used in the simulations

3.4.2. Results

In the first simulation results the HRR was cut of after a certain time and the fire extinguished, as can be seen in Figure 11. Further detail investigation showed that the mass flow boundary did not work properly since no oxygen entered the calculation domain. Only a velocity boundary was included. The developers of FDS were informed about this. In a first step it was stated that LTH had done an error in the inputfiles. In order to obtain good results LTH decided to move again back to the boundary condition volume flow and then the HRR was correctly predicted as in the test, as can be seen in Figure 12. When we checked the mass flow boundary condition about 6 months later, it could be seen that this boundary worked in a same way as the volume flow. A remaining error in the FDS simulations was the prediction of extinction. During the test the fire extinguished despite remaining fuel but this could not be predicted in FDS as the HRR was given as boundary.

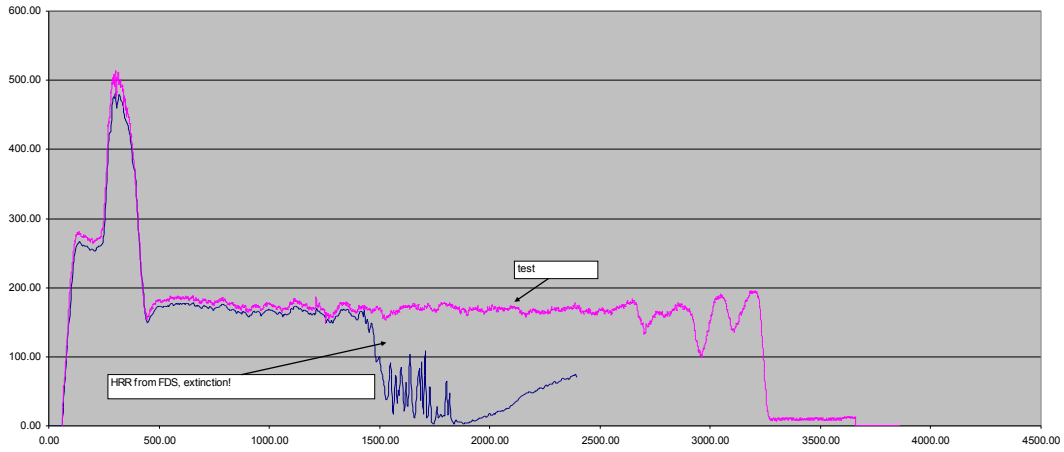

Figure 11 HRR as function of time for the simulation of Source D1 test with mass flow as boundary

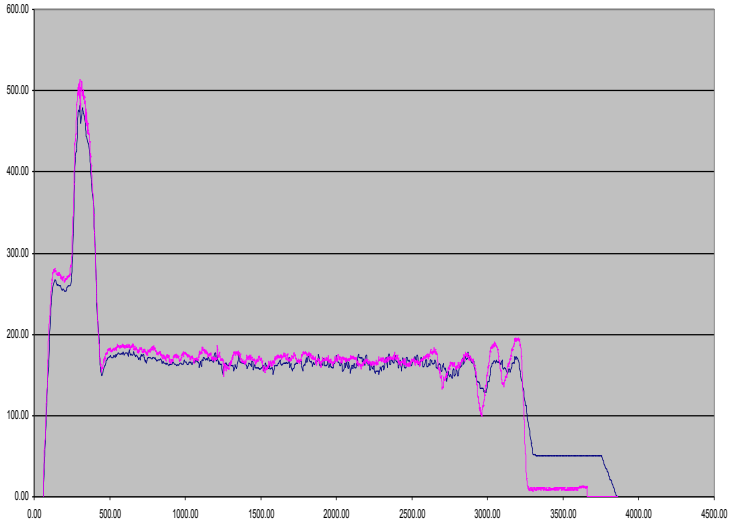

Figure 12 HRR as function of time for the simulation of Source D1 test with mass flow as boundary (pink line test, blue line FDS simulation)

In Figure 13 to Figure 16 the comparisons are given between test results and simulations.

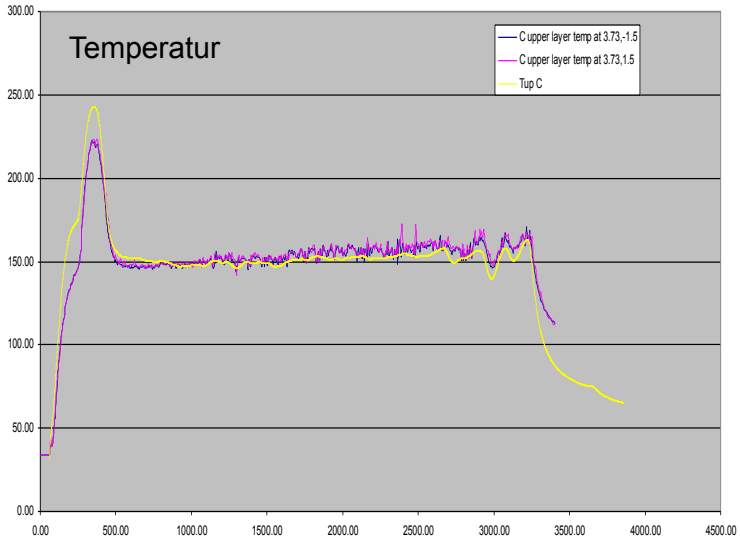

Figure 13 Temperature of hot gas layer as a function of time for the for PRISME source D1 test (yellow line, test)

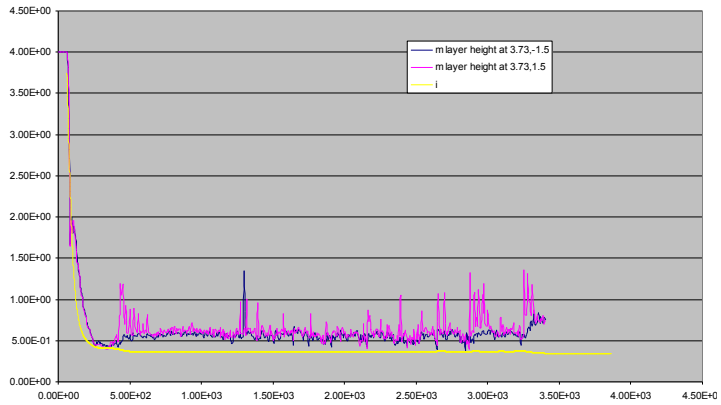

Figure 14 Smoke layer as a function of time for the for PRISME source D1 test (yellow line, test)

