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Impact of the balanced mechanical ventilation system on overpressure in airtight houses in case of fire

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De scriptie is een vervolg op het afstudeeronderzoek van Vincent van den Brink naar de consequenties van een goed isolerende luchtdichte gebouwschil voor de vluchtveiligheid van gebouwgebruikers in geval van brand. De maatschappelijke relevantie hiervan is het grootst in woningen, omdat dit relatief kleine brandcompartimenten zijn met een naar binnen draaiende toegangsdeur. Vincent van den Brink toonde in zijn afstudeeronderzoek aan dat bij een ontwikkelende brand grote overdrukken in een goed luchtdichte woning verwacht kunnen worden, waardoor de toegansgdeur niet geopend kan worden en het vluchten wordt belemmerd.

Nick Tenbült richt zich in dit onderzoek op de invloed van de ventilatie-installatie van de woning op de overdrukken die bij een ontwikkelende brand optreden. De verwachting is dat de ventilatie-installatie een luchtlekkageweg vormt, waardoor de overdrukken zullen afnemen.

Voor dit onderzoek zijn door Nieman RI voor enkele woningen uitgebreidere luchtdichtheidsmetingen conform NEN 2686 uitgevoerd. Dat wil zeggen dat naast een normale meting, met een afgedichte ventilatie-installatie, ook een meting met open toevoer- en afvoerventielen uitgevoerd is. Uit het verschil van deze twee metingen kan de druk-volumestroom karakteristiek van de ventilatie-installatie worden vastgesteld.

Vervolgens zijn zowel de bouwkundige lekheid als de lekheid van de ventilatie-installatie in een meerzonemodel (CFAST) opgenomen. Vanwege de afwijkende stromingsexponent van volumestromen via bouwkundige naden en kieren en via installatietechnische ventielen en luchtkanalen was daarvoor een iteratief proces nodig in CFAST.

Daarin is Nick Tenbült zeer goed geslaagd. Uit de resultaten blijkt dat de ventilatie-installatie wel enige verzwakking geeft op de luchtdichtheid, waardoor de drukpiek wordt gereduceerd, maar het effect ervan is relatief klein. Het effect is zelfs veel kleiner dan op voorhand werd verwacht. Met andere woorden: de door Vincent van den Brink getrokken conclusies blijven hiermee overeind.

Een uitermate relevante studie met goed onderbouwde conclusie.

<u>Beoordeling</u>
De metingen zijn verkregen van Nieman RI. Echter, de uitwerking van de verschilmetingen (met/zonder ventilatie-installatie) heeft Nick voor zijn eigen rekening genomen. Het iteratieve proces in CFAST, als gevolg van verschillen in stromingsexponent bij verschillende typen van luchtlekkages, is door Nick min of meer geautomatiseerd in een spreadsheet.

Het rapport is goed geschreven en leest prettig. De conclusie is helder verwoord. Kortom, een prima rapportage voor een 10 ect's onderzoek.

Onderdeel	**Score**
Structuur, doelstelling, uitgangspunten en randcondities	***8***
Geraadpleegde bronnen	***8***
Visie, concept, onderlinge verbanden	***7***
Uitwerking in simulaties	***9***
Leesbaarheid, lay-out, figuren en taalgebruik	***8***

Cijfer: 8

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7LS1M0 Master project – Building Physics and Services

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Where innovation starts

Nomenclature

A	leakage area (opening)	[m²]	
A_e	equivalent leakage area	[m²]	
A_{fire}	fire area	[m²]	
c_f	form factor	[-]	$(-1.0 < c_f < 1.0)$
c_p	specific heat capacity	[J/kg.K]	
C_w	air flow capacity 1Pa	[$Pa^n m^3/s$]	
C	air duct/grill capacity	[$Pa^n m^3/s$]	
D	Hydraulic diameter	[m]	
HRR	heat release rate	[kW]	
l	length	[m]	
n	flow exponent	[-]	$(0.5<n<1.0)$
ΔP	pressure difference	[Pa]	
ρ_a	density outside air	[kg/m^3]	
ρ_e	density outflowing air/gases	[kg/m^3]	
O	orifice coefficient	[-]	
Q_v	air volume flow	[m^3/h]	
T_a	temperature outside air	[K]	
T_e	temperature outflowing air/gases	[K]	
T_g	temperature inside air/smoke layer	[K]	
v	wind speed	[m/s]	
çi	resistance factor element i	[-]	
λ	wall resistance coefficient	[-]	
μ	Bernoulli coefficient	[-]	

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1. Abstract

Earlier studies toward airtight dwellings show some major concerns about the safety of occupants and fire service in case of a fire. With experiments and simulations pressure peaks in an early stage of the fire were experienced, which makes it harder for an occupant to escape from the building. The executed experiments and simulations focused on the building envelope and neglected balanced mechanical ventilation systems. This implicates that the fire scenario might be different from the scenarios experienced in previous studies and, thus the consequences for the safety of building occupants and fire service might be different.

