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Fire Induced Flow in Building Ventilation Systems

Master's Thesis

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Fast growing fires inside compartments with limited paths for expanded gases to escape leads to a rapid pressure rise. High pressure can cause smoke to flow through supply vents into the adjacent rooms and can also cause structural damage. In Finland, apartments are fitted with a distinctive double door system and the inner door opens inwards into the apartment. The opening of this door could be difficult under high pressure conditions and the effect of pressure on egress possibilities of occupants was an issue of discussion in Finland. Extensive studies have not been made to better understand the influence of ventilation networks on pressure and smoke spread possibilities. The main objective of this thesis work is to investigate the development of pressure during fires in residential buildings and the influence of ventilation networks on pressure and smoke spread through buildings. It also aims to validate the efficiency and accuracy of the CFD code, Fire Dynamics Simulator for modelling HVAC networks and provide fire safety designers with guidelines to model and simulate pressure development and ventilation system response. The first phase of studies deals with the validation of the HVAC module in FDS. The Swedish-FOA experimental studies of pressure rise in compartments and smoke spread via ventilation ducts are used as validation cases. The FOA experiments were conducted in a sealed test chamber of size 4.0m x 5.5m x 2.6m with different opening diameters to model leakage and different ventilation configurations. In the second phase of the thesis work, fire tests were carried out in a 1970s apartment building. Different types of fire situations were created by altering the ventilation duct configurations. The pressure, gas temperatures in the room, gas concentrations and outlet smoke temperatures were measured and the effects of fire pressure in the ventilation networks were studied. The leakage rates of the test apartment were determined using a multi-point blower door test. A numerical simulation of these tests were performed using FDS. The studies show that the pressures developed during a compartment fire can be high enough to pose risk to the safety of its inhabitants and also cause significant damage to property. It was also found that the ventilation systems play an important role in relieving the fire pressure. The possibility of egress of occupants is compromised as opening the inner door became difficult. The FDS validation model predictions of temperatures and pressure rise in compartment fires are within the range of acceptable uncertainty.	
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List of Symbols

Δp	Pressure difference, in Pa
ρ_a	density of air, in kg/m ³
$\dot{Q}$	Heat release rate, kW
$\dot{Q}_h$	heat transfer rate, kW/m ²
c_p	Specific heat of air at constant pressure, kJ/(Kg.K)
T_a	Temperature of air, in K
A	Area of the enclosure (floor + ceiling + walls), m ²
u	velocity in x-direction, m/s
L_j	length of the duct segment, m
K	dimensionless loss coefficient
K_{eff}	Effective or total loss coefficient
h	enthalpy of fluid, kJ
A_d	area of the duct segment, m ²
g	acceleration due to gravity m/s ²
m	mass, Kg
H_{eff}	effective heat of combustion, kJ/mol
u^+	non-dimensional stream wise velocity
y^+	non-dimensional wall normal distance
V_{leak}	Volume flow through the leak, m ³ /s
Δp_{leak}	pressure difference across the shell/ reference pressure for leakage air flow, Pa
A_{leak}	Estimated leak area, m ²
C_{leak}	discharge coefficient of the leak

Subscripts

i, k	nodes in the duct segment
j	duct segment
w	wall cell
eff	effective

1 Introduction

1.1 Background

Enclosure fires such as fires in apartments pose problems of smoke spreading through ventilation networks from one room to another due to pressure rise in the fire compartment. Enclosure fires can be classified into two phases of fire growth: fire development from a small initial fire to a fully developed fire (Figure 1: Phases of fire development. Source: Quintiere, 2006). Severity of enclosure fires depend on amount of fire load available (fuel controlled) or on the air supply to the confined space (ventilation controlled). The transition from well ventilated condition at the beginning to under ventilated condition produces large amounts of carbon monoxide. Even the energy release rate depends on the amount of oxygen available in the compartment (Karlsson & Quintiere, 2000).

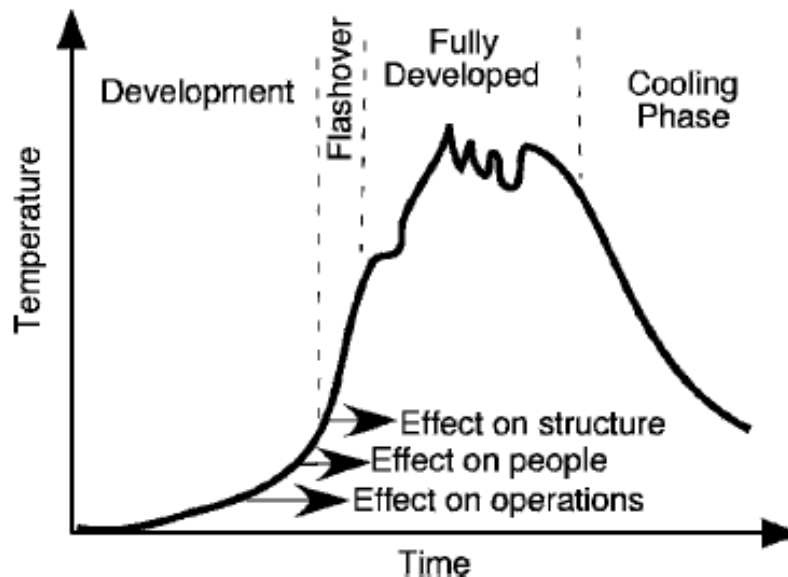


Figure 1: Phases of fire development. Source: Quintiere, 2006

Smoke movement in buildings can be caused due to a combination of various factors (Klote, 1997). These factors cause a pressure difference within the building thereby facilitating smoke movement. The most common factors are listed below.

Stack Effect: The stack effect is caused due to the difference between indoor and outdoor temperatures. The differences in temperatures creates a density difference of air which causes hydrostatic pressure difference over the height of the enclosure allowing vertical smoke spread.

Buoyancy: The phenomenon of warm air rising above the cold air is Buoyancy. This is the basis of all plume models such as the McCafferey Plume model.

Expansion: The energy released by a fire causes the air inside a compartment to expand thereby increasing the pressure in the compartment. If there are leaks to the adjacent compartments, the pressure will cause the smoke to move towards lower pressure zones.

Wind effect: The wind creates a pressure difference across the upstream and downstream sides of the building. This causes smoke to move in the opposite direction.

Pressure build up is proportional to the rate at which fire development occurs. Pressure rise is an underestimated phenomenon and many building codes do not consider it as a genuine risk. Studies have shown that the main reason for casualties in a fire situation is the smoke generated and its capacity to restrict the mobility, lower visibility and cause asphyxiation in a person trying to escape the fire. The smoke can also contain toxic gases such as Carbon-monoxide or Hydrogen Cyanide depending on the fire load. Even though, smoke is the more critical issue, it is linked with pressure build up in the room as it can induce a reverse flow of smoke through HVAC supply ducts thereby spreading to adjacent rooms.

1.2 Motivation

Fire has been the cause for loss of many lives and property. On 27th January, 1967, during a pre-flight test at Cape Canaveral, the crew of Apollo I spacecraft was killed in a fire accident. The report published by NASA (Thompson et al, 1967, pp. 4-6) about the Apollo 204 fire accident reports one of the causes of casualties as the inability to open the spacecraft hatch door due to increased pressure within the vessel. On the other hand, the inability of a fireman inside a fire compartment to open the inner door during trainings was also reported (Paloluoma, 2015).

Presently, fire safety of buildings is addressed in various ways depending on the type of construction. Compartmentation, fire stops, smoke detectors, sprinklers and fire alarms are among the well-known components of fire safety. Heat is not the only issue during an incident as the smoke that is released during fire is equally or perhaps more dangerous as it obscures the visibility of occupants trying to escape and the firefighters trying to locate the point of fire origin to suppress it. Ventilation systems carry and extract air throughout the building, making them easy carriers of gaseous fuel and smoke during a fire, thus introducing additional risks to be evaluated.

Usually fire experiments are done with an open door or window and there have been very few studies where experiments are conducted in a relatively closed compartment with forced or natural ventilation. Since most modern buildings are air tight and highly dependent on ventilation networks for air supply, it is essential to understand fire and smoke behaviour in compartment fires and the role of ventilation systems in alleviating risks.

Backovsky et al, 1989, studied the temperature profiles generated by fires in a closed room with forced ventilation and found that the fire behaviour is altered by the ventilation rate. Ventilation rate four times the stoichiometric rate was required for complete combustion of the fuel otherwise the fire became under ventilated and also created flames which separated from the source close to extinction called 'Ghosting flames'. Beyler, 1991, also conducted similar experiments to study the influence of ventilation on fire behaviour. CIBSE, 2003, also mentions that the CO production in ventilation controlled fire can go up to 0.25 kg/kg.

The heat generated during the fire causes rapid expansion of gases leads to increased pressure within an air tight enclosure. The increase in pressure can also cause structural

damage allowing the trapped hot gases to escape and giving the fire access to additional oxygen. In theory, the pressure increase is coupled to the average gas temperature through the ideal gas law

$$\frac{P}{T} = \text{constant} \quad (1)$$

In reality, the expansion depends both on the heat release rate $\dot{Q}$ and the heat losses. The pressure difference in a room can be obtained from (Tewarson, 1995, pp. 2-47)

$$\Delta p = \frac{1}{2\rho_a(CA_{vent})} \left(\frac{\dot{Q} - \dot{Q}_h}{c_p T_a} \right)^2 \quad (2)$$

The pressure in the room depends on the net heat input i.e. heat released – heat loss to the boundary walls. The rate of heat transfer, $\dot{Q}_h$ increases as the upper layer temperature increases. Also, if the area of convective heat transfer is high, i.e. the area of room is large, the hot layer is initially thin as heat transfer occurs only to the ceiling. If the heat release rate of the fuel remains constant then the pressure increases rapidly and then begins to reduce gradually. This phenomenon can be seen in the validation studies and the experiments described in this thesis work.

The issue of pressure rise in compartment fires was investigated using Fire Dynamics Simulator (FDS) and experimental data from the OECD-PRISME project (Wahlqvist et al. 2013). These experiments were, however, performed in an extremely controlled environment that is very different from common residential scenarios. Chow et al, 2008 performed numerical simulations of test 1 from the FOA (1996) experiments in FDS. In these studies the issue of leakage modelling and its effects on pressure were not addressed. This work aims to fill this knowledge gap.

1.3 Research objectives and approach

The first objective of this thesis is to investigate the effects of the fire induced pressure on smoke flow in HVAC networks, and the effectiveness of ventilation systems in tackling the issue of fire pressure. The issue of leakage in buildings and its contribution to pressure rise is also analysed. The second objective is to validate the use of the Computational Fluid Dynamics based fire simulation code Fire Dynamics Simulator (FDS) to predict compartment fire pressure and flows through ventilation systems. The final objective is to provide a reference for fire safety engineers using HVAC network modelling in FDS to analyse and design fire safety plans.

The experimental studies of 1996 and 1998, performed by the Swedish Defence Research establishment (FOA) form the reference for the initial phase of FDS validation studies. The FOA experiments were conducted in a sealed test chamber of size 4.0m x 5.5m x 2.6m with different opening diameters to model leakage and different ventilation configurations.

The tests performed for the PAHAHUPA project in a 1970s apartment building is the reference for the second phase of the studies. The pressure conditions in an actual building were investigated through a series of liquid and solid fuel tests and different ventilation configurations. These tests are then simulated using FDS to validate its use. Additionally, the experiments also measured the concentration of toxic gases produced during the fire.

Sensitivity studies using different fire parameters and building situations need to be studied as there is no generalized behaviour of fire. One must carefully consider all the factors affecting the performance of HVAC networks before modelling the system in FDS.

1.4 Scope and Limitations

The scope of this thesis work is the numerical modelling of the Swedish FOA experiments and the PAHAHUPA tests to validate the use of FDS in predicting pressures and smoke flows. The thesis work does not assess or study the behaviour of smoke after it passes through the exhaust duct. It also does not study the effects of fire or fire induced pressure on structures.

In FOA experiments, the fire became under-ventilated in few minutes from ignition and this lead to an increased CO production. This under-ventilated fire behaviour is not an aspect of focus in the FDS modelling. As the study focuses on the analysis and modelling of positive pressure variations, the toxic gas concentration predictions is not emphasised. The study also does not delve into the modelling of negative pressure peaks when they are coupled to the fire extinction due to the lack of oxygen. The use of grid size is limited to 10 cm as a smaller sized grid will need a lot more computational capacity, storage space and time than that which is available.

2 Regulations and Technologies

Regulations and technologies are the most important aspects of fire safety engineering and are different in each country. Regulations are the main works of reference that engineers depend on to ensure the safety of their technologies for public use. This chapter delves into the regulations for fire protection in buildings in Finland, Sweden and Russia. It also deals with technologies that are now at the disposal of fire safety engineers and early technologies of fire protection.

2.1 Regulations on Smoke and Fire management in Finland

In Finland regulations on fire and smoke spread management is governed by the Fire safety of Buildings standard E1 and Fire Safety of ventilation systems guidelines E7 from the Ministry of Environment (Ympäristöministerio).

2.1.1 Building Code: E1- Fire Safety of Buildings (2002)

The current version of Building Code: E1 is from 2011, but the English translation is only available for the 2002 version. The essential requirements of the building code E1 are:

- Load bearing construction of the structure shall sustain in case of a fire for a minimum imposed duration.
- Generation and spread of fire must be limited within the building and to the neighbours.
- The spread of fire to neighbouring construction works shall be limited.
- The occupants in construction works shall be able to leave the works or be rescued by other means.
- Safety of rescue teams in building works shall be taken into consideration.

The building code E1, categorizes buildings into fire classes P1, P2 and P3 based on their use and the permissible fire load in each type of building per square meter. The buildings in category P1 encompass a fire load over 1200 MJ/m². The buildings of category P2 are assumed to contain between 600MJ/m² to 1200 MJ/m². Finally, P3 fire class buildings must contain fire load below 600 MJ/m². It should be noted that the building categorization depends on the fire load being housed in it and can be different for two similar buildings with different fire loads. Also, any building can be constructed to be a P1 class building.

E1 also describes requirements for limiting fire spread across fire walls into fire compartments. The maximum area of a fire compartment is also described based on the type of building (Table 5.2.1, E1, 2002).

The building code E1 also regulates the number of occupants in a structure based on the category and number of storeys of the building.

A load bearing structure is required to be designed to correspond with the class requirement with reference to the standard temperature/time curve. Its conformity is attested by

- Testing
- Calculation
- Combining testing and calculation
- Use of an acceptable design method based on tables

A description of the load bearing structure requirement is mentioned in the Table 6.2.1 and the class requirements for fire separating building elements in the Table 7.2.1 of building code E1, 2011. Requirement for the internal surfaces of the building is also based on the type of use of the structure and the surface (Table 8.2.2. E1, 2002). The external walls and ventilation gaps also have similar requirements based on the fire class (Table 8.3.4. E1, 2002). The requirements of fire walls is specified in the Table 9.2.2 of building code E1, 2002. The roof coverings are required to be of class B_{ROOF} (t2). It allows lower classes for roofs if the building does not have a fireplace or in special cases.

E1 also has regulations regarding evacuation in case of a fire situation. E.g. the distance to an exit is determined along the shortest passable route. It also has the distance to the exit described, in Table 10.2.2 of building code E1, 2002, depending on the type of use of the building. The number of exits allowed is also regulated based on the number of storeys in the building and number of occupants leaving the area. Finally, the building code E1 gives the regulations for fire extinguishing systems, fire alarms and lighting of exits. Smoke extraction is required in all spaces which is used for evacuation to ensure life safety of occupants.

2.1.2 Building Code: E7- Fire Safety of Ventilation Systems, 2003

The building code E7 is a set of guidelines for fire safety of Ventilation systems. The essential aspects that are being addressed by the building code E7 are:

- Performance of ventilation ducts and components in fire.
- Limitation of fire spread
- Control of smoke spread

E7 describes the fire resistance requirements of the ducts, dampers and shafts. It also prescribes rules for preventing smoke spread and prevention of fire spread to other compartments.

The materials used for the ventilation ducts and the requirements on their sizes and thickness are classified according to the location of the ducts, and its role in the ventilation network. Ducts in locations that are critical with respect to fire have to be 1.25 mm thick. Fire resistant ventilation ducts are placed so that they remain in place for a minimum fire resistance period required of them. Extraction and exhaust ducts in critical areas of fire safety and areas with explosion hazard must be of fire resistance EI 120.

Materials which satisfy the requirements stated in paragraph 8.2 in E1 can be used as surface or cladding of external insulation of ventilation ducts. E7 also describes the fire resistance of extraction ducts based on its location such as the ducts in kitchens in P2 and P3 class buildings is EI 30, extraction ducts in critical locations and in spaces with an explosion hazard is EI 60. The restriction to prevent fire spread is also specified in E7 such as the connection made to the air ducts, the fire dampers used and the fire resistant ducts used.

It is required that dwelling, accommodation premises and care institutions must not be connected to central ventilation systems serving other categories of use of buildings. General ventilation of spaces posing fire risk and exits must not be connected to the central ventilation system. Local extraction ducts in critical areas of fire risk must be taken as a separate duct to the roof as directly as possible.

During design of shafts or casing structures the building elements must meet the requirements mentioned in building code E1. Ventilation ducts in shafts must have a fire resistance period in which no fire spread occurs from one compartment to another. If fire dampers are used in the ducts at shaft walls then no fire insulation is required. E7 also gives instructions on installation of ventilation ducts in a casing of light construction and requires fire dampers and fire resistant ducts to perform for a specified time period.

Fire Dampers

Ventilation ducts penetrating fire separating building elements are provided with a fire damper. E7 requires that the fire damper satisfy fire resistance period of fire separating building elements. If the integrity of fire damper is adequate but it does not meet the insulation requirements for building elements then penetration can be implemented by fire insulating ducts on both sides of the fire separating structure. Also if fire damper partly satisfies requirements, it can be taken into account while design of penetration. No insulation requirements are imposed on fire damper if duct size is a maximum of 200 cm². The closing temperature of the damper with thermal release mechanism needs to be 70 ± 5 °C.

Ventilation plants and chambers

The ventilation plants which house the central ventilation equipment must satisfy fire resistance requirements depending on the class of the building. E7 mentions the fire separating building elements that should be used for ventilation plant walls. It also describes other situations of building design and requirements pertaining to it.

Smoke Limitation

E7 states that the smoke spread via ventilation system may be prevented if the fire compartment or spaces are not connected to a common ventilation network.

Smoke spread in initial stages of fire can be limited by using devices that effectively restrict spread of smoke such as throttling devices. The flow that is specified in E7 through a throttling device is 42 dm³/s at 100 Pa pressure difference.

Also risers can be used as smoke damper if its vertical rise is 2.5 m and its diameter is a maximum of 10% of its length. Controlled fire dampers which are connected to smoke detectors can also be used to prevent smoke spread.

The limitations for smoke spread in fire compartment and spread of smoke from fire compartments for care institutions must take into account the limited ability of the occupants. E7 also requires that transferred or returned air from one compartment not be used as supply for another compartment. It also places certain requirements for use of heat recovery units. E7 also allows the use of the space between structures for air ducting but with certain fire resistance requirements and other conditions.

2.2 Comparison of regulations in Sweden and Russia

The regulations and standards are aspects of engineering which ought to be the similar for certain conditions but they are seldom so. The building fire safety regulations in each country is different with a large variation and in various aspects.

2.2.1 Swedish Building regulation: BFS 2011:26, BBR19, 2011

In Sweden, the fire safety regulation BFS 2011:26, BBR19 cover a lot more aspects of fire safety in comparison to Finland and Russia but this does not mean all aspects are covered. The same problems regarding fire pressure and smoke movement persist in all the regulations. The buildings are designed with a general condition that the individual events or stresses should not cause structural damage to the buildings fire protection. Structural damage could also lead to increased oxygen supply to the fire thereby deteriorating the situation more.

The Swedish regulations also have an 'Analytical design criteria' in which the client meets one or more provisions of verification of buildings fire protection, depending on deviations of design or safety margin of design, which are

- Qualitative assessment
- Scenario analysis
- Quantitative risk analysis

Usually, it is required that at least two of the above mentioned methods are employed unless the safety margin of the design is high or the deviations are limited. Also, it requires a fire documentation which includes every aspect of fire protection design considered and employed along with the preconditions of the structure.

The Swedish requirements also divides the buildings based on occupancy classes but during fire design also considers the ability of the occupants to evacuate the building in case of fire which can be quite different.

The occupancy classes are:

Occupancy class 1- Industrial, offices and warehouses

Occupancy class 2- Places of assembly which is further divided into classes 2A, 2B and 2C depending on the number of people occupying the fire compartment at any given instant. The ability of occupants to escape must also be taken into account.

Occupancy class 3- Dwellings. This includes single houses, multi dwelling houses, nursing homes, day care centres etc. It is assumed that people have the ability to escape without assistance but cannot be assumed to be awake.

Occupancy class 4 – Hotels, hostels and other temporary housing. Occupants not likely to have good local knowledge and cannot be assumed to be awake.

Occupancy class 5 – Healthcare environments. Occupants have limited ability to escape. This is further divided into classes 5b, 5c & 5d based on the different types of patients housed.

Occupancy class 6 – Places with increased probability of fire hazard such as textile mills, paper mills, factories etc.

Building classes and materials

The regulation classify buildings according to the need of protection as Br0 with very high need of protection, Br1 with high need, Br2 with moderate need, Br3 with low need of protection.

The structural elements are classified based on their fire resistance function as:

R – Load bearing capacity

RE – Load bearing capacity and integrity (airtightness)

REI – Load bearing capacity, integrity and insulation

E – Integrity

EI – Integrity and insulation

EI₁ or EI₂ – integrity and insulation for fire separating doors or windows.

EW – integrity and limited radiation

Performance of structural elements in fire is similar to Finnish regulations. A1, A2, B, C, D, E are the fire performance classes where A1 is the highest class and E the lowest class. Supplementary classes s1, s2, s3 are specified based on smoke generated by the structural element and classes d0, d1, d2 are specified based on the droplets generated or particles emitted by the structural element.

The Swedish regulations address the requirements for fire alarms and detection and requirements on stairways. The requirement on stairways is not addressed in the Finnish and Russian regulations. The recommendation for sprinkler systems and fire suppression systems are also given and the required system specifications are given in Table 5:561 of the regulation.

The ventilation systems requirements are brief and focus on the dampers used and the operation of fans during fire to exhaust smoke. The Swedish regulations detail the fire performance requirements for ventilation systems as well. The properties for HVAC systems are mentioned in Table 5:526 of the regulation.

The regulations also provide requirements and recommendations on the evacuation safety of occupants such as the design of escape routes, occupant load, escape through windows and exit signs.

2.2.2 Russian regulations: Smoke control norms (Taebnia, 2006)

In the Russian norms on smoke control more emphasis is placed on the egress and safety of the occupants. A clear description of the type of smoke exhaust and its details are given based on the structure.

The Russian norms do not emphasize on the type of material used for the exhaust ventilation ducts for fire protection. It only says that three types of materials can be used Flammable, Hard flammable and non-flammable materials. It also does not mention explicitly the length of insulation required in the ducts unlike in Finnish norms. There is a requirement of minimum fire resistance time of 15 minutes for transit ducts made of non-flammable materials. The concept of ‘Transit ducts’ refers to ducts that carry air from one compartment to another and crosses another fire compartment but without delivering air to that fire compartment. There is no such concept in the Finnish norms though there is a concept of providing the same fire resistance as the firewall, to the duct passing through two fire compartments.

Smoke exhaust system requirements are:

1. Corridors and hall ways of public, administrative and household buildings according to requirements of construction code Snip 2.08.01-89, Snip 2.08.02-89 and Snip 2.09.04-87. Corridors of length greater than 15m must have a smoke exhaust system.
2. Premises with a minimum area of 55 m² without natural ventilation that is occupied constantly and storage spaces with minimum area of 200 m² requires smoke exhaust.
3. Premises equipped with manual firefighting systems needs smoke to be exhausted from the bottom zone of the premises.

It also describes a set of spaces that don't need any smoke exhaust system.

1. Premises with smoke filling time more than required evacuation time or with a total area less than 200 m² equipped with automatic firefighting or with automatic gas fighting system.
2. Laboratories with maximum area of 36 m².
3. Premises connected to corridors or halls through access doors which have a smoke exhaust system.

Smoke can be exhausted by natural or mechanical ventilation depending on the type of application of the structure. Multi story buildings needs to have a mechanical smoke exhaust system along with libraries, storages, bookstores, archives with average specific weight of smoke exhausted equal to 7 N/m³ and temperature of 220° C.

Also, it is allowed to use main ventilation system as exhaust systems if they meet the requirements of airflow, safety and other specifications.

2.3 Summary of regulations

Fire induced pressure is not considered as a probable danger in any of the regulations but the issue of smoke is addressed. Fire dampers are the usual fire safety component and its implications on the conditions within a building are not accounted. Sweden has an unofficial design guideline of 1500 Pa of fire pressure for the strength of a structure (Fagergren, 2015). Finland and Russia do not have any guideline for fire pressure.

2.4 New building technology

The main aim of sustainable building industry has been to use the non-renewable materials efficiently, safeguard the health of the residents and reducing the waste that negatively impacts environment. Carter et al, 2011, try to define sustainability of buildings in terms of fire safety as: "Sustainability within the fire protection industry involves application of fire-safety systems and design measures that support and promote building characteristics that are environmentally friendly during the building's daily use."

Air tight, low energy buildings and high rise buildings are being constructed more and the architectural design and the green materials opted for construction may have unintended consequences impacting fire safety solutions and performance (Branz et al, 2012). For

example, an atrium in a building allows for faster smoke spread due to its design. Insulation materials such as Structurally Insulated Panels used to reduce energy have been reported to become additional fire load along with compromising the structural integrity of the structure. (Meacham et al, 2012).

Sustainable or Green buildings rating schemes do not address the issue of fire explicitly and therefore certain aspects regarding their fire performance remains unknown.

2.5 Dampers and new solutions

Fire dampers, which are active HVAC components, are increasingly being used in HVAC systems. These are, usually, thermally activated in the event of a fire. They try to isolate an area of the ventilation network and prevent the spread of smoke and fire. This leads to increased pressure in the fire room, the aspect of fire under investigation in this study. A new type of fire damper system uses a flame retardant cloth specially designed to exhaust smoke and thereby alleviate the pressures in the room to facilitate escape of occupants is quite promising. It can provide a means of smoke alleviation along with pressure control.

3 Numerical modelling of HVAC systems

3.1 Overview

HVAC systems are essential components in every building for providing thermal comfort and to maintain high indoor air quality through adequate ventilation. HVAC systems, except in small residential buildings, are usually complex network systems that require careful analysis of its effect on the indoor conditions. As they carry air throughout the building, they also play a very important role in ensuring fire safety of the structure. They can be pathways for smoke to spread into adjacent compartment. Alternatively, they can be used for exhausting the smoke and also to maintain stairwell pressure during evacuation.

There are two types of basic models used to predict the performance of a HVAC system: Mathematical model and Black box model (Homod, 2013). Mathematical models have been popular in analysing the behaviour of numerous phenomena in engineering, physics, ecology and various other fields. Numerical modelling of HVAC systems is based on the conservation laws of mass, energy and momentum. The mathematical models represent the relation between the specified inputs and the obtained outputs using mathematical equations of the laws. In general, modelling of HVAC systems involve high order models with dynamic, nonlinear behaviour with thermal inertia and time dependent quantities. Therefore, HVAC models are usually divided into two sub models of fluid flow and heat-mass transfer which are then combined according to the design of the solver.

Black box models use transfer functions on the real input/output data which yield coefficients which can be factored to provide the resonance frequencies and characterization of damping without actual knowledge of the internal conditions.

This is based purely on the available experimental data and is a process similar to fitting a model to the data. The mathematical methods involved in this are autoregressive moving averages, recurrent neural network models, fuzzy network models etc.

The numerical modelling of the HVAC systems in this thesis work was done using the HVAC solver of the Large Eddy Simulation (LES) based computational fluid dynamics code, Fire Dynamics Simulator (FDS).

3.2 FDS-HVAC module

The HVAC solver is based on the MELCOR program (Gauntt et al, 2000) which was designed to predict accidental scenarios in nuclear power plant containment buildings. The accuracy of MELCOR solver was demonstrated by its use in the network model software, Fire and smoke simulator (FSSIM) (Floyd, 2003). The implementation of MELCOR in FDS is mainly based on its implementation in FSSIM and its coupling with the CFD solver is based on the coupling used in GOTHIC, which is another containment software. The MELCOR solver uses an explicit solver for the conservation of mass and energy equations and an implicit solver for the conservation of momentum equations. (McGrattan et al, 2015 (b)).

The FDS-HVAC module models the ventilation network as a series of ducts and nodes. The nodes are placed at points where ducts intersect each other or the CFD computational domain. The ducts are uninterrupted domains of fluid flow which can encompass elbows, expansion/contraction fittings and various other fittings. The module does not presently store any mass. Therefore, mass flux into a duct is equal to the mass flux out of the duct.

The nodal conservation equations for mass, energy and momentum equations are as follows:

$$\sum_j \rho_j u_j A_j = 0 \quad (3)$$

$$\sum_j \rho_j u_j A_j h_j = 0 \quad (4)$$

$$\rho_j L_j \frac{du}{dt} = (P_i - P_k) + (\rho g \Delta z)_j + \Delta P_j + 0.5 K_j \rho_j |u_j| u_j \quad (5)$$

where ρ is the density, u is the duct velocity, A is the cross sectional area of the duct, h is enthalpy of fluid in the duct, P is the pressure and K is the loss coefficient of the duct. The subscripts j indicates the ducts in the calculation, i and k indicate the nodes of the duct.

The boundary conditions that are applied in the HVAC solver are on the pressure, temperature and species. For flow from the CFD domain to the HVAC duct, the temperature and species are the density weighted average of the adjacent cells on either side of the vent coupling the CFD and HVAC domains. For flow from duct to CFD domain the temperature and species are those of the duct. The pressure is the area weighted background pressure over the vent. The boundary conditions of the HVAC solver are as follows:

$$\rho_i = \frac{\sum_j \rho_j A_j}{\sum_j A_j}, \quad \bar{Y}_{\alpha,i} = \frac{\sum_j \bar{Y}_{\alpha,j} \rho_j A_j}{\sum_j \rho_j A_j}, \quad P_i = \frac{\sum_j P_j A_j}{\sum_j A_j} \quad (6)$$

$$h_i = \frac{\sum_j \rho_j A_j c_p(T_j, Y_j)}{\sum_j \rho_j A_j}; \quad \bar{T}_i = \frac{h_i}{c_p(\bar{T}_i, \bar{Y}_i)} \quad (7)$$

The main aspect in the HVAC modelling is the estimation of losses to ensure that flow through the duct is as expected. Appendix A – Pressure loss in a ventilation network, gives a procedure to calculate losses based on the equivalent length method.

3.3 Determination of input parameters for HVAC modelling

The input parameters to be used in the FDS-HVAC module form the basis of modelling and analysing a compartment fire scenario in FDS. Sometimes it might not be possible to model the duct behaviour exactly as in the experiments or as in real life application. Instead there are various ways in which this information can be conveyed to the solver. The most important requirement for modelling the fire performance of a building ventilation system is an accurate layout of the ventilation network along with the characteristics of all the ventilation components.

Below is a procedure for modelling the ventilation network:

1. First, we begin with enumerating the ducts as presented in the network diagram into various ducts and nodes. A node is placed where a duct connects the computational domain or where there are Tee joints. Also, FDS allows us to combine various ducts by specifying the effective loss of the network.
2. The position of the node and the order in which the nodes are specified are also important as it determines the behaviour of the system.
3. Duct specification such as diameter, length, roughness have to be known.
4. For modelling flows through HVAC networks, it is essential to know the volume flow through the ducts to proceed with any loss calculations. The friction losses are based on the volume flow and duct diameters. The volume flow through the ducts also affects the pressure in the room.
5. Another aspect to be noted is the dampers in the ducts and the position of its operation. During a fire scenario large volume of air is forced through the ducts and if the damper operates with a small opening the pressure loss can be high. The damper position provides us information regarding the regulated volume flow in the ducts and pressure loss associated with the damper position can be found in the damper loss charts provided by the manufacturer. Figure 43: Selection diagram of pressure loss for Zest Iris 80 damper shows the loss chart of an Iris damper.
6. Fan characteristics of the HVAC network must be specified. Usually the characteristics vary widely and are provided by the manufacturer or it should be specified in the experimental reports of study being modelled.
7. Losses specified in the input code and the pressure difference between entrance and exit nodes determines the volume flow rate in the ducts. The duct friction loss chart (based on the shape of the duct) gives the pressure loss values based on the volume flow under normal conditions and diameter of the duct. Velocity through the ducts can also be used to determine the loss (Appendix A – Pressure loss in a ventilation network). Care should be taken while finding the friction loss and the volume flow values as they are recorded in log-log chart.
8. The user must first try to match the initial volume flows in the ducts under normal conditions.
9. The user should have a clear understanding of the HVAC network of the enclosure to obtain precise predictions of fire pressures and smoke behaviour.
10. The HVAC module is quite sensitive and it is recommended to perform a set of sensitivity studies of the system parameters.
11. The HVAC solver can induce fluctuations in the pressure solution as it is solved separately. This can be addressed using the parameter `DT_HVAC` which causes FDS to use the value of `DT_HVAC` as the HVAC solver time step.

The losses in the ventilation network depend on the configuration of the ducts used and various fittings and bends along the network. These fittings can be a damper, louver etc. with each having a specific loss based on where it is located along the duct.

The losses used in the FDS input code above are estimates based on the damper opening and the friction losses and also comparison with the experimental behaviour as the aim was to model the experiments.

4 Validation Studies

4.1 FOA Series

The FDS validation studies are performed using two sets of Swedish-FOA Defence research establishment tests.

1. Pressure rise due to fire growth in a closed room (FOA, 1996).
2. An experimental study of smoke spread via ventilation ducts (FOA, 1998).

The first set of experiments (FOA, 1996) consists of three tests with t^2 fire curves of different fire growth rate. The fire room dimensions are 4.0m x 5.5m x 2.6m and the room has an opening of diameter 0.2m which corresponds to a leakage area of 0.031416 m² connected to a 0.2 m diameter and 2.2 m long tube at the end of which the temperature and velocities were measured. The fire room is divided into two parts with an opening of width 1.9 m from floor to ceiling in-between the volumes.

The second set of experiments (FOA, 1998) consisted of three series of tests:

Series 1: Fire room with circular opening to ambient. No ventilation

Series 2: Fire room with circular opening and exhaust ventilation system.

Series 3: Fire room with circular opening, supply and exhaust ventilation

The fire room dimensions are the same as that in FOA, 1996. Only the diameters of the openings was varied in the tests: 0.1 m, 0.15 m and 0.2 m, corresponding to different amount of leakages in a room. The opening was connected to a 0.32 m diameter and 3.2 m long tube connecting to the ambient. The opening was located at 0.6 m height from the floor on one wall of the room. The main purpose of the test was to study the pressure rise in a room due to fire growth and to study the smoke spread via ventilation ducts.

The fire source of the experiment was a 0.73 m long and 1 m wide fuel pan containing N-Heptane with a rim height of 0.05m. The fuel pans were cooled using water to ensure heat transfer to the pan was minimal. The T-square behaviour of the fire was achieved with the help of a lid over the fuel pan which was moved at a given rate thereby increasing the fuel burning area. The Heat release rate and the mass burning rate of the fuel was estimated as a function of fuel burning area. The Heat release rate per unit area was estimated to be 1600 KW. The experiments were also supported by zone models used to calculate the Hot Gas Layer temperatures.