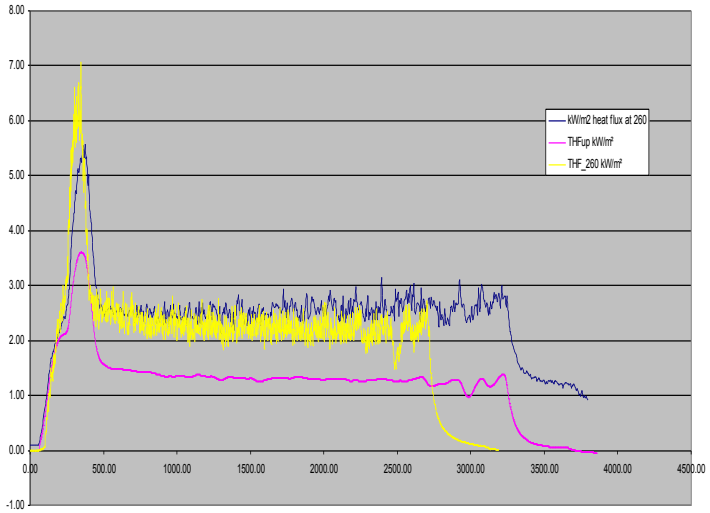

Figure 15 Heat flux data as a function of time for the for PRISME source D1 test (pink line, test)

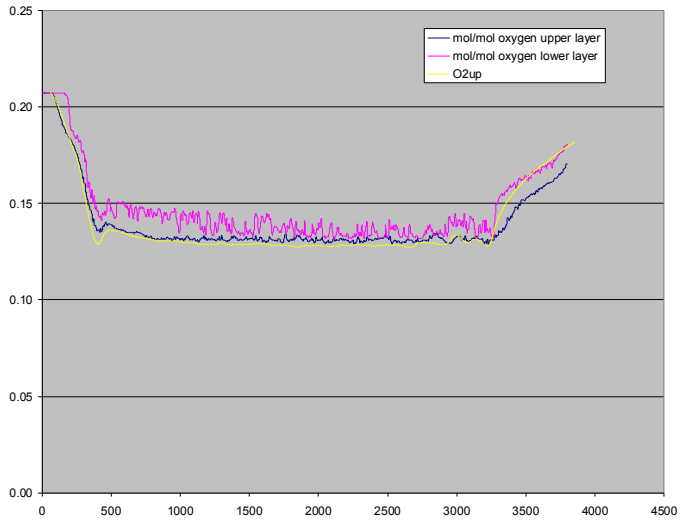

Figure 16 Oxygen data as a function of time for the for PRISME source D1 test (pink line, test)

3.4.3. Discussion

From these simulations it could be seen that FDS predicted rather well parameters such as temperature, smoke layer, oxygen concentration. However one should not forget that the boundaries conditions were matched with the experiment. In this case the challenge for the future would be to better predict HRR from pool fires and ventilation conditions. For the ventilation conditions we continued with the new ventilation module from FDS, developed by NIST and Hughes Associates. For the HRR we applied successfully together with VTT and Haugesund college for a research project on pool fire model development for FDS. The data given in the figures above was given as input in the BE1 and is reporting as a scientific article [7]

3.5. Simulations with Benchmark exercise 1 using ventilation module in FDS 5 and simulations using Ansys-CFX

The leak area from the fire room to surroundings was calculated using data from PRISME SOURCE – Ventilation Tests. Leakage between the fire room and surroundings was assumed to be a quadratic function of pressure difference. The calculated total leakage area from the fire room was in the order of 4 cm^2. The sensitivity of this parameter was tested by doing two more calculations with FDS, one with zero leakage, and one with 10 cm^2 leakage. As seen in Figure 17, the impact is quite large. When changing the total leakage with 4-6 cm^2, the first pressure peak in the experiment changes in the order of 50 Pa.

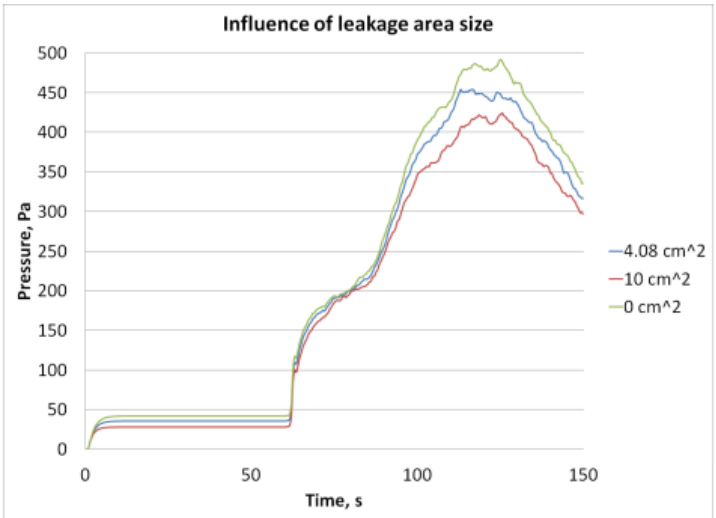

Figure 17 Influence of changing the room leak area in FDS.

Since the full ventilation system was modelled with FDS, it was necessary to compare the experimental data in every node of interest with the data produced with FDS, prior to the fire being ignited. If this proved to give a good prediction, the likelihood of getting good results when compared to the full experiment would be far larger. As seen in Table 3, the results agree very well with the experimental data. Only one node shows a relative pressure difference larger than 10%, though the pressure difference is only about 40 Pa.