Nieman Raadgevende Ingenieurs performed airtightness measurements, with and without mechanical vents included. With the data obtained from both measurements the equivalent surface are of mechanical vents can be calculated. The surface area is required to perform simulations in a multi zone-model, CFAST. However, in CFAST it is not possible to model flow exponents >0.5. This will result in an underestimation of the air flow and overestimation of the pressure. To solve this problem a correction model has been developed to change the surface of the openings for different pressure intervals. After running the correction model two times the air flow simulated in CFAST corresponds with the measurements.

The simulations that consider ventilation openings show little differences with the simulations that neglected ventilation openings. Due to the ventilation openings the pressure peak is reduced, but in an early stage of the fire development the pressure increase looks similar. For all three applied growth rates consideration of the mechanical ventilation openings cannot prevent exceedance of the threshold (30 Pascal) within roughly two minutes.

From the performed simulations can be concluded that, despite the fire growth rate and location of the fire, the pressure increase in airtight dwellings is too high in the first three minutes to assure safe evacuation of building occupants. The mechanical ventilation system has only an influence on the pressure peak, which can be reduced with a few hundreds of Pascal, depending on the fire scenario. The extension of available evacuation time is only a few seconds.

After this study conclusions from earlier studies can be upheld. Modern airtight buildings maintain a potential danger for building occupants due to high pressures which make it more difficult to escape. Smoke gas explosion and backdraft are still potential risks for fire services.

2. Introduction

2.1 Methodology

2.1.2 Problem field

Due to stricter legislation concerning the energy use of the built environment dwellings become better insulated and more airtight. The Passive house certificate is a method to certify dwellings with a high level of insulation and airtightness. Previous research about these passive houses show some major concerns about the safety of occupants and fire service in case of a fire in these dwellings (van den Brink, 2015), (FOD Binnenlandse Zaken, 2010). With experiments and simulations van den Brink experienced pressure peaks in an early stage of the fire, which makes it harder for an occupant to escape from the building. The consequences for the fire service, at the time they arrive, will be that the fire is probably gone out and is smouldering. An unexpected increase of oxygen, by opening a window or door, may cause a backdraft or gas explosion (van den Brink, 2015). These problems may cause potential dangerous situations for building occupants. However, the executed experiments and simulations were simplifications of reality, whereby balanced mechanical ventilation systems where neglected. The mechanical ventilation system may have influence on the airtightness of the building since the system is excluded when the airtightness is determined (NEN Connect, 1988). This implicates that the fire scenario might be different from the scenarios experienced in previous researches and, thus the consequences for the safety of building occupants and fire service might be different.

It is expected that the relatively large openings, required for mechanical ventilations, reduce the pressure built-up inside airtight dwellings significantly, therefore the following hypothesis is stated:

"The balanced mechanical ventilation system will influence the fire behaviour such that the pressure built up in modern airtight dwellings will not endanger the safety of building occupants and fire services".

2.1.2 Research question

To what extend has the mechanical balanced ventilation system an influence on the pressure increase during a developing fire in well insulated and airtight dwellings, in order to determine the consequences for safety of occupants and fire service?

2.1.3 Sub questions

I. What type of balanced mechanical ventilation system is commonly applied in airtight dwellings?
II. How does the mechanical ventilation system behave during fire in a modern airtight dwelling?
III. What is the airtightness bandwidth of commonly applied mechanical ventilation systems in airtight dwellings?
IV. What is the most suitable software to model a fire in passive houses?
V. To what extend has the fire growth rate influence on the maximum pressure and moment of the peak?
VI. To what extend has the location of the fire influence on the maximum pressure and the moment of the peak?
VII. What is the potential extension of the available safe evacuation time?

2.1.4 Research objective

Gain insight about the influence of the mechanical balanced ventilation system on the pressure increase during a fire in well insulated and airtight dwellings and gain insight into the consequences for the safety of building occupants and fire service.

2.1.5 Research method

To answer the formulated research question experiments would be a suitable method. However, due to the limited available time (10ECTS) of this master project, experimental data will be obtained from Nieman Raadgevende Ingenieurs. With this data simulations will be provided to solve the problem. In order to build a suitable simulation model a (literature) study is necessary for the following aspects:

- A representative balanced mechanical ventilation system, which is often used in modern airtight houses. To gain insight it is important to describe the components, dimensions, properties and process of the mechanical ventilation system.
- The behaviour of a mechanical ventilation system during a fire. Questions like, “Will the ventilation system keep working?”, “Will there be valves closed?”, “How does the ventilation system react to pressure changes?”, need to be answered to gain insight in the systems behaviour in case of a fire and potential consequences for the fire.
- A short comparison of software tools to find out which one is the most suitable for the described problem.
- Airtightness of mechanical ventilation systems. This can be obtained by performing two airtightness measurements for dwellings, one including the ventilation system and one excluding the ventilation system. The difference between the two measurements indicates the airtightness of the ventilation system. These measurements will be performed by Nieman Raadgevende Ingenieurs.

