CFD modelling of pressure rise in a room fire

Ying Zhen Li
CFD modelling of pressure rise in a room fire

Ying Zhen Li
Abstract

**CFD modelling of pressure rise in a room fire**

Pressure rise due to a fire in a room can cause severe problems with smoke spread to other spaces. A simple CFD model, Pressure Rise Simulator (PRS), is developed to simulate the fire-induced pressure rise in a single room with natural ventilation and mechanical ventilation. Test data from full scale tests performed by FOI [1] are used for validation. Comparison of the results with some FDS simulations is also performed. Further, the influence of room sizes, fire sizes, wall materials, openings and mechanical ventilation systems on the pressure rise and the pressure drop is investigated.

Key words: pressure rise, CFD, PRS, room size, fire size, wall material, opening, mechanical ventilation

**SP Sveriges Tekniska Forskningsinstitut**
SP Technical Research Institute of Sweden

SP Report 2015:08
ISSN 0284-5172
Borås 2015
## Contents

Abstract 3

Contents 4

Preface 5

Summary 6

1 Introduction 8

2 Theoretical model and the program PRS 9
   2.1 Pressure Rise Simulator (PRS) 9
   2.2 Simplified models 12

3 Theory related to pressure rise in FDS 13
   3.1 Basic models 13
   3.2 HVAC models 14

4 Validation of modeling 15
   4.1 FOI tests 15
   4.2 Numerical simulations 16
   4.3 FDS results 17
   4.4 PRS results 27
   4.5 Short summary 32

5 Parametrical study 33
   5.1 Effect of room size and fire size 33
   5.2 Effect of wall materials 34
   5.3 Effect of Openings 35
   5.4 Effect of mechanical ventilation 36
   5.5 Comparisons with the simplified models 37

6 Summary 40

7 References 42
Preface

This project was sponsored by VINNOVA through the Virtual Test Bed Project which is greatly acknowledged.

Acknowledgement to my colleague Prof. Haukur Ingason and Prof. Michael Först at SP Fire Research for their valuable comments and to FOI for the valuable large scale fire experiments.
Summary

To fill in the knowledge gap in the pressure rise in room fires, a simple CFD model, Pressure Rise Simulator (PRS), is developed to simulate the fire-induced pressure rise in a single room with natural ventilation or mechanical ventilation. Test data from full scale tests performed by FOI [1] are used for validation. Comparison of the results with some FDS simulations is also performed. Further, the influence of room sizes, fire sizes, wall materials, openings and mechanical ventilation systems on the pressure rise and the pressure drop is investigated.

The results show that PRS predicts both the pressure rise and pressure drop in the room very accurately. It also predicts the oxygen concentration and gas velocity through the duct very well. In contrast, FDS predicts the overpressure rise relatively well (slight undershooting in the simulations) but cannot predict the under-pressure using the extinction model.

The accuracy of the two simple equations, i.e. Eq. (21) and Eq. (25), are also compared to test results and PRS results. It can be concluded that Eq. (21) can only be used for estimation of pressure rise in a completely closed room with adiabatic boundaries. The maximum pressures estimated using Eq. (25) are much higher than test results, especially in the period of constant heat release rate. Therefore, both equations can only produce very rough estimation of the pressure rise and generally the results are highly overestimated.

The results show that a larger room could result in a greater pressure rise and also a greater pressure drop and the difference in pressure rise between different rooms decreases as the room size increases. The reason could be that in a larger room, the average temperature and average soot volume fraction is lower and thus the heat loss could be smaller. Meanwhile, the fire in a large room can sustain for a longer time and accumulate more heat which results in larger pressure drop after the fire is self-extinguished.

The maximum pressure rise for the fast curve is much higher than that for the medium curve, and the ratio ranges from 1.5 to 3. This indicates the importance of the fire growth rate on the pressure rise. However, the difference in the pressure drops is very limited. The reason could be that the total heat output in a room with a small opening before extinguishment is mainly dependent on the oxygen available. This amount of heat to a large extent determines the heat accumulated in the smoke inside the room. After extinguishment, the heat source is removed but the smoke is continually losing heat to the walls. This causes a sudden drop in the pressure.

The pressure rise and drop do not increase continually with the fire size. For small fire sizes, the pressure rise increases with the fire size. However, as the fire size reaches to a certain level the pressure rise and drop do not vary with the fire size. The reason is that before the fire reaches the maximum designed fire size, it has been self-extinguished.

For a given fire curve, the wall materials do not have too much influence on both pressure rise and pressure drop. An exception is mineral wool where the pressure rise is clearly higher than the others (the increase is around 15%). The reason is that the mineral wool is highly thermal resistant and results in much less heat loss to the internal walls than the others.

The pressure rise decreases rapidly with the increasing opening area. It can be concluded from the results that the opening size is the most influential factor on the pressure rise.
The pressure rise in the room with mechanical ventilation decreases with the increasing flow rates but this decreasing effect becomes insignificant for high flow rates. In most of the simulated cases, the pressure rise inside the room is higher than both the supply pressure and the exhaust pressure. Therefore both vents act as pressure release valves. However, in tests with supply pressures higher than the pressure rises, the supplied flows increase the pressure inside the room. Therefore the supply vent behaves differently for a low pressure rise and a high pressure rise inside the room.

For a given fire scenario, there are two solutions to reduce the pressure rise: (1) enlarging the openings for a room with natural ventilation, and (2) shutting off the supply flow and lowering the exhaust pressure for a room with mechanical ventilation.
1 Introduction

Pressure rise due to a fire in a room can result in major smoke spread to other spaces which hinders the evacuation and causes deaths in non-fire regions, especially for a fire initially occurred in a closed room with only ventilation ducts connected to other rooms. The pressure rise can be easily built up in case of a fire in such a single room. Due to the pressure difference, the smoke is pushed out through door cracks or HVAC (Heating, Ventilation and Air Conditioning) ducts to other rooms or spaces. In a room with a HVAC system, the pressure rise can easily cause the failure of the ventilation system, i.e. reverse flow in the supply ventilation system. This suggests that in these cases, the supply vent does not supply air any more, and instead the supply system “extracts” smoke from the fire room to non-fire regions through the supply vents. This problem can be serious in both residence building and public buildings, e.g. in a hospital where a large amount of patients have problems in mobility.

The fire-induced pressure rise in a room cannot be predicted well by simple empirical equations due to the complexity of the phenomenon. The key influencing factors include the fire curve (how fire develops), heat transfers to the enclosures, room size, and tightness of the room (gaps), and the ventilation system. Especially the dynamic heat transfer process is difficult to estimate using empirical models. CFD (Computational Fluid Dynamics) provides a possible way to estimate the pressure rise and resulting smoke spread to neighboring rooms. The main issue is how accurately a CFD tool can predict the pressure rise in such a single room, especially while a ventilation system exists. Rather limited work can be found on this topic despite its importance in fire safety design. Karlsson and Quintiere [2] presented simplified equations for pressure rise in a completely closed room and in a single room with a small opening based on some assumptions, but without any validation. Chow and Zou [3] simulated one test using FDS [4] (FDS 3.0) to study the pressure rise in closed chamber fires and they found that the input heat release rate to FDS is a key point. Note that no extinction model was applied and the fire was developed, exactly following the pre-defined heat release rate curves. Prétrel et al. [5] investigated the pressure variations caused by hydrocarbon pool fires in a well-confined and force-ventilated compartment based on two sets of large-scale fire tests.