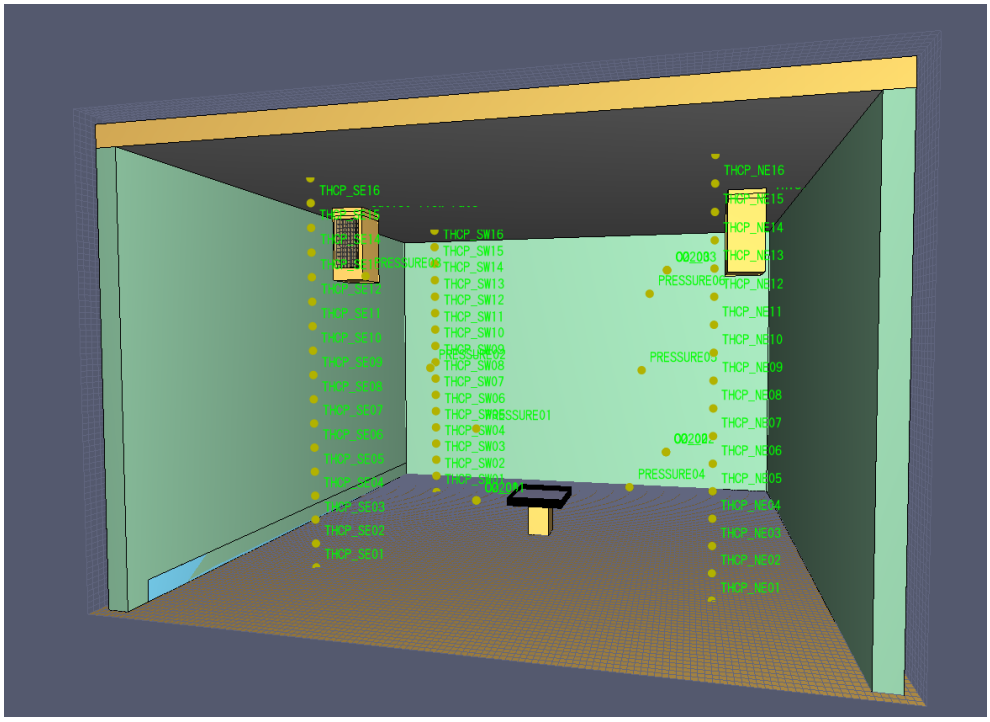

Figure 18 Geometry for the simulations with ventilation module.

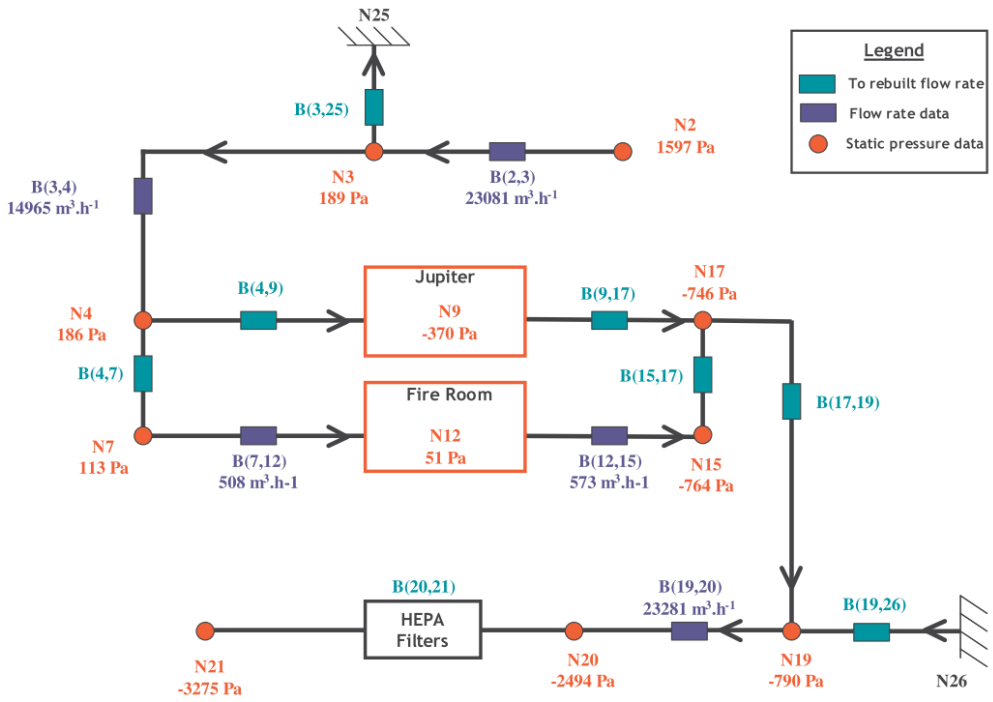

Figure 19 Layout of the ventilation network (courtesy of IRSN) and a comparison between FDS data and experimental data

	N2	N3	N4	N7	Fire room	N15	N17	N19	N20	N21
FDS, Pa	1575.73	191.71	188.81	162.77	35.5	-706.71	-726.09	-769.46	-2446.5	-3228.18
Experiment, Pa	1597	189	186	113	37.9	-764	-746	-790	-2494	-3275
Difference, %	1.33	1.43	1.51	**44.04**	6.33	7.50	2.67	2.60	1.90	1.43

Table 3 Comparison of FDS5 results and measured pressure in each ventilation node (courtesy to IRSN).

An overview of the temperatures calculated with both CFX and FDS compared to the experimental data can be seen in Figure 20. FDS manages to give a good prediction of the temperatures (within 10-15 %) on a relatively coarse grid (10 cm cubes), providing a good basis for evaluating the ventilation system behaviour. Unfortunately the same cannot be said about CFX. CFX over-predicts the temperature by far (30-50 %), however, it cannot be ruled out that errors made by the software operator influences this deviation. Also, the way CFX handles combustion, for example internally calculating heat of combustion, prevented use of the experimental value obtained. This will likely impact the temperatures in the fire room. Also, heat transfer to the surrounding walls has been taken into account, but it was unclear if it was properly set up even though initial tests were performed.