With the above mentioned aspects the simulation model will be built as accurate as possible, in order to achieve the goal of this research project.

Chapter 3 of this report contains theoretical background information to make the required knowledge around the subject comprehensible. In the next chapter the computational model is explained, along with the developed correction model. The results of performed simulations are explained in chapter 5. To be followed with a conclusion and discussion.

3. Theoretical background

3.1 Airtightness

To avoid energy waste by unwanted infiltration of outside air it is important to reduce air leakages through the building envelope. Most common leakages are cracks between different building elements such as walls, window frames and roof. Also movable parts such as windows and doors cause air leakages.

In the Netherlands airtightness of a dwelling is measured according NEN 2686, which describes the measurement method and criteria that have to be fulfilled during the measurement. In most cases a blower door test is performed whereby a fan is placed in the front door and sealed airtight in the frame. A schematic measurement setup is shown in figure 1. Two measurements will be performed, one time an overpressure is created in the dwelling by the fan and the other time the fan will create an under pressure. The pressure difference between the indoor and outdoor environment will be measured along with the leaking air volume for at least 6 times between 25 and 85 Pascal and intervals of 5-10 Pascal. With the initial conditions such as temperature and wind pressure the characteristic air flow over a pressure difference of 10 Pascal can be determined.

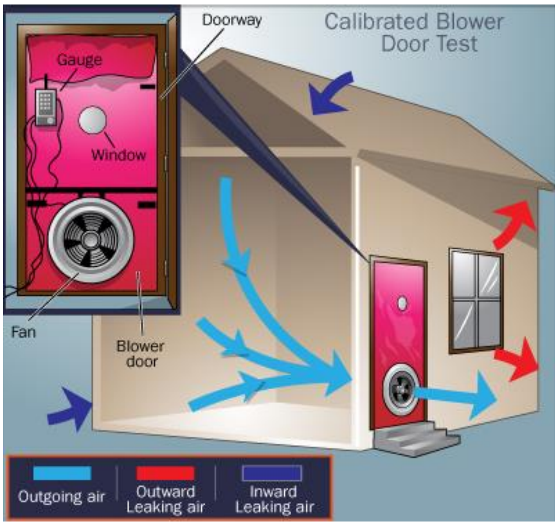

Figure 1 - Measurement setup Blower Door Test, source: (RedPoint LLC, 2017)

According NEN 2686 the mechanical ventilation system should be turned off during the measurement and openings towards the outside must be closed. Air flows through the mechanical ventilation system are forced and are therefore not considered as air leakages. However in daily use these openings are not closed and may have a significant influence on the development of a fire inside a dwelling. Therefore Nieman Raadgevende Ingenieurs performed some airtightness measurements whereby the openings of the mechanical ventilation system are not closed, in order to determine the difference in air leakage between the two situations. The results of these measurements will be discussed later on.

In the Netherlands the airtightness performance of dwellings is divided according NEN 2687 into three classes, namely basic, good and excellent. Passive houses can be compared with the excellent class. In table 1 the classes and their criteria are described.

Table 1 - Airtightness classes according to NEN 2687

Class	Volume of dwelling [m³]		Maximum value		Minimum value
	>	≤	$q_{v,10}$ [dm³/s]	$q_{v,10}$ [dm³/s.m²]	$q_{v,10}$ [dm³/s]
1. Basic		250	100	1.0	30
	250	500	150	1.0	50
	500		200	1.0	50
2. Good		250	50	0.6	
	250		80	0.4	
3. Excellent		250	15	0.15	
	250		30	0.15	

3.2 Passive house

Passive houses are characterized by their low energy demand and high level of thermal comfort at the same time, which is achieved by high level of insulation and airtightness of the building envelope. Along with heat recovery units and use of passive solar energy the annual heating and cooling demands are reduced, shown in figure 2. The Passive House Institute (PHI) is an independent research institute that develops the passive house concept and is responsible for certification of passive houses. To acquire the Passive house certificate several requirements have to be met, regarding energy demand, insulation level and airtightness as described in table 2.