In this project, a simple CFD model, Pressure Rise Simulator (PRS), is developed to simulate the fire-induced pressure rise in a single room with natural ventilation or mechanical ventilation. Test data from full scale tests performed by FOI [1] are used for validation. Comparison of the test data with numerical results obtained from FDS (Fire Dynamics Simulator) [4] simulations is also performed. Further, the influence of room sizes, fire sizes, wall materials, openings (e.g. door gaps) and mechanical ventilation systems on the pressure rise and the pressure drop is investigated.
2 Theoretical model and the program PRS

2.1 Pressure Rise Simulator (PRS)

A computer program, Pressure Rise Simulator (PRS), was developed to simulate the pressure rise and other parameters in a fire room. The theoretical model is presented here.

The pressure inside the room can be regarded as constant in general, although there could be some difference in different heights due to the buoyancy effect which however mostly can be ignored. This effect can be accounted for by use of a temperature factor which will be introduced later.

Ignoring the diffusion terms, the controlling equations are listed in the following.

Mass equation:

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} = \dot{m}_f
\]  

Species transport equation (mass fraction \(Y\)):

\[
\frac{\partial (\rho Y)}{\partial t} + \frac{\partial (\rho u Y)}{\partial x} = \dot{m}_f Y
\]  

Momentum equation:

\[
\frac{\partial (\rho u)}{\partial t} + \frac{\partial (\rho uu)}{\partial x} = -\frac{\partial p}{\partial x}
\]  

Energy equation:

\[
\frac{\partial (\rho e)}{\partial t} + \frac{\partial (\rho uh)}{\partial x} = \dot{Q}^m - \dot{Q}^\text{loss}
\]  

Thermodynamic equilibrium can be assumed for an ideal gas. The state equation for pressure can be expressed as:

\[
p = \frac{R}{M} \rho T
\]  

The mass flow rate through a vent or duct by natural ventilation or mechanical ventilation:

\[
\dot{m}_v = C_d \rho_v u_v A_v
\]  

The gas velocity can be obtained from the momentum equation and it can be expressed as:

\[
u_v = \sqrt{\frac{2\Delta p}{\xi \rho_v}}
\]
For natural ventilation (openings) the coefficient $\xi$ is equal to 1 and it is the flow coefficient for mechanical ventilation.

The heat loss to the wall per unit area can be expressed as:

$$\dot{q}_\text{loss}^* = \varepsilon_w (\dot{q}_r^* - \sigma T_w^4) + h_r (T_g - T_w)$$  \hspace{1cm} (8)

where the radiation to the wall per unit area is:

$$\dot{q}_r^* = X_r \dot{Q} / A + \varepsilon_g \sigma T_g^4 + (1 - \varepsilon_g) \sigma T_w^4$$  \hspace{1cm} (9)

Heat conduction inside the wall is simulated using an implicit method. The controlling equation can simply be expressed as:

$$\rho_s \varepsilon_s \frac{\partial T_r}{\partial t} = \frac{\partial}{\partial x} (k_s \frac{\partial T_r}{\partial x})$$  \hspace{1cm} (10)

with the boundary condition at the surface:

$$-k \frac{dT}{dx} = \dot{q}_\text{loss}^*$$  \hspace{1cm} (11)

The extinction criteria can be expressed as [6-8]:

$$Y_{O_2} \Delta H_{O_2} < c_p (T_{AFT} - T)$$  \hspace{1cm} (12)

where $T_{AFT}$ is the adiabatic flame temperature at the low flammability limit, regarded as 1600 K. During a fire in such an enclosure with small openings or ventilation rates, the oxygen level at upper level reaches this criteria first and thus the combustion at upper layer is suppressed. Then the oxygen level at lower level also drops to the limit. The time reaching the criteria at upper and lower level is different. Therefore it can be expected that the fire decreases gradually to zero. The duration is assumed to be approximately 15 seconds after comparison of simulation and test results. A sudden extinction, e.g. 0.01 seconds, could cause a huge decrease in pressure, however, a duration from 5 seconds to 30 seconds generally do not affect the results.

A temperature factor, $X_r$, is introduced to account for the effect of the vent height on the temperatures at the outlet, that is:

$$\Delta T_r = X_r \Delta T$$  \hspace{1cm} (13)

By default the temperature factor is set to 0.5. For a vent close to ceiling it can be set to 1 and for a vent close to floor, a value of 0.5 is recommended based on analysis of the FOI test data [1]. Numerical simulations indicates the maximum pressure rise is not sensitive to this value due to low temperature in the growth period.

The convective heat transfer at the boundaries can be expressed as:

$$h_r = \frac{k}{l} \text{Nu}$$  \hspace{1cm} (14)

For the walls, the Nusselt number, Nu, can be expressed as [9]:

\[ \text{Nu} = \frac{h \cdot L}{k} \]
\[ \text{Nu}_l = (0.825 + \frac{0.387 \text{Ra}^{1/6}_l}{[1 + (0.492 / \text{Pr})^{9/16}]^{8/27}})^2 \]  

and the Rayleigh number, Ra\(_l\), and the Prandtl number, Pr,:

\[ \text{Ra}_l = g \beta \Delta T l^3 \frac{\text{Pr}}{v^2}, \quad \text{Pr} = \frac{v}{a} \]

For ceiling, the Nusselt number can be expressed as [9]:

\[ \text{Nu}_l = 0.27 \text{Ra}^{1/4}_l \]

For floor, the Nusselt number can be expressed as [9]:

\[ \text{Nu}_l = 0.15 \text{Ra}^{1/3}_l \]

The emissivity is estimated using:

\[ \varepsilon_s = 1 - e^{-\kappa_s L_m} \]  

where the mean beam length, \( L_m \) (m), is defined as:

\[ L_m = 3.6 \frac{V_m}{A_m} \]  

and the absorption coefficient for soot, \( \kappa_s \), [10]:

\[ \kappa_s = 3.75 \frac{C_o}{C_2} X_r T \]

In the above equations, \( c_p \) is heat capacity (kJ/kgK), \( \rho \) is density (kg/m\(^3\)), \( t \) is time (s), \( x \) is the cartesian axis (m), \( u \) is velocity (m/s), \( k \) is heat conductivity (kW/(m K)), \( p \) is pressure (Pa), \( \text{Pr} \) is Prandtl number, \( g \) is gravitational acceleration(m/s\(^2\)), \( \bar{R} \) is universal gas constant (8.314 kJ/(kmol K)), \( M \) is molecular weight (kg/kmol), \( T \) is gas temperature in Kelvin (K), \( \epsilon \) is specific internal energy (kJ/kg), \( h \) is enthalpy (kJ/kg), \( Y \) is the species mass fraction, \( \Delta H_{O2} \) is heat released by consuming 1 kg oxygen (kJ/kg), \( \dot{Q} \) is heat release rate (kW), \( X_r \) is radiation fraction, \( A \) is wall surface area, \( V \) is room volume, \( h_c \) is convective heat transfer coefficient, \( \varepsilon \) is emissivity, \( X_s \) is the soot volume fraction, \( C_o \) is a constant varying between 2 and 6, dependent on the refractive index (a value of 4 is applied in PRS), \( C_2 \) is the Planck’s second constant, \( 1.4388 \times 10^{-2} \text{m-K} \). Subscripts \( e \) is exit vent, \( O_2 \) is oxygen, \( r \) is radiation, \( w \) is wall. Superscript (·) indicates per unit time and (”) per unit volume. Subscript s indicates solid.