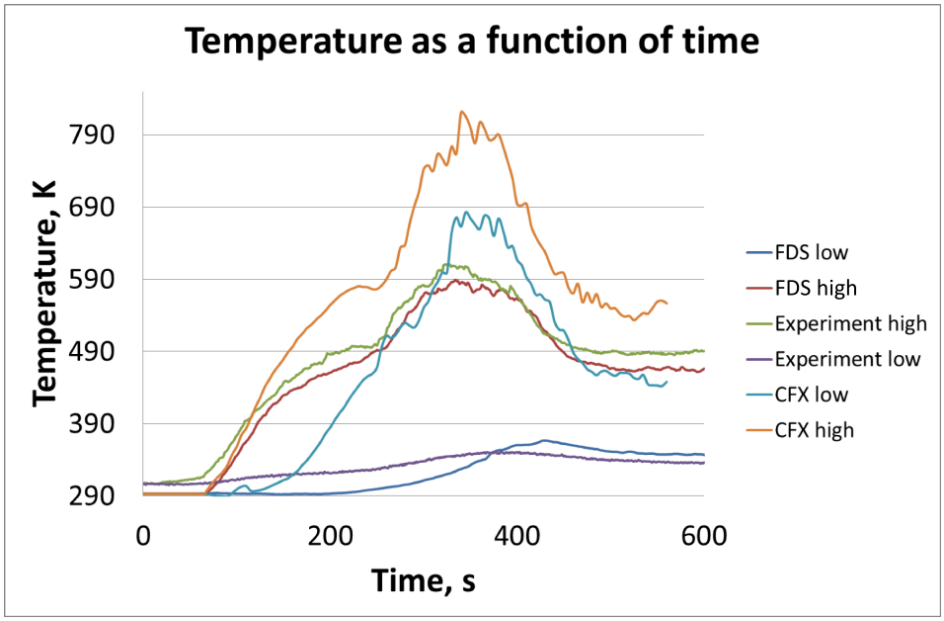

Figure 20 Temperature (highest and lowest measure point) as a function of time for the first 600 seconds.

Since full capabilities concerning ventilation system modelling is not present in CFX (simplifications were made at the in- and outlet branch, specifying appropriate boundary conditions to get realistic pressures in the fire room), only results from calculations made with FDS are presented when comparing pressure in fire room and mass flow in the ventilation branches. As seen in Figure 21, the calculated pressure in the fire room is very close to the experimental data. All pressure peaks are fairly well predicted, and this is using only data available prior to the fire being ignited (except for HRR).

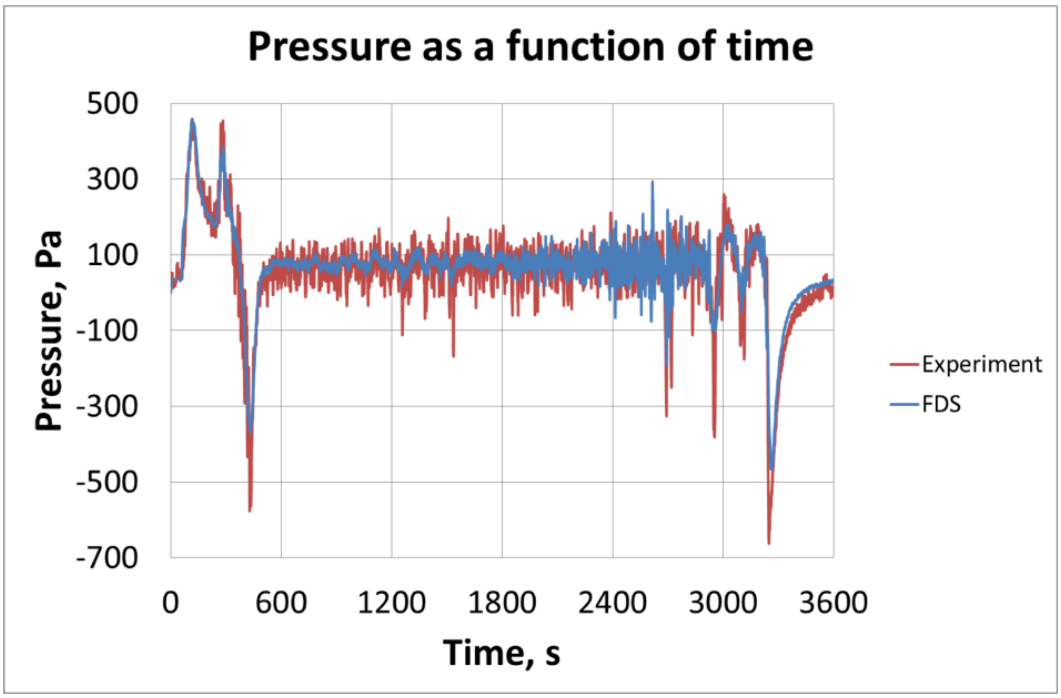

Figure 21 Pressure in the fire room as a function of time, the blue line is the pressure predicted with FDS.

Looking at the inlet and outlet branches (Figure 22) it is shown that FDS manages to predict the backflow in the inlet branch correctly. However, due to differences in the reported data from the experiment (actual measured mass flow not the same as reported in figure 3), the mass flow at the in- and outlet before the fire was ignited does not correspond to the FDS values. This in turn affects the "steady-state" mass flow in the later part of the experiment (after 600 seconds) making the FDS prediction somewhat incorrect. But it can be seen that the difference is constant, indicating that with the right starting values, FDS would give a better prediction.

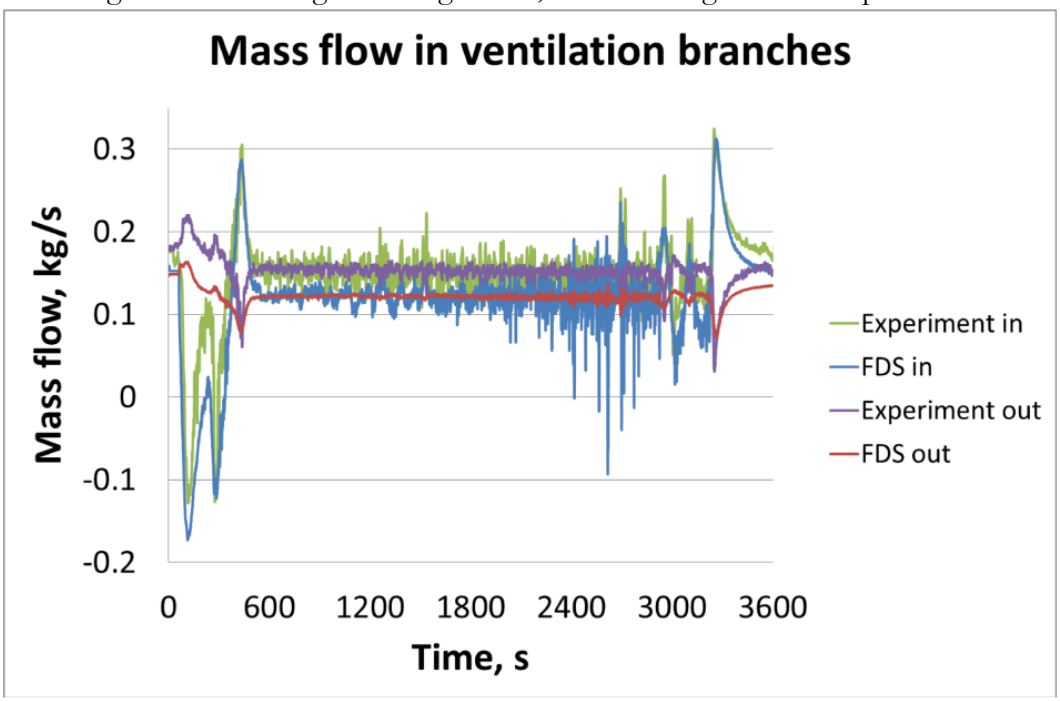

Figure 22 Mass flow in the ventilation branches as a function of time during the experiment.