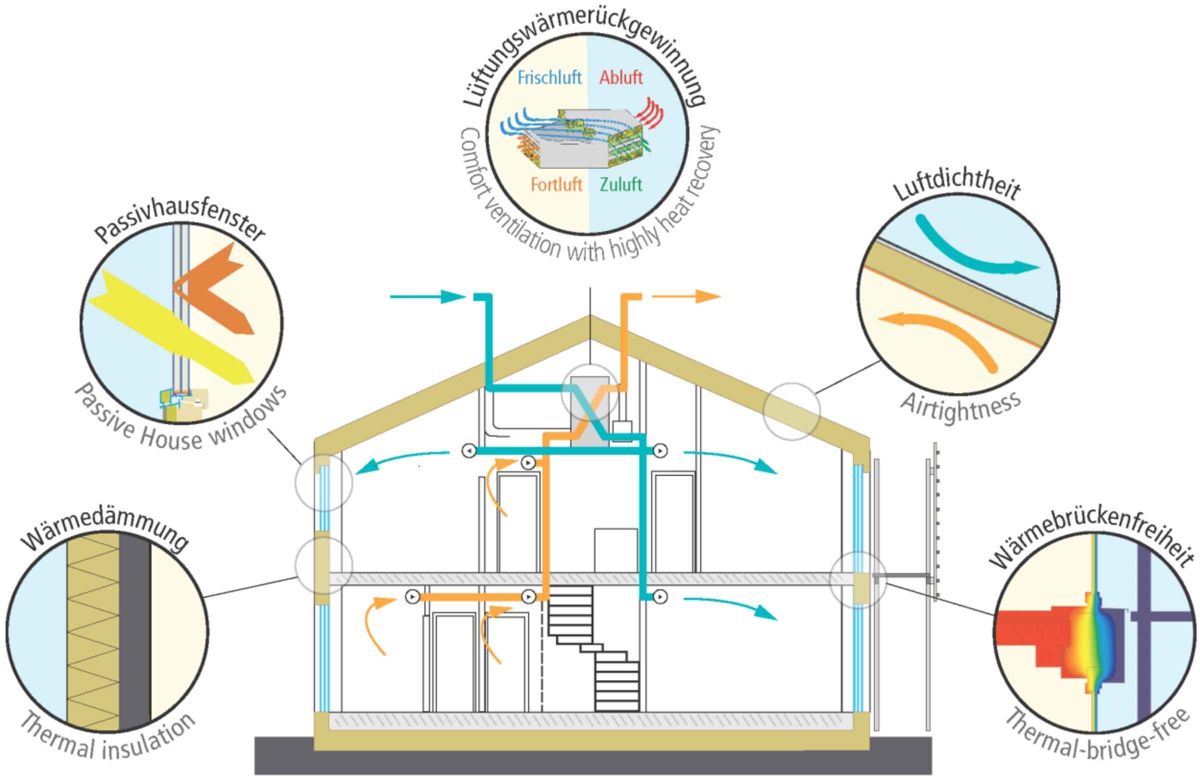

Figure 2 - Typical passive house solutions, source: (Passive House Institute, 2016)

The requirements regarding energy demands do not have a direct influence on fire behaviour, but the measures taken to achieve this requirements do. There are no specific criteria for these measures, however there are some standard measures that are often taken in passive house design and are related to heat transfer through the building envelope (U-value). Typical applied heat transfer values are:

- opaque building envelope ≤ 0.15 W/(m².K);
- windows ≤ 0.80W/(m².K) (Passive House Institute, 2016).

Table 2 - Requirements passive house certificate, source (Passive House Institute, 2016)

	Criteria
Annual Heating demand	≤ 15 kWh/m²
Annual Cooling + dehumidification demand	≤ 15 kWh/m²
Pressurization test result n_{50}	≤ 0.6 1/h (≈class 3 of table 1)

The influence of the high level insulation layer on the temperature increase during a fire is depending on the location of the layer. Insulation placed on the exterior side of walls with large thermal inertia will not influence the temperature increase (Debrouwere, 2012). If the insulation layer is placed on the interior side walls are not able to take up heat and the temperature increase will be higher.

Huizinga studied the behaviour of multi-layered glass during fire and concluded that the chance a smothered fire will occur is larger when multi-layered glazing is applied. This result in greater smoke development and increases the risk of gas explosion (Huizinga, 2012).

3.3 Air pressure

Dynamic air pressure differences have multiple causes, which can be divided into two categories. The first category contains normal pressure differences that always exist in a building and/or between building surroundings. The second category contains pressure difference caused by a fire (Svensson, 2005).