The list of tests in the FOA studies and their details are given below:

Table 1: FOA series 1 test configuration

Test Number	Fire	Leakage hole diameter
Test 1	T-square 1(k=0.035)	0.2 m
Test 2	T-square 2(k=0.075)	0.2 m
Test 3	T-square 3(k=0.085)	0.2 m

Table 2: FOA series 2 test configuration

Test Number	Fire	Leakage hole diameter	Exhaust network	Supply Network
Test 11	T-square 1	0.20 m	-	-
Test 12	T-square 1	0.15 m	-	-
Test 13	T-square 3	0.20 m	-	-
Test 14	T-square 3	0.15 m	-	-
Test 15	Constant area pool fire(0.50 m ²)	0.20 m	-	-
Test 21	T-square 3	0.20 m	Exhaust network 1	-
Test 22	T-square 3	0.15 m	Exhaust network 1	-
Test 23	T-square 3	0.15 m	Exhaust network 2	-
Test 31	T-square 1	0.10 m	Exhaust network 1	Supply network 1
Test 32	T-square 3	0.15 m	Exhaust network 1	Supply network 1
Test 33	T-square 3	0.20 m	Exhaust network 1	Supply network 1

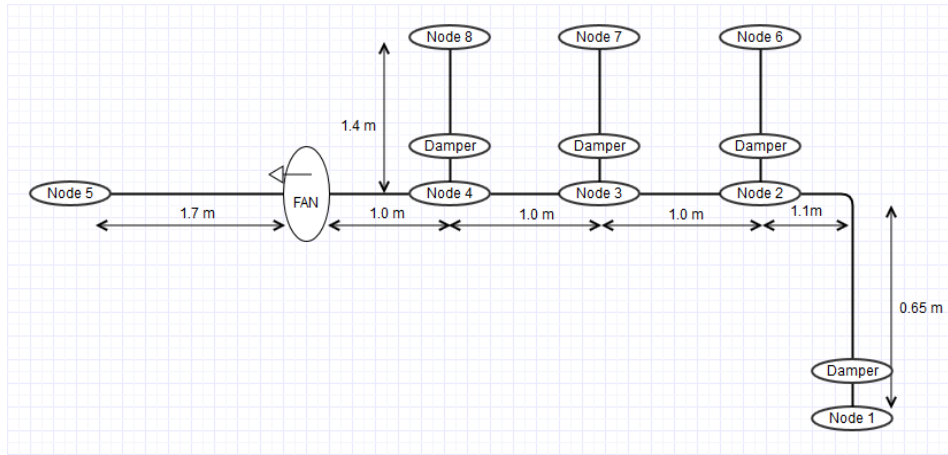


Figure 2: Exhaust ventilation network 1

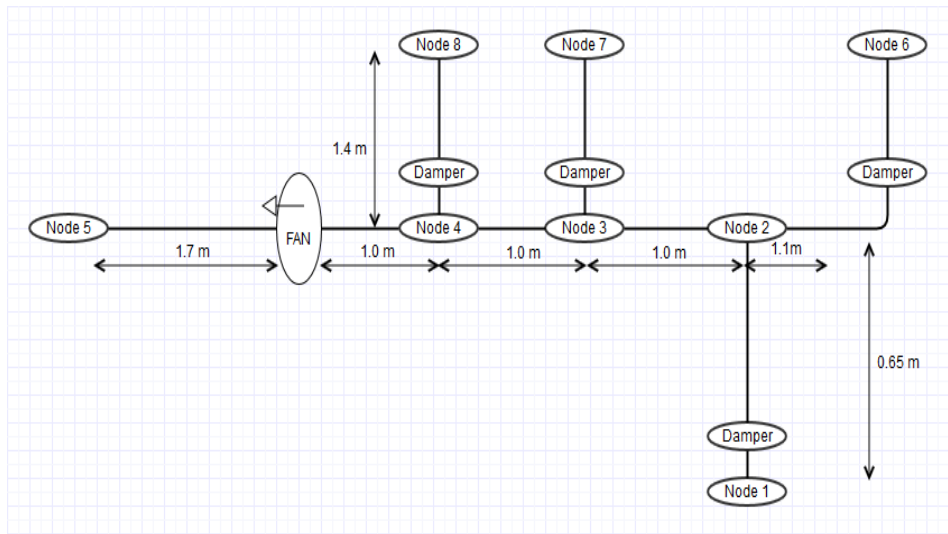


Figure 3: Exhaust ventilation network 2

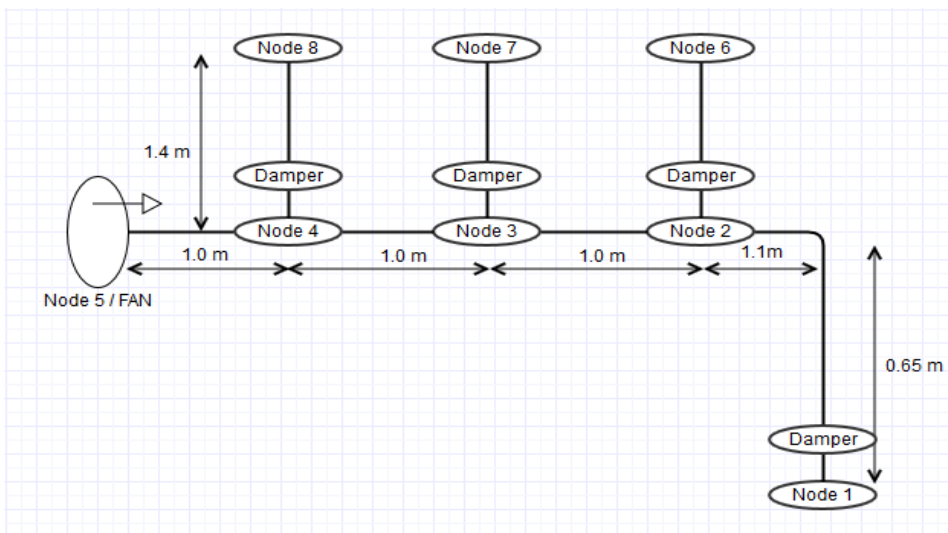


Figure 4: Supply ventilation network

The measurements made during the experiment are the pressure, gas temperatures, O₂ and CO concentrations and velocity and temperature of the hot gases at the circular opening to ambient. The gas temperatures were measured using thermocouples placed over a vertical line at a spacing of 0.5 m. The thermocouples used were Type-K, Chromel-Alumel of diameter 0.25 mm. These were protected using small square pieces of insulation to diminish effects of heat radiation. Two pressure probes were positioned at a height of 0.6 m below the ceiling and 0.6 m above the floor.

The O₂ and CO concentrations were measured using probes of open steel tubes connecting analyser of type PMA 10 for O₂ and BINOS-IR for CO. The probes were positioned 0.6 m below the ceiling. The velocity measurement in the fire room was made relative to the atmospheric pressure using a bi-directional probe.

The mechanical exhaust and supply ventilation system layouts are shown in Figures 1-3. The main ducts of the ventilation system were connected to the fire room and three other fictive compartments. The ducts connecting the fictive compartments ended in the open. The volume flow through the ducts was adjusted to 25 L/s before each test. Bidirectional probes and thermocouples were placed inside the ducts to measure the velocity and the temperature. The exhaust and supply fans characteristics are given below:

Pressure, Pa	310	190	18
Airflow, L/s	0	60	120

The plan view of the fire room used for the FOA experiments is shown below.

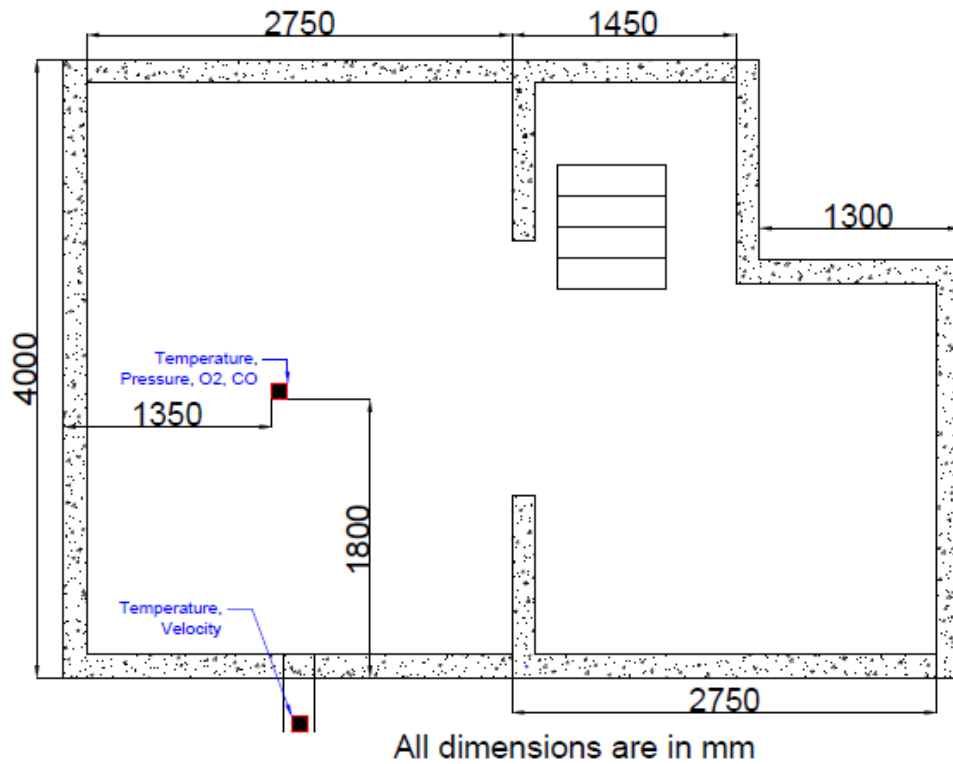


Figure 5: Fire room geometry and instrumentation

4.2 Aalto Experiments

4.2.1 Experimental series

Thirteen full scale compartment fire tests were conducted in an apartment building, constructed in the 1970s, from October 19th to October 22nd, 2015 in Kurikka, Finland. The experiments were made done under different ventilation conditions to study the effect of the ventilation on pressure rise in the apartment. The experiments with the liquid fuel were designed to last for three minutes. The solid fuel tests were conducted to provide data that corresponds better to a real fire. The solid fuel experiments were also a part of training routine for the local fire service involved in the project.

The experiments were conducted in two phases based on the type of fuel used. The first phase was a liquid fuel phase comprising of ten tests. The fuel used in the liquid fuel experiments was n-Heptane in a pan of dimension 0.7 m x 0.7 m shown in Figure 15: Fuel pan and the flame thermocouple. The amount of fuel used was 3.0 L to achieve a burn duration of 3 minutes after which the fuel was completely consumed. The first test though had 3.2 L of fuel. The cooling time for the fire room was estimated from initial FDS calculations to be around 20 minutes. In the second phase which had three tests, solid fuels were used. Tests 11 and 13 are analogous as Test 13 was conducted for the sake of repeatability and verification. The test 12 was performed in the closet of the apartment, and it was the last test of the campaign.

The tests were performed with three different configurations of the exhaust ducts as described in the test matrices (Table 3: Test configuration for liquid fuel experiments & Table 4: Test configuration for solid fuel experiments). Additional ducts of 0.5 m length were attached in front of the exhaust vents to facilitate the placement of instruments and to obtain more reliable velocity measurements. The length of the tube is insufficient to achieve a fully developed flow profile but it improves the accuracy of the velocity measurements.

The three duct configurations used were open (Figure 9: Exhaust ducts configurations – Open condition (left), Normal condition (right)), normal configuration with louver installed on the ducts (Figure 9: Exhaust ducts configurations – Open condition (left), Normal condition (right)) and a fully sealed condition (Figure 10: Completely sealed closet exhaust duct). The additional exhaust duct in the kitchen could be controlled using a knob and was always kept at zero position but there was still some leakage from this duct even in zero position. In the final round of liquid fuel tests i.e. Test 8, 9 and 10 the kitchen duct was further sealed (Figure 11: Completely sealed kitchen exhaust) to make the apartment as air tight as possible. To understand the effects of roof fan (Figure 12: Roof fan) on the pressure the tests 3, 4 and 10 were conducted with the roof fan switched off.

Table 3: Test configuration for liquid fuel experiments

Test No	Fuel	Bathroom exhaust duct	Closet exhaust duct	Roof fan	Comments
Test 1	Heptane 3.2 L	Open	Open	On	This test had a little extra fuel than the others, 3.2 L, instead of 3.0 L.
Test 2	Heptane 3.0 L	Open	Open	On	This is a repeat of test 1 to ensure similar values are obtained.
Test 3	Heptane 3.0 L	Open	Open	Off	This is repeat of test 2 but with roof fan off. Gravity flow.
Test 4	Heptane 3.0 L	Open	Open	Off	This is repeat of test 3.
Test 5	Heptane 3.0 L	Normal valve position	Normal valve position	On	The exhaust valves were placed onto the ducts again. It should be noted that the apartment is not a low energy construction. Leakage values are relatively higher.
Test 6	Heptane 3.0 L	Normal valve position	Normal valve position	On	
Test 7	Heptane 3.0 L	Normal valve position	Normal valve position	On	
Test 8	Heptane 3.0 L	Closed	Closed	On	With the roof fan on there could be small amounts of leakage through the ducts.
Test 9	Heptane 3.0 L	Closed	Closed	On	With the roof fan on there could be small amounts of leakage through the ducts.
Test 10	Heptane 3.0 L	Closed	Closed	Off	Kitchen hood was sealed.

Table 4: Test configuration for solid fuel experiments

Test No	Fuel	Bathroom exhaust duct	Closet exhaust duct	Roof fan	Comments
Test 11	Solid Fuel – PUR mattress of weight 3.82 kg.	Normal valve position	Normal valve position	On	Kitchen hood was tightly sealed, a deviation from normal operating conditions.
Test 13	Solid fuel test. Two mattresses of weight 2.65 and 2.604 kg.	Normal valve position	Normal valve position	On	This was a repeat of test 11.
Test 12	Solid Fuel test. PUR, paper, wood etc. burnt in the closet.	Normal valve position	Normal valve position	On	This was the last test. Kitchen hood was tightly sealed. Closet velocity measurement was removed. Caused severe structural damage.

4.2.2 Geometry

The height of the apartment was 2.57m, floor area of the apartment was 58.56 m² and the envelope area was 164.9 m² and this includes the floor and the ceiling areas as well. The concrete walls are shared with the adjacent apartment and the kitchen of the adjacent apartment was the control room during the fire tests. The wall thickness of the separating compartment was approximately 0.2 m and the interior wall thickness were 0.16m. The apartment had the typical Finnish two door system with the inner door opening inwards.

The apartment had two exhaust ducts in the bathroom and the other in the closet. The two ducts joined the exterior vertical exhaust which opened to the ambient. The layout of the apartment is shown in Figure 6: Experiment site geometry and instrumentation, along with the instrumentation setup for the experiment.

The dimensions of the rooms of the apartment are:

Living room: 5.36m x 3.98m

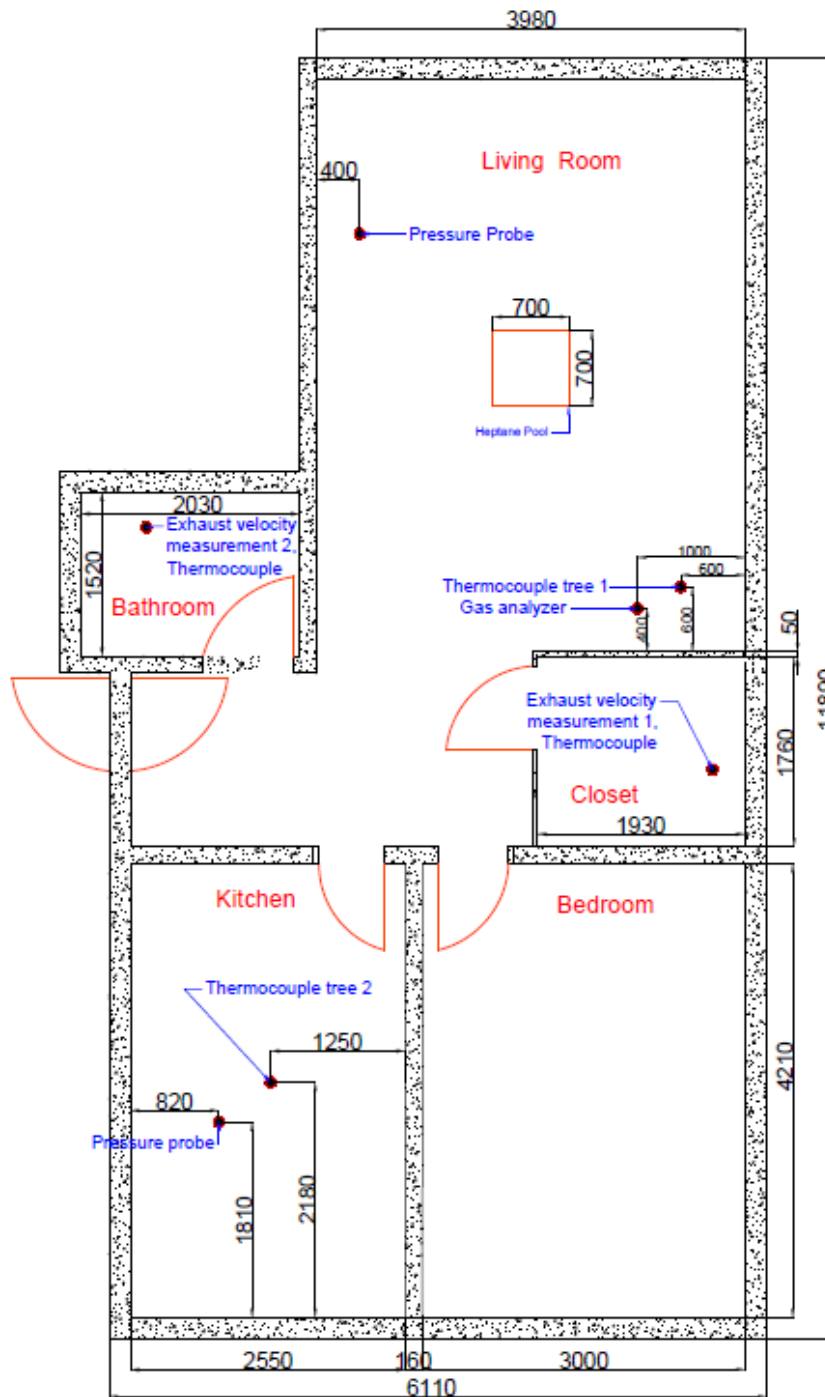
Bedroom: 4.37m x 3.0m

Kitchen: 4.37m x 2.55m

Aisle: 3.63m x 1.77m

Closet: 1.98m x 1.76m

Bathroom: 2.03m x 1.52m



All dimension are in mm

Figure 6: Experiment site geometry and instrumentation

4.2.3 Leakage Measurements

In the leakage measurement based on the standard SFS EN: 13829, a powerful variable speed fan is mounted onto the door of the apartment being tested and the windows and other exits of the room or apartment are sealed. The room is then pressurized or depressurized, this forces the air to flow in or out depending on the type of pressurization through all the leakages. A pressure gauge monitors the difference in pressure across the building envelope. The leakage flows are determined by monitoring the fan operation. The standard requires the leakage rates to be determined at 5 different pressures separated by 10 Pa difference. In this test the leakage rates were recorded from 30 Pa to 70 Pa. The value at 50 Pa is interpolated from the results obtained.

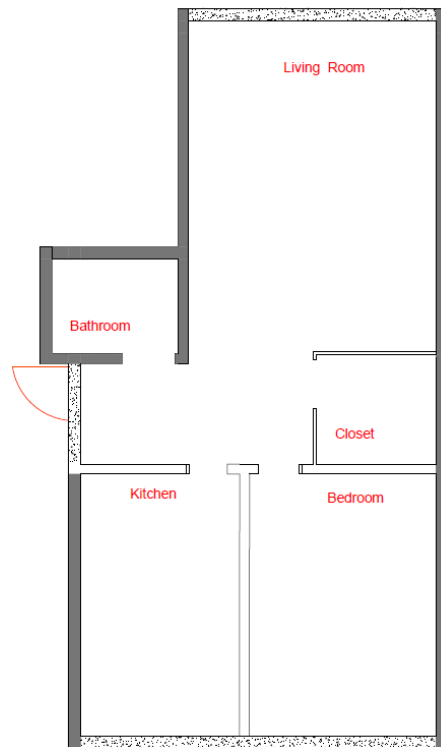


Figure 7: Major leakage paths in the apartment

The grey walls of the apartment envelope in Figure 7: Major leakage paths in the apartment are assumed to be non-leaky. The patched walls are assumed to be the main leak paths. The staircase and corridor was maintained at ambient pressure by opening the building's main door.

The leakage of the apartment was measured with different configurations of the HVAC ducts and inner door and a summary of the results is given in Table 5. The configuration of interest for determining leakage area is the one where HVAC ducts and inner door remain closed and the staircase is maintained at ambient pressure. The leakage in this configuration is estimated to be 121.1 L/s at 50 Pa pressure difference. At 70 Pa pressure difference, the leakage flow was 150.5 L/s.

Table 5: Leakage of the experiment site under various configurations of exhaust ducts

		Pressure type		
		Under pressure	Under pressure	Over pressure
HVAC ducts	Inner door	Corridor door to outside		
		Closed (L/s)	Open (L/s)	Open (L/s)
Open	Open	100.0	90.8	142.5
Open	Closed	92.2	79.7	136.7
Closed	Open	91.9	83.1	130.1
Closed	Closed	45.4	80.6	121.1

In the final report from the leakage tests, the leakage values at **50 Pa** was reported as **2.645 m³/hm²**. The maxima and minima of the leakage at 50 Pa was also reported as **2.538 m³/hm² – 2.758 m³/hm²**.

A point to be remembered is that the leakage specification in the building standards and regulations pertain to the leakage that occurs through the building façade. There are no regulations on leakage through inner walls of the compartment.

4.2.4 Ventilation

The apartment ventilation was a combination of Mechanical Exhaust Ventilation system and natural ventilation. The apartment had three main exhaust ducts in the bathroom, closet and the kitchen, but the kitchen exhaust remained closed in all tests. The exhaust duct height of the bathroom was 2.3±0.1 m. In the closet, the exhaust was located on the ceiling. The exhaust duct diameters are assumed to be 0.125 m, but the actual channel diameters throughout the building are not known.

A roof fan was also connected to the exhaust ducts of the bathroom (and probably kitchen as well). This conclusion is based on the behaviour of the closet duct which had a negative volume flow before the ignition due to the negative pressure within the compartment which indicates that the duct was connected to the ambient. The bathroom exhaust always had a positive volume flow when the roof fan was on and a negative volume flow when it was off. The exact ducting layout of the exhaust system remains uncertain, along with the characteristics of the fan.

The supply vent was located in the living room and connected to the ambient as shown in Figure 8: Supply vent in the living room. The supply vent was stuffed with wool to prevent any leakage.



Figure 8: Supply vent in the living room



Figure 9: Exhaust ducts configurations – Open condition (left), Normal condition (right)



Figure 10: Completely sealed closet exhaust duct

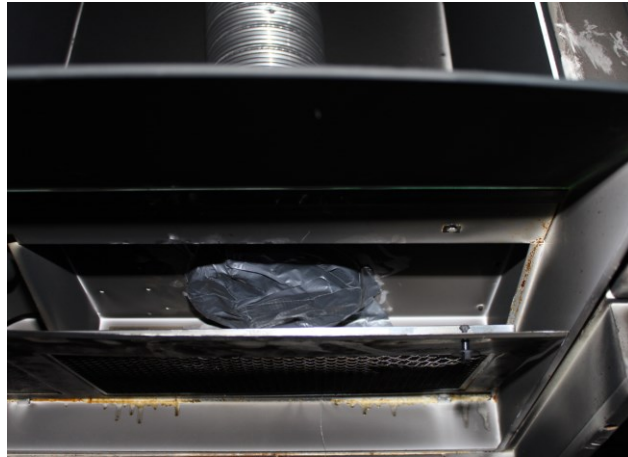


Figure 11: Completely sealed kitchen exhaust



Figure 12: Roof fan

4.2.5 Test Procedure

The experiments were designed such that each of the liquid fuel test lasted for approximately 3 minutes. The fuel pan was first filled with water to have a free rim height of 21 cm and the fuel was poured over it to ensure the fuel is not affected by the fuel pan heat conduction and also to prevent fuel boiling.

There was a fireman present in the apartment throughout the liquid fuel burns and was responsible for the ignition. As most of the hot gases would be concentrated in the upper zone of the fire room and as test durations were quite small, the lower zone (below 1m)

was sufficiently safe for a fireman with protective clothing to remain inside. Constant communication was maintained between the control room and fireroom.

The liquid tests were started by closing the doors. Then, the measurements were turned on, and after about one minute of baseline measurement, the fireman was asked to ignite the fire using a small torch.

Once the negative peak pressure was reached after the flame extinction, the measurements were stopped and data saved. The balcony door was opened to ventilate the smoke and gases. Positive pressure ventilation fans were also used to enhance smoke ventilation. The fire room was allowed to cool for at least 20 minutes after each test and the cooling time was increased after each test as the walls and especially the ceiling got hotter. The increase in wall and ceiling temperatures affects the heat transfer rates during the fire. The highest ceiling temperatures before the following tests were between 50 and 60 °C.

During the solid fuel tests, there was no one present in the fire room because much higher temperatures were expected. In these tests, the measurements were started while the apartment doors were open. After the one minute of baseline measurement, the solid fuel mattress was ignited by the fireman, again using the torch. After an established ignition, the fireman left the apartment to the staircase and closed the inner door. The time from ignition to the door closing was about 20 s.

4.2.6 Measurements and Instrumentation

The quantities that were measured during the experiments were gas pressure, gas temperature, O₂, CO₂ and CO concentrations and the exhaust velocity and temperatures in the exhaust ducts.

The pressure difference measurement was done using a Furness FCO 0508264-9 pressure probe that was connected to a room in the adjacent apartment which was maintained at ambient pressure. The probes can measure a maximum pressure range of -2500 Pa to 2500 Pa and the calibration uncertainties 0.97% to 1.03 % respectively. Two pressure probes were placed in the test apartment in the fire room (living room) and kitchen. The probes were placed at a height of 1.8 m from the floor. The probe in the fire room was placed 1.25 m away from the fuel pan and the second probe was placed in the centre of the kitchen. The pressure data was recorded every second.

The thermocouple tree consisting of 5 K-type thermocouples of 1.5 mm diameter were placed at the right corner of the fire room (Figure 6). The thermocouples were placed 50 cm apart from each other vertically. Another set of thermocouples were placed in the centre of the kitchen for comparison of values. Additionally, a thermocouple was also placed over the fuel pan to measure the flame temperature thereby providing us the ignition and extinction times. Thermocouples were also placed in the exhaust ducts for measuring the exhaust gas temperatures. The temperature data was collected at 1 second intervals.

The gas concentration measurements were done using a gas analyser. The probe for the gas analyser was placed at a height of 1.7 m on the right corner of the living room next to the thermocouple tree as indicated in Figure 6. The gas measurement data is obtained at 1 second interval and delay in the values measured was measured to be 16 seconds. In the final test, the CO₂ and CO levels had peaked above the calibrated maximum value of the analyser and hence could not be ascertained.

The velocity of the gases through the exhaust ducts were measured using a bi-directional probe with a pressure range of -500 Pa to 500 Pa. A thermocouple was also placed next to it to measure the exhaust gas temperatures. The calibration uncertainties of the probes were 1.96% and 2.2% for the closet and bathroom probes respectively.

The mass loss of fuel was measured using a load cell and the heat release rate is calculated from it as HRR is not a fundamental property of the fuel. Estimating HRR based on mass loss rate requires knowledge of heat of combustion (HoC) of Heptane. Here the HRR can be obtained as

$$\dot{Q} = \dot{m} * \Delta H_{eff} \quad (8)$$

The net heat of combustion of N-Heptane is 43500 KJ/mol. The peak heat release rates from the liquid fuel tests were estimated to be 1 MW and the averages about 700 kW.

The mass values were recorded at an interval of 2 seconds and then the values were interpolated to 1 second intervals for consistency with other data. From the obtained mass values, the mass loss rate (dm/dt) was determined using a polynomial least square fitting function. The load cell was protected from thermal damage using stone wool.

For the solid fuel tests the mass loss was not measured because the safety of the load cell could not be ensured. Therefore, only the flame temperature was measured. The solid fuels used were PUR mattress for the Tests 11 and 13. For test 12, the fire room was changed to the closet and the fuel burnt was a mattress, few wooden boards and paper. This test was done to simulate a condition which is quite common in actual fires.

The tests were recorded using video cameras placed inside the fire room and in the balcony. This provides us with visual data that can also be used for assessment of fire behaviour.



Figure 13: Thermocouple and Gas analyser



Figure 14: Exhaust velocity and temperature measurement - Bathroom



Figure 15: Fuel pan and the flame thermocouple



Figure 16: Window breakage after final test

4.2.7 Discussion

The experimental results, which are not presented in this thesis as such, show high repeatability in the results of heat release rates, temperatures and pressures. The tests can be broadly classified in to three groups based on the exhaust duct configurations. The pressures were highly dependent on the configuration of the exhaust ducts. The roof fan had negligible effect on the pressures. The highest pressure rise developed in the liquid fuel test was 960 Pa when the ducts were completely sealed.

The solid fuel tests yielded the highest pressure rises of the experiments. Pressure higher than 1600 Pa was developed in the tests with normal duct configuration. The final test in the closet led to structural damage as the window, including the frame, of the apartment was blown out of the wall when pressure exceeded 1400 Pa (Figure 16: Window breakage after final test).

The peak ceiling jet temperatures in the liquid fuel experiments were about 300 °C and the temperatures below 1.0 m were close to 50 °C. The ceiling jet temperatures were similar in the solid fuel tests as well but due to higher air entrainment, the gas temperatures were approximately 130 °C at 0.5 m from the floor. The smoke layer also recedes below 1m height.

The liquid fuel tests were always well ventilated. Under ventilated conditions occurred only during Test 12. The CO production also remained low in the liquid fuel test. The Test 12 produced the highest CO concentration of close to 5000 ppm.

It was the first time that fire experiments were conducted in an actual apartment to study pressure effects and it is also the first time that a structural damage of this extent has been reported. More tests need to be performed in the future under more controlled conditions in a relatively new construction with well-defined ventilation system to obtain and analyse the performance of newer buildings.

5 FDS Simulations

5.1 FOA Series

5.1.1 Description of FDS model

The FDS model of the FOA series was created according to the following procedure, which is recommended for this type of applications:

1. The volume of the room should represent the volume of the enclosure as accurately as possible. This is because the volume of oxygen in the room is important for enclosure fire development, as well as pressures.
2. If there are multiple rooms operating at different pressures then each room must be specified as a separate pressure zone.
3. The fuel burning characteristics, i.e. HRR, and the fire source dimensions must be ascertained for accurate prediction of temperatures.
4. A reasonable value of CO and soot yield must be chosen from the literature. Though the modelling of CO production during the under-ventilated regime is not accurate when using the simple chemistry model, it will still provide a reasonable estimate of the CO production during a well ventilated fire.
5. The materials of the boundaries and their properties need to be as accurate as possible because the conductivity of the boundary can be an important factor influencing the pressure.
6. The wall backside boundary conditions should be specified appropriately (BACKING=VOID/EXPOSED).
7. The combustion should be simulated without a specified auto ignition temperature (AIT) and use AIT if there are any ghosting flames or unwanted burning. The auto ignition temperatures of various fuels are available in Drysdale, 2011.
8. When using AIT, one needs to model the ignition source. It can be modelled as an obstruction (OBST) over the fuel pan with temperature of a typical flame i.e., 900 – 1500 °C. It is recommended to deactivate the ‘OBST’ immediately after ignition. This might require a few test runs to determine the proper time of ignition of the gas vapours.
9. In this work, the HVAC model is used to model the leakage in FOA tests as it was the most appropriate method for this application. The leakage value of the compartment is converted into an estimated leakage area and specified over a surface in the FDS model. Also, leakage area specification in FDS can be done by dividing the leakage into smaller leakages that are applied over different surfaces of the compartment being simulated. This allows more realistic modelling of the leakage paths as in reality there are multiple leakage paths.
10. The leakage of various types of houses can be gathered from either literature or from a leakage test of the enclosure being analysed. Leakage modelling heavily influences the pressures in the enclosure and small changes can cause significant variation in pressure. A way to verify the modelled leakage value with the tested leakage value is to model a leak test. (Appendix E – Leakage Test)

The compartment was modelled as in the experiments but the exact properties of the concrete is unknown hence the general properties available were utilized (Quintiere, 2006). The pressures are monitored using devices as in the experiments. The temperatures are modelled using the same size thermocouples and the insulation for the thermocouples from the direct radiation is done using Calcium Silicate boards.

In FDS, by default, a mixture of fuel and oxygen in any cell will react automatically. In FOA simulations, this led to burning at the leak outlet and other places in the fire room distant from the fuel source. Therefore, the AIT parameter was specified to enforce the ignition to occur only above the specified temperature (223 °C) thereby controlling unwanted combustion.

As the leakage areas are rarely multiples of the FDS mesh cells, they cannot be captured by the numerical mesh directly, and need to be modelled as a HVAC duct connecting the fire room to the ambient. In the FOA experiments, the room leakage was through a hole with varying diameters of 0.1 m, 0.15 m and 0.2 m, connected to a 3.2 m long duct. The leakage was modelled as a HVAC duct of the specified area leading to ambient. The leak area was defined over a vent on the right wall. Corresponding code is shown below:

```
% HVAC DUCT
&HVAC ID='WallHoleDuct',
TYPE_ID='DUCT',NODE_ID='OutflowNode','WallNode',
AREA=0.031416,LOSS=0.255,0.255,, LENGTH=0.15, ROUGHNESS=0.001, / 0.2
diameter hole in the wall
&HVAC ID='WallNode', TYPE_ID='NODE',
DUCT_ID='WallHoleDuct','OutflowDuct', LOSS=1.0, 1.0, XYZ=0.0,2.1,0.7 /
&HVAC ID='OutflowDuct', TYPE_ID='DUCT',
NODE_ID='WallNode','AmbientNode', AREA=0.0804, LOSS=2., 2.,LENGTH=3.2,
ROUGHNESS=0.001, / 0.32 diameter circular duct
&VENT ID='OutflowVent', XB=0.0, 0.0, 2.0, 2.2, 0.6, 0.8,
SURF_ID='HVAC', COLOR='RED'/
&HVAC ID='OutflowNode', TYPE_ID='NODE', VENT_ID='OutflowVent',
DUCT_ID='WallHoleDuct', LOSS=1.0, 1.0, XYZ=0.0, 2.1, 0.7, /
&HVAC ID='AmbientNode', TYPE_ID='NODE', DUCT_ID='OutflowDuct',
LOSS=1.0, 1.0, XYZ=0.0,2.1,0.7, AMBIENT=.TRUE. /
```

There are also other methods for leakage modelling such as the Localized leakage method and Bulk Leakage method. The localized leakage approach is useful in modelling leaks over a specific surface such as a door. This method uses the local pressure instead of the zone pressure and therefore one can define multiple leakage paths for different windows, along a door or when stack effect needs to be accounted for. It creates a duct of the specified area between the two vents. LEAK_ENTHALPY=.TRUE. maintains hot gas flowing out through the duct. (McGrattan et al., 2015(a), pp. 110).

```
% Localized leakage
&SURF ID='SURF1' /
&VENT XB = 0.0, 0.0, 2.0, 2.2, 0.6, 0.8, SURF_ID='SURF1', ID='VENT 1',
COLOR = 'RED' /
&HVAC ID='LEAK', TYPE_ID='LEAK', VENT_ID = 'VENT 1', VENT2_ID =
'AMBIENT', AREA=0.031416, LEAK_ENTHALPY=.TRUE., LOSS=1. /
```


In the pressure zone approach, pressure zones are specified by the user to model the leaks between the zones. This approach is intended to capture the bulk leakage that occurs through the walls. A leak between two zones is considered as a pair of HVAC vents with a loss coefficient of 1. A leak path should be specified between two solid surfaces in the zones. This can also be between a single pressure zone and the ambient. The zones are numbered as Zone 1, Zone 2 etc. and Zone 0 corresponds to the ambient (McGrattan et al., 2015(a), 109-110).

```
%Bulk Leakage
```

```
&ZONE XB=2.2,5, 7,10, 0,2.6, LEAK_AREA(0) =0.0234 /
```

The above line indicates that the defined zone (Zone 1) leaks to the ambient zone (Zone 0) through an area of 0.0234 m².

The exhaust/supply network is modelled as a set of 8 nodes, starting from the node which connects the computational domain (fire room, ENode) to the exit of the exhaust (Node 5). Each of the 7 ducts connect each of these nodes in the specified order. The first duct connecting the room and the duct after the bend is combined into a single duct as the losses due to the bend can be combined into a single loss in FDS. The losses are given as an effective entrance and exit loss corresponding to forward and reverse flows through the ducts. A roughness of 0.001 is assumed for all the ducts. In the above sample codes, the losses are to be changed as per calculated values for each particular case. The basis of the above HVAC modelling is the simplification of ventilation network that can be done in FDS

An example input code of a FDS-HVAC network for the exhaust network 1 (Figure 2: Exhaust ventilation network 1) is given below.