All the flow properties are solved by an iterative method similar to the density-based method for compressive flows.

The program PRS can predict the pressure rise in a room with natural ventilation or mechanical ventilation.
2.2  Simplified models

2.2.1  Closed room

In a closed room, by introducing the equation of state \( p = \rho RT \), the energy equation can be simply expressed as:

\[
\frac{c_v}{R} V \frac{dP}{dt} = \dot{Q} - \dot{q}_{\text{loss}} A_w
\]

(19)

where \( c_v \) is the heat capacity at constant volume. The heat loss term could be simply taken into account by use of a global heat loss fraction based on the total heat release rate, and an effective heat release rate is defined here:

\[
\dot{Q}_{\text{eff}} = \dot{Q} - \dot{q}_{\text{loss}} A_w = \xi \dot{Q}
\]

(20)

where \( \xi \) is the fraction of effective heat release rate contained in the air. The effective heat release rate in fact is the rate of net heat conserved in the air in the room.

Therefore Eq. (19) can be simplified into:

\[
\Delta P = \frac{R}{c_v V} \int \dot{Q}_{\text{eff}}(t) dt
\]

(21)

or for a constant effective heat release rate:

\[
\Delta P = \frac{R \dot{Q}_{\text{eff}} t}{c_v V}
\]

(22)

2.2.2  Single room with an opening

In a room with a small opening, by introducing the equation of state, the energy equation could be simplified into:

\[
\frac{c_v}{R} V \frac{dP}{dt} + \dot{m}_e c_p T_e = \dot{Q}_{\text{eff}}
\]

(23)

To obtain an analytical solution an assumption needs to be introduced. It may be assumed that the pressure inside the fire room reaches a quasi-steady state quite fast and thus we can ignore the temporal term (the derivative). Combining Eq. (23) with Eq. (7), we have:

\[
\Delta p = \frac{\xi}{2 \rho_e} \left( \frac{\dot{Q}_{\text{eff}}}{C_d c_p A_e T_e} \right)^2
\]

(24)

However, both exit density and exit temperature is unknown. Therefore in applications, it may be assumed that the outlet temperature approximates the initial room temperature. The above equation can then be simplified further:

\[
\Delta p = \frac{\xi}{2} \left( \frac{\dot{Q}_{\text{eff}}}{C_d c_p A_e \rho_e T_e} \right)^2
\]

(25)

Apparently, the assumption introduced could induce overestimation of the pressure rise.

Both the complete theoretical model and the simplified equation will be used latter for estimating the pressure rise.
3 Theory related to pressure rise in FDS

FDS [4] is widely used in the fire community. It is therefore chosen to carry out this study. FDS is developed by NIST together with VTT.

The basic theory is the same for all the CFD models. Here only models related to the pressure rise is discussed.

3.1 Basic models

With regard to the pressure, FDS uses a technique very different to most of other CFD codes. FDS divides the absolute pressure to a background pressure and a perturbation pressure [7]:

\[ p = \bar{p} + \tilde{p} \]  \hspace{1cm} (26)

The background pressure, \( \bar{p} \), is used in the equation of state to correlate pressure with density and temperature:

\[ \bar{p}(t) = \rho \bar{R} T \sum Y_i / M_i \]  \hspace{1cm} (27)

Further, the background pressure is used in the energy equation:

\[ \frac{\partial (\rho h)}{\partial t} + \frac{\partial (\rho u_i h)}{\partial x_i} = \frac{\partial \bar{p}}{\partial t} + u_i \frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_i} (k \frac{\partial T}{\partial x_i}) + \dot{Q}'' - \dot{Q}_{\text{loss}}, \quad i=1,2,3 \]  \hspace{1cm} (28)

However, the above energy equation is not explicitly solved in FDS, instead, the velocity divergence is abstracted and employed into the solution of momentum equation.

The perturbation pressure, \( \tilde{p} \), is only for calculation of the fluid field, i.e. solving the momentum equation. In reality, the perturbation pressure has limited physical meaning. It is more a term produced for correction of the velocity fields in the solution of the momentum equation.

FDS uses explicit time marching algorithm to solve the fire flows and quite large time step is applied in the code. The time-resolved pressure field is mostly an approximation and sometimes the approximation is far from reality. Using this fluctuating pressure could cause serious divergence in results. This should be the main reason why it divides the pressure into two parts. Another reason is that as Patankar [11] proposed that pressure results from most algorithms, e.g. the SIMPLE algorithm, are pressure difference rather than absolute pressure, which can be corrected easily in most cases but could be impossible for compressible flows or fire flows related to high pressure rise. In any cases, this measure is apparently stabilizing the algorithm. However, some faults on it could also exist and need to be checked.

Convective heat transfer is simply estimated using the following equation:

\[ h_c = \max[C |\Delta T|^{\frac{1}{3}}, \frac{k}{L} 0.037 \text{Re}^{\frac{4}{5}} \text{Pr}^{\frac{1}{3}}] \]  \hspace{1cm} (29)

where \( C \) is an empirical constant and \( L \) is geometrical scale.
3.2 HVAC models

An HVAC model has been incorporated to simulate the interaction of fire and a connected HVAC system since FDS 5.5.

The HVAC model embedded is based on the MELCOR hydraulic solver [4] that was developed for simulating accidents in nuclear power plant containment buildings, and the Fire and Smoke Simulator (FSSIM) [12] developed for simulating fire spread and smoke movement based on MELCOR.

An HVAC system is represented as a network of nodes and ducts. At each node, the conservation equations for mass, energy and momentum are:

\[ \sum \rho_j u_j A_j = 0 \]  
\[ \sum \rho_j u_j h_j = 0 \]  
\[ \rho_j L_j \frac{du_j}{dt} = (p_i - p_k) + \rho g \Delta z + \Delta p_j - \frac{1}{2} K \rho_j |u_j| u_j \]  

where \( u \) is duct velocity, \( A \) is duct area, and \( h \) is enthalpy of the fluid in the duct. Subscript \( j \) indicates a duct, the subscripts \( i \) and \( k \) indicate nodes. \( \Delta p \) is a source of momentum (a fan or blower), \( L \) is the length of the duct, and \( K \) is the friction loss coefficient for the duct.

Note that only the node equations are solved for a HVAC system. In reality, the HVAC model in FDS only simulates the movement of the flow accounting for the height difference, but without any consideration on the heat transfer and transient movement of smoke flows inside the ducts.

Therefore cautions should be taken while using the HVAC model in FDS.
4 Validation of modeling

4.1 FOI tests

Three full scale tests were carried out by FOI [1] in a well-sealed room only with a circular tube to outside to investigate the pressure conditions in a closed room due to a growing fire, see Figure 1.

4.1.1 Test room

The test room was 5.5 m long, 4 m wide and 2.6 m high, constructed with 0.15 m thick concrete [1]. Two partition walls divided the test room into two parts with a large opening connecting them. The large opening was 1.9 m high and approximately 2.4 m wide. A 2.2 m long circular tube of diameter 0.2 m was placed 0.6 m above the floor to simulate a crack of 12 mm from floor to ceiling.

4.1.2 Fire source

Rectangular heptane pools were used as the fire sources. The steel pan had a length of 0.73 m and width of either 0.75 m or 1 m. In the tests, a steel cover over the fuel pan was controlled step by step to approximate the fire designed. The rim of the steel pool was 5 cm high. Water was used to cool down the temperature of the steel pan and the rim.