Table 3 - Pressure differences

Normal pressure differences			
Difference between indoor and outdoor temperature	$\Delta P = \rho_0 \cdot g \cdot \Delta h \cdot 273 \cdot \frac{(T_1 - T_2)}{T_1 \cdot T_2}$	(1)	
Effect of wind	$\Delta P = 0.5 \cdot c_f \cdot \rho_a \cdot v^2$	(2)	The form factor varies between -1 (full negative pressure) and 1 (full positive pressure).
(Mechanical) ventilation	$Q_v = C_w \cdot (\Delta P)^n$	(3)	Flow factor n is 0.5 for turbulent air flows, large openings, and tends toward 1.0 for small openings, cracks.
Pressure difference due to fire			
Inhibited thermal expansion	$\Delta P = \frac{\left(HRR / (c_p \cdot T_e \cdot A_e)\right)^2}{2 \cdot \rho_e}$	(4)	
Thermal buoyancy force	$\Delta P = 353 \left(\frac{1}{T_a} - \frac{1}{T_g}\right) g \cdot h$	(5)	Thermal pressure difference over smoke layer with height h.

Difference between indoor and outdoor temperature
Indoor air is usually warmer than outdoor air. The warm air rises due to its lower density and create a higher pressure. The pressure difference between the inside and outsides strives towards an equilibrium. Hot air will flow to the outside through leakages or openings at the top (positive pressure) and cold air will flow to the inside through leakages or openings at the bottom (negative pressure). In between of these opening there is a neutral plane where the pressure will be zero (Svensson, 2005).

Effect of wind
Wind flows around a building cause pressure differences close to the building. At the wind side of vertical surfaces a positive pressure will occur, while at the leeward side negative pressure will occur, which is approximately half of the wind side pressure. At the sides negative pressures will occur that decrease towards the leeward side. Roofs with an angle of more than 45° have positive pressure on wind side and negative pressures at leeward side. For roofs with an angle smaller than 30° the pressure over the entire roof is negative (Svensson, 2005).

(Mechanical) ventilation
Fans are used to supply and extract air, hereby a pressure difference is created between the inside and outside environment. The total air flow volume through ducts is determined by equation 3 and depends on the air flow resistance of the total system, pressure difference and flow exponent of the openings. In the next paragraph more will be explained about the mechanical ventilation system.

Inhibited thermal expansion
Due to a fire smoke gases are heated up and start to expand. In a complete closed volume the gases are prevented from expanding which result in a pressure increase. The pressure increase can be calculated with equation 6.

$$\frac{p-p_a}{p_a} = \frac{HRR}{V \cdot \rho_a \cdot c_v \cdot T_a} \qquad (6)$$

However, it is seldom that rooms are completely closed which results in less pressure increase. To involve air leakage equation 4 from table 3 can be used to calculate pressure differences (Bengtsson, 2001).

Thermal buoyancy force
Hot gases have a lower density than unaffected air and as a result these gases rise upwards, called thermal buoyancy. In the top of the room a smoke layer is formed. The separation between the smoke layer and the unaffected air is called the neutral plane. Due to thermal buoyancy the temperature at the top of the smoke layer is higher than temperatures at the bottom (neutral plane). This temperature difference creates a pressure difference within the smoke layer, which can be calculated with equation 5 (Bengtsson, 2001).

3.4 Balanced mechanical ventilation system

3.4.1. General information

In modern airtight dwellings commonly balanced mechanical ventilation systems with heat recovery are installed. Both supply air and extracted air are forced flows created by a fan. The supply fan creates a positive pressure while the exhaust fan creates a negative pressure, this way air circulation is possible. The fans are placed in a box, called heat recovery unit, where heat recovery between air flows takes place. The air is supplied and extracted through ducts and grills, which are connected to the heat recovery unit. In a typical dwelling air is supplied to rooms where people stay, work, sleep etc. In rooms with the highest pollution the air is extracted, for example in toilets, bathroom and kitchen.

Ducts and grills cause resistances, a larger air flow resistance requires a higher pressure generated by the fan to supply or extract the desired air volume. The capacity of air flow resistances of a duct is determined by equation 7. For the capacity of a grill equation 8 should be applied.

$$C = \frac{A \cdot \sqrt{\frac{2}{\rho}}}{1 + \sqrt{\frac{\lambda \cdot l}{D} + \sum \varsigma_i}} \qquad (7)$$

$$C = A \cdot \mu \cdot \sqrt{\frac{2}{\rho}} \qquad (8)$$

$$\mu = \frac{1}{1 + \sqrt{\zeta_i}} \qquad (9)$$

In general ducts contain bends, bifurcations, grills and other attachments which increase the resistance of the system. To design an efficient system as possible the number of those pieces must be reduced to a minimum. Also in case of a fire the air flow through the ventilation system will be higher if the resistance is kept as low as possible, probably resulting in a smaller pressure increase in the dwelling.

Since most ventilation systems are different in size and composition it is difficult to determine a standard value or range for the air flow resistance. In the remainder of this study airtight measurements, performed by Nieman Raadgevende Ingenieurs, will be used to determine the air flow resistance and equivalent surface area of the openings. Later on these measurements and their results will be further explained.