Example input code for exhaust ventilation network

```
----- Exhaust Ventilation network -----

&HVAC ID='EWallHoleDuct', TYPE_ID='DUCT', NODE_ID='ENode','EWallNode',
AREA=0.007854,LOSS=0.0,0.0, LENGTH=0.15, ROUGHNESS=0.001 /
&HVAC ID='EWallNode', TYPE_ID='NODE', DUCT_ID='EWallHoleDuct','duct 1',
LOSS=0.,0.,XYZ=0.0,4.1,1.3 / DAMPER LOSS
&VENT ID='Event', XB=0.0,0.0,4.0,4.2,1.2,1.4, SURF_ID='HVAC',
COLOR='RED' /
&HVAC ID='ENode', TYPE_ID='NODE', VENT_ID='Event',
DUCT_ID='EWallHoleDuct', LOSS=1.0,1.0 /

&HVAC TYPE_ID = 'NODE', ID='node 2', DUCT_ID='duct 1','duct 2','duct
5',XYZ = -0.65,3.0,1.3, LOSS = 0,0 /
&HVAC TYPE_ID = 'NODE', ID='node 3', DUCT_ID='duct 2','duct 3','duct 6',
XYZ = -0.65,2.0,1.3, LOSS = 0,0 /
&HVAC TYPE_ID = 'NODE', ID='node 4', DUCT_ID='duct 3','duct 4','duct 7',
XYZ = -0.65,1.0,1.3, LOSS = 0,0 /
&HVAC TYPE_ID = 'NODE', ID='node 5', DUCT_ID='duct 4', XYZ = -
0.65,-1.7,1.3, LOSS = 1,1, AMBIENT=.TRUE./
&HVAC TYPE_ID = 'NODE', ID='node 6', DUCT_ID='duct 5', XYZ = -
1.75,3.0,1.3, LOSS = 1,1, AMBIENT=.TRUE. /
&HVAC TYPE_ID = 'NODE', ID='node 7', DUCT_ID='duct 6', XYZ = -
2.05,2.0,1.3, LOSS = 1,1, AMBIENT=.TRUE. /
```

```
&HVAC TYPE_ID = 'NODE', ID='node 8', DUCT_ID='duct 7', XYZ = -
2.05,1.0,1.3, LOSS = 1,1, AMBIENT=.TRUE. /
```

```
&HVAC TYPE_ID = 'DUCT', ID='duct 1', NODE_ID='EWallNode','node 2', LENGTH
= 1.75, AREA=0.007854, LOSS =17.2,17.2, ROUGHNESS=0.001, /
&HVAC TYPE_ID = 'DUCT', ID='duct 2', NODE_ID='node 2','node 3', LENGTH
= 1.0, AREA=0.01227, LOSS =0.0,0.0 ROUGHNESS=0.001 /
&HVAC TYPE_ID = 'DUCT', ID='duct 3', NODE_ID='node 3','node 4', LENGTH
= 1.0, AREA=0.02010, LOSS =0.0,0.0, ROUGHNESS=0.001 /
&HVAC TYPE_ID = 'DUCT', ID='duct 4', NODE_ID='node 4','node 5', LENGTH
= 2.7, AREA=0.02010 LOSS =0.0,0.0, ROUGHNESS=0.001, FAN_ID='E_FAN' /
&HVAC TYPE_ID = 'DUCT', ID='duct 5', NODE_ID='node 6','node 2', LENGTH
= 1.0, AREA=0.007854, LOSS =18.9,18.9, ROUGHNESS=0.001 /
&HVAC TYPE_ID = 'DUCT', ID='duct 6', NODE_ID='node 7','node 3', LENGTH
= 1.3, AREA=0.007854, LOSS =19.1,19.1, ROUGHNESS=0.001 /
&HVAC TYPE_ID = 'DUCT', ID='duct 7', NODE_ID='node 8','node 4', LENGTH
= 1.3, AREA=0.007854, LOSS =19.1,19.1, ROUGHNESS=0.001 /
```

```
&HVAC TYPE_ID='FAN', ID='E_FAN', MAX_PRESSURE=310, MAX_FLOW=0.130, /
fan curve is given in the experiments.
```

The heat release rate in the experiments was estimated based on the fuel burning area and was fitted to a t^2 curve corresponding to the equation $Q = (\alpha - \alpha_0)t^2$, with different α , fire growth coefficient, for each fire. Due to the uncertainty in the experiments, a relatively high uncertainty can be attributed to the HRR ramp values. The HRR ramps in FDS were adjusted to obtain a reasonable O_2 consumption curve as the HRR is dependent on O_2 . The description of tests and fires used in each test is given in Table 1 and Table 2. The simulated (FDS) and measured (Exp) HRR curves are compared in the figures below. Figures on the left compare the output (resulting) HRR with specified experimental HRR, and the figures on the right do the same for the FDS input HRR.

T-square 1: $\alpha=0.035$

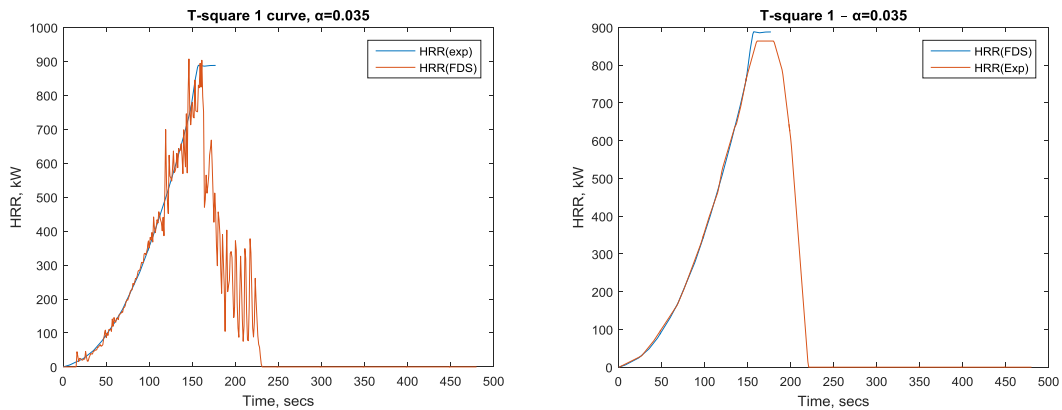


Figure 17: HRR_exp vs FDS output (left) and HRR_exp vs FDS input (right)

T-square 2: $\alpha=0.075$

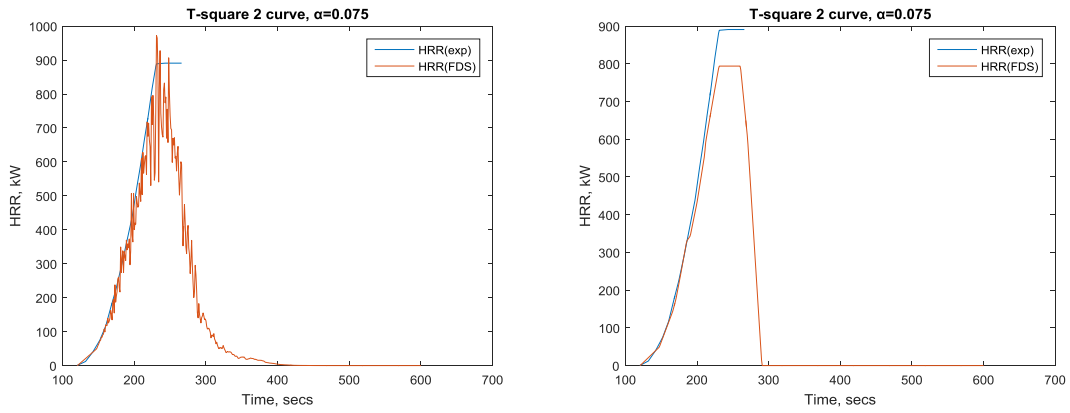


Figure 18: HRR_{exp} vs FDS output (left) and HRR_{exp} vs FDS input (right)

T-square 3 – $\alpha=0.085$

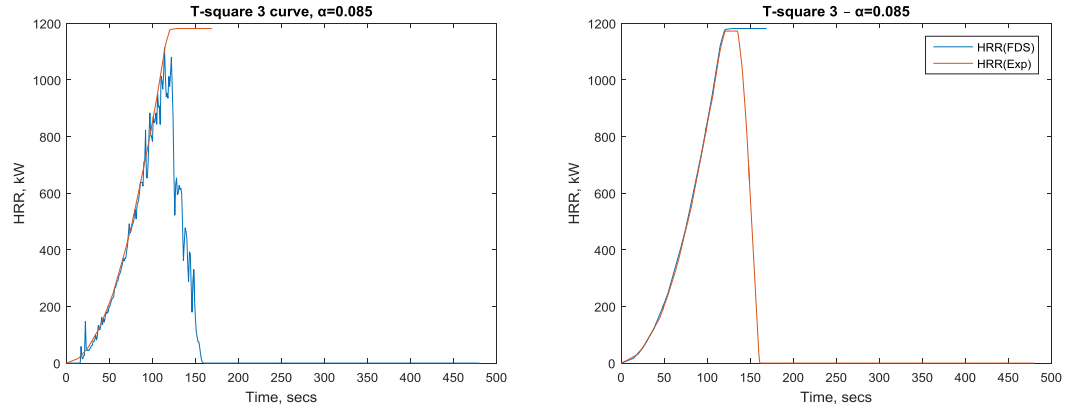


Figure 19: HRR_{exp} vs FDS output (left) and HRR_{exp} vs FDS input (right)

Constant HRR curve

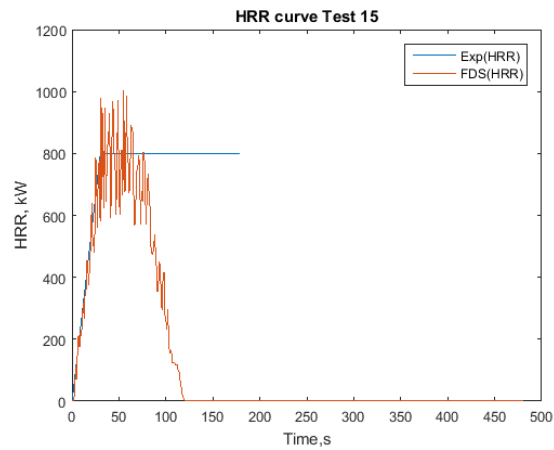


Figure 20: Pool fire, constant area (0.5 m^2) – Test 15

5.1.2 Simulation results of the FOA series

Simulations were carried out using the FDS 6.3.0 version and the results of the tests are presented according to the test series- FOA-1996 and FOA-1998 respectively. The computer used for the test was a personal computer with an AMD Phenom II x6 1055T processor with a speed of 2.8 GHz with an 8 GB ram. The CPU time for the FOA, 1996 and FOA, 1998 was approximately 8 hours. In FOA-1998 experiments the plots are according to the t^2 fire curves and the ventilation configurations.

FOA 1996: Pressure rise due to fire growth in a closed room.

The pressure, temperature oxygen consumption and the outlet velocity are presented. The peak positive pressures are in good agreement with the experimental values in this series for all the three tests (deviation < 10%). There is an over prediction with the peak temperatures. The experimental minima of O₂ curve is not reached using the default parameters. Adjusting the Critical Flame Temperature will yield better predictions. The peak positive velocity is lower than the experimental value. The results were smoothed over a period of 9 seconds in the experiments.

Test 1

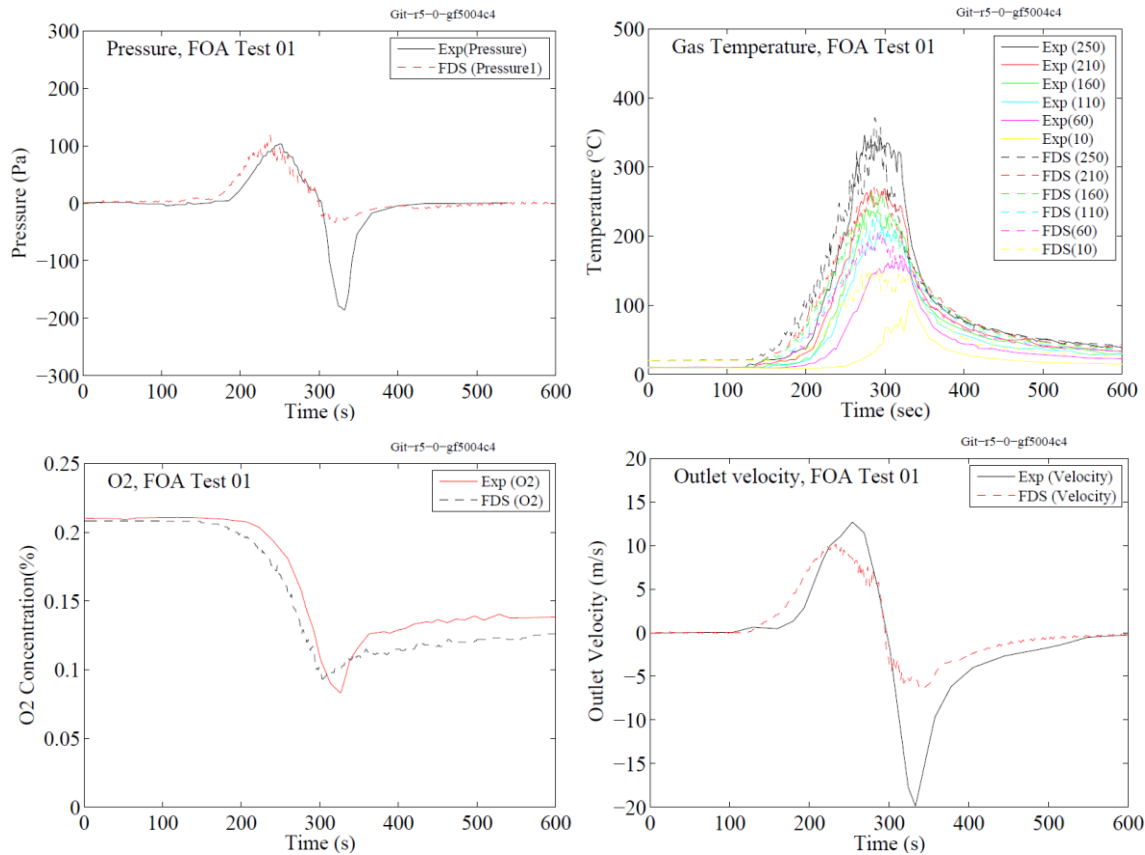


Figure 21: FOA-1996, $\alpha=0.035$ – Test 1, Experiment and FDS comparison

Test 2

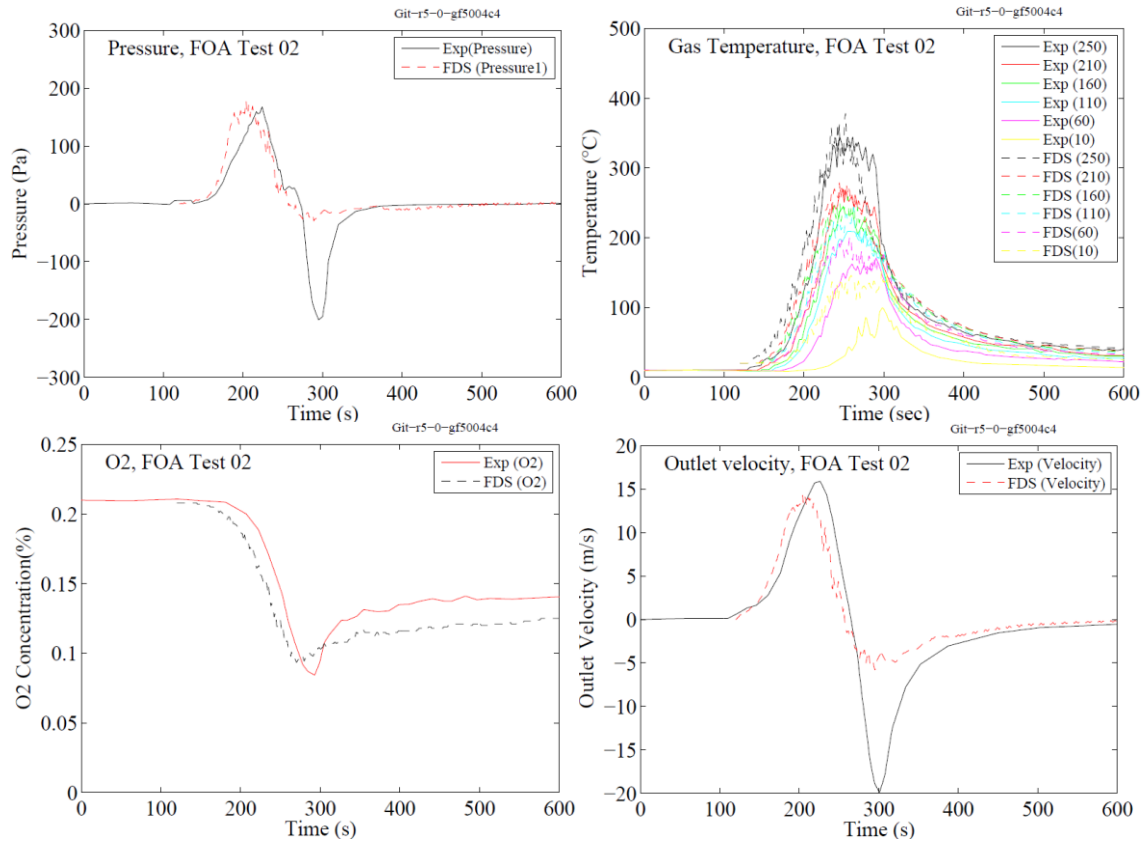
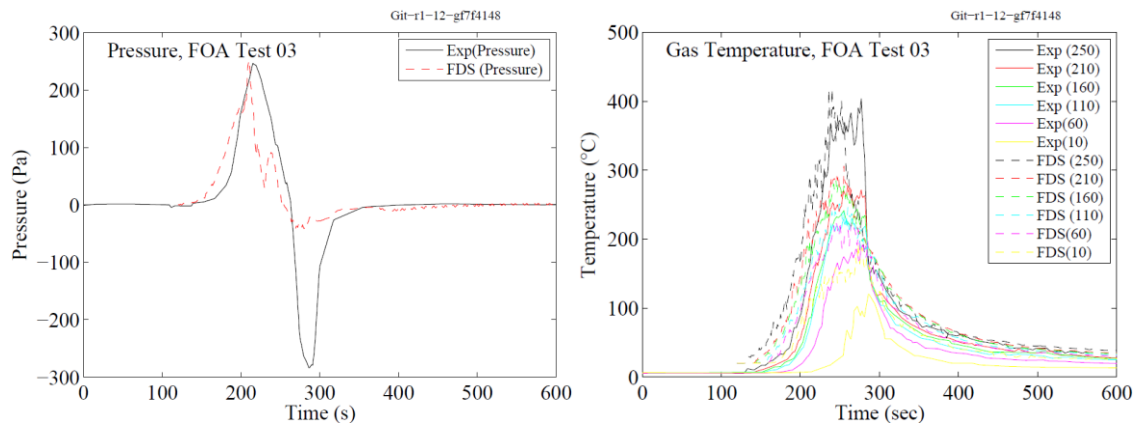


Figure 22: FOA-1996, $\alpha=0.035$ – Test 2, Experiment and FDS comparison

Test 3



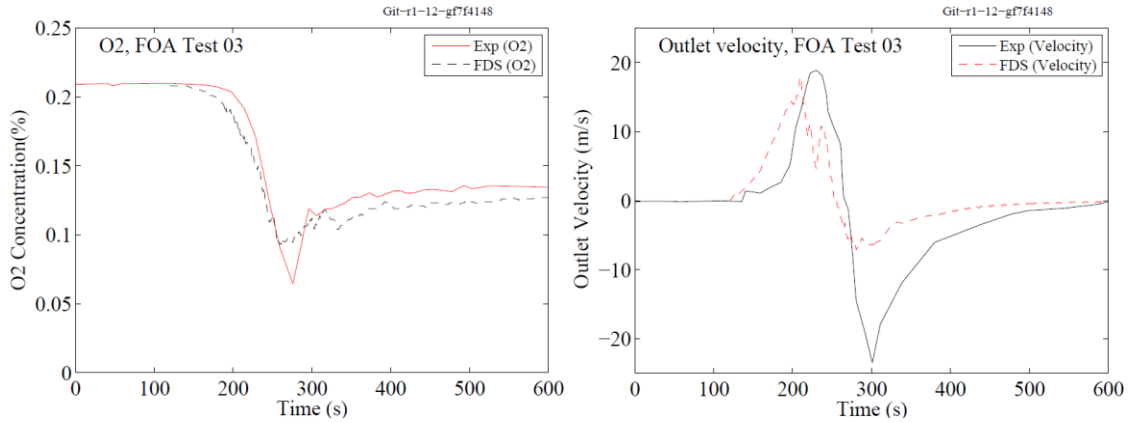


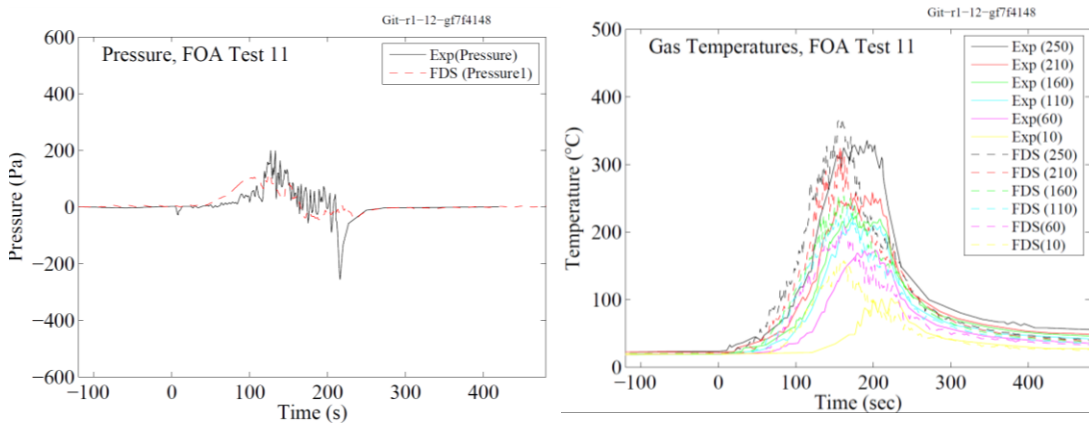
Figure 23: FOA-1996, $\alpha=0.035$ – Test 3, Experiment and FDS comparison

FOA, 1998: An experimental study of smoke spread via ventilation systems.

In Tests 11-15, the fire room was not connected to any ventilation system and only the opening diameters were varied. The pressure, temperature oxygen consumption and the outlet velocity are presented.

FOA Test 11

The HRR curve of Test 11 (FOA, 1998) is similar to that of Test 1 (FOA 1996) but in Test 11 the burning rate is different in the experiments as can be seen from the experiments. This could be due to the difference in the speed at which the lid of the pan is moved to increase the fuel burning area.



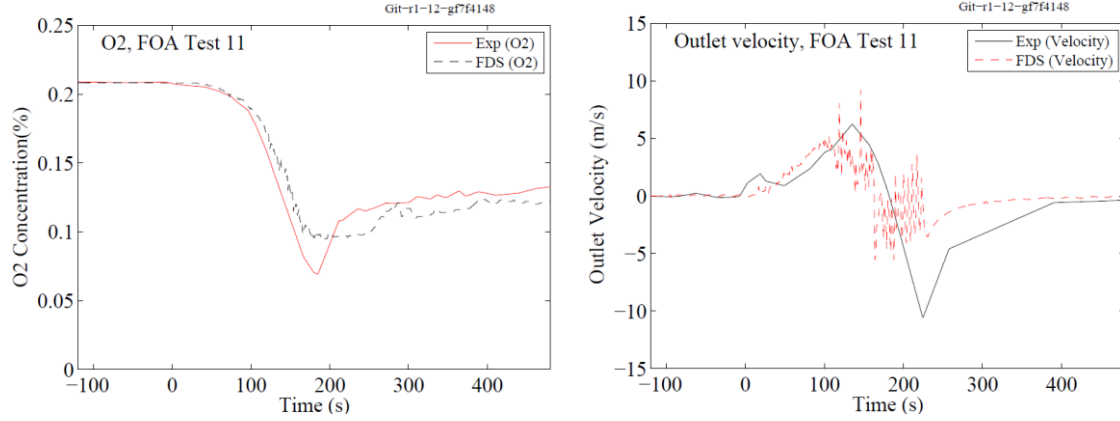


Figure 24: FOA-1998, $\alpha=0.035$ – Test 11, Experiment and FDS comparison

FOA Test 13

The HRR curve of Test 13 (FOA, 1998) is similar to that of Test 3 (FOA 1996) but in Test 13 the burning rate is different in the experiments. There is a time shift in FDS results due to modelling constraints.

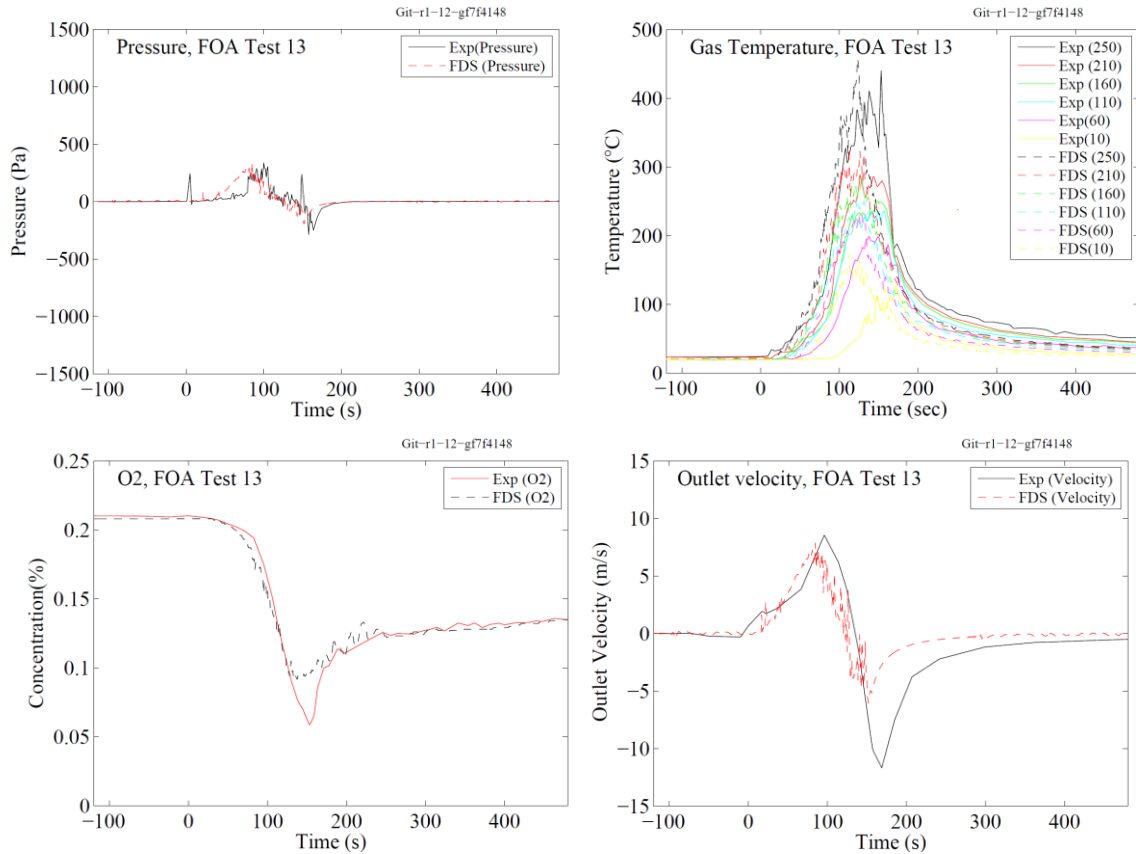


Figure 25: FOA-1998 $\alpha=0.085$ – Test 11, Experiment and FDS comparison

FOA Test 15

The Test 15 in the FOA series 2 experiments is taken as the base test to validate FDS capabilities of modelling pressure rise in compartments. The uncertainty regarding the HRR curves is very small as this is a constant pool area case. The FDS temperatures, pressures, velocity and even oxygen concentration are in good agreement with the experimental results. The under pressure remains an issue to be addressed and is not the focus of this study.

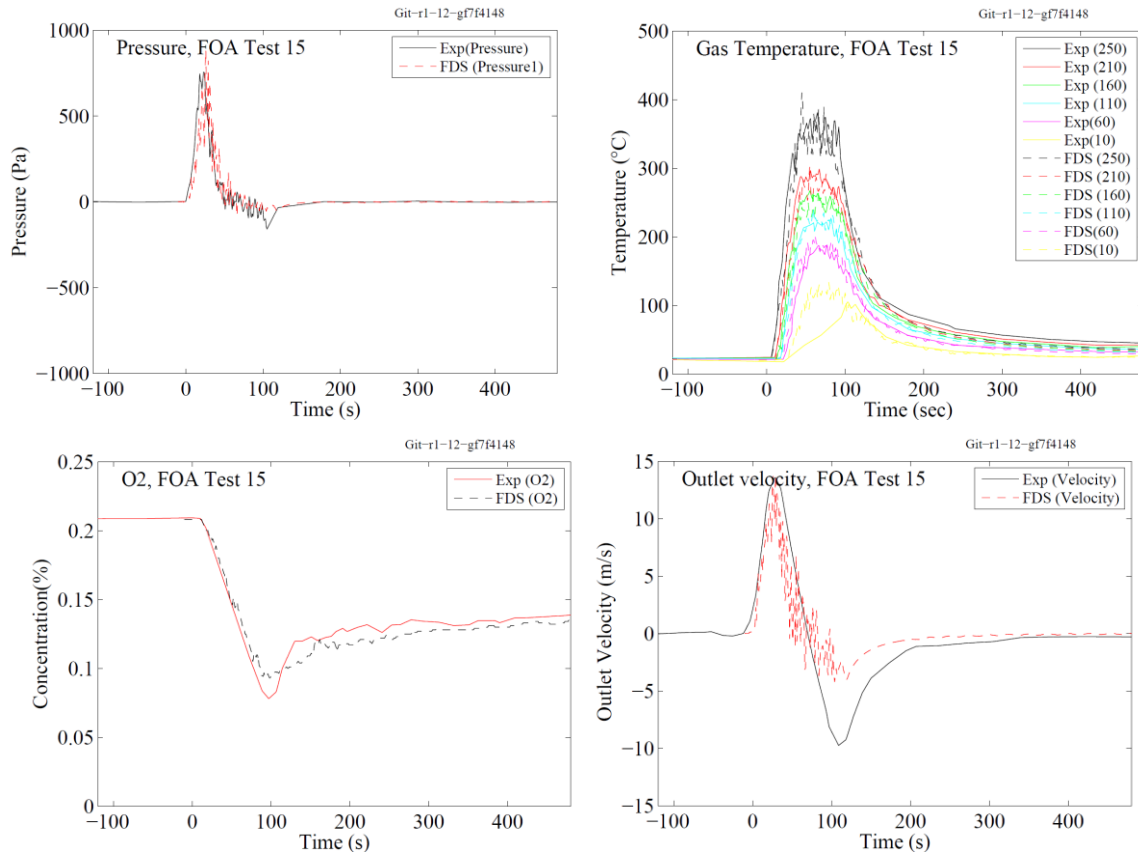


Figure 26: FOA-1998, constant pool area – Test 15, Experiment and FDS comparison

FOA Test 22

In Tests 21-23, the room is connected to an exhaust ventilation system and the flow in the ventilation system is tuned to 25 L/s at the start of each test. The pressure, temperature oxygen consumption and the outlet velocity from Test 22 presented.

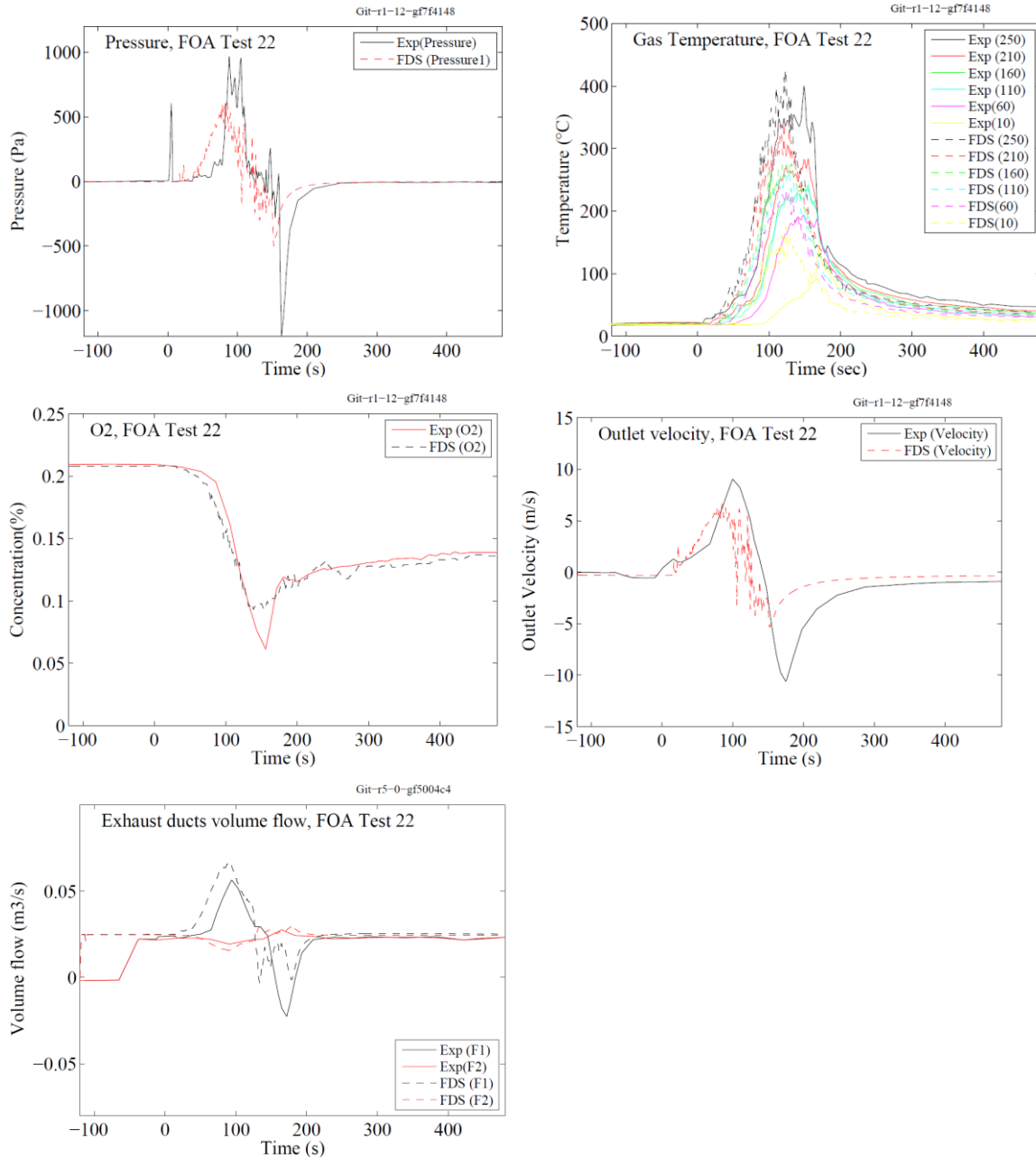


Figure 27: FOA-1998, $\alpha=0.085$ – Test 22, Experiment and FDS comparison

FOA Test 31

The fire room in tests 31-33 was connected to a supply and exhaust ventilation system. The flow in the supply and exhaust system are maintained at 25 L/s. The exhaust system in the last test (Test 33) is the alternate exhaust network shown in Figure 3: Exhaust ventilation network 2. The Test 31 has a growth rate, $\alpha=0.035$ and Tests 32 and 33 have a growth rate of $\alpha=0.085$. Only the plots from Test 31 are presented here.