Heat release rates in the tests were estimated using the controlled fuel surface area assuming that the heat release rate per unit fuel surface area is 1.6 MW [13], and the fire took 20 seconds to reach the maximum mass burning rate after a movement of the cover.

The fires were all self-extinguished in the tests due to the low oxygen concentration inside the room. A self-extinguishment occurs during a very short period. The extinguishment time can be identified according to the lowest oxygen concentration. It can also be found in the test data that the corresponding gas temperature inside the room suddenly decreased. After the extinguishment the oxygen concentration increases due to...
the incoming fresh air through the duct and the gas temperature decreases rapidly with
time.

4.1.3 Measurement

Pressure rises inside the room, gas temperatures, gas velocities and oxygen concentrations
were measured in the tests [1].

At pile A, 6 thermocouples of 0.25 mm type K were used to measure the vertical
temperature distribution (T1 to T6). In addition, oxygen analysis and pressure rise were
measured 2 m above the floor at Pile A (O1 and P1). Another pressure rise measurement
was installed 0.6 m away from pile A and at a height of 0.6 m above the floor (P2).
Close to the exit of the circular tube gas velocity (U1) and temperature (T7) were
measured at the centerline of the tube using bi-directional pressure tube.

Tests are summarized in Table 1.

<table>
<thead>
<tr>
<th>Test no.</th>
<th>Maximum fire size (MW)</th>
<th>t-squared coefficient (kW/s²)</th>
<th>Maximum Pressure rise (Pa)</th>
<th>O₂ (%)</th>
<th>T (ºC)</th>
<th>gas velocity (m/s)</th>
<th>Estimated extinction time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.88</td>
<td>0.035</td>
<td>-180 ~ 110</td>
<td>8</td>
<td>345/150</td>
<td>-20~13</td>
<td>200</td>
</tr>
<tr>
<td>2</td>
<td>0.88</td>
<td>0.075</td>
<td>-200~170</td>
<td>8.2</td>
<td>350/150</td>
<td>-20~16</td>
<td>160</td>
</tr>
<tr>
<td>3</td>
<td>1.17</td>
<td>0.085</td>
<td>-270 ~ 260</td>
<td>6.5</td>
<td>400/170</td>
<td>-23~19</td>
<td>150</td>
</tr>
</tbody>
</table>

4.2 Numerical simulations

In FDS, the room geometry is built up exactly as in the tests, with the exception of the
duct which is simulated using the HVAC model embedded in FDS. The reason is the
diameter of the duct is only 0.2 m. To simulate the duct flow accurately, the grids inside
the duct and in the room region beside the duct need to be very small, i.e. at least 2 cm for
the grid size. Further, the incompatibility of the grid sizes in the domain could cause
instability problems in FDS. To solve this, the straight duct is simulated using the HVAC
model. The flow through the pipe is simulated by the model presented previously, i.e.
simply by the pressure difference between the room and the ambient. The room model for
FDS is shown in Figure 2.

In PRS, the whole room is considered as one domain with a duct connected to ambient.
Simulation of the flow through the duct is also straightforward.

The other parameters in both FDS and PRS are the same as in the tests.

It should, however, be noted that the heat release rate curves obtained in the tests are
estimations rather than test data.
4.3 FDS results

Comparisons of the results obtained from the FOI tests and simulation results using FDS are presented in this section. The comparisons cover pressure rise, gas velocity in the duct, gas temperature measured in the room and the oxygen concentration in the duct.

4.3.1 Pressure rise

Comparisons of the pressure rises measured in the FOI tests and the FDS results for Test 1, Test 2 and Test 3 are presented in Figure 3, Figure 4 and Figure 5. P1 and P2 indicate the corresponding measurement positions, see Figure 1.

Different methods are used in the FDS simulations. At first, the gas phase extinction model is activated to simulate the fire extinction, as in a design the extinction time is not known. However, the results, i.e. Figures 3a, 4a, and 5a, are not satisfactory, and it cannot predict the under pressure at all, even if the fuel is cut off after 200 seconds. The reason is that by default the ignition source is everywhere, and therefore the combustion occurs in case that the local extinction criteria has not been reached. This results in re-ignition after fresh air flow is introduced through the duct when the room is under pressure. This phenomenon is unrealistic as the gas temperature is only around 200 – 300 °C which cannot activate the combustion by itself.

Therefore the ignition model is also introduced in the latter simulations, i.e. Figure 3b, Figure 4b and Figure 5b. The ignition model means that the gas will not ignite it by itself unless a certain temperature is reached. Therefore a small hot solid object is placed right above the fire source to initiate the combustion. This strategy can prevent the unrealistic re-ignition. However, significant overshooting of overpressure can be observed in all these simulations. Further, the under pressure still cannot be predicted well.

For test 1, in order to simulate the pressure drop, one simulation is carried out and both the ignition model and the extinction model are turned off. Therefore the fire strictly
follows the prescribed HRR curve. The results are shown in Figure 3c. Clearly, after the fire is cut off at 200 seconds there is a sudden decrease in the pressure which however is much lower than measured in the test 1.

In the growing periods, the pressures appear to rise much more rapidly than test data and the interval is around 15 to 20 seconds. This could be caused by the uncertainty in the heat release rate estimations.

Further, the FDS results show high instability despite that the grid size as small as 5 cm has been chosen in the simulations (approximately 20 grid points across the fire source in one direction) and the total grid number is around half million. There could be several reasons for the instability. The use of extinction criteria locally could cause high gradient through some grid points and the discrete phenomenon causes instability problem. Also, the large eddy simulation algorithm employed in FDS itself produces highly fluctuating results. FDS also separate the static pressure with the flow pressure. However in these cases, the flow field is highly associated with static pressure. These features of FDS could cause scaling up of the small pulsation and finally results in the fluctuating results as shown in Figure 3, Figure 4 and Figure 5.

It can be concluded that introducing the ignition model causes significant overshooting for pressure rise and thus is not recommended. From the practical point of view, the extinction time is also difficult to know in advance. Therefore the extinction model by default needs to be used despite the impossibility of simulating the under pressure. Therefore, in the following, only FDS results using the extinction model are presented for comparisons.

In short, FDS could be used to predict the pressure rise but has difficulty in predicting the under pressure.

(a) Gas phase extinction in FDS
(b) Gas phase extinction and ignition models in FDS

(c) No gas phase extinction and no ignition in FDS

Figure 3  Comparison of pressure rise measured in FOI test 1 with FDS results.
Figure 4  Comparison of pressure rise measured in FOI test 2 with FDS results.
Figure 5  
Comparison of pressure rise measured in FOI test 3 with FDS results.

4.3.2  
Gas velocity

Comparisons of the gas velocities measured in the FOI tests and the FDS results for Test 1, Test 2 and Test 3 are presented in Figure 6, Figure 7, and Figure 8. It also appears that the test data has a delay of around 20 seconds. FDS predicts the maximum gas velocity relatively well in spite of the slight undershooting. However, it cannot predict the incoming gas flow velocity well. The reason is straightforward as the under pressure cannot be predicted well.
Figure 6  Comparison of gas velocity measured in FOI test 1 with FDS results.

Figure 7  Comparison of gas velocity measured in FOI test 2 with FDS results.