3.4.2 System behaviour

Failure of the ventilation system can have multiple causes. At first, melting of PVC insulation of wires causes electrical short cutting. PVC will melt around 185°C, so at this point the ventilation system will probably be switched off. Second, heavily polluted smoke may cause damage to the engine of the fans, which result in engine failure. However a certain point of failure cannot be determined. A third cause for system failure may be the pressure increase inside the dwelling. Due to higher pressures the supply fan has to deliver more energy to keep working. Built in safety may shut down the fans or overheating of the engine may lead to failure. For the extraction fan an opposite effect occurs because the pressure increase reduces the pressure difference that has to be generated by the fan. This will probably not lead to failure and it is more likely that one of the other mentioned causes occur. Since the exact moment of system failure is uncertain and cannot be determined it is assumed that the ventilation system is shut down when the fire ignites. This simplification may not occur in reality but the expected results with this assumption are expected to be sufficient to achieve the objective of this study.

3.5 Assessment criteria for safe escape

To assure safe evacuation of building occupants the pressure may not exceed 50 Pascal. This limit is determined based on legislation for pressurized staircases. Hereby the force to open a door may not be larger than 100 Newton. So the maximum force on a door of roughly 2 m^2 is 50 N/m^2, which is equal to 50 Pascal. However, this is for doors that have to be pushed to open, in contrast to front doors of dwellings that have to be pulled to open. Since pulling is harder than pushing the limit of 50 Pascal is reduced to 30 Pascal, in order to assure safe evacuation of building occupants through the front door.

For single-family dwellings with people who can leave without assistance it is assumed that they have a total evacuation time of 3 minutes (Hagen & Witloks, 2014). Hereby the detection time is 2 minutes and evacuation time 1 minute.

If the pressure inside the dwellings exceeds 30 Pascal within 3 minutes after ignition safe escape of building occupants cannot be assured and measures have to be taken.

4. Computational Approach

4.1 Software

4.1.1 CFAST

The consolidated model of fire and smoke transport (CFAST) can be used to simulate the impact of past or potential fires in a building environment. With the two-zone model CFAST the time-evolving distribution of smoke, fire gases and temperatures are calculated throughout multiple compartments of a building during a fire (National Institute of Standards and Technology, 2016).

The compartments that can be simulated in CFAST can range from 1 m^3 to large spaces on the order of 1000 m^3. Ordinary differential equations are solved during the calculation to predict functions of time quantities such as pressure, layer height and temperatures. The differential equations are derived with the conservation of mass, conservation of energy, the ideal gas law and relations for density and internal energy (Peacock, Jones, Reneke, & Forney, 2005).

The data that is necessary to run the model is put in a primary data file. This data file is created by following the steps of the CFAST user interface. The data file contains information about the building geometry, connections between compartments, fire properties and specifications for detectors, sprinkles and targets (Peacock, Jones, Reneke, & Forney, 2005).

Table 4 - Data file CFAST

Building geometry	Compartment sizes
	Materials of constructions
	Material properties - Thermal conductivity - Specific heat capacity - Density - Thickness - Burning behaviour
Connections between compartments	Horizontal flows - Doors - Windows
	Vertical flows - Openings in floors and ceilings
	Mechanical ventilation connections
Fire properties	Fire size
	Species production rates
Detectors, sprinklers and targets	Position
	Size
	Heat transfer characteristics
	Flow characteristics for sprinklers

In CFAST the air flow through a vertically orientated vent (opening in walls) is computed with equation 11, by integrating Bernoulli's equation over the height of the opening. Here, O is the orifice coefficient taken to be 0.7 at all times.

$$\dot{m} = \int_b^t O \cdot \sqrt{2\rho \cdot \Delta P(z)} \cdot w \, dz \qquad (10)$$

Redefinition of equation 10 in the form of equation 3 results in a flow exponent of 0.5. This indicates that CFAST is only able to model 'large' openings with turbulent flows. The measurement results show flow exponents that are larger than 0.5, which will be unable to model according to equation 10. Modelling a flow exponent of 0.5 will lead to underestimation of the air flow volume at higher pressures as shown in figure 3, which will probably lead to even higher pressures.