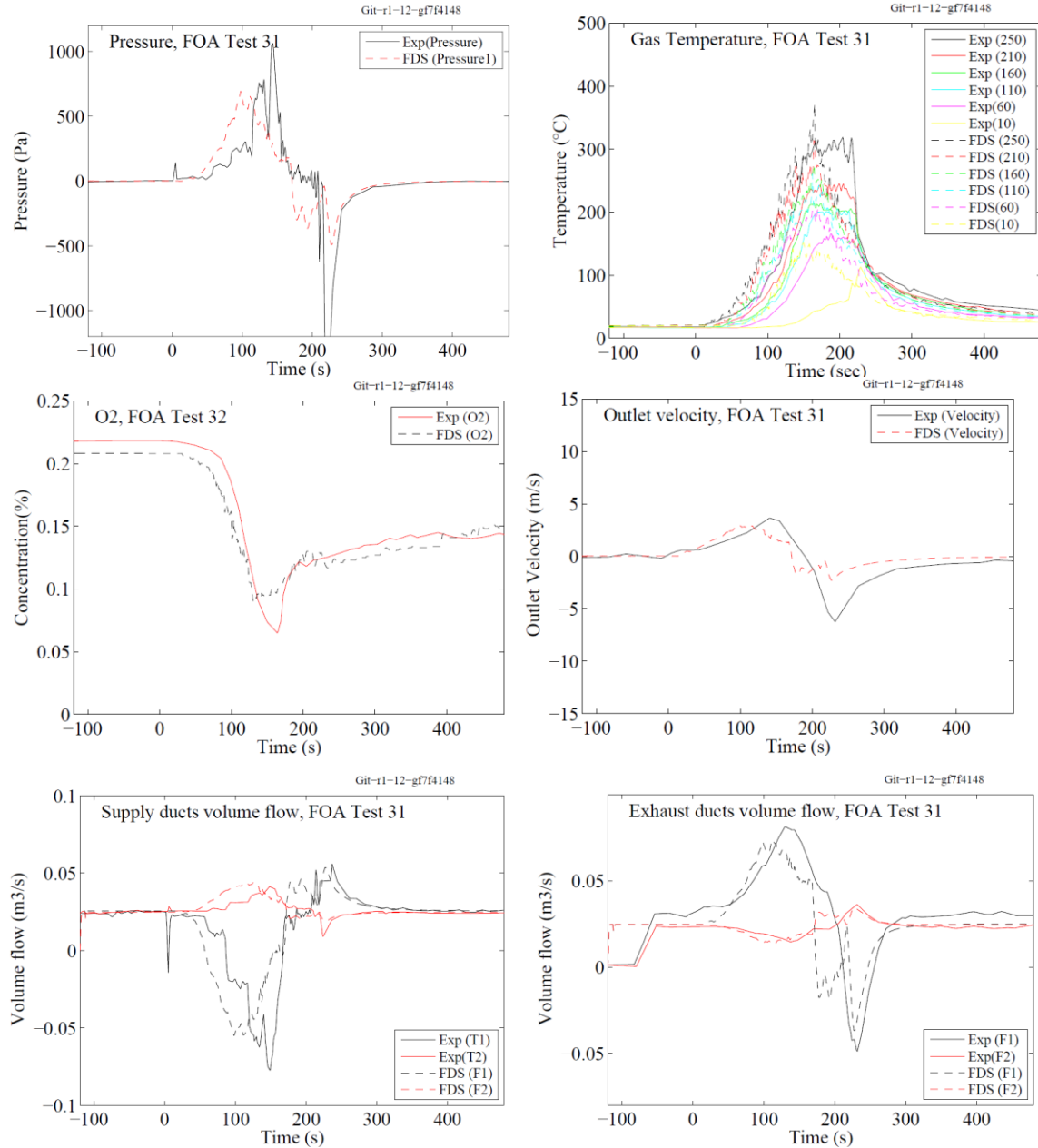


Figure 28: FOA-1998, $\alpha=0.035$ – Test 31, Experiment and FDS comparison

The scatter plots of the results show the prediction bias and standard deviation. The summarized set of scatterplots for the FOA simulations and Aalto experiments are presented in Section 5.3.

5.2 Aalto Experiments

5.2.1 Description of FDS model

The FDS models for the n-Heptane tests of the Aalto experiments are quite similar to the FOA series. The first aspect of focus in this FDS calculation was to achieve the correct heat release rates and temperatures in the fire room. This was validated using the temperature and gas concentration predictions, for which the existing level of model uncertainty is known and reported in the FDS Validation Guide. The fuel pan was modelled as a 0.7 m x 0.7 m burner with specified heat release rate per unit area varying over time according to the measured HRR (Equation 8).

The second aspect of focus was to achieve acceptable pressure predictions. The pressures are closely linked with the HRR and temperatures in the fire room. For pressure predictions, accurate modelling of the envelope leakage is essential. As the modelled leakage corresponds to the leakage of the building envelope only, it must be determined from the leakage measurements where the HVAC ducts were closed. Assuming that the flows through the leakage behave as flat plate orifice flows, the leakage area A_{leak} can be solved from the following equation

$$Q_{leak} = C_d A_{leak} \left(\frac{2}{\rho} \Delta p_{leak} \right)^{0.5} \quad (9)$$

where C_d is discharge coefficient and Δp_{leak} would be 50 Pa in case of standard test. The accuracy of the estimated leak area in the conditions similar to the leakage test can be checked by making a simulation of the actual leakage test (Appendix E – Leakage Test).

The main problem of the above-mentioned method for estimating A_{leak} is that the pressure differences during fires can be about one order of magnitude higher than the pressure differences used in the leakage tests. As a result, there is no guarantee that the gaps and cracks of the building envelope behave in a similar manner. Also, assuming a 1 mm gap size indicates that the flow Reynolds number is less than 1000 at 50 Pa but about 2000 at 500 Pa difference, thus indicating a transition from laminar to turbulent flow. In this situation, both C_d and the exponent of the pressure term in equation (9) can be different.

In this work, the leak area was calculated from equation (9) assuming $C_d = 0.6$, $\rho = 1.225 \text{ kg/m}^3$, $\Delta p = 70 \text{ Pa}$, and $Q_{leak} = 150.5 \text{ L/s}$, giving $A_{leak} = 0.0235 \text{ m}^2$.

The parameter DT_HVAC was used to stabilize the pressure fluctuations whenever the HVAC module is employed. This parameter is included from FDS 6.3.1 onwards.

The leakage was modelled using all the three leakage modelling methods but the plots of individual quantities are presented only for the Bulk Leakage method as it is physically more accurate to the situation being modelled. The temperature scatterplots for the other leakage models are presented for reference as the thermal modelling is the basis of verification.

Precise modelling of ventilation fan on the roof was difficult as no information regarding the roof fan was available. Only the velocity data measured during the experiment and it is to be noted that the flow was not fully developed flow. It can be seen from the experimental results that the roof fan does not influence fire pressures considerably. The small differences in fire pressure observed between Tests 1, 2 and Tests 3, 4 are due to the

changes in burning behaviour of the Heptane. Therefore, the initial volume flow through the duct can be estimated but the operating and stalling pressure cannot be known precisely.

There are two ducts in the apartment, one in the closet and the other in the bathroom and based on the behaviour of the closet duct prior to ignition, it can be deduced that the closet duct is connected directly to the ambient as there is a negative flow in the duct caused due to the negative pressure inside the building and is hence modelled as such. Only the bathroom duct connects to the roof duct which is connected to the exhaust roof fan. The main extraction duct length is only 1 m with an exhaust fan connected to it.

An estimate of the fan performance was made based on the initial extraction rates of the fan through the ducts. Assuming a net initial flow of 20 L/s through each duct. The estimates made for the fan are uncertain. A stalling pressure of 200 Pa and a maximum flow rate of 200 L/s was assumed for the fan. The flow rates in the ducts are close to the measured flow rates.

An example of the ventilation network is given below:

```
----- EXHAUST DUCT CLOSET -----

&HVAC ID='ClosetDuct1', TYPE_ID='DUCT',
NODE_ID='ClosetNode','ClosetOutNode', AREA=0.01227, LENGTH=0.4,
LOSS=0,0 /
&HVAC ID='ClosetDuct2', TYPE_ID='DUCT', NODE_ID='ClosetOutNode',
'AmbientNode1', AREA=0.01227, LENGTH=9, LOSS=5,5 /

&VENT ID='ClosetVent', XB = 5.4,5.6 , 4.6,4.8 , 2.6,2.6,
SURF_ID='HVAC',COLOR='RED' /
&HVAC ID='ClosetNode', TYPE_ID='NODE', DUCT_ID='ClosetDuct1',
VENT_ID='ClosetVent', LOSS=1,1 /
&HVAC ID='ClosetOutNode', TYPE_ID='NODE',
DUCT_ID='ClosetDuct1','ClosetDuct2', LOSS =1,1, XYZ=5.5,4.5,2.6 /
&HVAC ID='AmbientNode1', TYPE_ID='NODE', DUCT_ID='ClosetDuct2',
AMBIENT=.TRUE., LOSS=1,1,
XYZ = 5.8,8.5,8.0 /

----- EXHAUST DUCT BATHROOM -----

&HVAC ID='BRDuct1', TYPE_ID='DUCT', NODE_ID='BRNode','BROutNode',
AREA=0.01227, LENGTH=0.4, LOSS=0,0 /
&HVAC ID='BRDuct2', TYPE_ID='DUCT', NODE_ID='BROutNode', 'TeeNode',
AREA=0.01227, LENGTH=10, LOSS=5,5 /

&HVAC ID='BRNode', TYPE_ID='NODE', DUCT_ID='BRDuct1', VENT_ID='BRVent',
LOSS=1,1 /
&HVAC ID='BROutNode', TYPE_ID='NODE', DUCT_ID='BRDuct1','BRDuct2', LOSS
=1,1, XYZ=0.7,7.72,2.3 /

&VENT ID='BRVent', XB = 0.6,0.8 , 7.8,7.8 , 2.2,2.4, SURF_ID='HVAC',
COLOR='RED' /

&HVAC ID='TeeNode', TYPE_ID='NODE', DUCT_ID='BRDuct2','RoofDuct',
LOSS=1.0,1.0, XYZ=6.0,7.72,7.0 /
&HVAC ID='RoofDuct', TYPE_ID='DUCT', NODE_ID='TeeNode','AmbientNode',
LENGTH=1.0, AREA=0.049, LOSS=0.0,0.0, ROUGHNESS=0.001 /
&HVAC ID='AmbientNode', TYPE_ID='NODE', DUCT_ID='RoofDuct',
AMBIENT=.TRUE., XYZ=6.0,7.72,8.0, LOSS = 1,1 /
```

```
HVAC TYPE_ID='FAN', ID='E_FAN', MAX_PRESSURE=200, MAX_FLOW=0.200, /
fan curve
```

5.2.2 Simulation results

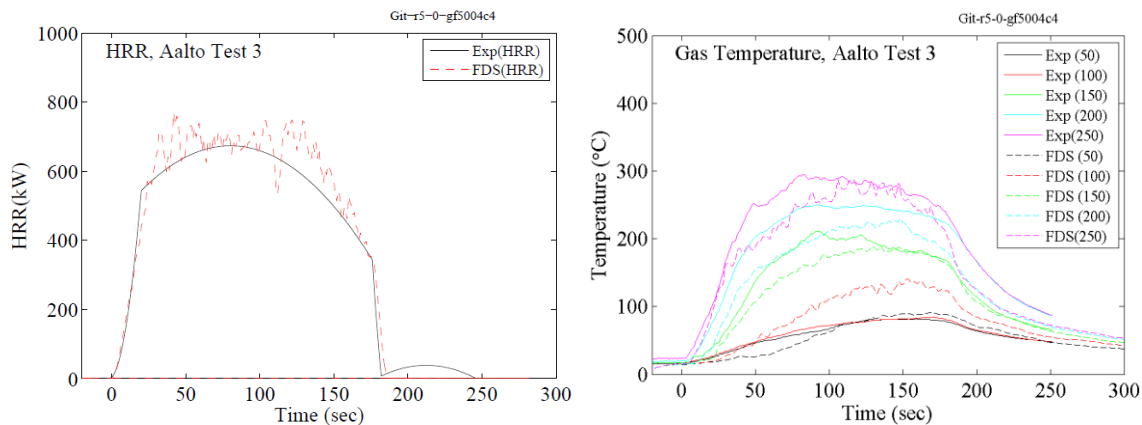
Simulations were carried out using the FDS version 6.3.2. The computer used for the test was a personal computer with an AMD Phenom II x6 1055T processor with a speed of 2.8 GHz with an 8 GB ram. The CPU time for the FOA, 1996 was approximately 36 hours utilizing 6 cores of the computer.

The simulations were performed with different leakage modelling methods to assess their differences. The applicability of each method must be assessed according to the situation under consideration. As thermal modelling is one of the critical factors in fire protection, the method which yields the best temperature values would be more accurate. Plots of measured quantities are shown for the Bulk leakage method. Only scatterplots are presented for the localized and HVAC leakage method.

The pressure predictions were different for each leakage model: with the Bulk Leakage model over predicting pressure and the HVAC and Localized leakage model under predicting pressures. The Test 3 pressure is over predicted with all the three leakage models. The heat release rates, oxygen predictions and duct velocities are within the acceptable limits of uncertainty. The temperatures are under predicted by 20-30 °C.

Test 3

In test 3 the ventilation ducts were open and the roof fan was switched off. The HRR matches the experimental HRR curve fit very well. There is a slight under prediction of temperatures initially and an overprediction of pressure.



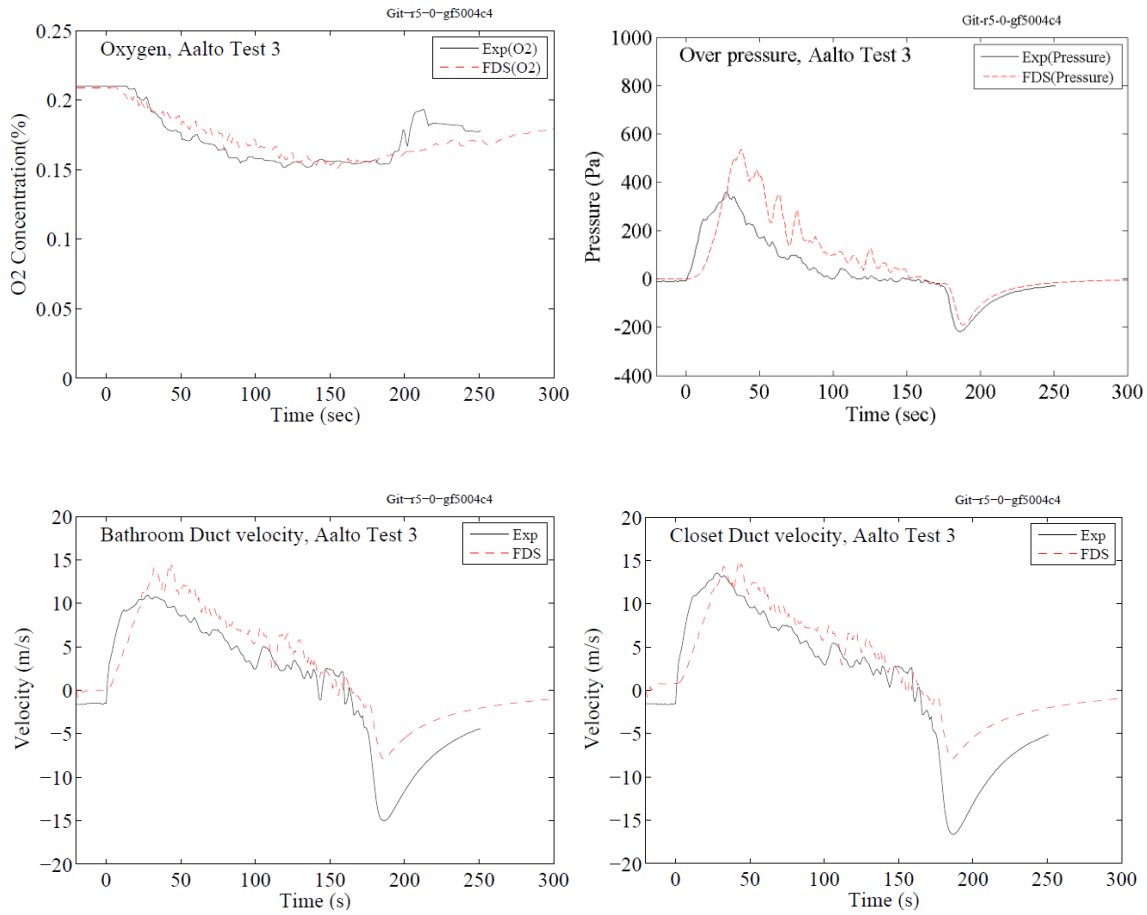
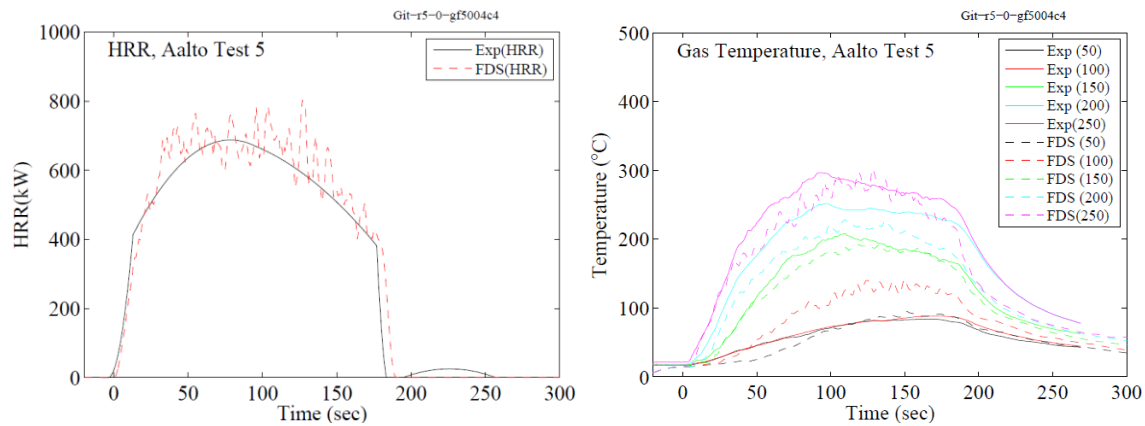


Figure 29: Aalto Test 3, Bulk Leakage model-Open duct configuration

Test 5

In test 5, the ventilation ducts had louvers attached and roof fan was ON in this test. The HRR matches the experimental fitted HRR curve. The temperatures are predicted well. There is an over-prediction of pressures.



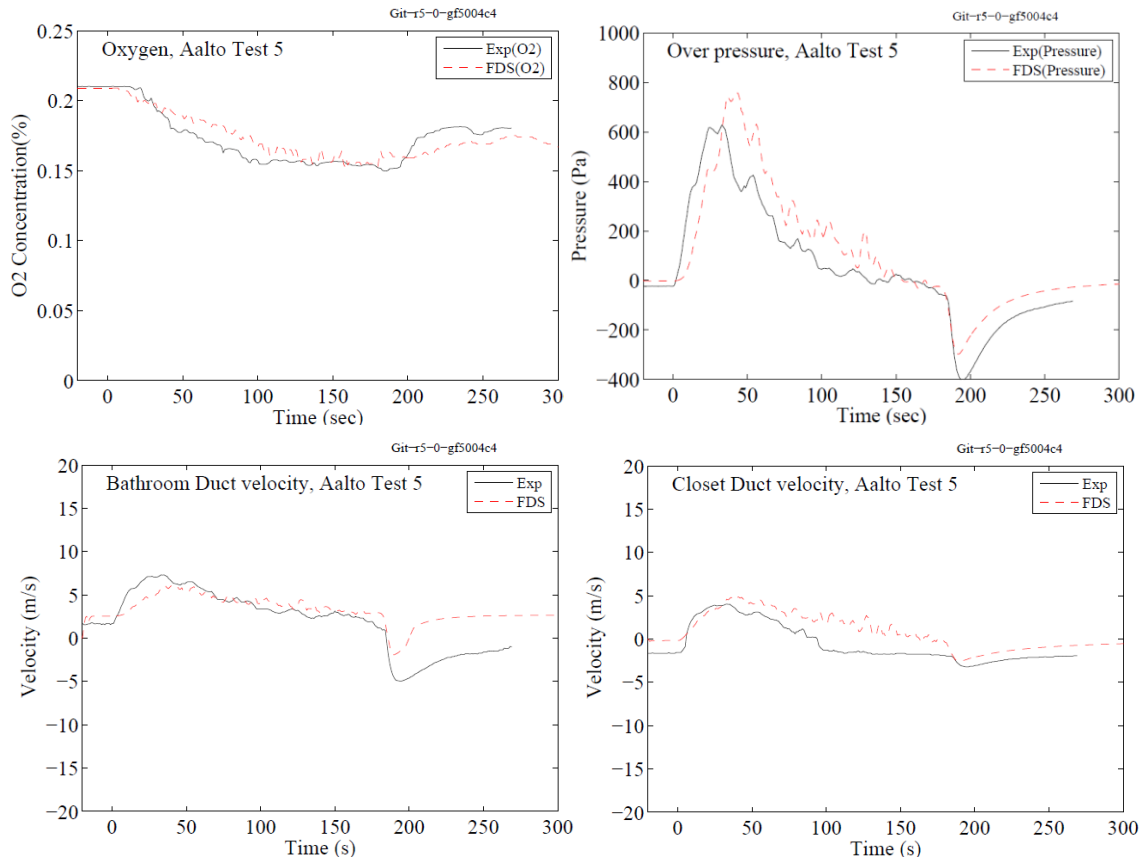
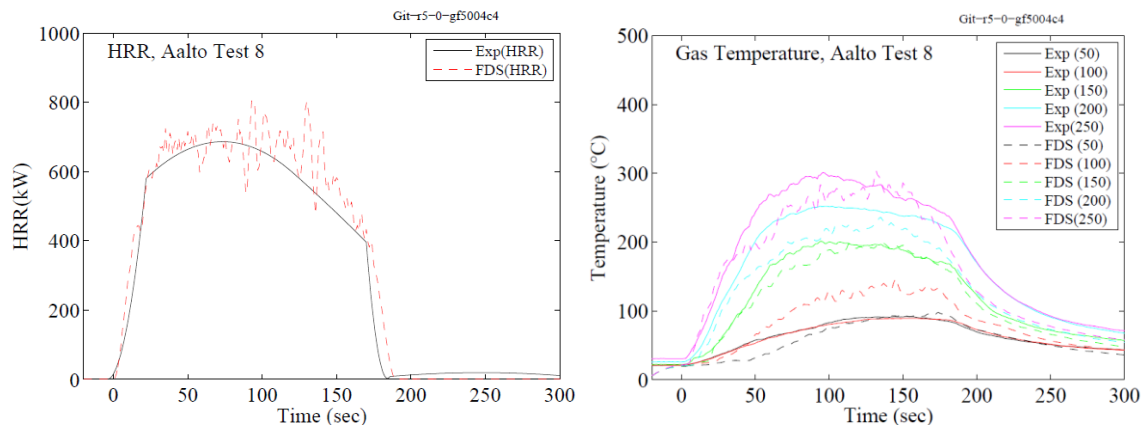


Figure 30: Aalto Test 5, Bulk Leakage model -Normal duct configuration

Test 8

In this test the ventilation ducts were closed to create an airtight condition. The HRR curve matched the experimental HRR curve. There is a slight underprediction of temperatures initially and an over-prediction of pressures.



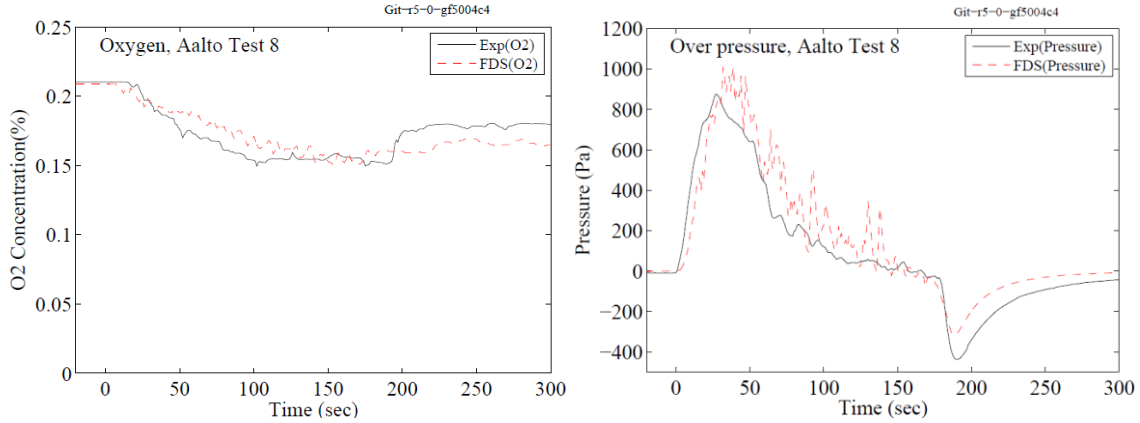


Figure 31: Aalto Test 8, Bulk Leakage model -Closed duct configuration

5.3 Results summary

The scatterplots for the Bulk Leakage method are presented below. The quantities presented are temperature, pressure, oxygen volume fractions, duct volume flow (FOA experiments) and velocities (FOA and Aalto experiments). There are three temperature scatterplots corresponding to temperature based on the ventilation configuration. The FOA studies have only two ventilation configurations: No ventilation and Forced ventilation. Also the duct velocities of Aalto experiments are summarized along with the leak velocities of FOA experiments. Additionally, the temperature and pressure scatterplots of the HVAC and Localized leakage method are presented for reference.

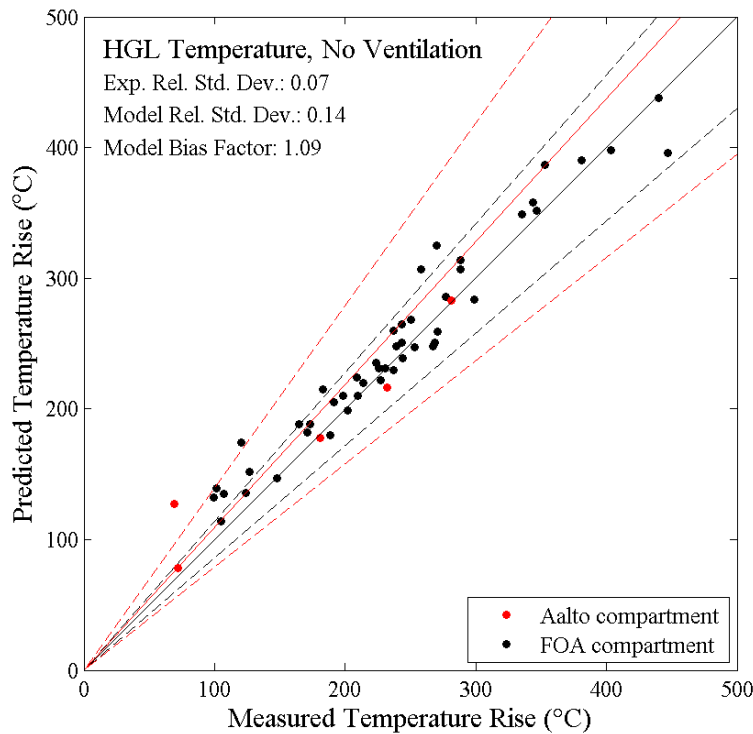


Figure 32: Temperature summary- No Ventilation

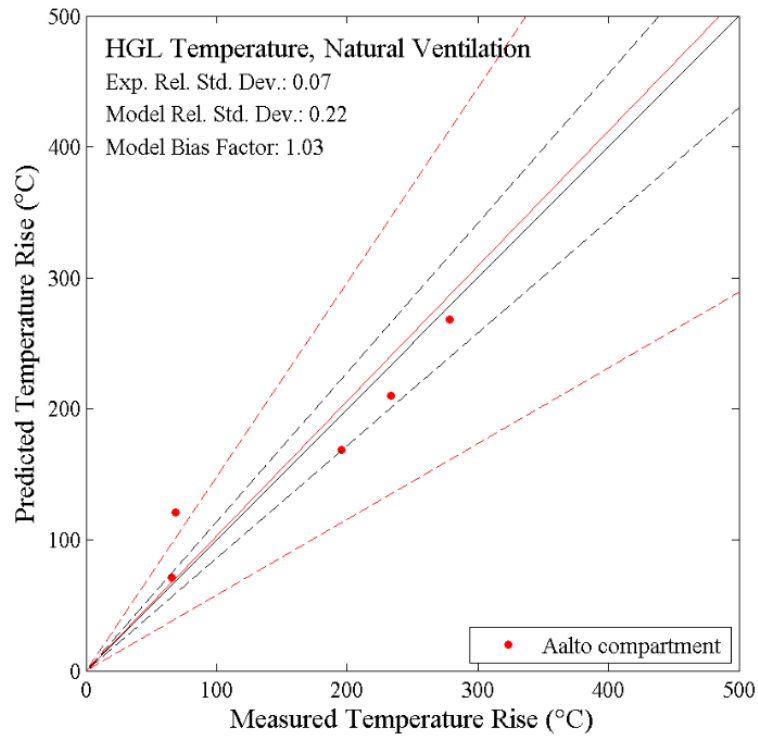


Figure 33: Temperature summary- Natural Ventilation

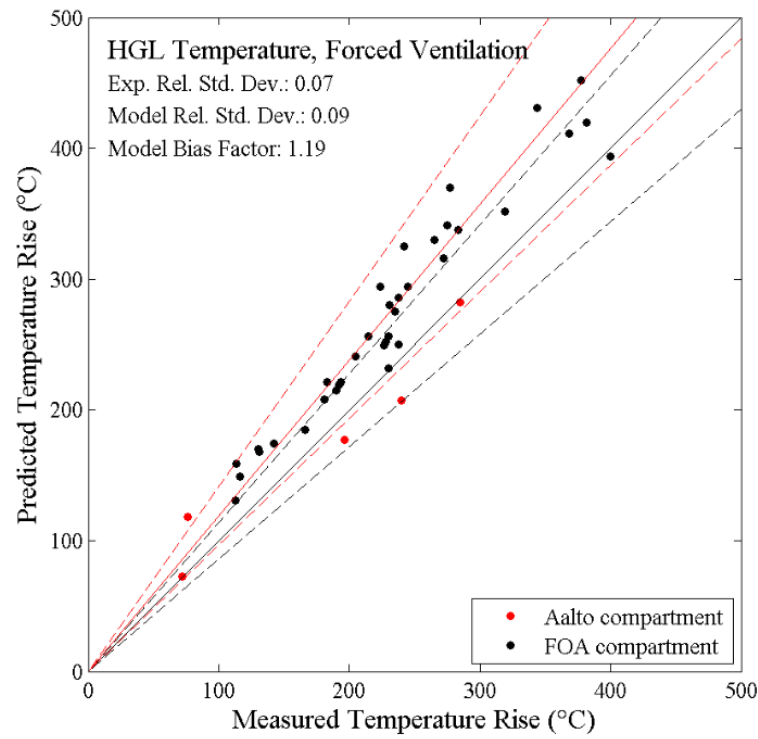


Figure 34: Temperature summary- Forced Ventilation

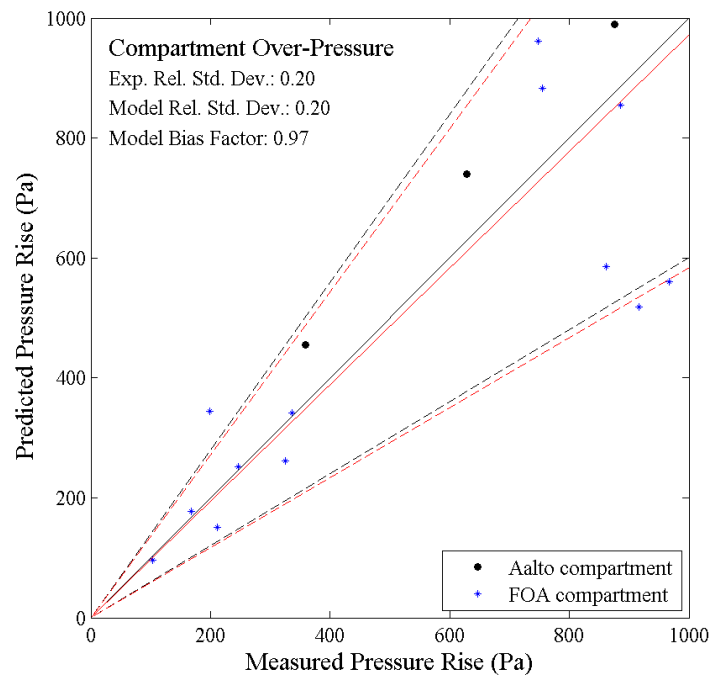


Figure 35: Pressure summary

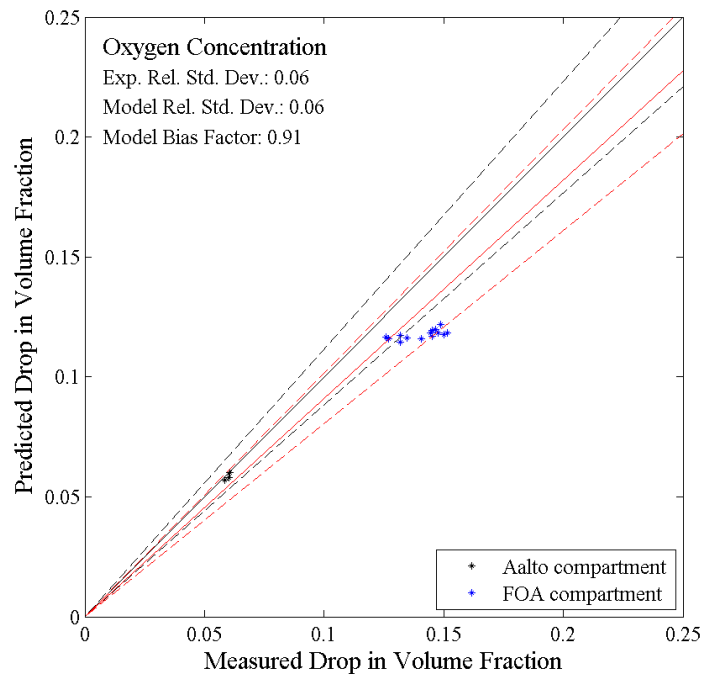


Figure 36: Oxygen volume fraction summary

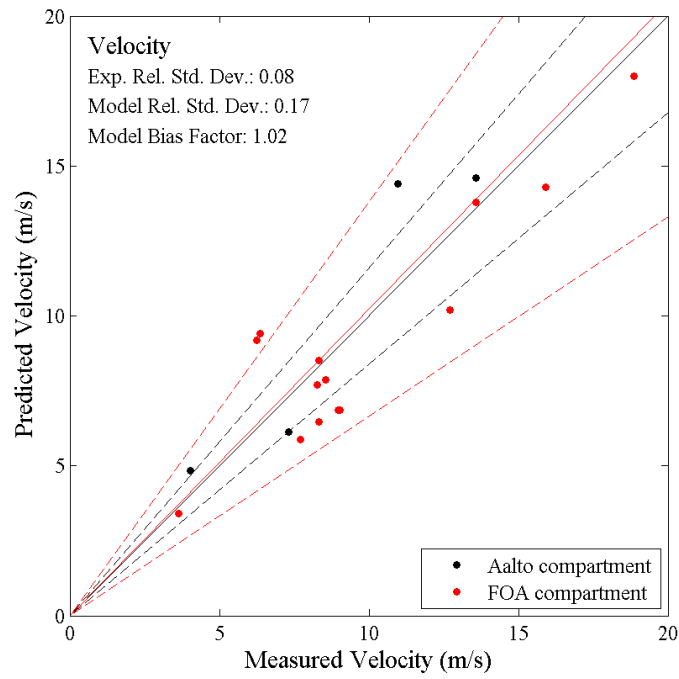


Figure 37: Leak velocity summary (FOA) and exhaust duct velocities (Aalto)