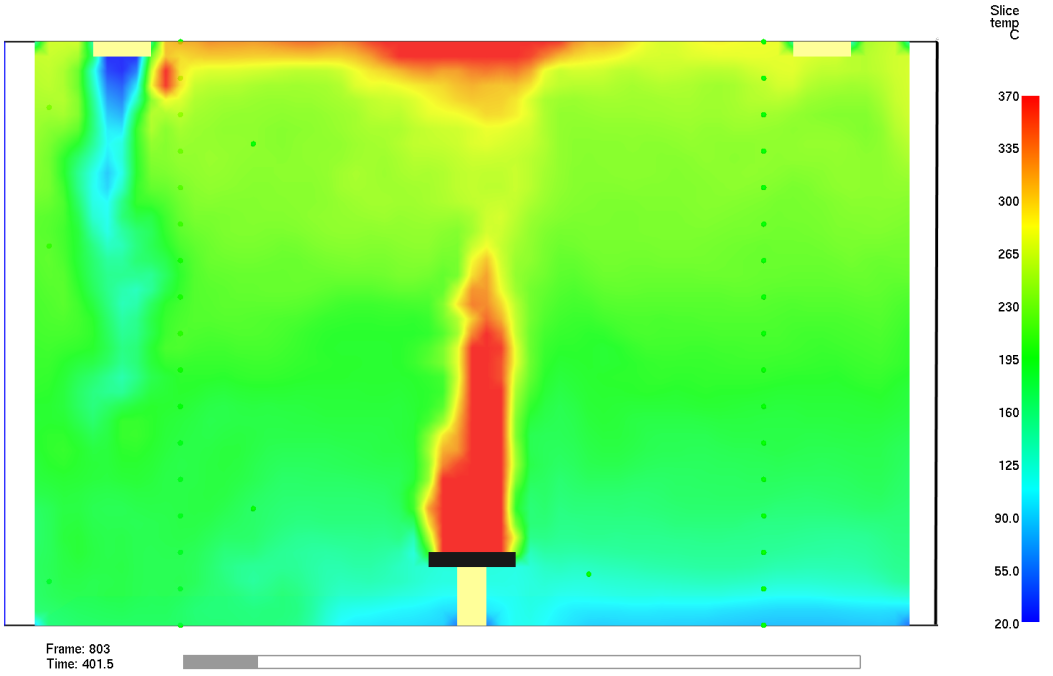

Figure 23 Snapshot of a temperature slice during the simulations done with FDS5. The incoming cold air is clearly visible at the top left corner.

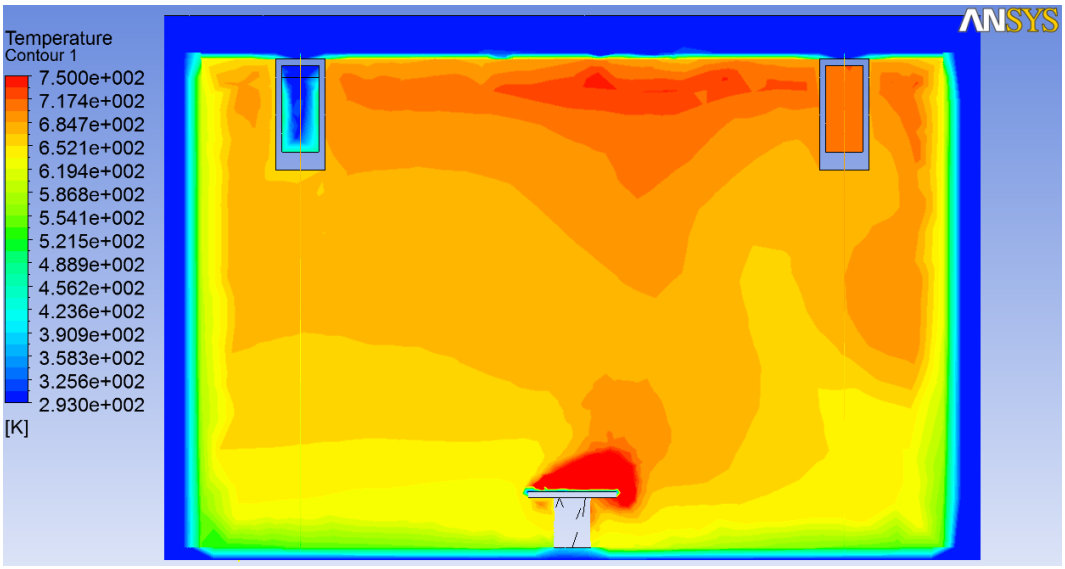

Figure 24 Snapshot of a temperature slice during the simulations done with CFX. The incoming cold air is clearly visible at the top left corner. It can also be seen that the temperature gradient from ceiling to floor is not as steep as shown with FDS5. The maximum temperature is also overestimated to a quite large degree.

4. Benchmark Exercise 2

4.1. Information on the simulations.

In this exercise a sensitivity analysis was made for a number of input and out parameters as prescribed by IRSN [9]. The input parameters are listed in Table 4 resulting in eight runs for each participants (Table 5) and the output parameters are listed in Table 6.