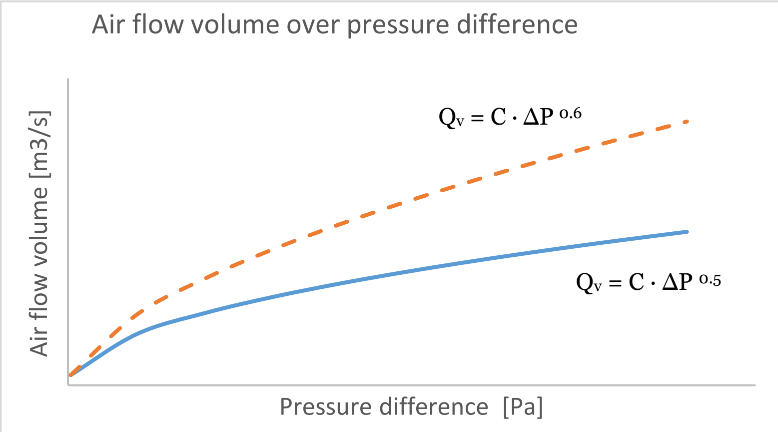

Figure 3 - Difference in air flow volume with different flow exponents

To increase the air flow volume a larger opening could be modelled, but this will lead to overestimation or partial overestimation and underestimation. Since the most recent version of CFAST, v.7.2, released on November 25th of 2016 it is possible to change the opening fraction of any vent as a function of time. This means that at multiple points the opening can be changed, which make it possible to model the measured air flow volumes. The possibility to change the opened fraction of an opening at multiple times makes CFAST a suitable software program to study the stated problem.

4.1.2 OZONE

OZONE is also a zone model and its intended use is to calculate the development of the gas temperature of a natural fire curve according to EN 1991-1-2. However user defined fires can also be applied in the software. Besides calculating gas temperatures OZONE is able to determine the thermal response of steel structures. With the determined steel temperatures structural calculations can be made in order to determine the structure's moment of failure. Aside from temperatures OZONE computes the pyrolysis rate, heat release rate, height of the smoke layer, oxygen mass, floor pressure and heat flux.

In OZONE it is possible to model building elements existing of multiple layers in contrast to CFAST where only one layer can be modelled. On the other hand in OZONE only one compartment/room can be modelled and openings can only be adjusted once by time or twice by temperature. The amount of input, workload and computational time are quiet similar to CFAST. Although OZONE's output is less suitable to analyse the stated problem. From the two suggested zone models CFAST is the most suitable program for this study.

4.1.3 CONTAM

CONTAM is in contrast to CFAST and OZONE not a tool to simulate fire development and consequences of fire. CONTAM is a multi-zone computer program to analyse indoor air quality and ventilation. The three main tasks that can be done with CONTAM are determining air flows, contaminant concentrations and personal exposure. An alternative method for simulating a fire in CONTAM is by adding a temperature curve to the model that is similar to the development of a fire. However, first this temperature curve must be obtained from a zone model such as OZONE or CFAST. This method will be a response to a result of the zone model and there will not be any interaction between the fire and the pressure increase, which makes CONTAM not suitable for this kind of problem.

4.1.4 FDS

Fire Dynamics Simulator (FDS) is in contrast to the other described programs a computational fluid dynamics (CFD) model of fire driven fluid flow. FDS solves only large eddies (Large Eddies Simulation, LES) with a form of Navier-Stokes equations and is suitable for low-speed, thermally driven flows (NIST, 2017). Air flows through cracks are most often laminar or contain small eddies, which makes FDS less suitable for this study since FDS only solves large eddies. Another disadvantage of using FDS is the required computational time, which may take many hours.

From the performed study to suitable programs can be concluded that CFAST is the most appropriate program for the remainder of this study towards the impact of mechanical ventilation on the pressure increase in a dwelling during a fire.

4.2 Model

Because it is difficult to determine the exact airtightness of a dwelling, by summing all cracks and small gaps between building elements, measurements performed by Nieman Raadgevende Ingenieurs will be used as input for the computational model. In the next paragraph these results will be discussed and described how they will be used in the model.

4.2.1 Measurement results Nieman

Nieman Raadgevende Ingenieurs performs every year many airtightness measurements in different types of dwellings according to NEN 2686. In four of these cases they also measured the airtightness of the dwellings with open mechanical vents in order to determine the air leakage through the mechanical ventilation system. The results of both types of measurement are shown in table 5 and 6, detailed results are added in attachment 1. The measured dwellings are located at different locations in the Netherlands, namely Epe (case 1), the Hague (case 2) and Rhenen (case 3 and 4).