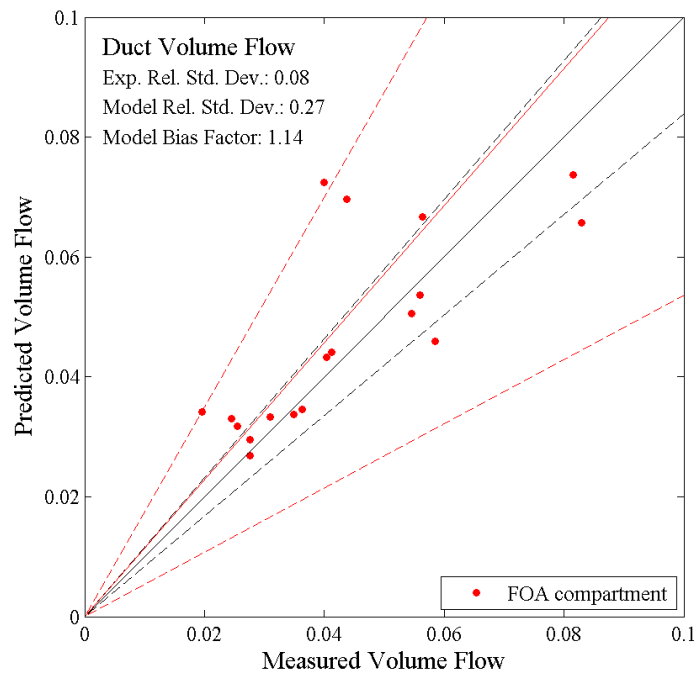


Figure 38: Duct Volume flow summary

Localized Leakage Temperatures

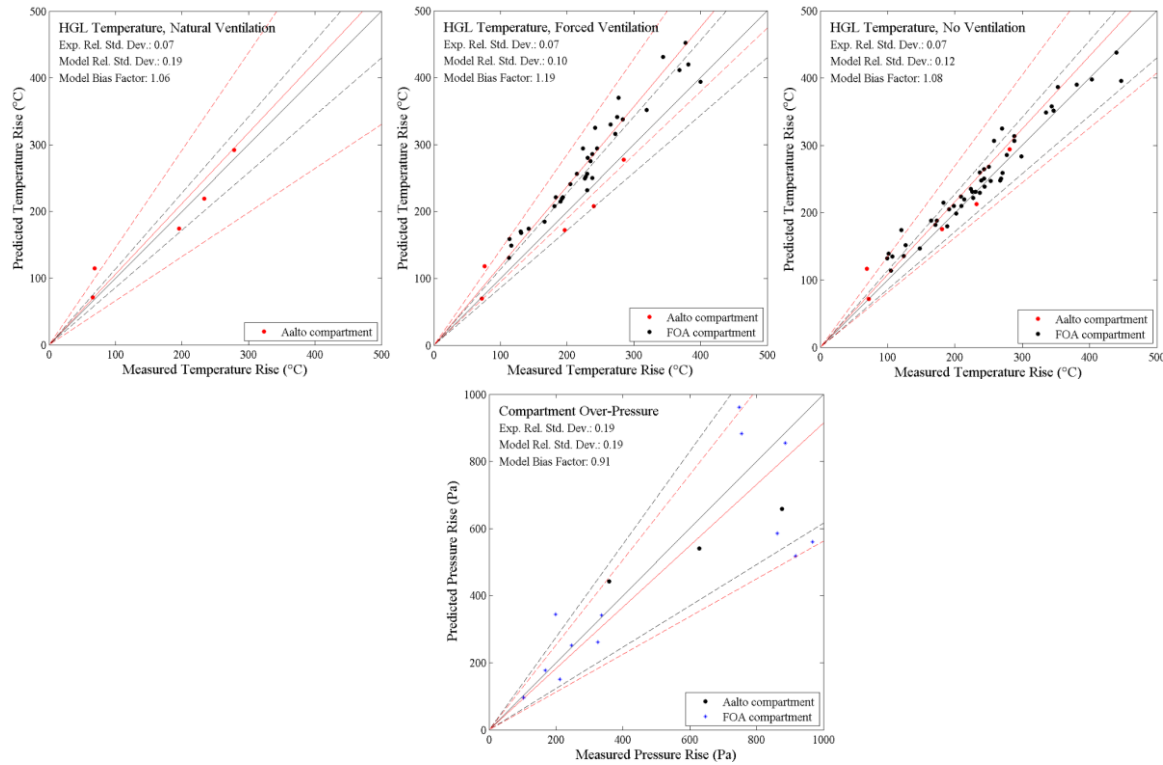


Figure 39: Temperature and Pressure scatterplots for localized leakage method

HVAC Leakage Temperatures

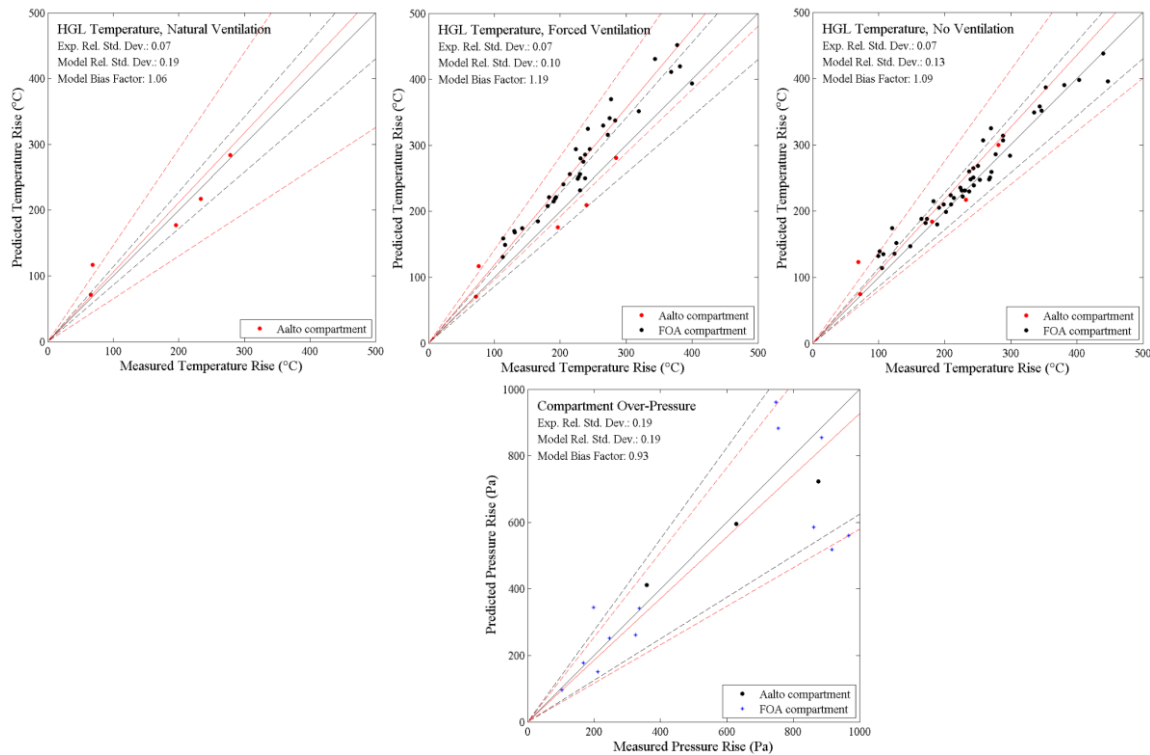


Figure 40: Temperature and Pressure scatterplot for HVAC leakage method

6 Discussion

6.1 Uncertainties in the validation experiments

The FOA tests provide great insight into the behaviour of pressure and smoke flow through ventilation networks. Yet there are some uncertainties which are quite common in experiments and this affects the validation study as well.

The first uncertainty with the FOA studies is the lack of concrete HRR or fuel MLR measurement. The HRR was estimated from the fuel burning area (FBA) which was controlled by a lid over the fuel surface moved at different speeds. Due to this limitation the O_2 concentration in the room was used as an alternate reference for the validation simulations.

Also, the experimental results show some inconsistency in the HRR within the same type of fires. As the HRR is controlled by changing the FBA, it can be prone to error as the lid movement speeds can vary and this has not been accounted for or specified. The HRR uncertainty can be demonstrated by examining the O_2 consumption curve. Test with the same estimated HRR produce different oxygen consumption curves (Figure 41). This means that the HRR is also different in each test. The effects are seen in the pressure variations in the tests. Test 21 and 13 have the same HRR curve and the same opening diameter of 0.20 m. The setup in Test 21 also has an exhaust ventilation connected that provides an additional path of pressure release. Yet the experimental pressure in Test 21 is greater than the pressure in Test 13. The same argument could be made for the other tests which have a mechanical exhaust or supply system. A reason for this could be that the Iris damper opening was smaller than the other tests thereby restricting the flow of hot air.

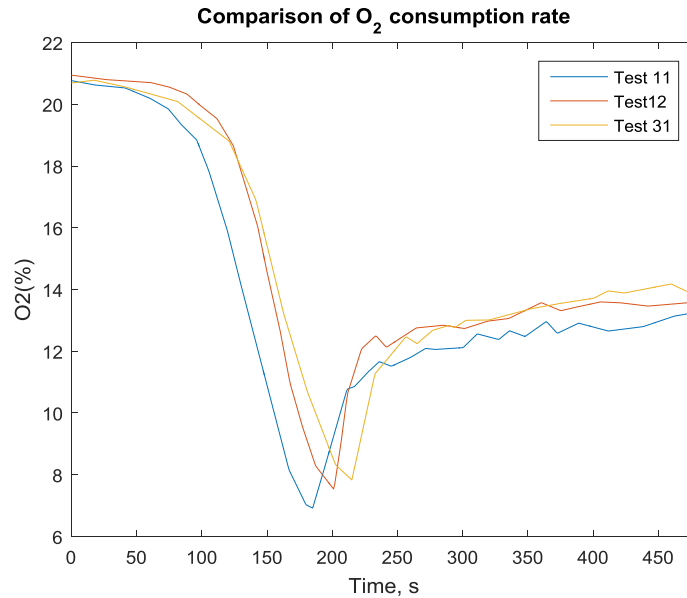


Figure 41: Comparison of O_2 consumption curves

The above argument brings us to another aspect of uncertainty in the experiments which is the damper position in the ventilation networks. Iris dampers were used to control the initial

volume flow in the exhaust ducts to 25 L/s but the exact details of the dampers are not known. The dampers were also not tuned to 25 L/s in all the experiments and this affects the pressure rise in the room. Therefore, the losses used in this study are estimates using the specified volume flow of 25 L/s and based on the damper pressure loss charts available.

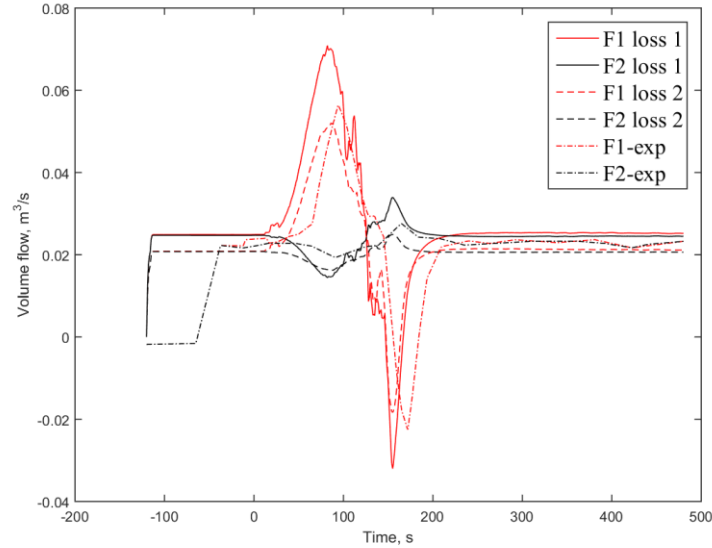


Figure 42: Volume flows at different loss values in the HVAC ducts F1, F2

Figure 42 demonstrates the sensitivity of the volume flow predictions on the loss coefficients through the ducts F1, F2 from the Test 22 of the FOA study. The duct F1 connects the fire room and F2 connects to the ambient. Loss 1 corresponds to a loss of 18.0 and Loss 2 corresponds to a loss of 40 in the duct F1. With a smaller loss the volume flows through the ducts are over predicted at peak pressure but the initial volume flow (25 L/s) that is specified in the experiment description is achieved. With a loss of 40, the initial volume flows rates are not 25 L/s initially but peak flow rates match. An engineer trying to simulate a similar situation should therefore try to acquire necessary information regarding the damper position to get the accurate loss.

The point to be noted here is that the duct F2 is connected to a fictive compartment in the experiment. This means that the reverse flow indicates smoke spread into adjacent compartments due to pressure rise. FDS prediction of the smoke spread into other compartments and smoke extracted by the fan would match exactly to the experimental results if the volume flow in the experiments was maintained exactly at 25 L/s. In a practical situation, accurate information about the HVAC networks might predict the smoke behaviour more accurately. Figure 43 shows the pressure loss values for an Iris 80 damper. Similar charts would be available for various other dampers and an engineer trying to simulate a similar situation should try to acquire necessary information regarding the damper position to get the accurate loss.

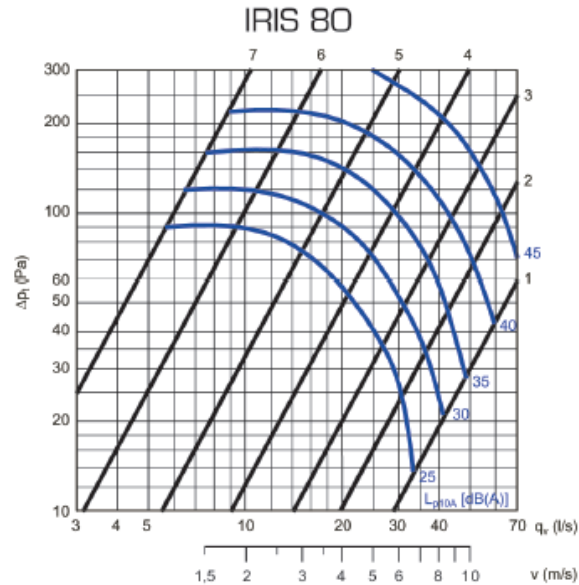


Figure 43: Selection diagram of pressure loss for Zest Iris 80 damper

The Aalto experiments provide us information about the performance of an actual apartment under fire. Here the uncertainties regarding the fire are probably smaller than in FOA, but the uncertainties regarding the experimental configurations and details are greater.

The HRR was not measured directly in these experiments either, but the fuel mass was measured using a load cell. This can be correlated to HRR using the heat of combustion. The uncertainty of the HRR is induced from the polynomial fitting used to find the MLR.

The second uncertainty is related to the ventilation system layout of the apartment. The exact specifications of the ventilation system, such as lengths and diameters of the ducts, duct components etc., were not available. Also, the roof fan characteristics were unknown. This introduces a significant uncertainty in the validation studies. A related aspect of experimental uncertainty were the sewers, which were sealed in the experiments to avoid uncontrolled leakages. In real fires, the water locks could be emptied by the increasing gas pressure, thus providing an additional path of leakage. However, this phenomenon was investigated by carrying out an additional simulation of the fire in normal ventilation conditions, and by adding a corresponding leakages at 500 Pa overpressure. The effect of sewers was found to be negligible.

The third aspect of uncertainty comes from the thickness and material properties of the walls. This do not, however, have a great influence on the pressures in the apartment.

The fourth and one of the most critical uncertainty is the increase in the leakage of the apartment under high pressure. In the FOA studies, the leak was a controlled aspect of the study and this makes it easier to model. In an actual building, the leak paths are unknown and the increase of leakage is hard to estimate. The leakage value at 50 Pa does not exactly represent the leakage that would occur at fire pressures.

6.2 Modelling Uncertainties

The limitations of the FDS model must also be understood and considered when using the results. The pressure in FDS is divided into a background pressure, obtained from the equation of state, and a perturbation pressure that drives the momentum equation and is used to obtain correct velocity fields. The pressure field of the HVAC system is solved separately. The coupling between the CFD and HVAC solvers can cause fluctuations due to the use of separate time integration schemes and it can be hard to differentiate between physical and numerical pressure peaks. According to the results, FDS over-predicted the pressure peaks especially in the Series 1 tests when the AIT was utilized. Therefore the Series 1 test were finally simulated without an AIT or ignitor. It is also difficult to model the fire ignition exactly as it happens in experiments. This can lead to delayed or as in the case of the FOA experiments, faster pressure peaks. It is not particularly beneficial to try to match the time stamps of a particular fire behaviour, such as pressure peaks, in compartment fire scenarios.

For the Aalto experiments, it was observed that compartment pressures are either under predicted or over predicted depending on the leakage modelling method. This is properly observed in the tests where the ventilation ducts were closed. Bulk leakage method tends to over predict compartment pressures whereas HVAC and Localized leakage method tends to under predict pressure. The Bulk leakage or HVAC leakage method would be more suitable options for modelling compartment fire scenarios as localized leakage is used for known leaks such as door cracks. In the FOA tests, the leakage was modelled using a HVAC duct, but the localized leakage model was also used to check for sensitivity. For the FOA tests, no variation was seen in pressure with leakage model.

In ventilation controlled fires of the FOA campaign, relatively large negative pressures were observed in the experiments at the time of fire extinction. These under-pressures were not predicted accurately by the default FDS model. This further lead to under-prediction of the velocity inflow through the leak hole. The under-pressure prediction for the Aalto experiments was closer to the experimental value without the use of AIT. This is because the fires were not under-ventilated in the Aalto Experiments.

In FDS, the local flame extinction depends on the specified critical flame temperature (CFT) value. CFT refers to the flame temperature at lower flammability limit i.e. lowest concentration fuel required in air for ignition. If a mixture of fuel and air in a cell does not yield the CFT specified then the combustion is suppressed (McGrattan et al, 2015 (b), pp. 42). It was observed that minima of FDS oxygen consumption curve does not match the experimental minima. Reducing the CFT yields a better oxygen consumption curve.

It was also observed that the FDS predictions of carbon monoxide production in ventilation controlled situation can be very erroneous because the CO yield can change significantly as the fire transitions from well ventilated phase to under ventilated phase. This dynamic aspect of CO production cannot be captured accurately using the default FDS simple chemistry model.

The FDS-HVAC module does not take into account the heat transfer that occurs to the duct walls. (McGrattan et al, 2015 (a)). It was observed in the FOA simulations that FDS tends to over predict the outlet temperature (Figure 44). In some other scenarios where ducts are

exposed to high temperatures from outside this might lead to lower prediction of exhaust gas temperatures.

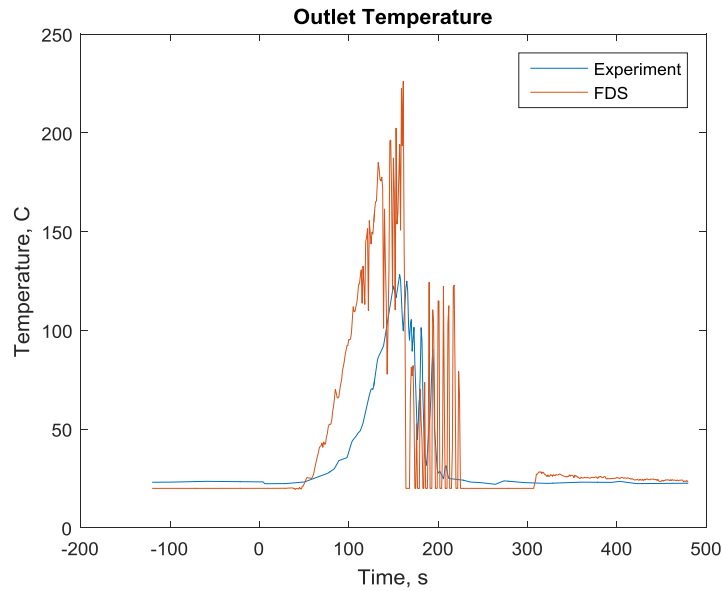


Figure 44: Comparison of outlet temperatures (Test 11)

Also, slight over predictions in room gas temperatures were observed, especially in fast growing fires. This could be due to excess radiation to the thermocouples or due to conductivity values attributed to the concrete walls. The properties of the boundary material were not known accurately.

7 Conclusion

This thesis deals with the fire induced pressure and its consequences in compartment fires. The subject was studied through numerical simulations using the CFD code Fire Dynamics Simulator. The practical objectives were to validate the capability of the Fire Dynamics Simulator code to predict the fire induced pressures and ventilation flows, and to create instructions for fire safety engineers carrying out such simulations. The validation was based on two sets of experimental data: First set consists of the FOA experiments, where liquid pool fires were burned in a closed room with different variations of ventilation conditions. The second set consists of apartment fire experiments that were carried out during this work in Kurikka. The thesis includes an overview of the HVAC modelling capabilities of the FDS code, descriptions of the experiments, results of the simulations, and a discussion about the findings.

Fire pressure was found to be a dangerous aspect of compartment fires with regards to life and property safety. In the FOA experiments the fire pressure ranges from 100 Pa to 1200 Pa depending on the ventilation conditions and fire growth rate. The fire pressure range of 400 Pa to 1600 Pa was observed during the Aalto experiments depending on the ventilation conditions alone. Compartment fire pressure was seen to depend on the heat release rate of the fire along with the leakage rate of the structure and the ventilation of the compartment. The pressure was also sensitive to the room of fire origin as the closet fire caused the highest pressure of 1600 Pa.

The simulation of the FOA compartment fires with ventilation system in FDS shows the sensitivity of HVAC module to the loss values specified to the exhaust ducts. A ventilation system in FDS is created using a set of node and ducts placed according to the ventilation layout. This work provides guidelines for engineers to model HVAC system and for determining the duct parameters for the ventilation system.

Leakage of the compartment boundaries was found to be another critical parameter affecting the pressure rise. Experimental determination of the leakage area can be challenging because the leakage flow in fire situation can be quite different than during the standardized leakage measurement, due to the order of magnitude higher pressures in fires. Here, the leakage area was calculated using the orifice equation. The simulations of the Aalto experiments highlighted the performance of the three different leakage modelling methods in FDS. For instance, the height and the area of the leakage vent in HVAC model was found to affect the temperatures in the compartment. Bulk leakage model tends to over predict the pressure in all cases.

The predictions of a numerical model are always accompanied with uncertainty. The model bias factor for gas temperatures from the simulations was estimated to be 1.09 for cases without ventilation, 1.03 for the cases with natural ventilation and 1.19 for the cases with forced ventilation. Other bias factors include: compartment over pressure 0.97, oxygen volume fraction 0.96, leak and duct velocity 1.02, and duct volume flow 1.14. Sensitivity studies made for the constant pool case (FOA Test 15) show that when the fire is well specified, the uncertainties in FDS predictions are very low.

The methods used in this thesis work to simulate the compartment fire scenario can be used to predict fire pressures with reasonable accuracy. Information regarding the envelope

leakage, ventilation layout of the building and possible fire loads would be needed to make a good assessment of fire pressure. Fire Dynamics Simulator can be reliably used in building fire pressure predictions.

The issue of pressure rise in modern buildings has to be investigated to understand the sensitivity of fire pressure in air tight buildings. Realistic fire scenarios with solid fuels should be studied to gain insight into the actual pressure that could be encountered. Further investigation into the performance of the HVAC module with various duct components such as dampers and aircoils need to be performed as well. Sensitivity studies should be performed by changing the default FDS parameters to analyse FDS capabilities entirely. The performance of the complex chemistry model to predict CO production in ventilation controlled fires and the suppression model to predict the under pressures could also be analysed.

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Appendix A – Pressure loss in a ventilation network

For modelling a HVAC ventilation network in FDS, it is essential to know the pressure loss caused by various components and friction in a ventilation duct. The total losses can be calculated using a HVAC software such as TRNSYS or manually. The FDS

FDS-HVAC Governing equations (McGrattan et al, 2015 (b))

The nodal conservation equations for mass, energy and momentum equations are as follows:

$$\sum_j \rho_j u_j A_j = 0 \quad (1)$$

$$\sum_j \rho_j u_j A_j h_j = 0 \quad (2)$$

$$\rho_j L_j \frac{du}{dt} = (P_i - P_k) + (\rho g \Delta z)_j + \Delta P_j + 0.5 K_j \rho_j |u_j| u_j \quad (3)$$

where ρ is the density, u is the duct velocity, A is the cross sectional area of the duct, h is enthalpy of fluid in the duct, P is the pressure and K is the loss coefficient of the duct. The subscripts j indicates the ducts in the calculation, i and k indicate the nodes of the duct.

The

Below the procedure to calculate the losses in a ventilation network of fig 1 is described. This is an exhaust ventilation network with round ducts.

1. First, we begin with enumerating the ducts as presented in the network diagram into various ducts and nodes. A concept to be remembered, is that a node is placed when there is a duct connects the computational domain or where there are components or at Tee joints.
2. Also, it is essential to know the typical volume flow through the ducts to proceed with any calculations. The volume flow for this calculation is taken to be 25 l/s.
3. The duct friction loss chart (based on the shape of the duct) gives the pressure loss values based on the volume flow and diameter of the duct. Velocity through the duct can also be used to determine the loss. The friction loss chart is plotted on the log-log axes.
4. This value obtained from the Friction chart is multiplied with the length of the duct as most of the charts give the pressure loss per meter.
5. And this value of friction loss is added with pressure losses other components to get the total loss for a duct.
6. The obtained pressure loss must be converted to the non-dimensional loss coefficient, K . This loss coefficient is used in the FDS-HVAC inputs.

THEORY AND MATHEMATICAL BASIS

The pressure loss in the HVAC ducts is calculated based on Bernoulli's equation as the flow is incompressible.

$$\frac{P_1}{\rho g} + Z_1 + \frac{v_1^2}{2g} = \frac{P_2}{\rho g} + Z_2 + \frac{v_2^2}{2g} + H_l \quad (4)$$

H_l = Head loss which is caused due to friction.

If the static pressure at two points in the HVAC network is known then it is possible to calculate the head loss. This is also the major loss in a ducting system.

The pressure loss in a duct is caused due to fluid friction and momentum change due to change in direction or velocity caused by components in the duct.

$$\Delta p_t = \Delta p_{friction} + \Delta p_{momentum} \quad (5)$$

The friction loss can be evaluated using the Darcy Weisbach equation:

$$\Delta P = \frac{fL}{D} \left(\frac{\rho V^2}{2} \right) \quad (6)$$

Where f = friction factor and is a function of Reynolds number, $Re = \rho VD/\mu$ and the relative surface roughness of the pipe. To calculate the Reynolds number in a non-circular duct, the hydraulic diameter can be used: $D_h = \frac{4A}{W_p}$

Where A is the cross sectional area of the duct, W_p = wetted perimeter of the duct

The friction factor, f , can be calculated using the Colebrook-White equation:

$$\frac{1}{\sqrt{f}} = 2 \log_{10} \left(\frac{\epsilon}{3.7D} + \frac{2.51}{Re\sqrt{f}} \right) \quad (7)$$

The surface roughness of the duct depends on the material used. The most commonly used HVAC duct material is GI sheet with an absolute roughness, $\epsilon = 0.00015$ per meter.

In FDS the losses are a pair of numbers which specify the dimensionless loss coefficients. The first number specifies the loss from the node 1 to node 2 i.e., the downstream pressure loss and the second number specifies the upstream pressure loss.

Also, the flow rate in FDS does not store mass in the HVAC networks. An advantage of this is that two or more ducts with the same flowrate can be combined even if there are bends, expansion fittings or any other components by using an effective loss coefficient for the combined duct length with a representative effective area (A_{eff}).

$$K_{eff} = \sum_i K_i \frac{A_{eff}}{A_i} \quad (8)$$

Where I is a fitting and A_i is the area associated with the fitting loss.

If a rectangular duct is used instead of a circular duct, as is the usual case, then the equivalent diameter needs to be calculated. If the volumetric flowrate and frictional pressure loss is same in the rectangular duct as in the circular duct then they are considered equivalent. Using the equivalent diameter, one can find the frictional pressure drop in the ducts from the Fig 2.

$$D_e = 1.3 \frac{(a * b)^{0.625}}{(a + b)^{0.25}} \quad (9)$$

For oval ducts, the equivalent diameter is:

$$D_e = 1.3 \frac{(A)^{0.625}}{(P)^{0.25}} \quad (10)$$

Where $A = \frac{\pi b^2}{4} + b(a - b)$ and $P = \pi b + 2(a + b)$

a, b are the sides of the duct. It is always better to have the aspect ratio (a/b) of the duct as close to unity as possible.

MINOR LOSSES

The calculation of pressure loss due to friction is quite straightforward but it the calculation of minor loss coefficient of various fittings in the

Here the minor losses are the losses due to bends and various types of fittings (elbows, enlargements, contractions, branches, dampers etc.) are calculated based on the flowrate through the duct. This is the simplest way of calculation of minor losses.

In turbulent flows, the dynamic loss is proportional to the square of the velocity.

$$\Delta P_d = K \left(\frac{\rho V^2}{2} \right) \quad (11)$$

Where K is the dynamic loss coefficient.

Elbows: The bends generally used in ventilation networks are 90 degree elbows. The pressure drop across a bend is a function of W/H which is the width and height of the bend exit/entrance cross section and the inner and outer radius at the bend.

$$\Delta P_{d,b} = C_b \left(\frac{\rho V^2}{2} \right) \quad (12)$$

where C_b is the loss coefficient of the bend. The values of C_b or ζ can be found from graphs or tables.

Enlargements/Contraction: Sudden enlargement/contraction also leads to loss of pressure and this can be calculated using the Borda Carnot equation:

$$\text{Enlargement: } \Delta P_{d,e} = (\rho V^2 / 2) \left(1 - \frac{A_1}{A_2} \right)^2 \quad (13)$$

$$\text{Contraction: } \Delta P_{d,c} = (\rho V^2 / 2) \left(1 - \frac{A_2}{A_c} \right)^2 = (\rho V^2 / 2) \left(\frac{1}{C_c} - 1 \right) \quad (14)$$

where A_c is the area of the vena contracta and C_c is the contraction coefficient

The value of C_c , depends on A_1 and A_2 , calculated by Weisbach is given in the table below:

Table 6: Contraction coefficient

A_2/A_1	C_c
0.1	0.624
0.5	0.681
0.8	0.813
1.0	1.0

Pressure loss due to contraction is the more difficult one to accurately calculate as a number of factors influence it and one might not always have all the required information about the

duct network. In our calculation we assume a sudden contraction as no information is available about the networks.

Miscellaneous: Dampers, heating coils and other miscellaneous fittings have different losses and are dependent on the manufacturer. Usually the losses are specified by the manufacturer.

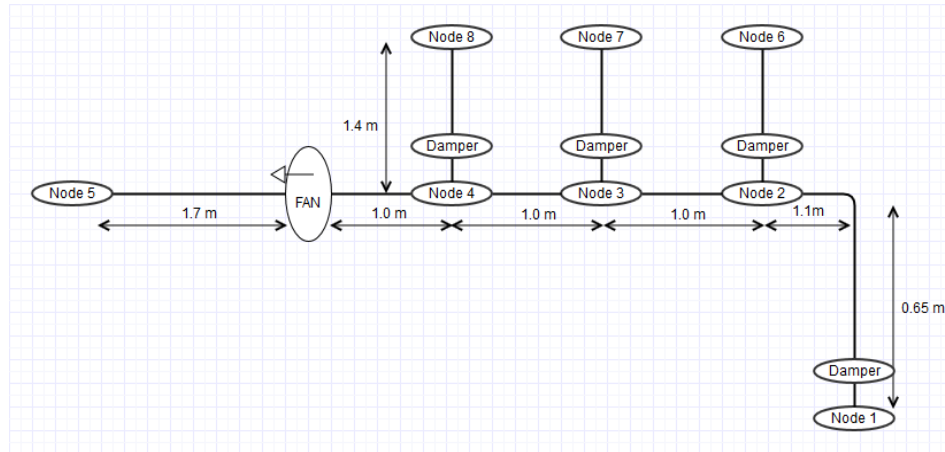


Figure 1: Exhaust ventilation network

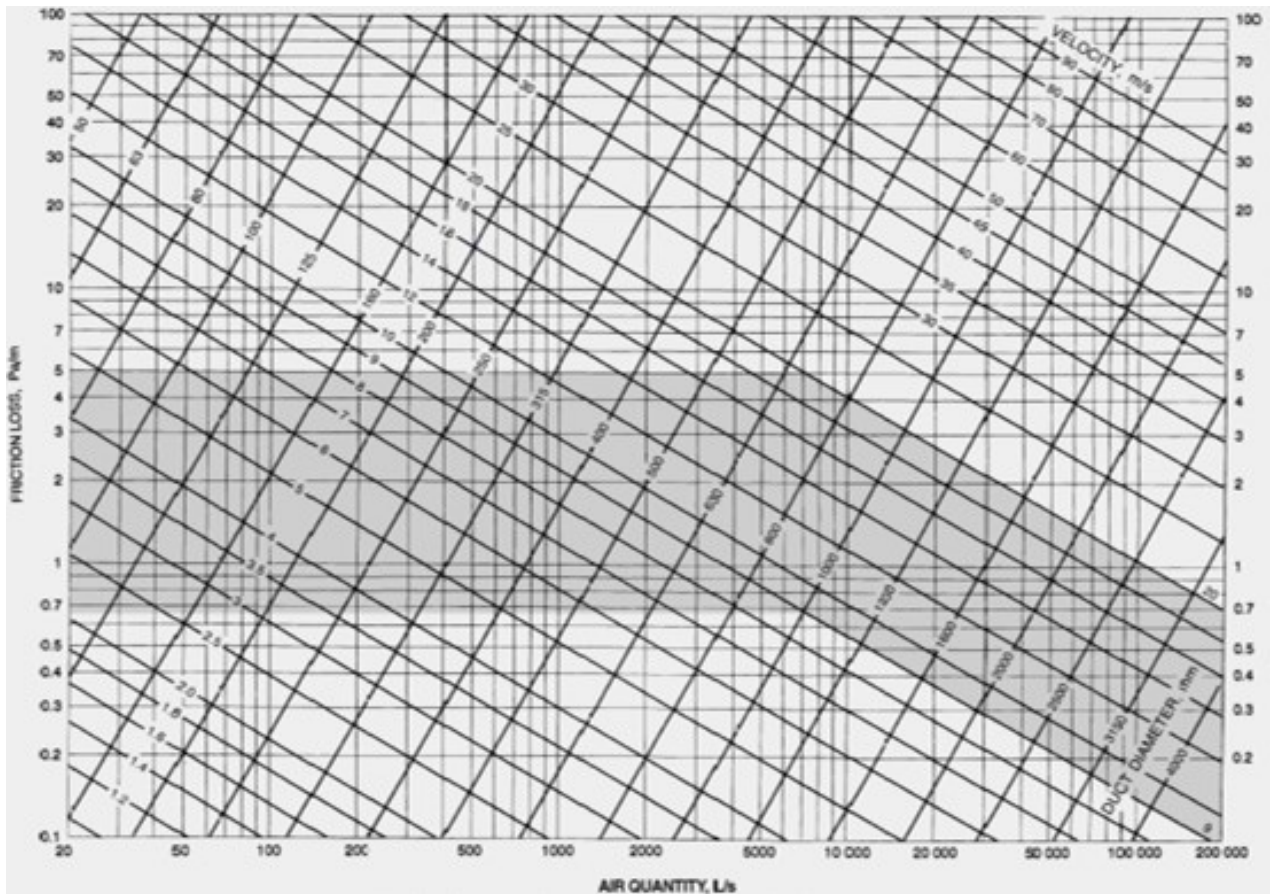


Figure 2: Duct friction loss chart (round ducts). Source: ASHRAE Handbook Fundamentals

The roughness values for various types of ducts are also given in the ASHRAE Handbook Fundamentals.

The pressure loss of a fire damper depends on the specific type of damper used in the ducts. Usually, the pressure loss values of the dampers are given by the manufacturer. The damper loss values used here is assumed and does not pertain to the actual value of the damper used in the experiment.

An example loss calculation for the exhaust network in Figure 2: Exhaust ventilation network 1 is given below.

PRESSURE LOSS CALCULATIONS

Duct 1: LENGTH=1.75m, DIAMETER=0.1m, AREA=0.007854, Volume flow, $V_f=25$ l/s, rounded bend (rb) and expansion (exp) + Damper

1. From experiments it is known that the 1st duct has a volume flow of 25 L/s.

2. From the friction chart (Figure 1) the value of friction loss can be obtained to be around 1.6-1.8 Pa/m based on the duct diameter and volume flow rate. This is then multiplied with the length of the duct to give the actual loss.

$$K_1 = 1.7 * 0.65 = 1.105 \text{ Pa}$$

$$\text{Loss, } K_1 = 1.7 * 1.75 = 2.975 \text{ Pa}$$

3. For minor losses, the velocity through the duct is needed.

$$V_1 = 4 * V_f / (\pi * d^2), V_f = \text{volume flow in m/s}$$

$$= 4 * 0.025 / (3.1416 * 0.1^2) = 3.183 \text{ m/s}$$

$$K_{rb} = \Delta P_{d,b} = C_b \left(\frac{\rho V_1^2}{2} \right) = 0.5 * 0.5 * 1.27 * 3.183 = 1.01 \text{ Pa}$$

$$K_{exp} = (1 - A_1/A_2)^2 * \rho V_1^2 / 2$$

$$A_1 = (3.1416 * 0.1^2) / 4 = 0.007854 \text{ m}^2$$

$$A_2 = (3.1416 * 0.125^2) / 4 = 0.01227 \text{ m}^2$$

$$K_{exp} = 0.5 * 1.27 * 3.183 * (1 - (0.007854 / 0.01227))^2 = 0.2618$$

4. Adding up the losses from friction and the duct components gives us the pressure loss of the duct.

$$K_{1\text{total}} = 2.975 + 1.01 + 0.2618 + 3 = 7.2468 \text{ Pa}$$

5. The pressure loss has to be converted to non-dimensional loss coefficient (K). The pressure loss equals the last term of equation 3.

$$0.5 K_j \rho_j |u_j| u_j = 7.2468 \text{ Pa}$$

The velocity and the density are known and can be used to find the value of K .

$$K = 1.16$$

Similarly, the loss coefficients for the other ducts can also be determined. A sample pressure loss calculation for other ducts are also given below.