Figure 8  Comparison of gas velocity measured in FOI test 3 with FDS results.
### 4.3.3 Gas temperature

Comparisons of the gas temperatures measured in the FOI tests and the FDS results for Test 1, Test 2 and Test 3 are presented in Figure 9, Figure 10 and Figure 11. Note that T1 to T6 indicate the corresponding thermocouples, see Figure 1. It can be seen that the temperatures are predicted well by FDS in the growth period but not in the decay period as the fire continues to burn in the vicinity of the vent, especially for Test 2 and Test 3.

![Comparison of temperature measured in FOI test 1 with FDS results.](image-url)

*Figure 9  Comparison of temperature measured in FOI test 1 with FDS results.*
Figure 10  Comparison of temperature measured in FOI test 2 with FDS results.
4.3.4 Oxygen concentration

Comparisons of the oxygen concentration measured in the FOI tests and the FDS results for Test 1, Test 2 and Test 3 are presented in Figure 12, Figure 13 and Figure 14. The oxygen concentration are predicted well by FDS in the growth period of the fire but not in the decay period of the fire as the fire continues to burn in the vicinity of the vent. The minimum oxygen concentration predicted in FDS is higher than the test data. This may
indicate that a slightly lower value for the adiabatic temperature in the extinction criteria could be used. There also appears to be a delay for the test data.

Figure 12  Comparison of oxygen concentration measured in FOI test 1 with FDS results.

Figure 13  Comparison of oxygen concentration measured in FOI test 2 with FDS results.

Figure 14  Comparison of oxygen concentration measured in FOI test 3 with FDS results.
4.4 PRS results

Comparisons of the results obtained from the FOI tests and simulation results using the Pressure Rise Simulator (PRS) are presented in this section. The comparisons cover pressure rise, gas velocity in the duct, gas temperature measured in the room and the oxygen concentration in the duct. The results can directly be used to compare with the FDS results presented in Section 4.3.

4.4.1 Pressure rise

Comparisons of the pressure rises measured in the FOI tests and the PRS results for Test 1, Test 2 and Test 3 are presented in Figure 15, Figure 16 and Figure 17. The red lines are the results simulated by PRS.

Clearly, the PRS results predicts the whole pressure rise curve very well for all the tests, including the maximum pressure and the minimum pressure.

Further, the delay of approximately 20 seconds for the test data is very clear. This should be mainly due to the uncertainty in HRR estimations. For better comparison, the corrected PRS results by shifting a few seconds (20 seconds for Test 1, 15 second for Test 2, and 20 second for Test 3) are also presented (the blue lines). After the shift, the agreement between the test data and PRS becomes better.

![Figure 15: Comparison of pressure rise measured in FOI test 1 with FDS results.](image)
Figure 16  Comparison of pressure rise measured in FOI test 2 with FDS results.

Figure 17  Comparison of pressure rise measured in FOI test 3 with FDS results.

4.4.2  Gas velocity

Comparisons of the gas velocities in the duct measured in the FOI tests and the PRS results for Test 1, Test 2 and Test 3 are presented in Figure 18, Figure 19, and Figure 20. The red lines are the results simulated by PRS.

Clearly, the PRS results predicts the whole velocity curve very well for all the tests, including the maximum gas velocity and the minimum gas velocity. In case the delay is corrected, very good agreement can be found for the gas velocities.
Figure 18  Comparison of gas velocity measured in FOI test 1 with FDS results.

Figure 19  Comparison of gas velocity measured in FOI test 2 with FDS results.

Figure 20  Comparison of gas velocity measured in FOI test 3 with FDS results.
4.4.3 Gas temperature

Comparisons of the gas temperatures in the duct measured in the FOI tests and the PRS results for Test 1, Test 2 and Test 3 are presented in Figure 21, Figure 22, and Figure 23. The red lines are the results simulated by PRS.

It can be seen that the PRS results correlate well with the gas temperatures measured at T1. In fact it is not really possible to compare the results directly. Note that the PRS results correspond to the average room temperature but the test data corresponds to the temperatures measured at different vertical locations in the room next to the fire room, see Figure 1. Therefore the PRS results are reasonable.

Figure 21 Comparison of temperature measured in FOI test 1 with FDS results.

Figure 22 Comparison of temperature measured in FOI test 2 with FDS results.
4.4.4 Oxygen concentration

Comparisons of the oxygen concentration measured in the FOI tests and the PRS results for Test 1, Test 2 and Test 3 are presented in Figure 24, Figure 25 and Figure 26. The oxygen concentration are predicted well by PRS during the whole period of the fire. There also appears to a delay for the test data. If the PRS results are shifted for a short period, e.g. 20 seconds in test 1, the PRS results perfectly match the test results.
Figure 25  Comparison of oxygen concentration measured in FOI test 2 with FDS results.

Figure 26  Comparison of oxygen concentration measured in FOI test 3 with FDS results.

4.5  Short summary

PRS predicts the pressure rise in the room very accurately. It also predicts the oxygen concentration and gas velocity through the duct very well.

In contrast, FDS predicts the overpressure rise relatively well (slight undershooting in the simulations) but cannot predict the under-pressure using the extinction model.

The simple equation, i.e. Eq. (21), cannot be used to predict the pressure rise.
5 Parametrical study

In the following, a parametrical study is carried out to investigate the effect of room size, fire size, openings, mechanical ventilation and wall materials on the pressure rise in a room.

By default, the simulated scenario corresponds to a room with dimensions of 2.4 m (W) × 3.6 m (L) × 2.4 m (H), a t-squared fire curve, gypsum boards as wall materials, an opening (a door gap) with area of 0.005 m² (1 m wide and 5 mm high gap). The soot yield is set to be 0.04 and CO yield to be 0.01. The heat of combustion is set to be 25 MJ/kg, in representation of a furniture fire.

The t-squared fire curves with a upper limit are used. The fire curve can be expressed as:

\[
Q(t) = \begin{cases} 
\alpha t^2, & \alpha t^2 \leq \dot{Q}_{\text{max}} \\
\dot{Q}_{\text{max}}, & \alpha t^2 > \dot{Q}_{\text{max}} 
\end{cases}
\]

The coefficient \( \alpha \) is 0.0467 for fast curve and 0.012 for medium curve. In the simulations different maximum heat release rate (fire size) \( \dot{Q} \), is used. As the extinction model is applied as a sub-model in PRS, the actual heat release rate is different with the designated one, that is, after a fire is extinguished the heat release rate will drop to zero in a few seconds as depicted in Section 2. The fuel supply will vary accordingly.

The properties for the wall materials are listed in Table 2.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Conductivity W/mK</th>
<th>Density kg/m³</th>
<th>Heat of capacity J/kgK</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gypsum board</td>
<td>0.48</td>
<td>1440</td>
<td>840</td>
<td>Plaster gypsum [14]</td>
</tr>
<tr>
<td>Concrete</td>
<td>1.0</td>
<td>2100</td>
<td>880</td>
<td>Average value [14]</td>
</tr>
<tr>
<td>Wood</td>
<td>0.147</td>
<td>640</td>
<td>2800</td>
<td>Yellow pine [14]</td>
</tr>
<tr>
<td>Mineral wool</td>
<td>0.038</td>
<td>170</td>
<td>750</td>
<td>PAROC FPS 17</td>
</tr>
</tbody>
</table>

5.1 Effect of room size and fire size

Table 3 shows the simulated scenarios with different room and fire sizes and the results for the pressure rise and pressure drop.