Input parameters	Ref. value	Lower value	Upper value
Mass Loss Rate [kg/s]	exp. value	-10 %	+10 %
Radiative fraction	0.35	0.3	0.4
Wall conductivity [W/m/K]	1.5	1.07	1.93
Wall heat capacity [J/kg/K]	1000	800	1200
Wall emissivity	0.7	0.5	0.9
Ventilation flow rate [m^3/h]	560	500	620

Table 4 Variation of the input parameters

RUN	Mass Loss Rate [kg/s] $\dot{m}''$	Rad. fraction [-] χ_r	Wall conduc. [W/m/K] k_w	Wall heat capa. [J/kg/K] $C_{p,w}$	Wall emis. [-] ε_w	Ventilation [m^3/h] Q_v
1	-10%	0.3	1.93	800	0.9	620
2	10%	0.3	1.07	800	0.5	620
3	-10%	0.4	1.07	800	0.9	500
4	10%	0.4	1.93	800	0.5	500
5	-10%	0.3	1.93	1200	0.5	500
6	10%	0.3	1.07	1200	0.9	500
7	-10%	0.4	1.07	1200	0.5	620
8	10%	0.4	1.93	1200	0.9	620

Table 5 Variation of the input parameters for each run in the fractional experimental design involving eight simulations.

Variable	Location	Comment
Temperature (K)	mean value at (3.75,4.5,Z)	max. value over time
	mean value at (3.75,4.5,Z)	mean value, t ∈ [1500 s, 2500 s]
Oxygen molar frac.	upper layer or (3.75,1.5,3.3)	minimum value over time
Wall temperature (K)	north wall, (4,6,2.6)	maximum value over time
Rad. heat flux (W/m^2)	north wall, (4,6,2.6)	maximum value over time
Tot. heat flux (W/m^2)	north wall, (4,6,2.6)	maximum value over time
Relative pressure (Pa)	global variable	mean value, t ∈ [1500 s, 2500 s]
	global variable	maximum value over time
	global variable	minimum value over time

Table 6 Output variables chosen for the sensitivity exercise

The background information for the simulations is the following:

- Version used parallel FDS 5.4.0 dated June 2009 (svn 4213)
- MPI version compiled with Linux Intel v 10 compiler and MPI library
- Run on the LUNARC cluster
    - 252 nodes with 4 processors per node.
    - Each processor is an Intel Xeon 5160 with a clock frequency of 3.0 Ghz.
    - The memory is 4 GB per node

The boundary conditions were quite similar as in the BE1 exercises from paragraph 3.4.1 and are summarised as follows:

- HRR input through MLRPUA and EHOC (from IRSN document)
- VOLUME_FLUX used as boundary for the volume flow
- Input flow constant input corresponding with the value from BE2, so no backflow inserted.
- Output flow – open boundary
- 4 grid system with 10 cm cells
- Only limited analysis done by LTH i.e. no FFD (was done by IRSN) but towards a user uncertainty.
- No pressure reported as we have the open boundary for the output flow which means that the pressures in the room are not correct.

4.2. Results of the Benchmark exercise 2

The results are given below as table 7, which included the limited analysis done by LTH. Further analysis was done by IRSN and will be part of a publication. This publication has not been approved in the consortium and this will be done in the PRISME 2 project.

	T1 (K)	T2(K)	XO2	T wall (K)	RHF	THF
RUN						
1	445	391	0.1524	344	1.86	3.61
2	499	424	0.1389	365	1.83	5.84
3	449	397	0.1412	357	1.82	3.65
4	499	429	0.1289	352	1.80	5.71
5	471	404	0.1419	338	1.38	4.51
6	473	414	0.1274	361	2.56	4.79
7	467	403	0.1518	343	1.28	4.27
8	466	402	0.1376	344	2.38	4.45
Mean	471	408	0.1400	350	1.86	4.60
StDev	20	13	0.0091	10	0.44	0.83
Proc StDev%	4.21	3.27	6.53	2.74	23.46	18.07

Table 7 LTH results of sensitivity analysis and statistical evaluation of the results.

	T1(C)	T2(C)	T wall (C)
RUN			
1	172	118	71
2	226	151	92
3	176	124	84
4	226	156	79
5	198	131	65
6	200	141	88
7	194	130	70
8	193	129	71
Mean	**198**	**135**	**77**
StDev	**20**	**13**	**10**
Proc StDev%	**10.01**	**9.88**	**12.40**

Table 8 LTH results of sensitivity analysis and statistical evaluation of the results with respect to temperature expressed in degrees C.

Key for Table 7 **and** Table 8

T1 and T2 are the layer temperatures, respectively hot and cold layer.

Twall wall temperature

XO2 oxygen concentration

RHF radiative heat flux

THF total heat flux

4.3. Discussion

The BE mark 2 taught us especially how important it is to run a sensitivity analysis on input data. This is not always done when performing safety analysis. A factor, which influences more than it is expected, is in fact the emissivity of the wall. The spread of results is rather limited when it is concerning temperatures, if expressed in degrees K, but larger when it is concerning different type of heat flux and gas concentrations. Also if one looks to the temperature when expressed in degrees C the spread is larger and one should for this case count with a simulation uncertainty of at least 10% for temperature.

5. Benchmark Exercise 3

This benchmark exercise only started at the end of PRISME 1 and was not yet finished at the time of reporting. The reporting and tasks will be part of the PRISME 2 project.

6. Other simulations at LTH

6.1. Flash over levels in INTEGRAL 4 tests

When the consortium discussed the set-up of the INTEGRAL test 1 and 4 LTH performed a set of simple correlation in order to give feedback to IRNS on the flashover levels and the size of the pool fire. By using the Thomas flashover criteria for natural ventilation [12] and applied to the fire room in the INTEGRAL test we got the following results:

- Using 1 door the flashover level would be 2052 kW
- Using 2 doors the flashover level would be 2870 kW
- Using 3 doors the flashover level would be 3685 kW

Of course it is understood that we have for this test mechanical ventilation but the values gave a rough idea and indication for the level of flashover and could be compared with the test results.

When comparing these values with the values calculated with Sylvia it could be seen that the lower flashover value was already close to the value of 1750-1900 kW for a 1.5 m^2 pool fire. Therefore it was recommended to IRSN not to use the largest pool fire but to limit the level to a 1 m^2 pool fire which would give around 1370 to 1420 kW. However it was stated that room condition could result to a higher level of the pool fire, which also happened in the actual test where flashover did occur.

6.2. Blind simulations of INTEGRAL 4 test

In addition to the prediction of flashover level we also did a blind simulation of the INTEGRAL 4 test in order to predict the room conditions before the test was conduced. As input the data from IRSN on the HRR of the pool fire was used as well as ventilation conditions in the description of the tests. Results were presented at the project meeting group (PRG) and are summarised below.