Duct 2: $L = 1 \text{ m}$, $d = 0.125$, $V_f = 50 \text{ l/s}$, expansion

$$K_3 = 2 * 1 = 2 \text{ Pa}$$

$$K_{exp} = (1 - A_1/A_2)^2 * \rho V_1^2 / 2$$

$$V_1 = 4 * 0.05 / (3.1416 * 0.125^2) = 4.074 \text{ m/s}$$

$$A_1 = (3.1416 * 0.125^2) / 4 = 0.01227 \text{ m}^2$$

$$A_2 = (3.1416 * 0.165^2) / 4 = 0.02138 \text{ m}^2$$

$$K_{exp} = 0.5 * 1.27 * 4.074 * (1 - 0.01227 / 0.02138)^2 = 1.734 \text{ Pa}$$

$$K_{2\text{total}} = 3.734 \text{ Pa}$$

Duct 3: $L = 1 \text{ m}$, $d = 0.165$, $V_f = 75 \text{ l/s}$

$$K_3 = 1.2 * 1 = 1.2 \text{ Pa} = K_{3\text{total}}$$

Duct 4: $L = 2.7 \text{ m}$, $d=0.165$, $V_f = 100 \text{ l/s}$

$$K_4 = 2.7 * 1 = 2.7 \text{ Pa} = K_{4\text{total}}$$

Duct 5/6/7: $L = 1.3 \text{ m}$, $d=0.1$, $V_f = 25 \text{ l/s}$ + Damper

$$K_5 = 1.7 * 1.3 = 2.21 \text{ Pa}$$

$$K_{5\text{total}} = \text{Damper} + K_7 = 2.21 + 3 = 5.21 \text{ Pa}$$

$$K_6 = 1.7 * 1.3 = 2.21 \text{ Pa}$$

$$K_{6\text{total}} = \text{Damper} + K_8 = 2.21 + 3 = 5.21 \text{ Pa}$$

$$K_7 = 1.7 * 1.3 = 2.21 \text{ Pa}$$

$$K_{7\text{total}} = \text{Damper} + K_9 = 2.21 + 3 = 5.21 \text{ Pa}$$

Note:

1. This is not the accurate loss in the network. A few assumptions made as the complete details of the ventilation network is not provided. In such a case, if the FDS tests are being run to validate FDS-HVAC capabilities then trial and error is recommended.
2. The damper values used here do not represent the actual damper values of the system. The damper used in the system is an iris damper and the exact model number is not known. The values used in the FDS input code were adjusted iteratively to yield the appropriate volume flows through the ducts.
3. The duct 1 and 2 can be combined to form a single duct and the losses can be specified as a single effective loss.

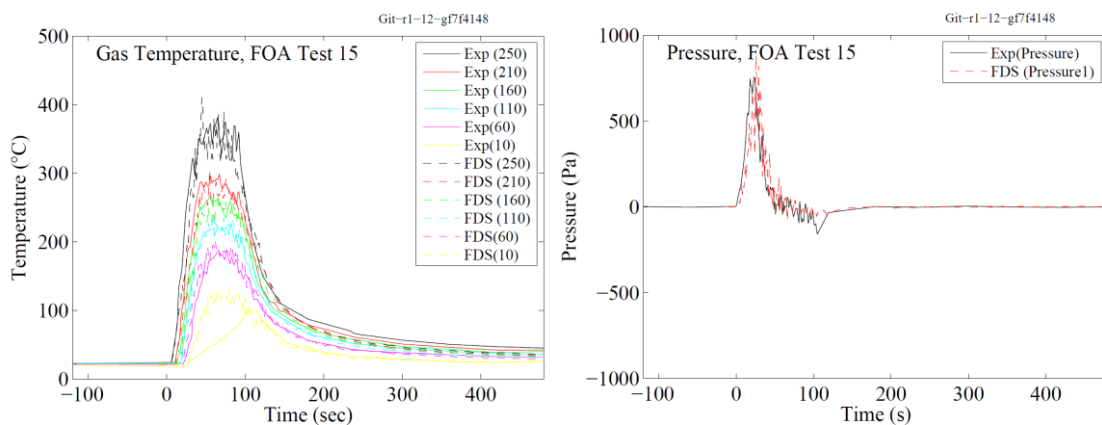
Appendix B – Sensitivity Studies for Test 15

Sensitivity studies are usually a good way to test various possibilities and address concerns regarding performance of a code. The sensitivity studies, Test 15 from the FOA experiments, were made to test the common queries engineers would have while simulating various compartment fire scenarios. The aspects that can influence the fire characteristics are the auto ignition temperature, Critical flame temperature for better oxygen consumption curves, carbon monoxide production rate for better prediction of under ventilated CO production, the change of ambient temperature and using better insulating concrete properties. The sensitivity studies are:

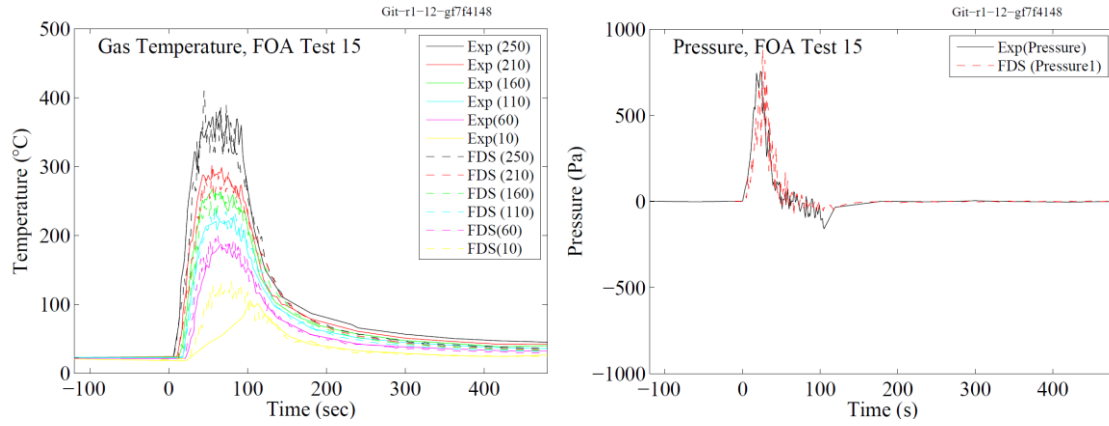
- a. Actual test – AIT = 223 C, CFT = default, CO_YIELD = 0.01, Thermal conductivity = 1.7, Ambient temperature = 20 C
- b. SS1: AIT = 250 C, other parameters remain the same.
- c. SS2: CFT = 1100, AIT = 223 C, other parameters remain the same.
- d. SS3: AIT = default (zero), CFT = default, other parameters remains the same.
- e. SS4: AIT = 223 C, CFT = default, CO_YIELD = 0.1, other parameters remain the same.
- f. SS5: Wall properties changed from the actual test. Thermal conductivity, 0.7, of medium dense cement used.
- g. SS6: Different ambient (-15 C) and room temperatures (20C). The other parameters are same as in actual test.

The pressures and results are not highly sensitive to the various changes in parameters as it is mainly dependent on the HRR which remains the same. The results of the different sensitivity study cases are displayed below:

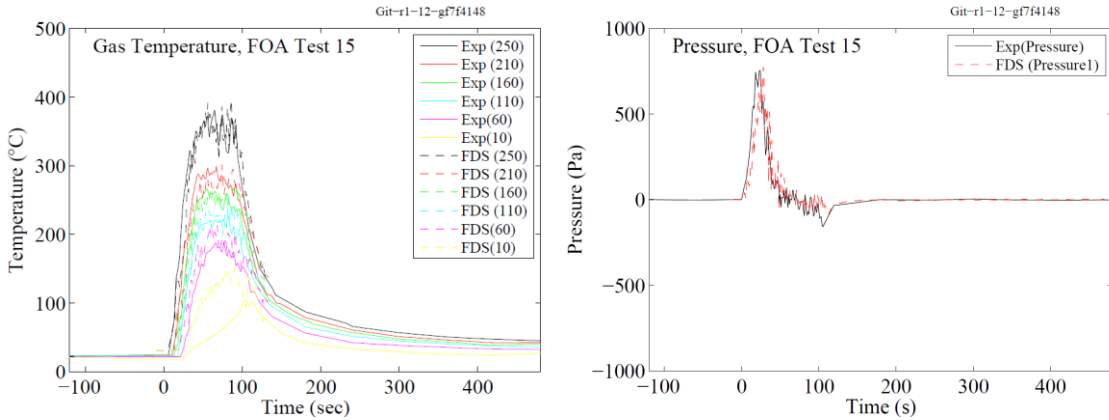
Case a: Actual test - AIT = 223 C, CFT = default, CO_YIELD = 0.01, Thermal conductivity = 1.7, Ambient temperature = 20 C



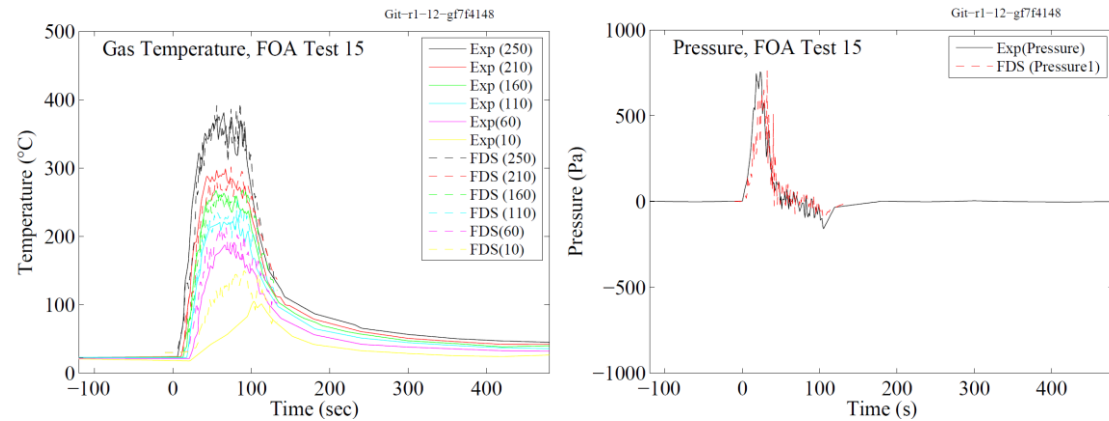
Case b: SS1 - AIT = 250 C, CFT = default, CO_YIELD =0.01, Thermal conductivity = 1.7, Ambient temperature = 20 C.



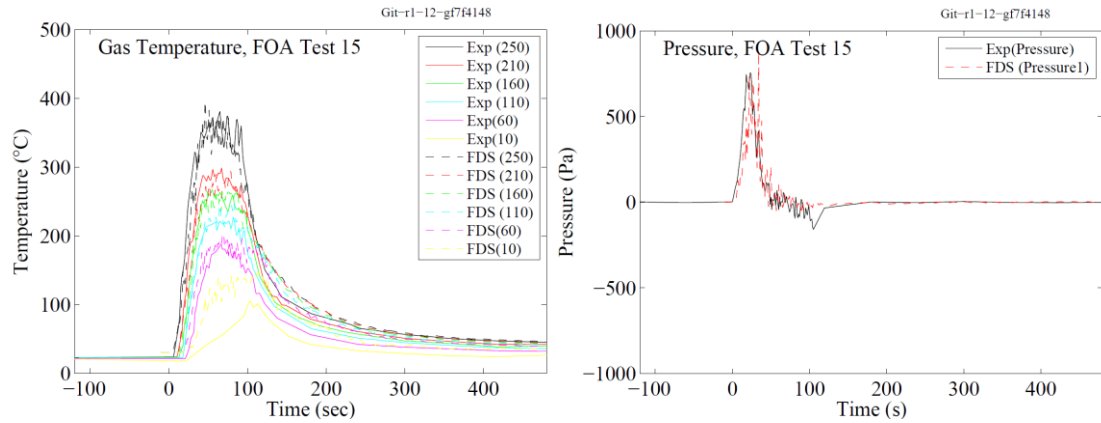
Case c: SS2- AIT = 223 C, CFT = 1100, CO_YIELD =0.01, Thermal conductivity = 1.7, Ambient temperature = 20 C.



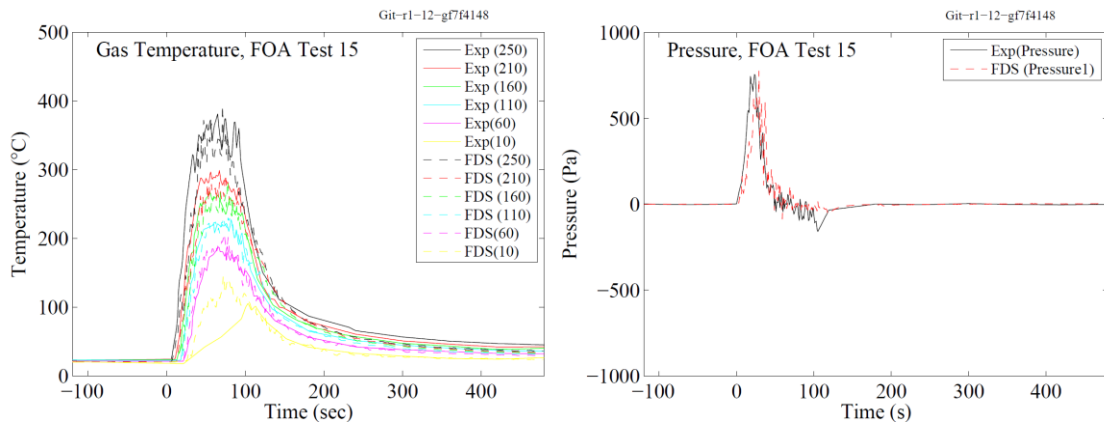
Case d: SS3 - AIT = default (zero), CFT = default,



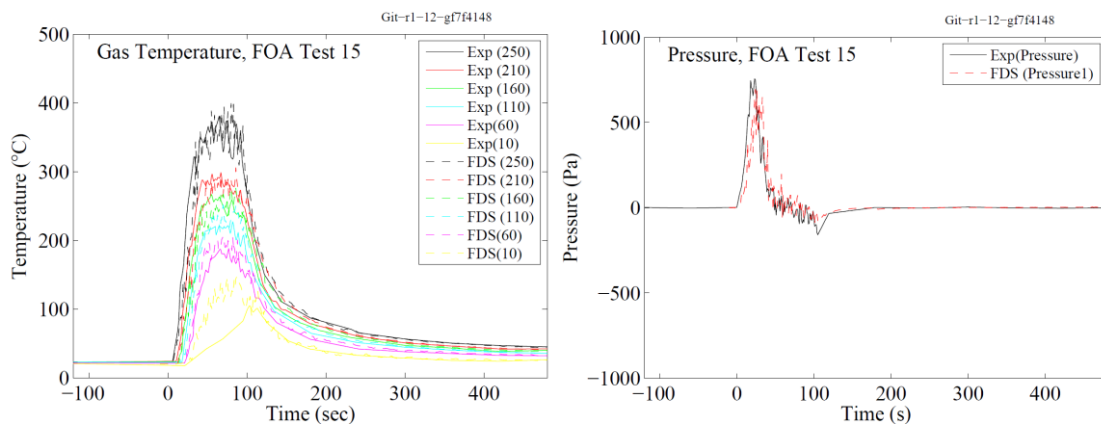
Case e: SS4 - AIT = 223 C, CFT = default, CO_YIELD =0.1



Case f: SS5 - AIT = 223 C, CFT = default, CO_YIELD =0.01, Thermal conductivity = 0.7, Ambient temperature = 20 C



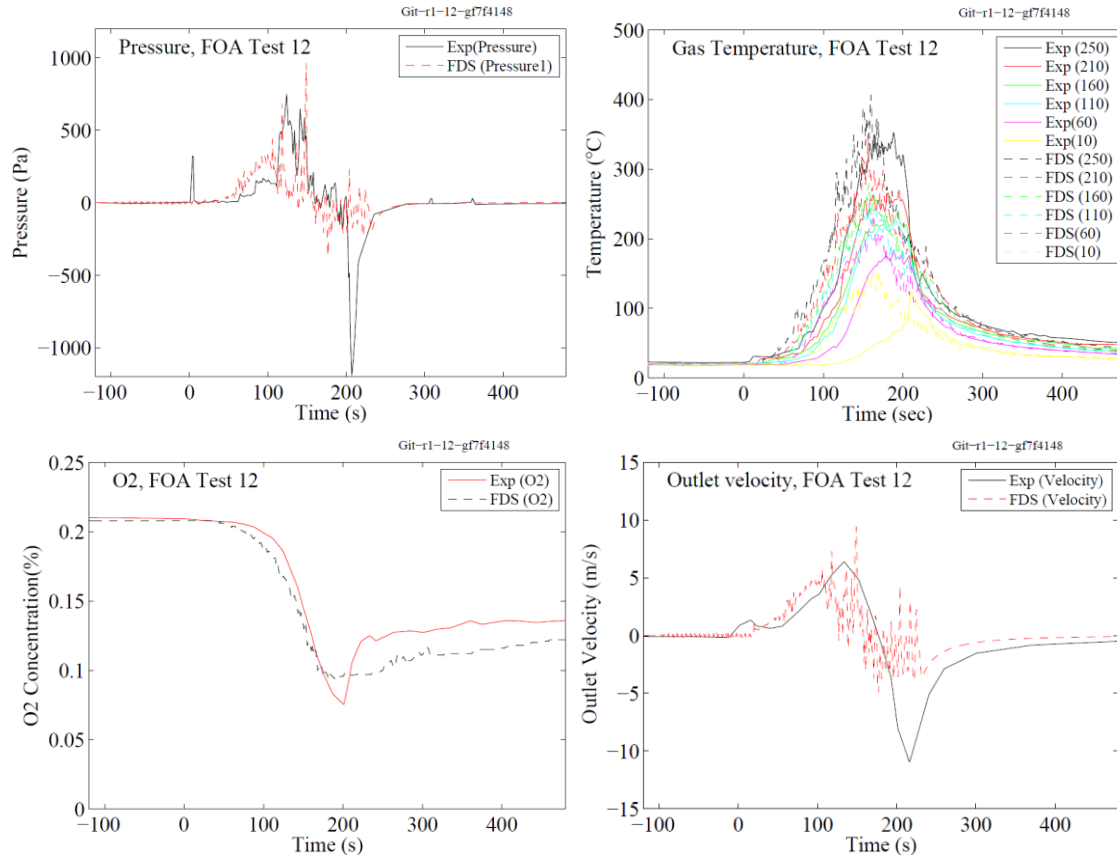
Case g: SS6 - Different ambient (-15 C) and room temperatures (20C). The other parameters are same as in actual test.



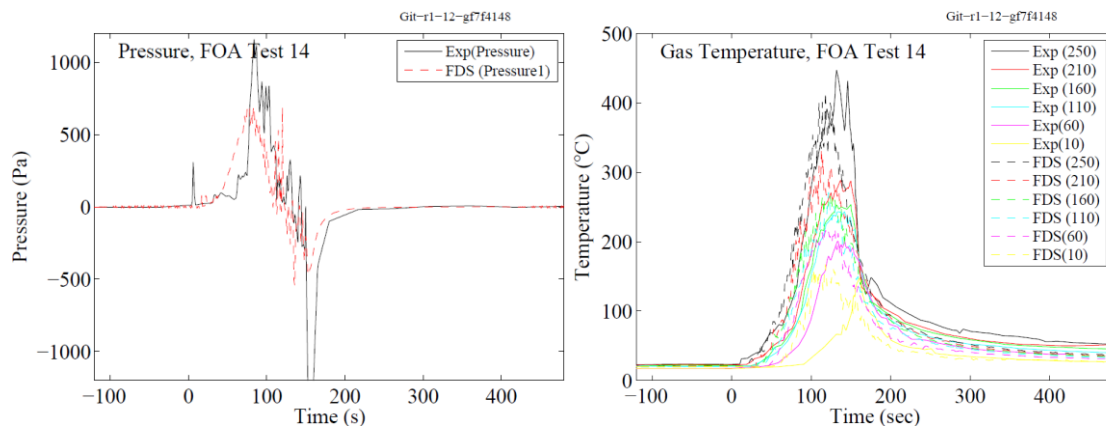
Appendix C – FOA experiments validation plots

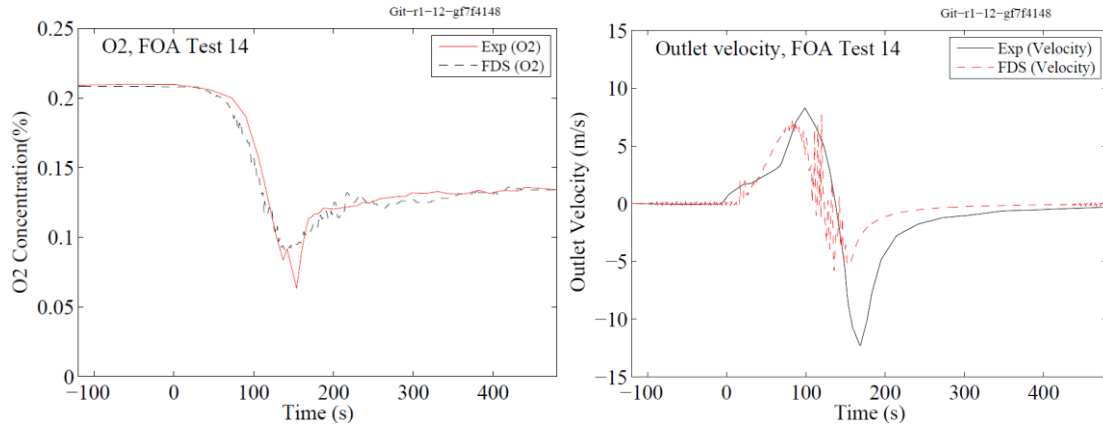
The FDS validation plots of the FOA tests 12, 14, 21, 23, 32 and 33 are presented here. The pressure, temperature, O2 volume fraction and the velocity are the basic quantities. The exhaust duct volume flows are presented for Test 21, 23, 32 and 33. Supply duct volume flows are presented for Test 32 and 33 only.

Test 12

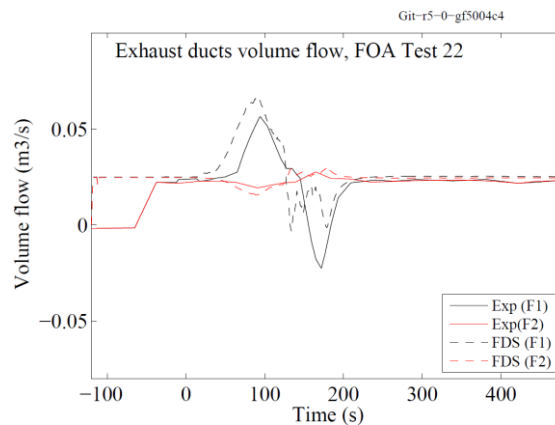
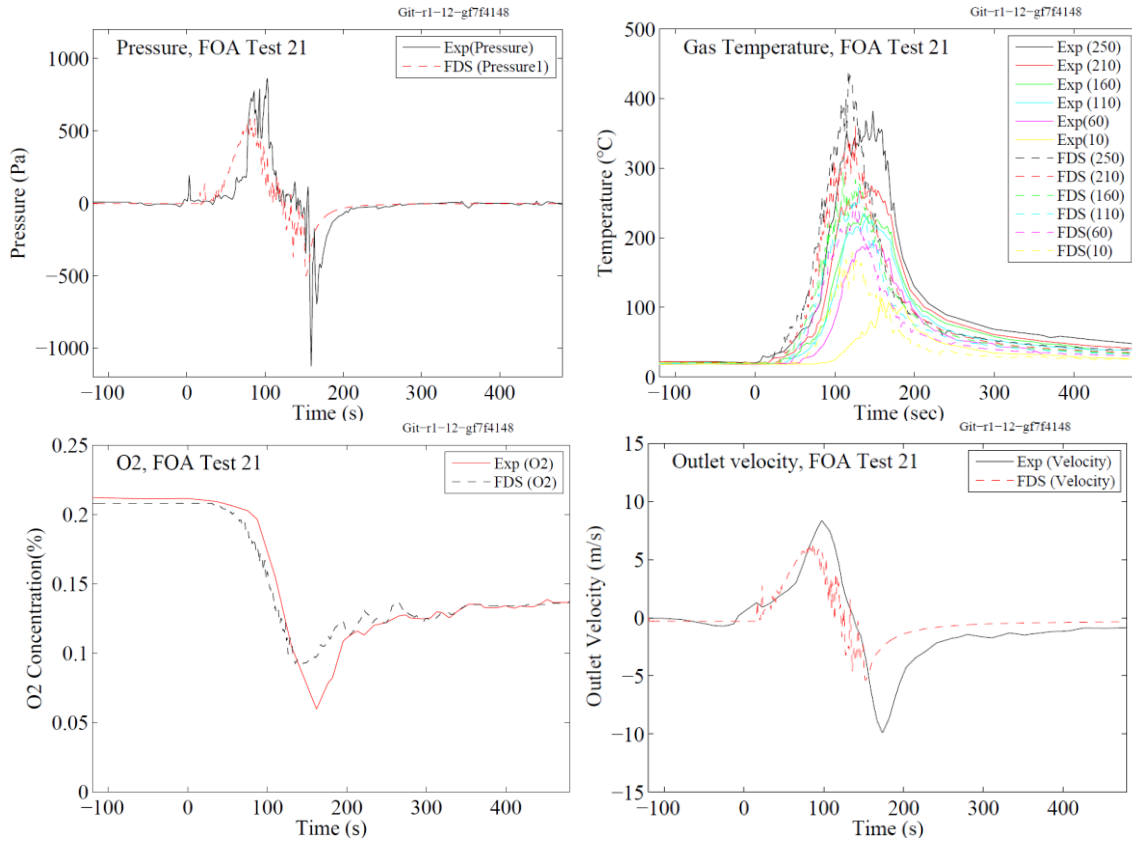


Test 14

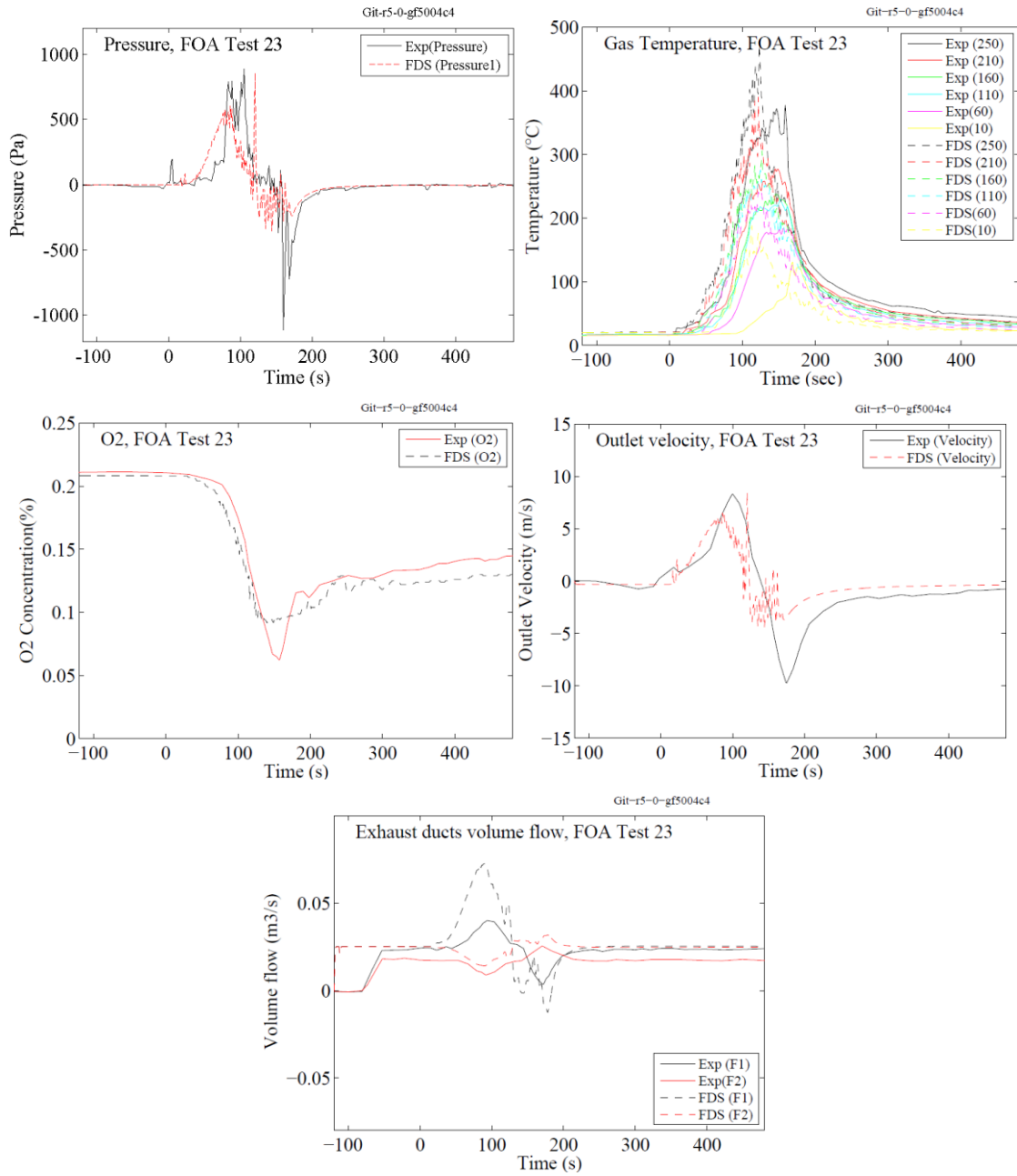




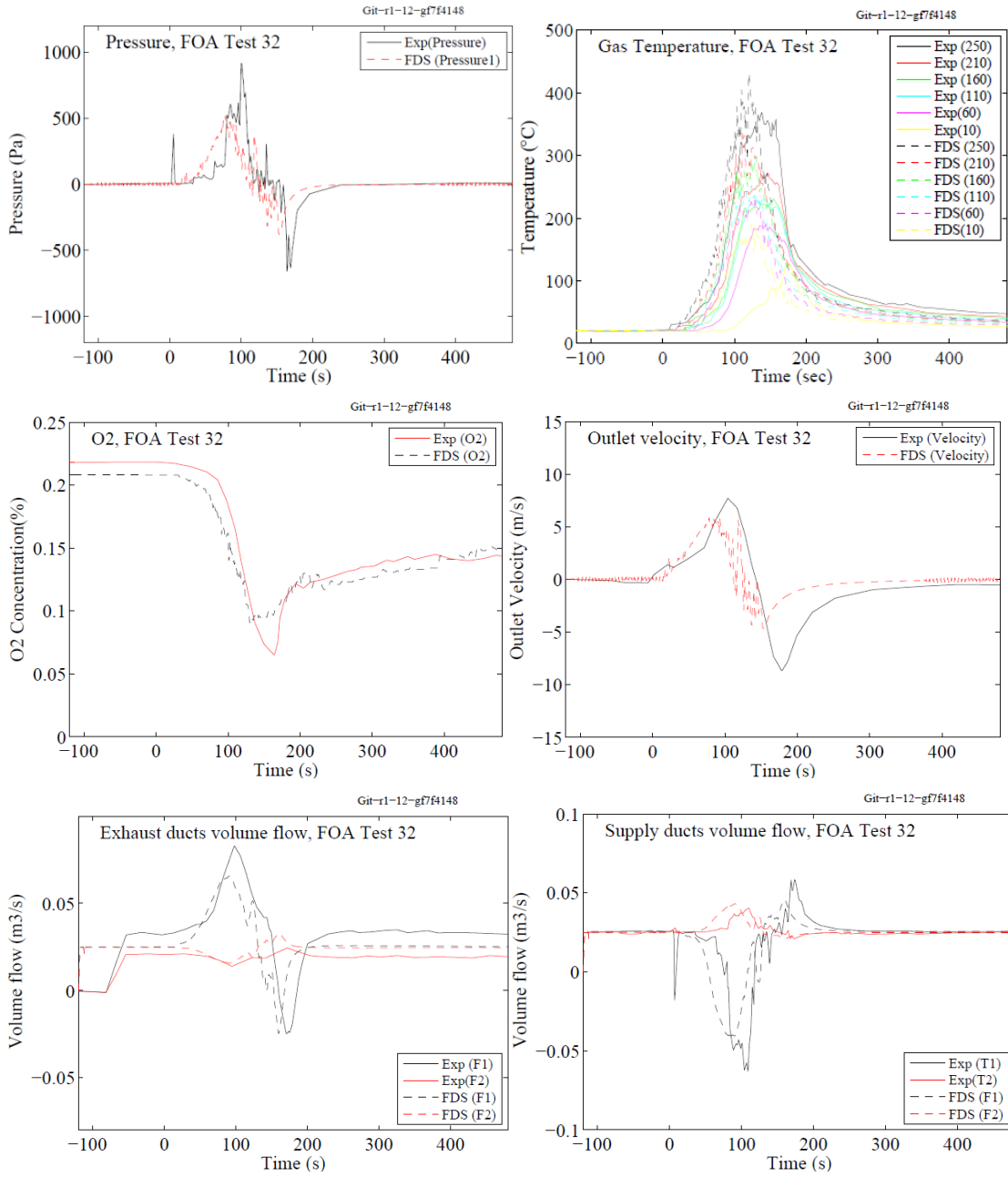
Test 21



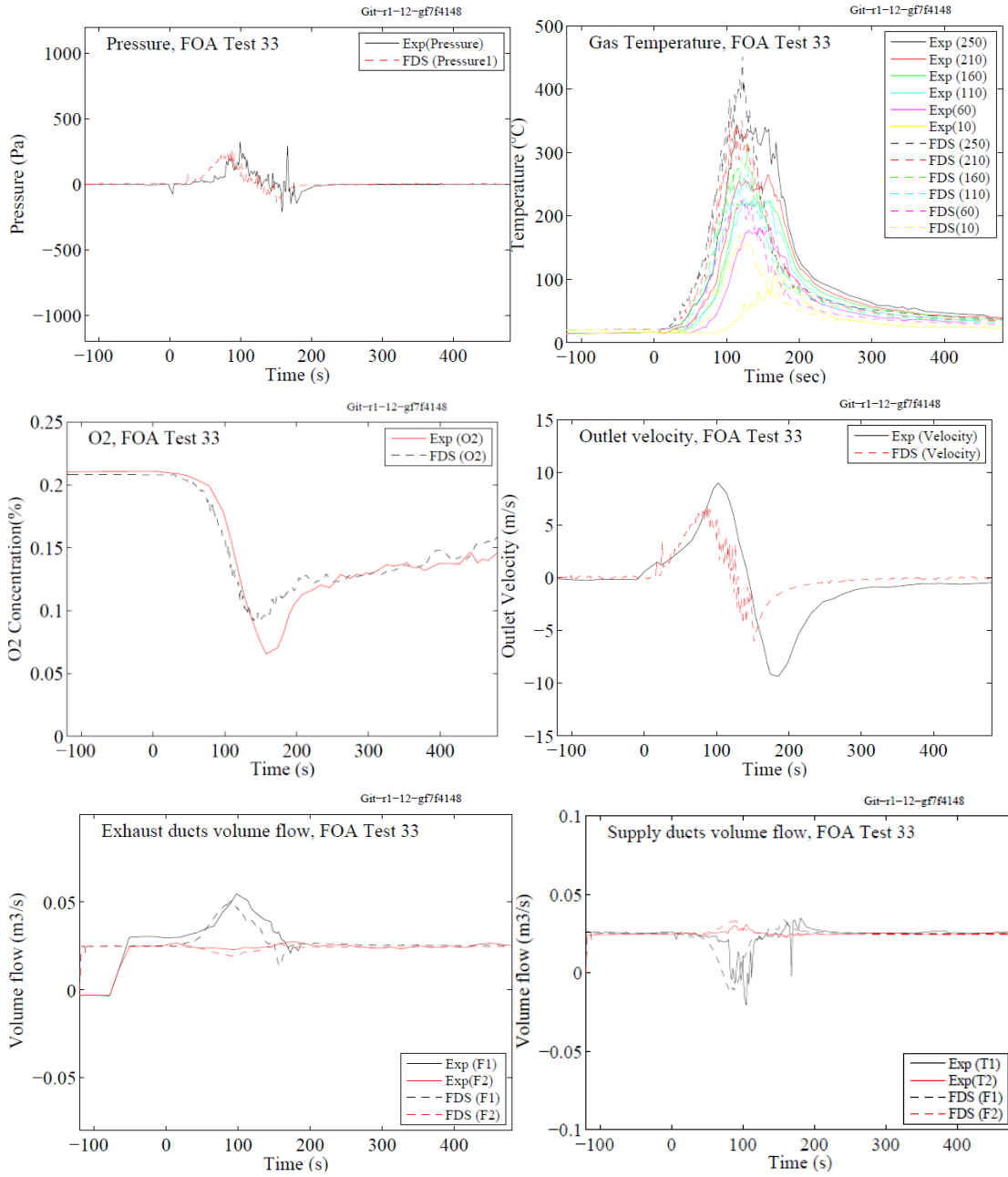
Test 23



Test 32



Test 33



Appendix D – FDS input files - FOA simulations

Test 15: Constant pool fire case

Grid cell size: $dx = dy = dz = 0.1$ m
Combustion chamber: 4.0m x 6.0m x 2.6m
Leak diameter = 0.2m