Comparing results of different room size shows that a larger room corresponds to a greater pressure rise and also a greater pressure drop (absolute value), and the difference in pressure rise between different rooms decreases as the room size increases. The reason could be that in a larger room, the average temperature and average soot volume fraction is lower and thus the heat loss could be smaller. Meanwhile, the fire in a large room can sustain for a longer time and accumulate more heat which results in larger pressure drop after the fire is self-extinguished.

Comparing results of fast curve and medium curve shows that the maximum pressure rise for the fast curve is much higher than that for the medium curve, and the ratio ranges from 1.5 to 3. This indicates the importance of the fire growth rate on the maximum pressure rise. However, the difference in the pressure drops is very limited. The reason could be that the total heat output in a room with a small opening before extinguishment is mainly dependent on the oxygen available. This amount of heat to a large extent
determines the heat accumulated in the smoke inside the room. After extinguishment, the heat source is removed but the smoke is continually losing heat to the walls. This causes a sudden drop in the pressure.

Comparing results of different fire sizes (maximum heat release rates) with same fire curves shows that the pressure rise and drop do not increase continually with the fire size. For small fire sizes, the pressure rise increases with the fire size. However, as the fire size reaches to a certain level the pressure rise and drop do not vary with the fire size. The reason is that before the fire reaches the fire size, it has been self-extinguished.

Table 3  Pressure rise with different room sizes and fire curves.

<table>
<thead>
<tr>
<th>Test</th>
<th>Room size W×L×H</th>
<th>Fire size</th>
<th>Fire curve</th>
<th>Wall material</th>
<th>Opening area</th>
<th>Pressure rise</th>
<th>Pressure drop</th>
</tr>
</thead>
<tbody>
<tr>
<td>101</td>
<td>2.4×3.6×2.4</td>
<td>300</td>
<td>Fast</td>
<td>Gypsum</td>
<td>0.005</td>
<td>1622</td>
<td>-994</td>
</tr>
<tr>
<td>102</td>
<td>2.4×3.6×2.4</td>
<td>300</td>
<td>Medium</td>
<td>Gypsum</td>
<td>0.005</td>
<td>514</td>
<td>-992</td>
</tr>
<tr>
<td>103</td>
<td>4.8×3.6×2.4</td>
<td>300</td>
<td>Fast</td>
<td>Gypsum</td>
<td>0.005</td>
<td>3026</td>
<td>-1591</td>
</tr>
<tr>
<td>104</td>
<td>4.8×3.6×2.4</td>
<td>300</td>
<td>Medium</td>
<td>Gypsum</td>
<td>0.005</td>
<td>1233</td>
<td>-1585</td>
</tr>
<tr>
<td>105</td>
<td>4.8×3.6×2.4</td>
<td>300</td>
<td>Fast</td>
<td>Gypsum</td>
<td>0.005</td>
<td>3495</td>
<td>-2008</td>
</tr>
<tr>
<td>106</td>
<td>4.8×7.2×2.4</td>
<td>300</td>
<td>Medium</td>
<td>Gypsum</td>
<td>0.005</td>
<td>2415</td>
<td>-2006</td>
</tr>
<tr>
<td>107</td>
<td>2.4×3.6×2.4</td>
<td>100</td>
<td>Fast</td>
<td>Gypsum</td>
<td>0.005</td>
<td>465</td>
<td>-258</td>
</tr>
<tr>
<td>108</td>
<td>2.4×3.6×2.4</td>
<td>600</td>
<td>Fast</td>
<td>Gypsum</td>
<td>0.005</td>
<td>1622</td>
<td>-1788</td>
</tr>
<tr>
<td>109</td>
<td>2.4×3.6×2.4</td>
<td>900</td>
<td>Fast</td>
<td>Gypsum</td>
<td>0.005</td>
<td>1622</td>
<td>-1788</td>
</tr>
<tr>
<td>110</td>
<td>2.4×3.6×2.4</td>
<td>100</td>
<td>Medium</td>
<td>Gypsum</td>
<td>0.005</td>
<td>344</td>
<td>-260</td>
</tr>
<tr>
<td>111</td>
<td>2.4×3.6×2.4</td>
<td>600</td>
<td>Medium</td>
<td>Gypsum</td>
<td>0.005</td>
<td>514</td>
<td>-1228</td>
</tr>
<tr>
<td>112</td>
<td>2.4×3.6×2.4</td>
<td>900</td>
<td>Medium</td>
<td>Gypsum</td>
<td>0.005</td>
<td>514</td>
<td>-1228</td>
</tr>
</tbody>
</table>

5.2  Effect of wall materials

Table 4 shows the simulated cases and results with different wall materials. The results show that for a given fire curve, the wall materials do not have too much influence on both pressure rise and pressure drop. The largest difference can be found for the mineral wool where the pressure rise is apparently higher than the others (the increase is around 15%). The reason is that the mineral wool is highly thermal resistant and results in less heat loss to the internal walls.

Table 4  Pressure rise with different wall materials.

<table>
<thead>
<tr>
<th>Test</th>
<th>Room size W×L×H</th>
<th>Fire size Q</th>
<th>Fire curve</th>
<th>Wall material</th>
<th>Opening area</th>
<th>Pressure rise</th>
<th>Pressure drop</th>
</tr>
</thead>
<tbody>
<tr>
<td>201</td>
<td>2.4×3.6×2.4</td>
<td>300</td>
<td>Fast</td>
<td>Concrete</td>
<td>0.005</td>
<td>1579</td>
<td>-1102</td>
</tr>
<tr>
<td>202</td>
<td>2.4×3.6×2.4</td>
<td>300</td>
<td>Medium</td>
<td>Concrete</td>
<td>0.005</td>
<td>491</td>
<td>-1099</td>
</tr>
<tr>
<td>203</td>
<td>2.4×3.6×2.4</td>
<td>300</td>
<td>Fast</td>
<td>Wood</td>
<td>0.005</td>
<td>1613</td>
<td>-906</td>
</tr>
<tr>
<td>204</td>
<td>2.4×3.6×2.4</td>
<td>300</td>
<td>Medium</td>
<td>Wood</td>
<td>0.005</td>
<td>508</td>
<td>-922</td>
</tr>
<tr>
<td>205</td>
<td>2.4×3.6×2.4</td>
<td>300</td>
<td>Fast</td>
<td>Mineral wool</td>
<td>0.005</td>
<td>1842</td>
<td>-1099</td>
</tr>
<tr>
<td>206</td>
<td>2.4×3.6×2.4</td>
<td>300</td>
<td>Medium</td>
<td>Mineral wool</td>
<td>0.005</td>
<td>597</td>
<td>-1100</td>
</tr>
<tr>
<td>101</td>
<td>2.4×3.6×2.4</td>
<td>300</td>
<td>Fast</td>
<td>Gypsum</td>
<td>0.005</td>
<td>1622</td>
<td>-994</td>
</tr>
<tr>
<td>102</td>
<td>2.4×3.6×2.4</td>
<td>300</td>
<td>Medium</td>
<td>Gypsum</td>
<td>0.005</td>
<td>514</td>
<td>-992</td>
</tr>
</tbody>
</table>
5.3 Effect of openings

Table 5 shows the simulated scenarios and results for different openings. This opening could be a door gap and/or a window gap. Clearly, the opening size has a dramatic influence on the pressure rise and drop.

Table 5 Pressure rise with different opening sizes.