The set-up of the Integral 4 test is given below in Figure 25. The following simulation conditions were used:

- HRR used from IRSN report for 1m^2 pool fire, see Figure 26
- Ventilation conditions from the integral pre-test conditions.
- Small pressure relief opening in corridor for pressure compensation
- 4 grids on 4 CPUs
- Parallel version of June 2009 used
- 1200 seconds run

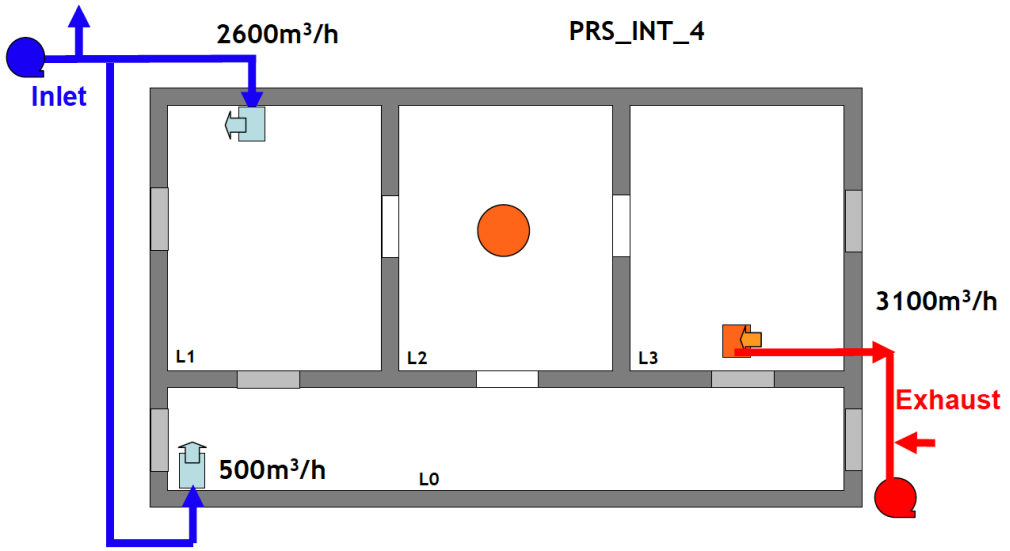

Figure 25 set-up of the INTEGRAL 4 test.

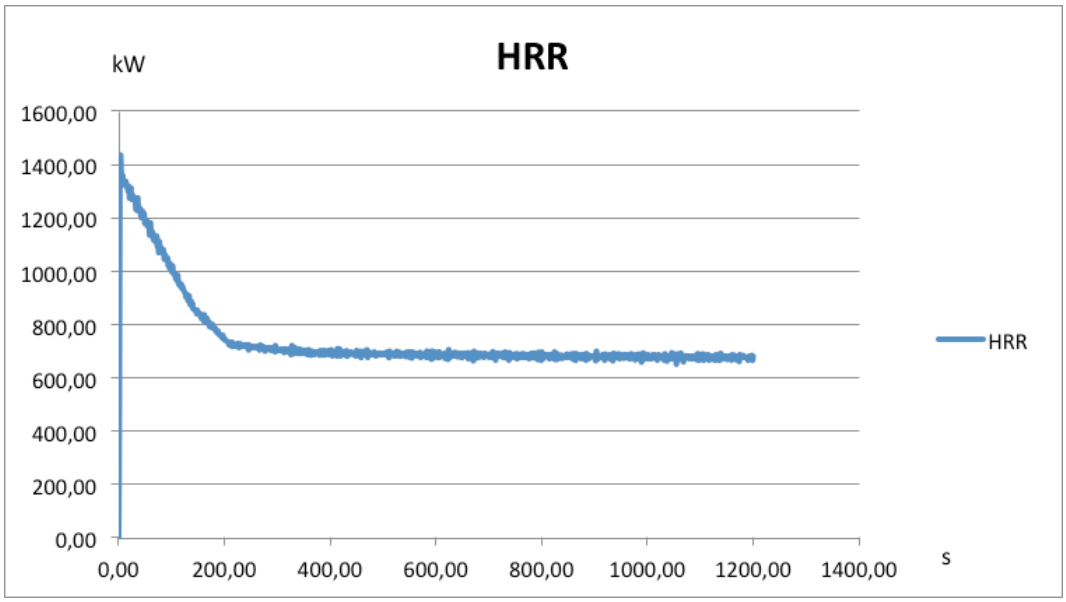

Figure 26 HRR used in the blind simulation, based upon information received from IRSN

Results of the simulation are given in Figure 27 and Figure 28. When comparing with the test results we can conclude that the temperatures are around 200 to 250 degrees C too low (Test results are information from the consortium meetings).

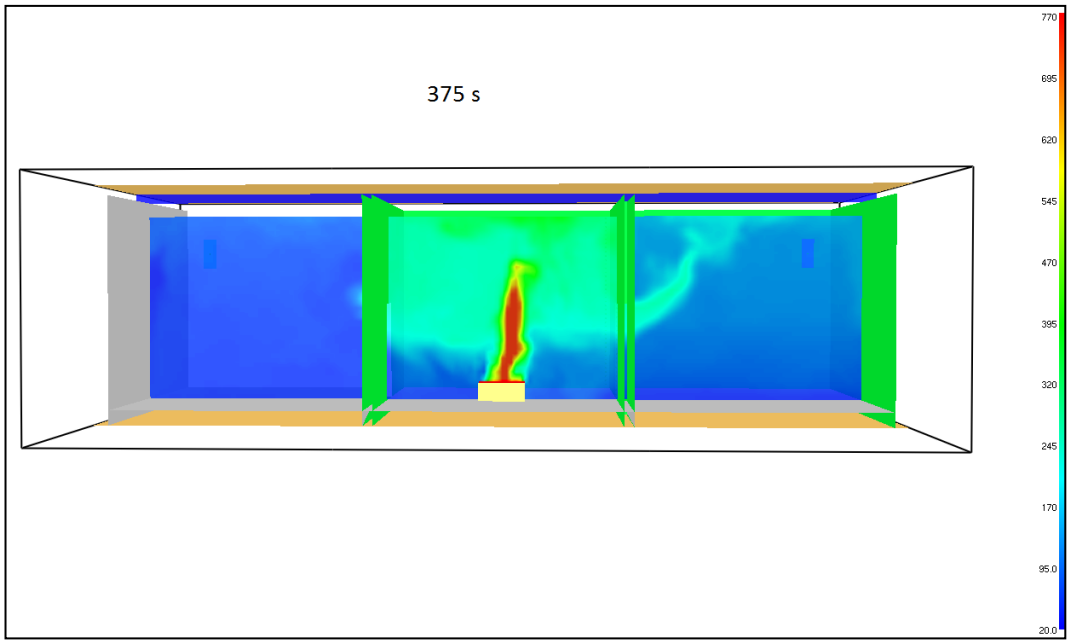

Figure 27 Snapshot and temperature profile at 375 s when the HRR is at a constant level.