&HEAD CHID = 'Test_15', TITLE='Test 15 - FOA, Sweden' / 0.5m² fire source and 0.2m diameter opening

Mesh

&MESH ID='FOA Test 15', IJK = 40,55,26, XB = 0.0,4.0,0,5.5,0,2.6 / Room
&TIME T_END=480., T_BEGIN = -120 /
&MISC TMPA = 20.0 /

&DUMP SMOKE3D=.TRUE.,
NFRAMES = 490,
DT_HRR = 1.0,
DT_DEVC = 1.0,
DT_SLCF = 2.0,
DT_BNDF = 1.0,
DT_PART = 1000000.0,
DT_PL3D = 1000000.0,
DT_ISOF = 1000000.0 / time steps for the outputs

&PRES MAX_PRESSURE_ITERATIONS=50,
VELOCITY_TOLERANCE=0.00001,
CHECK_POISSON=.TRUE.,
RELAXATION_FACTOR=1 /

&ZONE XB = 0,3,0,4,0,2/

-----Fire room Geometry -----
&OBST XB = 0,1.05, 2.6,2.75, 0,2.6, SURF_ID='NL_CONCRETE' / CENTRE WALL 1
&OBST XB = 2.95,4, 2.6,2.75, 0,2.6, SURF_ID='NL_CONCRETE' / CENTRE WALL 2
&OBST XB = 0,4, 0,0, 0,2.6, SURF_ID = 'L_CONCRETE' / LEFT WALL
&OBST XB = 0,2.7, 5.5,5.5, 0,2.6, SURF_ID = 'L_CONCRETE' / RIGHT WALL
&OBST XB = 2.7,4.0, 4.2,5.5, 0,2.6 SURF_ID = 'L_CONCRETE' / RIGHT WALL
&OBST XB = 0,0.0, 0,5.5, 0,2.6, SURF_ID = 'L_CONCRETE' / FRONT WALL
&OBST XB = 4,4,0,4.2,0,2.6, SURF_ID = 'L_CONCRETE' / BACK WALL
&OBST XB = 2.7,2.7,4.2,5.5,0,2.6, SURF_ID = 'L_CONCRETE' / BACK WALL
&OBST XB = 0,4, 0,5.5, 2.6,2.6, SURF_ID = 'L_CONCRETE' / ROOF

Thermocouple insulators

&OBST XB = 1.7,1.8,1.4,1.4,0.0,0.2, SURF_ID = 'INSULATION_MAT' /
&OBST XB = 1.7,1.8,1.4,1.4,0.5,0.7, SURF_ID = 'INSULATION_MAT' /
&OBST XB = 1.7,1.8,1.4,1.4,1.0,1.2, SURF_ID = 'INSULATION_MAT' /
&OBST XB = 1.7,1.8,1.4,1.4,1.5,1.7, SURF_ID = 'INSULATION_MAT' /
&OBST XB = 1.7,1.8,1.4,1.4,2.0,2.2, SURF_ID = 'INSULATION_MAT' /
&OBST XB = 1.7,1.8,1.4,1.4,2.4,2.55, SURF_ID = 'INSULATION_MAT' /

Pan rims

&OBST XB = 2.4, 2.4, 3.0,4.0, 0.0,0.2, SURF_ID='INERT' /
&OBST XB = 2.4, 3.22, 3.0,3.0, 0.0,0.2, SURF_ID='INERT', /
&OBST XB = 3.22, 3.22, 3.0,4.0, 0.0,0.2, SURF_ID='INERT', /
&OBST XB = 2.4, 3.22, 4.0,4.0, 0.0,0.2, SURF_ID='INERT', /

----- FIRE SOURCE -----

&REAC FUEL='N-HEPTANE', AUTO_IGNITION_TEMPERATURE = 223.0
CO_YIELD = 0.01, SOOT_YIELD = 0.037, FYI= 'Heptane C₇ H₁₆' /

&SURF ID= 'fire', HRRPUA=1600, RAMP_Q='PoolRamp', COLOR='RED', TMP_FRONT=98.0,/
&RAMP ID='PoolRamp', T=-30.0, F=0.0 /
&RAMP ID='PoolRamp', T=0.0, F=0.0 /
&RAMP ID='PoolRamp', T=30.0, F=1.0 /
&RAMP ID='PoolRamp', T=80.0, F=1.0 / FDS ramps the HRR linearly.
&RAMP ID='PoolRamp', T=105.0, F=0.1 /

```

&RAMP ID='PoolRamp', T=120.0, F=0.0      /
&RAMP ID='PoolRamp', T=3600.0,F=0.0      /

&VENT XB=2.4,2.9, 3.0,4.0, 0.00,0.00, SURF_ID='fire',      /

Fuel Ignitor
&OBST XB=2.4, 2.7, 3.0, 4.0, 0.20, 0.20, DEVC_ID='HotSurfTimer',
SURF_ID6='INERT','INERT','INERT','INERT','HOT_SURF','INERT' / top piece
&DEVC ID='HotSurfTimer', XYZ=2.6,3.5,0.0, QUANTITY='TIME', SETPOINT= 5.0,
INITIAL STATE=.TRUE. /
&SURF ID='HOT_SURF', TMP_FRONT=900.0,      TMP_INNER=900.0,      TAU_T=0.1,
RAMP T='HotRamp', COLOR='RED'      /
&RAMP ID='HotRamp' T=-20.0, F=0.0      /
&RAMP ID='HotRamp' T= -5.0, F=0.0      /
&RAMP ID='HotRamp' T= -4.5, F=1.0      /
&RAMP ID='HotRamp' T= 5.0, F=1.0      /
&RAMP ID='HotRamp' T= 6.0, F=0.0      /
&RAMP ID='HotRamp' T=2000.0,F=0.0 /

```

----- MATERIALS -----

```

&MATL ID= 'CONCRETE',
FYI              = 'Quintiere, Fire Behavior, Table 7.6'
CONDUCTIVITY     = 1.7,
SPECIFIC_HEAT    = 0.75,
DENSITY          = 2200. /

&SURF ID          = 'NL_CONCRETE',
MATL_ID           = 'CONCRETE',
COLOR             = 'SEA GREEN',
BACKING           = 'EXPOSED',
THICKNESS         = 0.15 /

&SURF ID          = 'L_CONCRETE',
MATL_ID           = 'CONCRETE',
BACKING           = 'VOID',
THICKNESS         = 0.15 /

&SURF ID          = 'INSULATION_MAT',
MATL_ID           = 'CSB',
COLOR             = 'BLACK',
BACKING           = 'EXPOSED',
THICKNESS         = 0.01 /

CALCIUM_SILICATE_BOARD
&MATL ID          = 'CSB',
EMISSION          = 0.9,
DENSITY           = 225.,
CONDUCTIVITY      = 0.21,
SPECIFIC_HEAT     = 0.84, /

```

----- LEAK & HVAC DUCT -----

```

&VENT ID='OutflowVent',      XB=0.0,0.0, 2.0,2.2, 0.6,0.8,      SURF_ID='HVAC',
COLOR='RED' /
&HVAC ID='OutflowNode',      TYPE_ID='NODE',      VENT_ID='OutflowVent',
DUCT ID='WallHoleDuct',      LOSS=1.0,1.0, /
&HVAC ID='WallNode',         TYPE_ID='NODE',      DUCT_ID='WallHoleDuct','OutflowDuct',
LOSS=1.0,1.0,      XYZ=0.0,2.1,0.7, /

&HVAC ID='WallHoleDuct',      TYPE_ID='DUCT',      NODE_ID='OutflowNode','WallNode',
AREA=0.031416,      LOSS=0.,0.,      LENGTH=0.15,      ROUGHNESS=0.001, / 0.2 diameter hole in
the wall
&HVAC ID='OutflowDuct',      TYPE_ID='DUCT',      NODE_ID='WallNode','AmbientNode',
AREA=0.0804,      LOSS=0.,0.,      LENGTH=3.2,      ROUGHNESS=0.001, / 0.32 diameter
circular duct

&HVAC ID='AmbientNode',      TYPE_ID='NODE',      DUCT_ID='OutflowDuct', LOSS=1.0,1.0,
XYZ=0.0,2.1,0.7, AMBIENT=.TRUE. /

```

----- OUTPUT -----

Volume flow

```
&DEVC XB=0.0,0.0, 2.0,2.2, 0.6,0.8, QUANTITY='VOLUME FLOW', ID='Vflow_Tot' /
&DEVC XB=0.0,0.0, 2.0,2.2, 0.6,0.8, QUANTITY='VOLUME FLOW -', ID='Vflow_Minus' /
&DEVC XB=0.0,0.0, 2.0,2.2, 0.6,0.8, QUANTITY='VOLUME FLOW +', ID='Vflow_Plus' /
```

Pressure

```
&DEVC ID='PRESS1', QUANTITY='PRESSURE', XYZ=1.8,1.35,0.65 /
&DEVC ID='PRESS2', QUANTITY='PRESSURE', XYZ=1.8,1.35,2 /
&DEVC ID='PRESS_1', QUANTITY='PRESSURE', TIME_AVERAGED=.FALSE.,
XYZ=1.8,1.35,0.65 /
```

Thermocouple

```
&PROP ID='TC', BEAD_EMISSIVITY=0.9, BEAD_DIAMETER=0.00025, /

&DEVC ID='TEMP0' QUANTITY='THERMOCOUPLE' XYZ=1.75,1.35,0.15,
PROP_ID = 'TC' /
&DEVC ID='TEMP1' QUANTITY='THERMOCOUPLE' XYZ=1.75,1.35,0.55,
PROP_ID = 'TC' /
&DEVC ID='TEMP2' QUANTITY='THERMOCOUPLE' XYZ=1.75,1.35,1.05,
PROP_ID = 'TC' /
&DEVC ID='TEMP3' QUANTITY='THERMOCOUPLE' XYZ=1.75,1.35,1.55,
PROP_ID = 'TC' /
&DEVC ID='TEMP4' QUANTITY='THERMOCOUPLE' XYZ=1.75,1.35,2.05,
PROP_ID = 'TC' /
&DEVC ID='TEMP5' QUANTITY='THERMOCOUPLE' XYZ=1.75,1.35,2.45,
PROP_ID = 'TC' /
```

Temperature

```
&DEVC ID='T0' QUANTITY='TEMPERATURE' XYZ=1.75,1.35,0.1 /
&DEVC ID='T1' QUANTITY='TEMPERATURE' XYZ=1.75,1.35,0.6 /
&DEVC ID='T2' QUANTITY='TEMPERATURE' XYZ=1.75,1.35,1.1 /
&DEVC ID='T3' QUANTITY='TEMPERATURE' XYZ=1.75,1.35,1.6 /
&DEVC ID='T4' QUANTITY='TEMPERATURE' XYZ=1.75,1.35,2.1 /
&DEVC ID='T5' QUANTITY='TEMPERATURE' XYZ=1.75,1.35,2.5 /
```

Leak quantities measurements

```
&DEVC ID='LEAK_VEL', QUANTITY='U-VELOCITY', XYZ=0.05,2.1,0.65/
&DEVC ID='TEMP_OUT', QUANTITY='THERMOCOUPLE' XYZ=0.05,2.1,0.65, PROP_ID
='TC' /
```

Gas species

```
&DEVC ID='O2', QUANTITY='MASS FRACTION', SPEC_ID='OXYGEN',
XYZ=2,1.35,2 /
&DEVC ID='O2vol', QUANTITY='VOLUME FRACTION', SPEC_ID='OXYGEN', XYZ=2,1.35,2 /
&DEVC ID='COvol', QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON MONOXIDE',
XYZ=2,1.35,2 /
&DEVC ID='COvolppm', QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON MONOXIDE',
UNITS='ppm', CONVERSION_FACTOR=1000000, XYZ=2,1.35,2 /
```

Duct output quantities

Ambient node

```
&DEVC ID='DuctVel', QUANTITY='DUCT VELOCITY', DUCT_ID='OutflowDuct'
/
&DEVC ID='DuctVflow', QUANTITY='DUCT VOLUME FLOW', DUCT_ID='OutflowDuct' /
&DEVC ID='DuctTemp', QUANTITY='DUCT TEMPERATURE', DUCT_ID='OutflowDuct' /
&DEVC ID='NodeTempA', QUANTITY='NODE TEMPERATURE', NODE_ID='AmbientNode' /
```

Room node

```
&DEVC ID='DuctVelR', QUANTITY='DUCT VELOCITY', DUCT_ID='WallHoleDuct' /
&DEVC ID='DuctVflowR', QUANTITY='DUCT VOLUME FLOW', DUCT_ID='WallHoleDuct' /
&DEVC ID='DuctTempR', QUANTITY='DUCT TEMPERATURE', DUCT_ID='WallHoleDuct' /
&DEVC ID='NodeTempR', QUANTITY='NODE TEMPERATURE', NODE_ID='OutflowNode' /
```

Outflow node

```
&DEVC ID='OutflowNodeP', QUANTITY='NODE PRESSURE', NODE_ID='OutflowNode' /
&DEVC ID='WallNodeP', QUANTITY='NODE PRESSURE', NODE_ID='WallNode' /
&DEVC ID='AmbientNodeP', QUANTITY='NODE PRESSURE', NODE_ID='AmbientNode' /
```

Heat Flux

```
&DEVC XB=2.4,2.9, 3.0,4.0, 0.00,0.00, QUANTITY='GAUGE HEAT FLUX', STATISTICS='SURFACE
INTEGRAL',ID='qdotave', IOR=+3 /
&DEVC XYZ=2.65,3.55,0.0, IOR=+3, QUANTITY='GAUGE HEAT FLUX',ID='qdotmiddle'/

BNDF QUANTITY='BURNING RATE' /
BNDF QUANTITY='GAUGE HEAT FLUX' /
BNDF QUANTITY='WALL TEMPERATURE' /

&SLCF QUANTITY='TEMPERATURE', PBX=2.5 /
&SLCF QUANTITY='VELOCITY', VECTOR=.TRUE., PBX=2.5 /
&SLCF QUANTITY='PRESSURE', PBX=2.5 /
&SLCF QUANTITY='HRRPUV', PBX=2.5 /
&SLCF QUANTITY='TEMPERATURE', PBX=2.1 /
&SLCF QUANTITY='VELOCITY', VECTOR=.TRUE., PBX=2.1 /

&SLCF PBX=3.5, QUANTITY='HRRPUV', CELL_CENTERED=.TRUE. /
&SLCF PBX=3.5, QUANTITY='VOLUME FRACTION', SPEC_ID= 'N-HEPTANE', CELL_CENTERED=.TRUE. /
&SLCF PBX=3.5, QUANTITY='TEMPERATURE', CELL_CENTERED=.TRUE. /
&SLCF PBX=3.5, QUANTITY='HRRPUV' /
&SLCF PBX= 2.5, QUANTITY='VOLUME FRACTION', SPEC_ID= 'CARBON DIOXIDE' /
&SLCF PBX= 2.5, QUANTITY='VOLUME FRACTION', SPEC_ID= 'CARBON MONOXIDE' /
&SLCF PBX= 2.5, QUANTITY='VOLUME FRACTION', SPEC_ID= 'OXYGEN' /
&SLCF PBX= 2.5, QUANTITY='VOLUME FRACTION', SPEC_ID= 'N-HEPTANE' /
&TAIL/
```

Test 31: Fire room connected to exhaust and supply ventilation network

```
Grid cell size: dx = dy = dz = 0.1 m
Combustion chamber: 4.0m x 6.0m x 2.6m
Leak diameter = 0.2m
Exhaust and supply ventilation
&HEAD CHID = 'Test 31', TITLE='PRESSURE RISE DUE TO FIRE GROWTH IN A CLOSED ROOM -
Exhaust ventilation' /
&MESH ID='FOA_31', IJK = 40, 55, 30, XB = 0.0, 4.0, 0, 5.5,0,3 / 10 cm

&TIME T_END=480.0, T_BEGIN = -120 /
&MISC TMPA=20.0 /
&DUMP SMOKE3D=.TRUE.,
      NFRAMES= 100,
      DT_PART=1.0,
      DT_HRR = 1,
      DT_DEVC = 1,
      DT_SLCF=2.0,
      DT_BNDF=100000.0,
      DT_PL3D=1000000.0,
      DT_ISOF=1000000.0 / time steps for the outputs

&PRES MAX_PRESSURE_ITERATIONS=50,
      VELOCITY_TOLERANCE=0.0001,
      CHECK_POISSON=.TRUE.,
      RELAXATION_FACTOR=1 /
&ZONE XB = 0, 3, 0, 4, 0, 2/

----- Fire Specifications -----

&REAC FUEL='N-HEPTANE', AUTO_IGNITION_TEMPERATURE = 223.0,
      CO_YIELD = 0.01, SOOT_YIELD = 0.037,
      FYI= 'Heptane C_7 H_16' /
      Drysdale, D., An Introduction to Fire Dynamics, 3rd Edition, Wiley 2011
      Table 6.2, page 233: n-Heptane AIT, 255 C, 248 C, 223 C different sizes
      of the vessel. => 250 C is good enough for us.

&SURF ID= 'fire1', HRRPUA=1600, RAMP_Q='PoolRamp1', COLOR='RED', TMP_FRONT=98.0,/
&SURF ID= 'fire2', HRRPUA=1600, RAMP_Q='PoolRamp2', COLOR='RED', TMP_FRONT=98.0,/
&SURF ID= 'fire3', HRRPUA=1600, RAMP_Q='PoolRamp3', COLOR='RED', TMP_FRONT=98.0,/
```



```

&VENT SURF_ID = 'fire1', XB = 2.4,2.6,3,4,0,0 COLOR='GREEN', IOR=3 /
&VENT SURF_ID = 'fire2', XB = 2.6,2.8,3,4,0,0, COLOR='PURPLE',IOR=3 /
&VENT SURF_ID = 'fire3', XB = 2.8,3.0,3,4,0,0, COLOR='BLACK', IOR=3 /

&RAMP ID='PoolRamp1', T=0.0, F=0.0 /
&RAMP ID='PoolRamp1', T=26.21, F=0.088 /
&RAMP ID='PoolRamp1', T=40.38, F=0.21 /
&RAMP ID='PoolRamp1', T=67.612, F=0.5 /
&RAMP ID='PoolRamp1', T=75.44, F=0.63 /
&RAMP ID='PoolRamp1', T=95.0, F=1.0 /
&RAMP ID='PoolRamp1', T=180.0, F=1.0 /
&RAMP ID='PoolRamp1', T=220.0, F=0.0 /
&RAMP ID='PoolRamp1', T=600.0, F=0.0 /

&RAMP ID='PoolRamp2', T=0.0, F=0.0 /
&RAMP ID='PoolRamp2', T=97.0, F=0.02 /
&RAMP ID='PoolRamp2', T=107, F=0.25 /
&RAMP ID='PoolRamp2', T=116.91, F=0.45 /
&RAMP ID='PoolRamp2', T=122, F=0.62 /
&RAMP ID='PoolRamp2', T=137.0, F=1.0 /
&RAMP ID='PoolRamp2', T=190.0, F=1.0 /
&RAMP ID='PoolRamp2', T=220.0, F=0.0 /
&RAMP ID='PoolRamp2', T=600.0, F=0.0 /

&RAMP ID='PoolRamp3', T=0.0, F=0.0 /
&RAMP ID='PoolRamp3', T=136 F=0.0 /
&RAMP ID='PoolRamp3', T=141.62 F=0.162 /
&RAMP ID='PoolRamp3', T=148.11 F=0.396 /
&RAMP ID='PoolRamp3', T=160, F=0.7 /
&RAMP ID='PoolRamp3', T=200, F=0.7 /
&RAMP ID='PoolRamp3', T=220, F=0.000 /
&RAMP ID='PoolRamp3', T=600.0, F=0.000 /

&OBST XB=2.4,2.6, 3.0,3.4, 0.20,0.20,
SURF_ID6='INERT','INERT','INERT','INERT','HOT_SURF','INERT', CTRL_ID='HOT_SURF' / top
piece
&OBST XB=2.4,2.6, 3.6,4.0, 0.20,0.20,
SURF_ID6='INERT','INERT','INERT','INERT','HOT_SURF','INERT', CTRL_ID='HOT_SURF' / top
piece

&DEVC ID='HotSurfTimer', XYZ=2.6,3.5,0, QUANTITY='TIME'/
&SURF ID='HOT_SURF', TMP_FRONT=900.0, COLOR='RED', TMP_INNER=900.0, TAU_T=0.1,
RAMP_T='HotRamp' /
&RAMP ID='HotRamp' T= 5.0, F=0.0 /
&RAMP ID='HotRamp' T=10.0, F=1 /
&RAMP ID='HotRamp' T=22.0, F=1 /
&RAMP ID='HotRamp' T=30.0, F=0 /
&RAMP ID='HotRamp' T=95.0, F=0 /
&RAMP ID='HotRamp' T=100.0, F=0 /
&RAMP ID='HotRamp' T=180.0, F=0 /
&RAMP ID='HotRamp' T=2000.0, F=0.0 /

&CTRL ID='HOT_SURF', FUNCTION_TYPE='CUSTOM', INPUT_ID='HotSurfTimer', RAMP_ID='TimeRamp'
/
&RAMP ID='TimeRamp' T= -2.0, F=-1.0 /
&RAMP ID='TimeRamp' T= 14.0, F=1.0 /
&RAMP ID='TimeRamp' T= 25.0, F=1.0 /
&RAMP ID='TimeRamp' T= 26.0, F=-1.0 /
&RAMP ID='TimeRamp' T= 94.0, F=-1.0 /
&RAMP ID='TimeRamp' T= 140.0, F=-1.0 /
&RAMP ID='TimeRamp' T= 210, F=-1.0 /
&RAMP ID='TimeRamp' T=2000.0, F=-1.0 /

&OBST XB=2.59,2.61, 3.0,4.0, 0.0,0.1, SURF_ID='INERT', / rims between pans
&OBST XB=2.79,2.81, 3.0,4.0, 0.0,0.1, SURF_ID='INERT', / rims between pans
&OBST XB=2.99,3.01, 3.0,4.0, 0.0,0.1, SURF_ID='INERT', / rims between pans

&OBST XB = 2.4,2.4, 3,4, 0,0.2, SURF_ID='INERT' / PAN RIMS
&OBST XB=2.4,3.22, 3.0,3.0, 0.0,0.2, SURF_ID='INERT', /
&OBST XB=3.22,3.22, 3.0,4.0, 0.0,0.2, SURF_ID='INERT', /
&OBST XB=2.4,3.22, 4.0,4.0, 0.0,0.2, SURF_ID='INERT', /

```

----- Fire room Geometry -----

```
&OBST XB = 0,1.05, 2.6,2.75, 0,2.6, SURF_ID='NL_CONCRETE' / CENTRE WALL 1
&OBST XB = 2.95,4, 2.6,2.75, 0,2.6, SURF_ID='NL_CONCRETE' / CENTRE WALL 2
&OBST XB = 0,4, 0,0, 0,2.6, SURF_ID = 'L_CONCRETE' / LEFT WALL
&OBST XB = 0,2.7, 5.5,5.5, 0,2.6, SURF_ID = 'L_CONCRETE' / RIGHT WALL
&OBST XB = 2.7,4.0, 4.2,5.5, 0,2.6 SURF_ID = 'L_CONCRETE' / RIGHT WALL
&OBST XB = 0,0.0, 0,5.5, 0,2.6, SURF_ID = 'L_CONCRETE' / FRONT WALL
&OBST XB = 4,4,0,4.2,0,2.6, SURF_ID = 'L_CONCRETE' / BACK WALL
&OBST XB = 2.7,2.7,4.2,5.5,0,2.6, SURF_ID = 'L_CONCRETE' / BACK WALL
&OBST XB = 0,4, 0,5.5, 2.6,2.6, SURF_ID = 'L_CONCRETE' / ROOF
```

Thermocouple insulators

```
&OBST XB = 1.7,1.8,1.4,1.4,0.9,1.05, SURF_ID = 'INSULATION_MAT' /
&OBST XB = 1.7,1.8,1.4,1.4,1.4,1.55, SURF_ID = 'INSULATION_MAT' /
&OBST XB = 1.7,1.8,1.4,1.4,1.9,2.05, SURF_ID = 'INSULATION_MAT' /
&OBST XB = 1.7,1.8,1.4,1.4,2.4,2.55, SURF_ID = 'INSULATION_MAT' /
```

Pan rims

```
&OBST XB = 2.4,2.4,3,4,0,0.2, SURF_ID='INERT' /
&OBST XB=2.4,3.22, 3.0,3.0, 0.0,0.2, SURF_ID='INERT', /
&OBST XB=3.22,3.22, 3.0,4.0, 0.0,0.2, SURF_ID='INERT', /
&OBST XB=2.4,3.22, 4.0,4.0, 0.0,0.2, SURF_ID='INERT', /
```

----- Material Properties -----

```
&MATL ID = 'CONCRETE',
FYI = 'Quintiere, Fire Behavior, Table 7.6'
CONDUCTIVITY = 1.7,
SPECIFIC_HEAT = 0.75,
DENSITY = 2200. /

&SURF ID = 'NL_CONCRETE',
MATL_ID = 'CONCRETE',
COLOR = 'SEA GREEN',
BACKING = 'EXPOSED',
THICKNESS = 0.15 /

&SURF ID = 'L_CONCRETE',
MATL_ID = 'CONCRETE',
BACKING = 'VOID',
THICKNESS = 0.15 / this thickness corresponds to heat transfer
characteristics of the wall (how the 1D solid phase solver views it). The OBST thickness
is geometry of the wall.

&SURF ID = 'INSULATION_MAT'
MATL_ID = 'CSB'
COLOR = 'BLACK'
BACKING = 'EXPOSED'
THICKNESS = 0.1 /

CALCIUM_SILICATE_BOARD
&MATL ID = 'CSB'
EMISSION = 0.9

DENSITY = 225.
CONDUCTIVITY = 0.21
SPECIFIC_HEAT = 0.84 /
```

-----Wall Leakage -----

```
&HVAC ID='LeakHoleDuct', TYPE_ID='DUCT', NODE_ID='OutflowNode','LeakNode',
AREA=0.007854,
LOSS=0.255,0.255,, LENGTH=0.5, ROUGHNESS=0.001, / 0.2 diameter hole in the wall
&HVAC ID='LeakNode', TYPE_ID='NODE', DUCT_ID='LeakHoleDuct','OutflowDuct', LOSS=1.0,1.0,
XYZ=0.0,2.1,0.7, /

&HVAC ID='OutflowDuct', TYPE_ID='DUCT', NODE_ID='LeakNode','AmbientNode', AREA=0.0804,
LOSS=0.0,0.0, LENGTH=3.2, ROUGHNESS=0.001, / 0.32 diameter circular duct
```

```

&VENT ID='OutflowVent', XB=0.0,0.0, 2.0,2.2, 0.6,0.8, SURF_ID='HVAC', COLOR='RED'/
&HVAC ID='OutflowNode', TYPE_ID='NODE', VENT_ID='OutflowVent', DUCT_ID='LeakHoleDuct',
LOSS=1.0,1.0, /
&HVAC ID='AmbientNode', TYPE_ID='NODE', DUCT_ID='OutflowDuct', LOSS=1.0,1.0,
XYZ=0.0,2.1,0.7, AMBIENT=.TRUE. /

&SLCF QUANTITY='TEMPERATURE', PBY=0.1 /
&SLCF QUANTITY='VELOCITY', VECTOR=.TRUE., PBY=0.1 /

----- Supply Ventilation network -----

&HVAC ID='SWallHoleDuct', TYPE_ID='DUCT', NODE_ID='SWallNode','SNode',
AREA=0.007854,LOSS=0.0,0.0, LENGTH=0.15, ROUGHNESS=0.001 /
&HVAC ID='SWallNode', TYPE_ID='NODE', DUCT_ID='SWallHoleDuct','Sduct 1',
LOSS=0.,0.,XYZ=0.0,2.1,1.7 / DAMPER LOSS
&VENT ID='SVent', XB=0.0,0.0, 2.0,2.2, 1.6,1.8, SURF_ID='HVAC', COLOR='RED'/
&HVAC ID='SNode', TYPE_ID='NODE', VENT_ID='SVent', DUCT_ID='SWallHoleDuct', LOSS=1.0,1.0
/

&HVAC TYPE_ID = 'NODE', ID='Snode 2', DUCT_ID='Sduct 1','Sduct 2','Sduct 5',XYZ = -
0.65,0.35,1.7, LOSS = 0,0 /
&HVAC TYPE_ID = 'NODE', ID='Snode 3', DUCT_ID='Sduct 2','Sduct 3','Sduct 6', XYZ = -
0.65,-0.65,1.7, LOSS = 0,0 /
&HVAC TYPE_ID = 'NODE', ID='Snode 4', DUCT_ID='Sduct 3','Sduct 4','Sduct 7', XYZ = -
0.65,-1.65,1.7, LOSS = 0,0 /
&HVAC TYPE_ID = 'NODE', ID='Snode 5', DUCT_ID='Sduct 4', XYZ = -0.65,-2.65,1.7, LOSS =
1,1, AMBIENT=.TRUE./
&HVAC TYPE_ID = 'NODE', ID='Snode 6', DUCT_ID='Sduct 5', XYZ = -1.75,0.35,1.7, LOSS =
1,1, AMBIENT=.TRUE. /
&HVAC TYPE_ID = 'NODE', ID='Snode 7', DUCT_ID='Sduct 6', XYZ = -2.05,-0.65,1.7, LOSS
= 1,1, AMBIENT=.TRUE. /
&HVAC TYPE_ID = 'NODE', ID='Snode 8', DUCT_ID='Sduct 7', XYZ = -2.05,-1.65,1.7, LOSS =
1,1, AMBIENT=.TRUE. /

&HVAC TYPE_ID = 'DUCT', ID='Sduct 1', NODE_ID = 'Snode 2','EWallNode', LENGTH = 1.75,
AREA=0.007854, LOSS =18.4,18.4, ROUGHNESS=0.001, /
&HVAC TYPE_ID = 'DUCT', ID='Sduct 2', NODE_ID = 'Snode 3','Snode 2', LENGTH = 1.0,
AREA=0.01227, LOSS =0.0,0.0 ROUGHNESS=0.001 /
&HVAC TYPE_ID = 'DUCT', ID='Sduct 3', NODE_ID = 'Snode 4','Snode 3', LENGTH =
1.0,AREA=0.02010, LOSS =0.0,0.0, ROUGHNESS=0.001 /
&HVAC TYPE_ID = 'DUCT', ID='Sduct 4', NODE_ID = 'Snode 5','Snode 4', LENGTH = 1.0,
AREA=0.02010 LOSS =0.0,0.0, ROUGHNESS=0.001, FAN_ID='E_FAN' /
&HVAC TYPE_ID = 'DUCT', ID='Sduct 5', NODE_ID = 'Snode 2','Snode 6', LENGTH =
1.0,AREA=0.007854, LOSS =19.0,19.0, ROUGHNESS=0.001 /
&HVAC TYPE_ID = 'DUCT', ID='Sduct 6', NODE_ID = 'Snode 3','Snode 7', LENGTH =
1.3,AREA=0.007854, LOSS =19.0,19.0, ROUGHNESS=0.001 /
&HVAC TYPE_ID = 'DUCT', ID='Sduct 7', NODE_ID = 'Snode 4','Snode 8', LENGTH =
1.3,AREA=0.007854, LOSS =19.0,19.0, ROUGHNESS=0.001 /

&HVAC TYPE_ID='FAN', ID='S_FAN', MAX_PRESSURE=310, MAX_FLOW=0.130 / fan curve is given in
the experiments.

```

----- Exhaust Ventilation network -----

```

&HVAC ID='EWallHoleDuct', TYPE_ID='DUCT', NODE_ID='ENode','EWallNode',
AREA=0.007854,LOSS=0.0,0.0, LENGTH=0.15, ROUGHNESS=0.001 /
&HVAC ID='EWallNode', TYPE_ID='NODE', DUCT_ID='EWallHoleDuct','duct 1',
LOSS=0.,0.,XYZ=0.0,4.1,1.3 / DAMPER LOSS
&VENT ID='EVent', XB=0.0,0.0, 4.0,4.2, 1.2,1.4, SURF_ID='HVAC', COLOR='RED'/
&HVAC ID='ENode', TYPE_ID='NODE', VENT_ID='EVent', DUCT_ID='EWallHoleDuct', LOSS=1.0,1.0
/

&HVAC TYPE_ID = 'NODE', ID='node 2', DUCT_ID='duct 1','duct 2','duct 5',XYZ = -
0.65,3.0,1.3, LOSS = 0,0 /
&HVAC TYPE_ID = 'NODE', ID='node 3', DUCT_ID='duct 2','duct 3','duct 6', XYZ = -
0.65,2.0,1.3, LOSS = 0,0 /
&HVAC TYPE_ID = 'NODE', ID='node 4', DUCT_ID='duct 3','duct 4','duct 7', XYZ = -
0.65,1.0,1.3, LOSS = 0,0 /
&HVAC TYPE_ID = 'NODE', ID='node 5', DUCT_ID='duct 4', XYZ = -0.65,-1.7,1.3, LOSS =
1,1, AMBIENT=.TRUE./

```

```

&HVAC TYPE_ID = 'NODE', ID='node 6', DUCT_ID='duct 5', XYZ = -1.75,3.0,1.3, LOSS = 1,1,
AMBIENT=.TRUE. /
&HVAC TYPE_ID = 'NODE', ID='node 7', DUCT_ID='duct 6', XYZ = -2.05,2.0,1.3, LOSS =
1,1, AMBIENT=.TRUE. /
&HVAC TYPE_ID = 'NODE', ID='node 8', DUCT_ID='duct 7', XYZ = -2.05,1.0,1.3, LOSS = 1,1,
AMBIENT=.TRUE. /

```

```

&HVAC TYPE_ID = 'DUCT', ID='duct 1', NODE_ID = 'EWallNode','node 2', LENGTH = 1.75,
AREA=0.007854, LOSS =17.6,17.6, ROUGHNESS=0.001, /
&HVAC TYPE_ID = 'DUCT', ID='duct 2', NODE_ID = 'node 2','node 3', LENGTH = 1.0,
AREA=0.01227, LOSS =0.0,0.0, ROUGHNESS=0.001 /
&HVAC TYPE_ID = 'DUCT', ID='duct 3', NODE_ID = 'node 3','node 4', LENGTH =
1.0,AREA=0.02010, LOSS =0.0,0.0, ROUGHNESS=0.001 /
&HVAC TYPE_ID = 'DUCT', ID='duct 4', NODE_ID = 'node 4','node 5', LENGTH = 2.7,
AREA=0.02010, LOSS =0.0,0.0, ROUGHNESS=0.001, FAN_ID='E_FAN' /
&HVAC TYPE_ID = 'DUCT', ID='duct 5', NODE_ID = 'node 6','node 2', LENGTH =
1.0,AREA=0.007854, LOSS =18.9,18.9, ROUGHNESS=0.001 /
&HVAC TYPE_ID = 'DUCT', ID='duct 6', NODE_ID = 'node 7','node 3', LENGTH =
1.3,AREA=0.007854, LOSS =19.1,19.1, ROUGHNESS=0.001 /
&HVAC TYPE_ID = 'DUCT', ID='duct 7', NODE_ID = 'node 8','node 4', LENGTH =
1.3,AREA=0.007854, LOSS =19.1,19.1, ROUGHNESS=0.001 /

```

```

&HVAC TYPE_ID='FAN', ID='E_FAN', MAX_PRESSURE=310, MAX_FLOW=0.130, / fan curve is given
in the experiments.