<table>
<thead>
<tr>
<th>Test</th>
<th>Room size W×L×H</th>
<th>Fire size</th>
<th>Fire curve</th>
<th>Wall material</th>
<th>opening area m²</th>
<th>Pressure rise Pa</th>
<th>Pressure drop Pa</th>
</tr>
</thead>
<tbody>
<tr>
<td>301</td>
<td>2.4×3.6×2.4</td>
<td>300</td>
<td>Fast</td>
<td>Gypsum</td>
<td>0.005</td>
<td>1622</td>
<td>-994</td>
</tr>
<tr>
<td>302</td>
<td>2.4×3.6×2.4</td>
<td>300</td>
<td>Fast</td>
<td>Gypsum</td>
<td>0.010</td>
<td>408</td>
<td>-271</td>
</tr>
<tr>
<td>303</td>
<td>2.4×3.6×2.4</td>
<td>300</td>
<td>Fast</td>
<td>Gypsum</td>
<td>0.020</td>
<td>103</td>
<td>-68</td>
</tr>
<tr>
<td>304</td>
<td>2.4×3.6×2.4</td>
<td>300</td>
<td>Fast</td>
<td>Gypsum</td>
<td>0.030</td>
<td>46</td>
<td>-30</td>
</tr>
<tr>
<td>305</td>
<td>2.4×3.6×2.4</td>
<td>300</td>
<td>Fast</td>
<td>Gypsum</td>
<td>0.040</td>
<td>26</td>
<td>-17</td>
</tr>
<tr>
<td>306</td>
<td>2.4×3.6×2.4</td>
<td>300</td>
<td>Fast</td>
<td>Gypsum</td>
<td>0.050</td>
<td>13</td>
<td>-11</td>
</tr>
<tr>
<td>307</td>
<td>2.4×3.6×2.4</td>
<td>300</td>
<td>Fast</td>
<td>Gypsum</td>
<td>0.005</td>
<td>514</td>
<td>-992</td>
</tr>
<tr>
<td>308</td>
<td>2.4×3.6×2.4</td>
<td>300</td>
<td>Fast</td>
<td>Gypsum</td>
<td>0.010</td>
<td>125</td>
<td>-260</td>
</tr>
<tr>
<td>309</td>
<td>2.4×3.6×2.4</td>
<td>300</td>
<td>Fast</td>
<td>Gypsum</td>
<td>0.020</td>
<td>32</td>
<td>-66</td>
</tr>
<tr>
<td>310</td>
<td>2.4×3.6×2.4</td>
<td>300</td>
<td>Fast</td>
<td>Gypsum</td>
<td>0.030</td>
<td>14</td>
<td>-29</td>
</tr>
<tr>
<td>311</td>
<td>2.4×3.6×2.4</td>
<td>300</td>
<td>Fast</td>
<td>Gypsum</td>
<td>0.040</td>
<td>8</td>
<td>-17</td>
</tr>
<tr>
<td>312</td>
<td>2.4×3.6×2.4</td>
<td>300</td>
<td>Fast</td>
<td>Gypsum</td>
<td>0.050</td>
<td>5</td>
<td>-11</td>
</tr>
</tbody>
</table>

Figure 27 and Figure 28 shows the pressure rise as a function of opening size for the fast curve and the medium curve respectively. Clearly, for both fire curves, the pressure rise decreases rapidly with the increasing opening area.

Figure 27 Pressure rise as a function of opening area for the fast curve fire.
5.4 Effect of mechanical ventilation

Table 6 shows the simulated scenarios with mechanical ventilation and the results for the pressure rise and pressure drop. The supply pressure and exhaust pressure are set to be +400 Pa and -300 Pa, and the initial room pressure is maintained at 50 Pa. Both the supply vent and the exhaust vent are of rectangular shape with dimensions of 0.2 m x 0.2 m, and they have a same designed flow rate (initial flow rate). The parameters considered in this series of simulations are fire size, fire curve and ventilation flow rate. For a given flow rate the flow coefficient for the ventilation system can be easily determined.

Table 6 Pressure rise with different mechanical ventilation and fire sizes.

<table>
<thead>
<tr>
<th>Test</th>
<th>Room size WxLxH</th>
<th>Fire size</th>
<th>Fire curve</th>
<th>Wall material</th>
<th>Designed ventilation Flow rate *</th>
<th>Pressure rise</th>
<th>Pressure drop</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>m m m</td>
<td>kW</td>
<td>m m m</td>
<td>m m m</td>
<td>m m m</td>
<td>m m m</td>
<td>m m m</td>
</tr>
<tr>
<td>401</td>
<td>2.4 x 3.6 x 2.4</td>
<td>300</td>
<td>Fast</td>
<td>Gypsum</td>
<td>150</td>
<td>3244</td>
<td>-2091</td>
</tr>
<tr>
<td>402</td>
<td>2.4 x 3.6 x 2.4</td>
<td>300</td>
<td>Fast</td>
<td>Gypsum</td>
<td>300</td>
<td>930</td>
<td>-602</td>
</tr>
<tr>
<td>403</td>
<td>2.4 x 3.6 x 2.4</td>
<td>300</td>
<td>Fast</td>
<td>Gypsum</td>
<td>450</td>
<td>530</td>
<td>-345</td>
</tr>
<tr>
<td>404</td>
<td>2.4 x 3.6 x 2.4</td>
<td>100</td>
<td>Fast</td>
<td>Gypsum</td>
<td>150</td>
<td>1087</td>
<td>-563</td>
</tr>
<tr>
<td>405</td>
<td>2.4 x 3.6 x 2.4</td>
<td>100</td>
<td>Fast</td>
<td>Gypsum</td>
<td>300</td>
<td>453</td>
<td>-296</td>
</tr>
<tr>
<td>406</td>
<td>2.4 x 3.6 x 2.4</td>
<td>100</td>
<td>Fast</td>
<td>Gypsum</td>
<td>450</td>
<td>404</td>
<td>-222</td>
</tr>
<tr>
<td>407</td>
<td>2.4 x 3.6 x 2.4</td>
<td>300</td>
<td>Medium</td>
<td>Gypsum</td>
<td>150</td>
<td>1106</td>
<td>-2100</td>
</tr>
<tr>
<td>408</td>
<td>2.4 x 3.6 x 2.4</td>
<td>300</td>
<td>Medium</td>
<td>Gypsum</td>
<td>300</td>
<td>455</td>
<td>-607</td>
</tr>
<tr>
<td>409</td>
<td>2.4 x 3.6 x 2.4</td>
<td>300</td>
<td>Medium</td>
<td>Gypsum</td>
<td>450</td>
<td>407</td>
<td>-342</td>
</tr>
<tr>
<td>410</td>
<td>2.4 x 3.6 x 2.4</td>
<td>100</td>
<td>Medium</td>
<td>Gypsum</td>
<td>150</td>
<td>834</td>
<td>-567</td>
</tr>
<tr>
<td>411</td>
<td>2.4 x 3.6 x 2.4</td>
<td>100</td>
<td>Medium</td>
<td>Gypsum</td>
<td>300</td>
<td>436</td>
<td>-294</td>
</tr>
<tr>
<td>412</td>
<td>2.4 x 3.6 x 2.4</td>
<td>100</td>
<td>Medium</td>
<td>Gypsum</td>
<td>450</td>
<td>372</td>
<td>-221</td>
</tr>
</tbody>
</table>

*Supply pressure and exhaust pressure are set to be +400 Pa and -300 Pa.