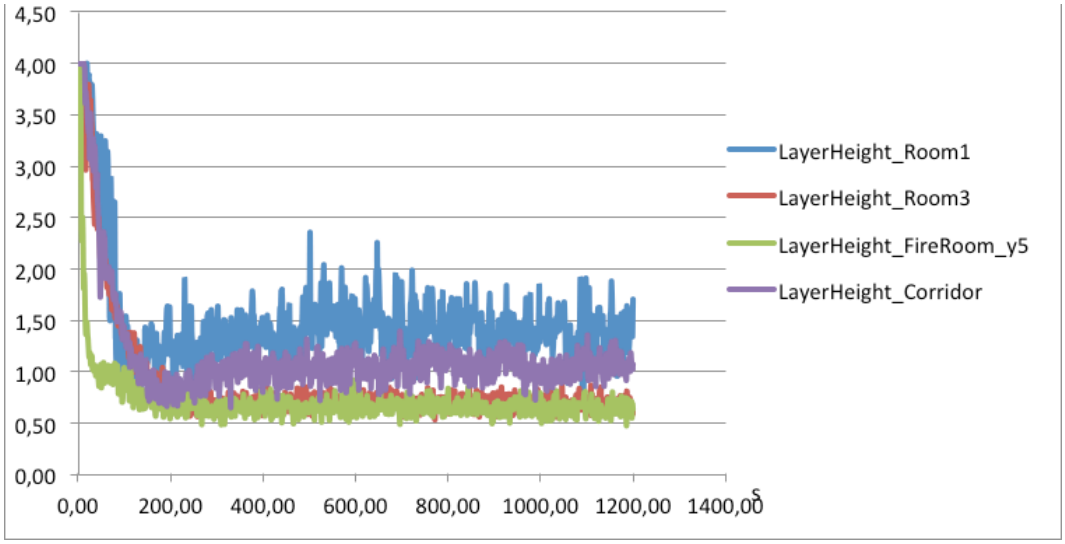

Figure 28 Smoke gas layer (m) in the different rooms at 375 s.

7. Future actions

The future actions in the PRISME 2 project should focus on obtaining more information on the so-called user errors in the different software packages and the so-called overall validation of the software by third parties. This can only be done introducing at least some type of blind or a priori simulation of a number of tests to be conducted in the PRISME 2 project.

8. Conclusions

The main conclusion of this part study are summarised below:

1. Without a ventilation module connected to FDS, FDS can only predict the conditions in the underventilated fires of the PRISME project if one has access to both the ventilation and HRR during the test. If done so the results are very good in comparison with the experiments as could be seen in the benchmark 1 exercise results from LTH. It should however be noted that this is not available when a fire safety engineer makes a fire safety design of a building. A ventilation module is hence necessary to obtain satisfactory results.

2. However, the possibility of simulating a tightly sealed fire room connected to a ventilation network using FDS has been presented with great success. Using only data collected before the fire was ignited (except for HRR), FDS manages to correctly predict the pressure peaks in the fire room and also effects on the ventilation system itself, for example backflow in the inlet branch. Furthermore, the importance of correctly simulating the leak area of the tightly sealed experimental setup has been presented. The leakage area calculated using the experimental data from the "PRISME SOURCE – Ventilation Tests" proved to be very accurate when conducting the CFD calculations with FDS. Changing the leakage area only slightly greatly impacted the pressure in the fire room. In summary, using FDS with its new HVAC capabilities is a very good approach to predict the ventilation system behaviour, showing great potential for future use in fire protection engineering and research both in nuclear power plants but of course also in traditional public buildings, tunnels, residential buildings, etc. This shows that the results of this project can be disseminated outside the nuclear power plant application.

3. Regarding CFX, there are several possible sources of error. First and foremost, the user error cannot be discarded. It is still needed to get a better understanding of the combustion- and heat transfer options (for example, the heat of combustion is suspected to be too high compared to the experiments) and to put it into use for full-scale, transient fire modelling. Also, a coarse grid has been used due to the long calculation times compared to FDS, this also introduces an error that cannot be ignored. Better understanding and use of CFX was one goal set out in this project, and this learning process will continue in future work.

4. The open simulations conducted in this project before the INTEGRAL series by LTH were not so successful. The reason was very easy. The HRR provided as input to these open simulations did not correspond at all to the results from the experiment. However the results from LTH with FDS were in line with the open simulation conducted by IRSN using the ISIS code.

5. Blind or closed simulations are necessary to be conducted as well as simulation performed by different users with the same software. This will give us better levels of uncertainty, which can be used in fire performance based design to determine e.g. safety factors.

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Acronyms

Brandforsk: Swedish Board for Fire Research

CFD: Computational Fluid Dynamics

FDS: Fire Dynamics Simulator software programme

FSE: Fire Safety Engineering

IRSN: Institut de radioprotection et de sûreté nucléaire

NBSG: National Fire safety group (composed av SSM, SKB and nuclear power plants at Oscarshamn, Forsmark and Ringhals)

NEA: Nuclear energy agency

OECD: Organisation for Economic Co-operation and Development

ISO: International Standardisation Organisation

QRA: Qualitative Risk Analysis

SKB: Svensk kärnbränslehantering AB (Swedish Nuclear Fuel and Waste Management Company)

SSM: Strålsäkerhetsmyndigheten (Swedish Radiation Protection Agency)

SVN: Apache Subversion (formerly called Subversion, command name svn) is a revision control system initiated in 2000 by CollabNet Inc. Developers use Subversion to maintain current and historical versions of files such as source code, web pages, and documentation

TS: Technical Specification