```

----- Output-----

```

&BNDF QUANTITY='BURNING RATE' /
&BNDF QUANTITY='GAUGE HEAT FLUX' /
&BNDF QUANTITY='WALL TEMPERATURE' /

```

```

&SLCF PBX=2.5, QUANTITY='TEMPERATURE', CELL_CENTERED=.TRUE. /
&SLCF PBX=1.5, QUANTITY='VELOCITY', VECTOR=.TRUE., CELL_CENTERED=.TRUE. /
&SLCF PBX=3.1, QUANTITY='VELOCITY', VECTOR=.TRUE., CELL_CENTERED=.TRUE. /
&SLCF PBZ=2.6, QUANTITY='VELOCITY', VECTOR=.TRUE., CELL_CENTERED=.TRUE. /
&SLCF PBX=3.1, QUANTITY='PRESSURE', CELL_CENTERED=.TRUE. /
&SLCF PBX=1.9, QUANTITY='PRESSURE', CELL_CENTERED=.TRUE. /
&SLCF PBX=2.5, QUANTITY='HRRPUV', CELL_CENTERED=.TRUE. /
&SLCF PBX=3.1, QUANTITY='TEMPERATURE' /
&SLCF PBX=0.2, QUANTITY='VELOCITY', VECTOR=.TRUE. /
&SLCF PBX= 2.5, QUANTITY='VOLUME FRACTION', SPEC_ID= 'CARBON DIOXIDE' /
&SLCF PBX= 2.5, QUANTITY='VOLUME FRACTION', SPEC_ID= 'NITROGEN' /
&SLCF PBX= 2.5, QUANTITY='VOLUME FRACTION', SPEC_ID= 'WATER VAPOR' /
&SLCF PBX= 2.5, QUANTITY='VOLUME FRACTION', SPEC_ID= 'OXYGEN' /
&SLCF PBX= 1.35, QUANTITY='VOLUME FRACTION', SPEC_ID= 'OXYGEN' /

```

```

&DEVC ID='PRESS1', QUANTITY='PRESSURE', XYZ=1.8,1.35,0.65 /
&DEVC ID='PRESS2', QUANTITY='PRESSURE', XYZ=1.8,1.35,2 /
&DEVC ID='PRESS_1', QUANTITY='PRESSURE', XYZ=1.8,1.35,0.65, TIME_AVERAGED=.FALSE. /

```

Volume flow

```

&DEVC XB=0.0,0.0, 2.0,2.2, 0.6,0.8, QUANTITY='VOLUME FLOW', ID='Vflow_Tot' /
&DEVC XB=0.0,0.0, 2.0,2.2, 0.6,0.8, QUANTITY='VOLUME FLOW -', ID='Vflow_Minus' /
&DEVC XB=0.0,0.0, 2.0,2.2, 0.6,0.8, QUANTITY='VOLUME FLOW +', ID='Vflow_Plus' /

```

Thermocouple

```

&PROP ID='TC', BEAD_EMISSIVITY=0.9, BEAD_DIAMETER=0.00025 /

```

```

&DEVC ID='TEMP0' QUANTITY='THERMOCOUPLE' XYZ=1.75,1.35,0.1, PROP_ID = 'TC' /
&DEVC ID='TEMP1' QUANTITY='THERMOCOUPLE' XYZ=1.75,1.35,0.6, PROP_ID = 'TC' /
&DEVC ID='TEMP2' QUANTITY='THERMOCOUPLE' XYZ=1.75,1.35,1.1, PROP_ID = 'TC' /
&DEVC ID='TEMP3' QUANTITY='THERMOCOUPLE' XYZ=1.75,1.35,1.6, PROP_ID = 'TC' /
&DEVC ID='TEMP4' QUANTITY='THERMOCOUPLE' XYZ=1.75,1.35,2.1, PROP_ID = 'TC' /
&DEVC ID='TEMP5' QUANTITY='THERMOCOUPLE' XYZ=1.75,1.35,2.5, PROP_ID = 'TC' /

```

```

&DEVC ID='T0' QUANTITY='TEMPERATURE' XYZ=1.75,1.35,0.1 /
&DEVC ID='T1' QUANTITY='TEMPERATURE' XYZ=1.75,1.35,0.6 /
&DEVC ID='T2' QUANTITY='TEMPERATURE' XYZ=1.75,1.35,1.1 /
&DEVC ID='T3' QUANTITY='TEMPERATURE' XYZ=1.75,1.35,1.6 /

```

```

&DEVC ID='T4'          QUANTITY='TEMPERATURE'          XYZ=1.75,1.35,2.1 /
&DEVC ID='T5'          QUANTITY='TEMPERATURE'          XYZ=1.75,1.35,2.5 /

&DEVC XB = 0.0,0.0, 2.0,2.2, 0.6,0.8, QUANTITY='VOLUME FLOW', ID='Vflow_Tot' /
&DEVC XB = 0.0,0.0, 2.0,2.2, 0.6,0.8, QUANTITY='VOLUME FLOW -', ID='Vflow_Minus' /
&DEVC XB = 0.0,0.0, 2.0,2.2, 0.6,0.8, QUANTITY='VOLUME FLOW +', ID='Vflow_Plus' /

&DEVC ID='O2', QUANTITY='VOLUME FRACTION', SPEC_ID='OXYGEN', XYZ=2,1.35,2 /
&DEVC ID='CO', QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON MONOXIDE', XYZ=2,1.35,2 /
&DEVC ID='O2', QUANTITY='MASS FRACTION', SPEC_ID='N-HEPTANE', XYZ=2.5,3.5,1 /
&DEVC ID='COvolppm', QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON MONOXIDE', UNITS='ppm',
CONVERSION_FACTOR=1000000, XYZ=2,1.35,2 /

```

Ventilation network output

```

&DEVC ID='DuctVelS', QUANTITY='DUCT VELOCITY', DUCT_ID='SWallHoleDuct' /
&DEVC ID='NodeTempS', QUANTITY='NODE TEMPERATURE', NODE_ID='SNode' /
&DEVC ID='DuctVflowS', QUANTITY='DUCT VOLUME FLOW', DUCT_ID='SWallHoleDuct' /
&DEVC ID='DuctTempS', QUANTITY='DUCT TEMPERATURE', DUCT_ID='SWallHoleDuct' /

&DEVC ID='DuctVelR', QUANTITY='DUCT VELOCITY', DUCT_ID='EWallHoleDuct' /
&DEVC ID='NodeTempR', QUANTITY='NODE TEMPERATURE', NODE_ID='ENode' /
&DEVC ID='DuctVflowR', QUANTITY='DUCT VOLUME FLOW', DUCT_ID='EWallHoleDuct' /
&DEVC ID='DuctTempR', QUANTITY='DUCT TEMPERATURE', DUCT_ID='EWallHoleDuct' /

&DEVC ID='LeakVel', QUANTITY='DUCT VELOCITY', DUCT_ID='OutflowDuct' /
&DEVC ID='LeakVflow', QUANTITY='DUCT VOLUME FLOW', DUCT_ID='OutflowDuct' /
&DEVC ID='LeakTemp', QUANTITY='DUCT TEMPERATURE', DUCT_ID='OutflowDuct' /
&DEVC ID='LeakTempR', QUANTITY='NODE TEMPERATURE', NODE_ID='OutflowNode' /

&DEVC ID='SDuctVel1', QUANTITY='DUCT VELOCITY', DUCT_ID='Sduct 1' /
&DEVC ID='SDuctVflow1', QUANTITY='DUCT VOLUME FLOW', DUCT_ID='Sduct 1' /
&DEVC ID='SDuctTemp1', QUANTITY='DUCT TEMPERATURE', DUCT_ID='Sduct 1' /
&DEVC ID='SNodePr1', QUANTITY='NODE PRESSURE', NODE_ID='AmbientNode' /

&DEVC ID='SDuctVel2', QUANTITY='DUCT VELOCITY', DUCT_ID='Sduct 2' /
&DEVC ID='SDuctVflow2', QUANTITY='DUCT VOLUME FLOW', DUCT_ID='Sduct 2' /
&DEVC ID='SDuctTemp2', QUANTITY='DUCT TEMPERATURE', DUCT_ID='Sduct 2' /
&DEVC ID='SNodePr2', QUANTITY='NODE PRESSURE', NODE_ID='node 2' /

&DEVC ID='SDuctVel3', QUANTITY='DUCT VELOCITY', DUCT_ID='Sduct 3' /
&DEVC ID='SDuctVflow3', QUANTITY='DUCT VOLUME FLOW', DUCT_ID='Sduct 3' /
&DEVC ID='SDuctTemp3', QUANTITY='DUCT TEMPERATURE', DUCT_ID='Sduct 3' /
&DEVC ID='SNodePr3', QUANTITY='NODE PRESSURE', NODE_ID='node 3' /

&DEVC ID='SDuctVel4', QUANTITY='DUCT VELOCITY', DUCT_ID='Sduct 4' /
&DEVC ID='SDuctVflow4', QUANTITY='DUCT VOLUME FLOW', DUCT_ID='Sduct 4' /
&DEVC ID='SDuctTemp4', QUANTITY='DUCT TEMPERATURE', DUCT_ID='Sduct 4' /
&DEVC ID='SNodePr4', QUANTITY='NODE PRESSURE', NODE_ID='node 4' /

&DEVC ID='SDuctVel5', QUANTITY='DUCT VELOCITY', DUCT_ID='Sduct 5' /
&DEVC ID='SDuctVflow5', QUANTITY='DUCT VOLUME FLOW', DUCT_ID='Sduct 5' /
&DEVC ID='SDuctTemp5', QUANTITY='DUCT TEMPERATURE', DUCT_ID='Sduct 5' /
&DEVC ID='SNodePr5', QUANTITY='NODE PRESSURE', NODE_ID='node 5' /

&DEVC ID='SDuctVel6', QUANTITY='DUCT VELOCITY', DUCT_ID='Sduct 6' /
&DEVC ID='SDuctVflow6', QUANTITY='DUCT VOLUME FLOW', DUCT_ID='Sduct 6' /
&DEVC ID='SDuctTemp6', QUANTITY='DUCT TEMPERATURE', DUCT_ID='Sduct 6' /
&DEVC ID='SNodePr6', QUANTITY='NODE PRESSURE', NODE_ID='node 6' /

&DEVC ID='SDuctVel7', QUANTITY='DUCT VELOCITY', DUCT_ID='Sduct 7' /
&DEVC ID='SDuctVflow7', QUANTITY='DUCT VOLUME FLOW', DUCT_ID='Sduct 7' /
&DEVC ID='SDuctTemp7', QUANTITY='DUCT TEMPERATURE', DUCT_ID='Sduct 7' /
&DEVC ID='SNodePr7', QUANTITY='NODE PRESSURE', NODE_ID='node 7' /

&DEVC ID='SNodePr8', QUANTITY='NODE PRESSURE', NODE_ID='node 8' /

```

```

&DEVC ID='DuctVel1',    QUANTITY='DUCT VELOCITY',    DUCT_ID='duct 1' /
&DEVC ID='DuctVflow1',    QUANTITY='DUCT VOLUME FLOW', DUCT_ID='duct 1' /
&DEVC ID='DuctTemp1',    QUANTITY='DUCT TEMPERATURE', DUCT_ID='duct 1' /
&DEVC ID='NodePr1',    QUANTITY='NODE PRESSURE',    NODE_ID='AmbientNode' /

&DEVC ID='DuctVel2',    QUANTITY='DUCT VELOCITY',    DUCT_ID='duct 2' /
&DEVC ID='DuctVflow2',    QUANTITY='DUCT VOLUME FLOW', DUCT_ID='duct 2' /
&DEVC ID='DuctTemp2',    QUANTITY='DUCT TEMPERATURE', DUCT_ID='duct 2' /
&DEVC ID='NodePr2',    QUANTITY='NODE PRESSURE',    NODE_ID='node 2' /

&DEVC ID='DuctVel3',    QUANTITY='DUCT VELOCITY',    DUCT_ID='duct 3' /
&DEVC ID='DuctVflow3',    QUANTITY='DUCT VOLUME FLOW', DUCT_ID='duct 3' /
&DEVC ID='DuctTemp3',    QUANTITY='DUCT TEMPERATURE', DUCT_ID='duct 3' /
&DEVC ID='NodePr3',    QUANTITY='NODE PRESSURE',    NODE_ID='node 3' /

&DEVC ID='DuctVel4',    QUANTITY='DUCT VELOCITY',    DUCT_ID='duct 4' /
&DEVC ID='DuctVflow4',    QUANTITY='DUCT VOLUME FLOW', DUCT_ID='duct 4' /
&DEVC ID='DuctTemp4',    QUANTITY='DUCT TEMPERATURE', DUCT_ID='duct 4' /
&DEVC ID='NodePr4',    QUANTITY='NODE PRESSURE',    NODE_ID='node 4' /

&DEVC ID='DuctVel5',    QUANTITY='DUCT VELOCITY',    DUCT_ID='duct 5' /
&DEVC ID='DuctVflow5',    QUANTITY='DUCT VOLUME FLOW', DUCT_ID='duct 5' /
&DEVC ID='DuctTemp5',    QUANTITY='DUCT TEMPERATURE', DUCT_ID='duct 5' /
&DEVC ID='NodePr5',    QUANTITY='NODE PRESSURE',    NODE_ID='node 5' /

&DEVC ID='DuctVel6',    QUANTITY='DUCT VELOCITY',    DUCT_ID='duct 6' /
&DEVC ID='DuctVflow6',    QUANTITY='DUCT VOLUME FLOW', DUCT_ID='duct 6' /
&DEVC ID='DuctTemp6',    QUANTITY='DUCT TEMPERATURE', DUCT_ID='duct 6' /
&DEVC ID='NodePr6',    QUANTITY='NODE PRESSURE',    NODE_ID='node 6' /

&DEVC ID='DuctVel7',    QUANTITY='DUCT VELOCITY',    DUCT_ID='duct 7' /
&DEVC ID='DuctVflow7',    QUANTITY='DUCT VOLUME FLOW', DUCT_ID='duct 7' /
&DEVC ID='DuctTemp7',    QUANTITY='DUCT TEMPERATURE', DUCT_ID='duct 7' /
&DEVC ID='NodePr7',    QUANTITY='NODE PRESSURE',    NODE_ID='node 7' /

&DEVC ID='NodePr8',    QUANTITY='NODE PRESSURE',    NODE_ID='node 8' /
&DEVC ID='heatflux',    QUANTITY='NET HEAT FLUX', XYZ = 2.5,3.5,0, IOR=3 /

&TAIL /

```

Appendix E – Leakage Test

A leakage test can be performed to verify the accuracy of the leakage area calculated. As the leakage is the most critical parameter of compartment fire modelling, it is always better to verify the modelled leakage flows.

Leak Test:

1. The enclosure should be modelled as per dimensions.
2. A fan needs to be modelled to pressurize the enclosure to 50 Pa.
3. The area of the leak must be modelled using one of the three leakage modelling methods available.
4. Comparison measured volume flow with the experimental volume flow will indicate the accuracy of the leakage model.
5. The leakage value depends on the pressure and volume flow rate of the blower fan and the fan specifications needs to be known.

A sample FDS input of the leak test is shown below.

```
&HEAD CHID='LT_HVAC', TITLE='Test 1 of the Aalto fire experiments' /

&MESH ID='K_Test 1', XB=0,6,0,12,0,2.6, IJK=30,60,13 /
&TIME T_END=40.0, T_BEGIN= 0 /

&DUMP SMOKE3D = .TRUE.,
      NFRAMES = 100,
      DT_PART = 1.0,
      DT_HRR = 2.0,
      DT_SLCF = 1.0,

----- GEOMETRY -----
Back Wall
&VENT XB = 0.0,6.0 , 0.0,0.0 , 0.0,2.6, SURF_ID='CONCRETE_1' /

Right Wall
&VENT MB='XMAX', SURF_ID='CONCRETE_1' /

Front Wall - Living room
&VENT XB = 2.02,6.0 , 12,12 , 0.0,2.6, SURF_ID='L_CONCRETE' /

Center wall - Kitchen and Bedroom
&OBST XB = 2.6,2.6 , 0.0,4.4 , 0.0,2.6, SURF_ID='CONCRETE' /

Left Wall - Kitchen
&OBST XB = 0.0,0.0 , 0.0,4.4 , 0.0,2.6, SURF_ID='CONCRETE_1' /

Front Wall - Kitchen
&OBST XB = 0.0,1.55 , 4.4,4.4 , 0.0,2.6, SURF_ID='CONCRETE' /

Front Wall - Bedroom
&OBST XB = 3.65,6, 4.4,4.4 , 0.0,2.6, SURF_ID='CONCRETE' /

Closet
&OBST XB = 4.0,6, 6.2,6.2 , 0.0,2.6, SURF_ID='MDF' /

Front Wall- Closet
&OBST XB = 4.0,4.0 , 5.2,6.2 , 0.0,2.6, SURF_ID='MDF' /

Center Wall - Living room/Bathroom
&OBST XB = 2.02,2.02 , 6.2,7.8 , 0.0,2.6, SURF_ID='CONCRETE' /

Center Wall - Living room/Bathroom
&OBST XB = 2.02,2.02, 7.8,12, 0.0,2.6, SURF_ID='CONCRETE_1' /
```

```

Left Wall - Bathroom
&OBST XB = 0.0,0.0 , 6.2,7.8 , 0.0,2.6, SURF_ID='CONCRETE_1' /

Back Wall - Bathroom
&OBST XB = 0.0,2.02 , 7.8,12 , 0.0,2.6, SURF_ID='CONCRETE_1' /

Front Wall - Bathroom
&OBST XB = 0.0,1.2 , 6.2,6.2 , 0.0,2.6, SURF_ID='CONCRETE' /

Roof
&VENT MB = 'ZMAX', SURF_ID= 'RCONCRETE' /

Door
&OBST XB=0,0, 4.4,6.2, 0.0,2.6 , SURF_ID='CONCRETE' /

----- MATERIAL SPECIFICATIONS -----
&MATL ID = 'CONCRETE',
  FYI                                = 'Quintiere, Fire Behavior, Table 7.6'
  CONDUCTIVITY                       = 0.7,
  SPECIFIC_HEAT                      = 0.75,
  DENSITY                            = 2200. /

&SURF ID = 'CONCRETE',
  MATL_ID = 'CONCRETE',
  THICKNESS = 0.16,
  BACKING = 'EXPOSED'
  COLOR = 'BEIGE' /

&SURF ID = 'CONCRETE_1',
  MATL_ID = 'CONCRETE',
  THICKNESS = 0.2,
  BACKING = 'VOID'
  COLOR='BEIGE' /

&SURF ID = 'I_CONCRETE',
  MATL_ID = 'CONCRETE',
  THICKNESS = 0.2,
  BACKING = 'VOID'
  COLOR='BEIGE' /

&SURF ID = 'RCONCRETE',
  MATL_ID = 'CONCRETE',
  THICKNESS = 0.2,
  BACKING = 'VOID'
  TMP_INNER=20,
  COLOR='BEIGE' /

&MATL ID = 'MDF',
  FYI                                = 'Makeitfrom.com'
  CONDUCTIVITY                       = 0.3,
  SPECIFIC_HEAT                      = 1.7,
  DENSITY                            = 750.0 /

&SURF ID = 'MDF',
  MATL_ID = 'MDF',
  THICKNESS = 0.1,
  BACKING = 'EXPOSED'
  COLOR='BEIGE' /          MEDIUM DENSITY FIBERBOARD

----- LEAKAGE -----

&HVAC ID = 'LEAKDUCT1', TYPE_ID='DUCT', NODE_ID='LEAKNODE1','OUTFLOWNODE1', AREA=0.0234,
LENGTH =0.2, ROUGHNESS=0.001 /
&HVAC ID='LEAKNODE1', TYPE_ID='NODE', VENT_ID='LEAKVENT1', DUCT_ID='LEAKDUCT1', LOSS = 1,1
/
&VENT ID='LEAKVENT1', XB = 3.0,5.8 , 12,12 , 0.0,2.4, SURF_ID='HVAC', COLOR='RED' /
&HVAC ID='OUTFLOWNODE1', TYPE_ID = 'NODE', DUCT_ID='LEAKDUCT1', AMBIENT=.TRUE., LOSS=1,1,
XYZ = 4.0,12,1.3 /

```



```

----- SUPPLY FAN -----
&HVAC ID='FanDuct', TYPE_ID='DUCT', NODE_ID='OUTNODE','SNODE', AREA =0.25, LOSS = 1,1,
LENGTH=0.2, ROUGHNESS=0.01, FAN_ID='S_FAN' /
&HVAC ID='SNODE', TYPE_ID='NODE', DUCT_ID='FanDuct', VENT_ID='SVENT', LOSS=1,1 /
&VENT ID='SVENT', XB = 2.2,2.8, 12,12, 0.2,0.6, SURF_ID='HVAC', COLOR='RED' /
&HVAC ID='OUTNODE', TYPE_ID = 'NODE', DUCT_ID='FanDuct', AMBIENT=.TRUE., LOSS=1,1, XYZ =
0.0,4.9,1.5 /
&HVAC TYPE_ID='FAN', ID='S_FAN', MAX_PRESSURE=60, MAX_FLOW=0.500 / fan curve
-----

&SLCF QUANTITY='PRESSURE', PBX =3.0 /
&SLCF QUANTITY='TEMPERATURE', PBX=3.2 /
&SLCF QUANTITY='HRRPUV', PBY=9.0 /

&DEVC ID='PRESS_1', QUANTITY='PRESSURE', XYZ=4.02,10.4,2.0 /
&DEVC ID='PRESS_2', QUANTITY='PRESSURE', XYZ=0.82,2.0,2.0 /

&DEVC ID='LeakVel', QUANTITY='DUCT VELOCITY',DUCT_ID='LEAKDUCT1' /
&DEVC ID='LeakVflow', QUANTITY='DUCT VOLUME FLOW', DUCT_ID='LEAKDUCT1'/
&DEVC ID='LeakTemp', QUANTITY='DUCT TEMPERATURE', DUCT_ID='LEAKDUCT1' /
&DEVC ID='LeakTempR', QUANTITY='NODE TEMPERATURE',NODE_ID='LEAKNODE1' /
&DEVC ID='NodePR', QUANTITY='NODE PRESSURE', NODE_ID='LEAKNODE1' /

&TAIL /

```

Appendix F – FDS input file – Aalto experiments

The FDS input file for the Test 5 with normal ventilation is presented here. The characteristics of the fan was iteratively modified to obtain a reasonable prediction of duct velocities.

```
&HEAD CHID='Exp_Test_5', TITLE='Test 5 of the Kurikka fire experiments' /

This test simulates a condition the normal operating conditions of the ventilation ducts.
In this test the louvers/valves are attached to the ducts. This causes a reduction in the
duct area and this effect is included as a pressure loss.

&MESH ID='K_Test 5', XB=0,6,0,12,0,2.6, IJK=60,120,26 /

&TIME T_END=300.0, T_BEGIN= -20 /
&MISC TMPA =6.0, DT_HVAC=2/
&INIT XB=0,6,0,12,0,2.6, TEMPERATURE = 16 /

&DUMP SMOKE3D = .TRUE.,
      NFRAMES = 100,
      DT_PART = 1.0,
      DT_HRR = 1.0,
      DT_DEVC = 1.0,
      DT_SLCF = 1.0,
      DT_BNDF = 1000000,
      DT_PL3D = 1000000,
      DT_ISOF = 1000000,

&PRES MAX_PRESSURE_ITERATIONS = 50,
      VELOCITY_TOLERANCE = 0.001,
      CHECK_POISSON=.TRUE.,
      RELAXATION_FACTOR = 1 /

----- FIRE SPECIFICATIONS -----

&REAC FUEL = 'N-HEPTANE',
      CO_YIELD = 0.01, SOOT_YIELD = 0.037 /
      FYI: HEPTANE = C7H16

&SURF ID= 'fire', HRRPUA=1400, COLOR='RED', TMP_FRONT=98.0, RAMP_Q='PoolRamp'/
&RAMP ID='PoolRamp', T=0.0, F=0.0 /
&RAMP ID='PoolRamp', T=13.0, F=0.6 /
&RAMP ID='PoolRamp', T=35.0, F=1.0 /
&RAMP ID='PoolRamp', T=120.0, F=1.0 /
&RAMP ID='PoolRamp', T=178.0, F=0.55 /
&RAMP ID='PoolRamp', T=185.0, F=0.0 /
&RAMP ID='PoolRamp', T=360.0, F=0.0 /

&VENT XB = 3.9,4.6 , 8.8,9.5 , 0.0,0.0, SURF_ID='fire', IOR=3, COLOR='RED' /
&OBST XB = 3.9,3.9 , 8.8,9.5 , 0.0,0.2 /
&OBST XB = 4.6,4.6 , 8.8,9.5 , 0.0,0.2 /
&OBST XB = 3.9,4.6 , 8.8,8.8 , 0.0,0.2 /
&OBST XB = 3.9,4.6 , 9.5,9.5 , 0.0,0.2 /

----- LEAKAGE -----

&ZONE XB=2.2,5,7,10,0,2.6, LEAK_AREA(0) =0.0234 / Leakage is defined over the pressure
zone

----- EXHAUST DUCT CLOSET -----

&HVAC ID='ClosetDuct1', TYPE ID='DUCT', NODE ID='ClosetNode','ClosetOutNode',
AREA=0.01227, LENGTH=0.4, ROUGHNESS=0.001, LOSS=0,0 /
&HVAC ID='ClosetDuct2', TYPE ID='DUCT', NODE ID='ClosetOutNode', 'AmbientNode1',
AREA=0.01227, LENGTH=15, ROUGHNESS=0.001, LOSS=5,5 /
```

```

&VENT ID='ClosetVent', XB = 5.4,5.6 , 4.6,4.8 , 2.6,2.6, SURF_ID='HVAC',COLOR='RED' /
&HVAC ID='ClosetNode', TYPE_ID='NODE', DUCT_ID='ClosetDuct1', VENT_ID='ClosetVent',
LOSS=65,65 /
&HVAC ID='ClosetOutNode', TYPE_ID='NODE', DUCT_ID='ClosetDuct1','ClosetDuct2', LOSS =0,0,
XYZ=5.5,4.5,2.6 /
&HVAC ID='AmbientNode1', TYPE_ID='NODE', DUCT_ID='ClosetDuct2', AMBIENT=.TRUE.,
LOSS=1,1, XYZ = 5.8,8.5,8.0 /

```

----- EXHAUST DUCT BATHROOM -----

```

&HVAC ID='BRDuct1', TYPE_ID='DUCT', NODE_ID='BRNode','BROutNode', AREA=0.01227,
LENGTH=0.4, ROUGHNESS=0.001, LOSS=0,0 /
&HVAC ID='BRDuct2', TYPE_ID='DUCT', NODE_ID='BROutNode', 'TeeNode', AREA=0.01227,
LENGTH=15, ROUGHNESS=0.001, LOSS=3,3 /

&HVAC ID='BRNode', TYPE_ID='NODE', DUCT_ID='BRDuct1', VENT_ID='BRVent', LOSS=35,35 /
&HVAC ID='BROutNode', TYPE_ID='NODE', DUCT_ID='BRDuct1','BRDuct2', LOSS =0,0,
XYZ=0.7,7.72,2.3 /

&VENT ID='BRVent', XB = 0.6,0.8 , 7.8,7.8 , 2.2,2.4, SURF_ID='HVAC', COLOR='RED' /

&HVAC ID='TeeNode', TYPE_ID='NODE', DUCT_ID='BRDuct2','RoofDuct', LOSS=2.0,2.0,
XYZ=6.0,7.72,7.0 /
&HVAC ID='RoofDuct', TYPE_ID='DUCT', NODE_ID='TeeNode','AmbientNode', LENGTH=1.0,
AREA=0.049, LOSS=0.0,0.0, ROUGHNESS=0.001, FAN_ID='E_FAN' /
&HVAC ID='AmbientNode', TYPE_ID='NODE', DUCT_ID='RoofDuct', AMBIENT=.TRUE.,
XYZ=6.0,7.72,8.0, LOSS = 1,1 / Ambient node located on the roof of the building.

&HVAC TYPE_ID='FAN', ID='E_FAN', MAX_PRESSURE=200, MAX_FLOW=0.200, / fan curve

```

----- GEOMETRY -----

```

Back Wall
&VENT XB = 0.0,5.8 , 0.0,0.0 , 0.0,2.6, SURF_ID='CONCRETE_1' /

Right Wall
&VENT MB='XMAX', SURF_ID='CONCRETE_1' /
OBST XB = 5.8,5.8 , 0.0,12 , 0.0,2.6, SURF_ID='CONCRETE_1' /

Front Wall - Living room
&OBST XB = 2.02,5.8 , 12,12 , 0.0,2.6, SURF_ID='L_CONCRETE' /

Center wall - Kitchen and Bedroom
&OBST XB = 2.6,2.6 , 0.0,4.4 , 0.0,2.6, SURF_ID='CONCRETE' /

Left Wall - Kitchen
&OBST XB = 0.0,0.0 , 0.0,4.4 , 0.0,2.6, SURF_ID='CONCRETE_1' /

Front Wall - Kitchen
&OBST XB = 0.0,1.55 , 4.4,4.4 , 0.0,2.6, SURF_ID='CONCRETE' /

Front Wall - Bedroom
&OBST XB = 3.65,5.8 , 4.4,4.4 , 0.0,2.6, SURF_ID='CONCRETE' /

Closet
&OBST XB = 4.0,5.8 , 6.2,6.2 , 0.0,2.6, SURF_ID='MDF' /

Front Wall- Closet
&OBST XB = 4.0,4.0 , 5.2,6.2 , 0.0,2.6, SURF_ID='MDF' /

Center Wall - Living room/Bathroom
&OBST XB = 2.02,2.02 , 6.2,7.8 , 0.0,2.6, SURF_ID='CONCRETE' /

Center Wall - Living room/Bathroom
&OBST XB = 2.02,2.02 , 7.8,12 , 0.0,2.6, SURF_ID='CONCRETE_1' /

Left Wall - Bathroom
&OBST XB = 0.0,0.0 , 6.2,7.8 , 0.0,2.6, SURF_ID='CONCRETE_1' /

Back Wall - Bathroom
&OBST XB = 0.0,2.02 , 7.8,12 , 0.0,2.6, SURF_ID='CONCRETE_1' /

```

Front Wall - Bathroom
&OBST XB = 0.0,1.2 , 6.2,6.2 , 0.0,2.6, SURF_ID='CONCRETE' /

Roof
&VENT MB = 'ZMAX', SURF_ID= 'RCONCRETE' /

Door
&OBST XB=0,0, 4.4,6.2, 0.0,2.6 , SURF_ID='CONCRETE' /

----- MATERIAL SPECIFICATIONS -----

&MATL ID = 'CONCRETE',
FYI = 'Quintiere, Fire Behavior, Table 7.6'
CONDUCTIVITY = 0.7,
SPECIFIC_HEAT = 0.75,
DENSITY = 2200. /

&SURF ID = 'CONCRETE',
MATL_ID = 'CONCRETE',
THICKNESS = 0.16,
BACKING = 'EXPOSED'
COLOR = 'BEIGE' /

&SURF ID = 'CONCRETE_1',
MATL_ID = 'CONCRETE',
THICKNESS = 0.2,
BACKING = 'VOID'
COLOR='BEIGE' /

&SURF ID = 'L_CONCRETE',
MATL_ID = 'CONCRETE',
THICKNESS = 0.2,
BACKING = 'VOID'
COLOR='BEIGE'
LEAK_PATH=1,0 /

&SURF ID = 'RCONCRETE',
MATL_ID = 'CONCRETE',
THICKNESS = 0.2,
BACKING = 'VOID'
TMP_INNER=23,
COLOR='BEIGE' /

&MATL ID = 'MDF',
FYI = 'Makeitfrom.com'
CONDUCTIVITY = 0.3,
SPECIFIC_HEAT = 1.7,
DENSITY = 750.0 /

&SURF ID = 'MDF',
MATL_ID = 'MDF',
THICKNESS = 0.1,
BACKING = 'EXPOSED'
COLOR='BEIGE' / MEDIUM DENSITY FIBERBOARD

----- OUTPUT-----

&SLCF QUANTITY='PRESSURE', PBX =3.0 /
&SLCF QUANTITY='TEMPERATURE', PBX=3.2 /
&SLCF QUANTITY='HRRPUV', PBX=9.0 /

&DEVC ID='PRESS1', QUANTITY='PRESSURE', XYZ=4.02,10.4,2.0 /
&DEVC ID='PRESS2', QUANTITY='PRESSURE', XYZ=0.82,2.0,2.0 /

&DEVC ID='PRESS1AVG', QUANTITY='PRESSURE', XYZ=4.02,10.4,2.0, TIME_AVERAGED=.FALSE. /
&DEVC ID='PRESS2AVG', QUANTITY='PRESSURE', XYZ=0.82,2.0,2.0, TIME_AVERAGED=.FALSE. /

Thermocouple

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&PROP ID='TC', BEAD_DIAMETER=0.0015 /

&DEVC ID='TEMP11', QUANTITY='THERMOCOUPLE', XYZ=5.4,6.8,0.5 /
&DEVC ID='TEMP12', QUANTITY='THERMOCOUPLE', XYZ=5.4,6.8,1.0 /
&DEVC ID='TEMP13', QUANTITY='THERMOCOUPLE', XYZ=5.4,6.8,1.5 /
&DEVC ID='TEMP14', QUANTITY='THERMOCOUPLE', XYZ=5.4,6.8,2.0 /
&DEVC ID='TEMP15', QUANTITY='THERMOCOUPLE', XYZ=5.4,6.8,2.5 /

&DEVC ID='TEMP21', QUANTITY='THERMOCOUPLE', XYZ=1.4,2.2,0.55 /
&DEVC ID='TEMP22', QUANTITY='THERMOCOUPLE', XYZ=1.4,2.2,1.05 /
&DEVC ID='TEMP23', QUANTITY='THERMOCOUPLE', XYZ=1.4,2.2,1.55 /
&DEVC ID='TEMP24', QUANTITY='THERMOCOUPLE', XYZ=1.4,2.2,2.05 /
&DEVC ID='TEMP25', QUANTITY='THERMOCOUPLE', XYZ=1.4,2.2,2.45 /

&DEVC ID='O2', QUANTITY='MASS FRACTION', SPEC_ID='OXYGEN', XYZ=5.4,6.6,1.8 /
&DEVC ID='O2vol', QUANTITY='VOLUME FRACTION', SPEC_ID='OXYGEN', XYZ=5.4,6.6,1.8 /
&DEVC ID='COvol', QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON MONOXIDE',
XYZ=5.4,6.6,1.8 /
&DEVC ID='CO2vol', QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON DIOXIDE',
XYZ=5.4,6.6,1.8 /
&DEVC ID='COvolppm', QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON MONOXIDE',
UNITS='ppm', CONVERSION_FACTOR=1000000, XYZ=2,1.35,2 /

&DEVC ID='CDuctVel', QUANTITY='DUCT VELOCITY', DUCT_ID='ClosetDuct1' /
&DEVC ID='CDuctTemp', QUANTITY='DUCT TEMPERATURE', DUCT_ID='ClosetDuct1' /
&DEVC ID='CDuctVolflow', QUANTITY='DUCT VOLUME FLOW', DUCT_ID='ClosetDuct1' /
&DEVC ID='CNodeTemp', QUANTITY='NODE TEMPERATURE', NODE_ID='ClosetOutNode' /
&DEVC ID='TempTN', QUANTITY='NODE TEMPERATURE', NODE_ID='TeeNode' /

&DEVC ID='BRDuctVel', QUANTITY='DUCT VELOCITY', DUCT_ID='BRDuct1' /
&DEVC ID='BRDuctTemp', QUANTITY='DUCT TEMPERATURE', DUCT_ID='BRDuct1' /
&DEVC ID='BRDuctVolflow', QUANTITY='DUCT VOLUME FLOW', DUCT_ID='BRDuct1' /
&DEVC ID='BRNodeTemp', QUANTITY='NODE TEMPERATURE', NODE_ID='BROutNode' /
&DEVC ID='BRAmbTemp', QUANTITY='NODE TEMPERATURE', NODE_ID='AmbientNode' /

&DEVC ID='RDuctVel', QUANTITY='DUCT VELOCITY', DUCT_ID='RoofDuct' /
&DEVC ID='RDuctTemp', QUANTITY='DUCT TEMPERATURE', DUCT_ID='RoofDuct' /
&DEVC ID='RDuctVolflow', QUANTITY='DUCT VOLUME FLOW', DUCT_ID='RoofDuct' /

&TAIL /
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