The results show that the pressure in the room varies significantly with the flow rate in a range of 300 m³/h but does not vary too much after the flow rate increases to 450 m³/h. In most of the simulated cases, the pressure rise inside the room is higher than both the supply pressure and the exhaust pressure. Therefore both vents act as pressure release
valves. However, in tests with supply pressures higher than the pressure rises, the
supplied flows increase the pressure inside the room. Therefore the supply vent behaves
differently for a low pressure rise and a high pressure rise inside the room.

FDS simulations with HVAC models were also performed and results show that the
simulated pressure rises are generally lower than the PRS results, as shown in the
validation in Section 4.

5.5 Comparisons with the simplified models

5.5.1 Closed room

In this section, a comparison of Eq. (21) with PRS is presented for a closed room.

Two fire scenarios are simulated for a room with dimensions of 2.4 m (W)×3.6 m (L)×2.4
m(H). The first scenario corresponds to a fire with a constant heat release rate of 100 kW
and the second is a fire with a fast curve to 100 kW and then keeping at that level. In both
cases, the heat release rate is set to zero after 300 seconds.

Another more realistic simulation is also conducted using PRS with the extinction model
and the gypsum board as the wall boundaries. In this case, the fire is not forced to
extinguish after 300 seconds. Instead the extinction model is activated.

Figure 29 and Figure 30 show results for the first and second scenario respectively.
Clearly, the same trend can be found in both scenarios. The PRS results with adiabatic
boundaries and Eq. (21) matches perfectly. However, in another simulation with Gypsum
board as the wall boundaries, the PRS results are much lower than those estimated by Eq.
(21). Even after accounting for the heat loss by multiplying the heat release rate by a
factor $\xi$ of, e.g. 0.65, the values estimated by Eq. (21) only become slightly better and still
far away from the PRS results, as according to Eq. (21), the pressure rise is proportional
to the effective heat release rate.

In summary, Eq. (21) can only be used for estimation of pressure rise in a room with
adiabatic boundaries, and it cannot be used for estimation of pressure rise in a typical
room.

![Figure 29](image) Comparison of PRS and the simple model Eq. (21) in the first
scenario.
5.5.2 Single room with an opening

In this section, a comparison of Eq. (24) and Eq. (25) with test data and PRS results is presented for a room with a small opening. The fraction, $\xi$, defined in Eq. (20), is set as 0.65 to account for the heat loss. While using Eq. (24), the density and temperature estimated using PRS is used in calculation.

Figure 31 shows the comparison of the predicted pressures by the equations with test data for FOI test 1. The maximum pressures estimated using the simple models are much higher than the FOI test results, especially in the period of constant heat release rate. The ratio of maximum pressure in the estimations to the measured data is around 7.7. The negative pressure cannot be predicted using the simple model. Note that a value of 0.65 is used for the fraction, $\xi$. A lower value will result in underestimation of pressure at early stage and a higher value tend to overestimate it. Choosing 0.65 is to obtain better correlation at the early stage.

Figure 31  Comparison of FOI test 1 and the simple models Eqs. (24) and (25).
Figure 32 shows the comparison of the predicted pressures by the equations with PRS results for test 301 (Table 5). The maximum pressures estimated using the simple models are much higher than the PRS results, especially in the period of constant heat release rate. The ratio of maximum pressure in PRS to that in the estimations is around 2.3.

Comparing the two figures may indicate that the simple models obtain better predictions for high pressures.

![Graph showing comparison of pressures](image)

**Figure 32** Comparison of PRS test 301 and the simple models Eqs. (24) and (25).

In summary, Eqs. (24) and (25) highly overestimate the pressure rise, and can only be used to roughly estimate the pressure rise in a single room at the early stage of a fire. The uncertainty of the results are very high. The main reason is that the time derivative term is ignored while obtaining the equations.
6 Summary

To fill in the knowledge gap in the pressure rise in room fires, a simple CFD model, Pressure Rise Simulator (PRS), is developed to simulate the fire-induced pressure rise in a single room with natural ventilation or mechanical ventilation. Test data from full scale tests performed by FOI are used for validation. Comparison of the results with some FDS simulations is also performed. Further, the influence of room sizes, fire sizes, wall materials, openings and mechanical ventilation systems on the pressure rise and the pressure drop is investigated.

The results show that PRS predicts both the pressure rise and pressure drop in the room very accurately. It also predicts the oxygen concentration and gas velocity through the duct very well. In contrast, FDS predicts the overpressure rise relatively well (slight undershooting in the simulations) but cannot predict the under-pressure using the extinction model.

The accuracy of the two simple equations, i.e. Eq. (21) and Eq. (25), are also compared to test results and PRS results. It can be concluded that Eq. (21) can only be used for estimation of pressure rise in a completely closed room with adiabatic boundaries. The maximum pressures estimated using Eq. (25) are much higher than test results, especially in the period of constant heat release rate. Therefore, both equations can only produce very rough estimation of the pressure rise and generally the results are highly overestimated.

The results show that a larger room could result in a greater pressure rise and also a greater pressure drop and the difference in pressure rise between different rooms decreases as the room size increases. The reason could be that in a larger room, the average temperature and average soot volume fraction is lower and thus the heat loss could be smaller. Meanwhile, the fire in a large room can sustain for a longer time and accumulate more heat which results in larger pressure drop after the fire is self-extinguished.

The maximum pressure rise for the fast curve is much higher than that for the medium curve, and the ratio ranges from 1.5 to 3. This indicates the importance of the fire growth rate on the pressure rise. However, the difference in the pressure drops is very limited. The reason could be that the total heat output in a room with a small opening before extinguishment is mainly dependent on the oxygen available. This amount of heat to a large extent determines the heat accumulated in the smoke inside the room. After extinguishment, the heat source is removed but the smoke is continually losing heat to the walls. This causes a sudden drop in the pressure.

The pressure rise and drop do not increase continually with the fire size. For small fire sizes, the pressure rise increases with the fire size. However, as the fire size reaches to a certain level the pressure rise and drop do not vary with the fire size. The reason is that before the fire reaches the maximum designed fire size, it has been self-extinguished.

For a given fire curve, the wall materials do not have too much influence on both pressure rise and pressure drop. An exception is mineral wool where the pressure rise is clearly higher than the others (the increase is around 15%). The reason is that the mineral wool is highly thermal resistant and results in much less heat loss to the internal walls than the others.

The pressure rise decreases rapidly with the increasing opening area. It can be concluded from the results that the opening size is the most influential factor on the pressure rise.
The pressure rise in the room with mechanical ventilation decreases with the increasing flow rates but this decreasing effect becomes insignificant for high flow rates. In most of the simulated cases, the pressure rise inside the room is higher than both the supply pressure and the exhaust pressure. Therefore both vents act as pressure release valves. However, in tests with supply pressures higher than the pressure rises, the supplied flows increase the pressure inside the room. Therefore the supply vent behaves differently for a low pressure rise and a high pressure rise inside the room.

For a given fire scenario, there are two solutions to reduce the pressure rise: (1) enlarging the openings for a room with natural ventilation, and (2) shutting off the supply flow and lowering the exhaust pressure for a room with mechanical ventilation.
7 References

SP Technical Research Institute of Sweden
Our work is concentrated on innovation and the development of value-adding technology. Using Sweden's most extensive and advanced resources for technical evaluation, measurement technology, research and development, we make an important contribution to the competitiveness and sustainable development of industry. Research is carried out in close conjunction with universities and institutes of technology, to the benefit of a customer base of about 9000 organisations, ranging from start-up companies developing new technologies or new ideas to international groups.