Table 5 - Results airtightness measurements according NEN 2686, performed by Nieman

Vents closed	Case 1	Case 2	Case 3	Case 4
User surface [m^2]	124	121.9	119	125.9
$q_{v,10}$ [dm^3/s]	84.9	34.0	82.3	58.5
$q_{v,10}$ [dm^3/s.m^2]	0.685	0.279	0.692	0.465
Flow exponent (n) [-]	0.593	0.654	0.593	0.636
Air permeability coefficient (C) [m^3/s]	0.0236	0.0073	0.021	0.0137

Table 6 - Results airtightness measurements with mechanical vents opened, performed by Nieman

Vents open	Case 1	Case 2	Case 3	Case 4
$q_{v,10}$ [dm^3/s]	91.1	47.8	87.0	65.2
$q_{v,10}$ [dm^3/s.m^2]	0.735	0.392	0.731	0.518
Flow exponent (n) [-]	0.587	0.622	0.587	0.608
Air permeability coefficient (C) [m^3/s]	0.0217	0.01	0.0226	0.0163

The difference between both measurements is the air flow leaking through the ventilation system. The airflow is determined by equation 3, whereby n is the flow exponent. For laminar air flows the flow exponent is 1.0 and for turbulent flows 0.5. It is expected that air flowing through the ventilation system is turbulent and will have a flow exponent of 0.5. The difference in air flow volume can be calculated for every pressure difference by implementing the flow exponent and air permeability coefficient, given in table 5 and 6, in equation 3. Now the air volume flowing through the mechanical ventilation system is known along with a flow exponent of 0.5 a regression analysis can be performed, in order to find the air permeability coefficient for the air flow through the ventilation system.

After performing the regression analyses C is known and equation 8 and 9 can be used to determine the equivalent surface area of the mechanical vents. In order to calculate the equivalent surface area of 'regular' leakage equation 11 is used. The total surface area of openings exists of 'regular' leakage and leakage through mechanical vents. In table 7 the surface area for both 'openings' are shown. In attachment 4 one calculation is elaborated.

$$A_e = \frac{C \cdot \sqrt{\rho}}{2^n} \qquad (11)$$

Table 7 - Calculated equivalent surface area leaks and vents

Equivalent surface area	Case 1	Case 2	Case 3	Case 4
Leaks (cm^2)	157.9	51.1	153	96.4
Mechanical vents (cm^2)	26.1	36.9	21.2	19.4
Leaks (cm^2/m^2)	1.27	0.42	1.29	0.77
Mechanical vents (cm^2/m^2)	0.21	0.30	0.18	0.15

Analysis of the results shows that case 2 has the best performance regarding airtightness. It is expected that dwellings with a high airtightness level are potentially the most dangerous for building occupants in case of a fire. Therefore case 2 will be used during simulations and in the remainder of this study. It is expected that the other three cases are somewhere in between the results of case 2 and a traditional dwelling. The calculated surface of leakages in table 7 form the initial openings in the simulations that will be made.

4.2.2 Geometry

In figure 4 floorplans of case 2 are depicted. In order to simplify the model some rooms are merged to reduce the number of compartments. In figure 5 the simplified distribution of compartments can be seen. CFAST uses the definition 'compartment' for an enclosure (room), this does not mean the compartments are equal to fire compartments according to the Dutch Building Code. The assumed height of all compartments is 2.6 meter.

Figure 4 - Floorplans case 2

Figure 5 – Simplified Floorplans case 2

4.2.3 Materials & Properties

In CFAST walls, floor and ceiling can only be assigned with one material and hereby all walls of a compartment will be the same. Modern dwellings are usually well-insulated, which may influence the temperature increase. However, based on previous studies it is expected that in an early stage of the fire a pressure peak occurs, therefore a short simulation time is sufficient. In this short time period the first layer of partitions will be thermal thick, so it is reliable to model only the first layer. The first layer of walls exist of gypsum board and floors and ceilings exist of concrete. Properties of these used materials are given in table 8. All compartments use the same materials for walls, floor and ceiling.

Table 8 - Material properties

Partition	Material	Thermal conductivity [W/m.K]	Thickness [mm]	Density [kg/m³]	Specific heat capacity [kJ/kg/K]	Emissivity [-]
Wall	Gypsum board	0.17	12	800	0.9	0.9
Floor	Concrete	1.5	200	2300	0.9	0.9
Ceiling	Concrete	1.5	200	2300	0.9	0.9

4.2.4 Vents

The total surface area of openings towards outside is based on the performed airtight measurements and is 87 cm². This area is divided over the compartments to ratio separation surface, which contains external walls and roof. In this case compartment 4 will have the largest opening because this compartment has the largest separation surface existing of walls and the entire roof. To create a small crack the openings are spread out over the entire height of the compartment. The openings per compartment are as follows:

Compartment 1: 24.2 cm² → width 0.093 cm

Compartment 2: 12.6 cm² → width 0.048 cm

Compartment 3: 11.6 cm² → width 0.045 cm

Compartment 4: 38.6 cm² → width 0.148 cm

Also openings between compartments are modelled. Between compartment 2 and 3 a closed door is assumed with a gap of 2x85 cm at the bottom. Furthermore, there is a connection from compartment 1 to 2 and from 2 to 4 of 3.8 m², which represents the staircase. In figure 6 a 3D-image of the model can be seen, whereby all openings are displayed in pink.

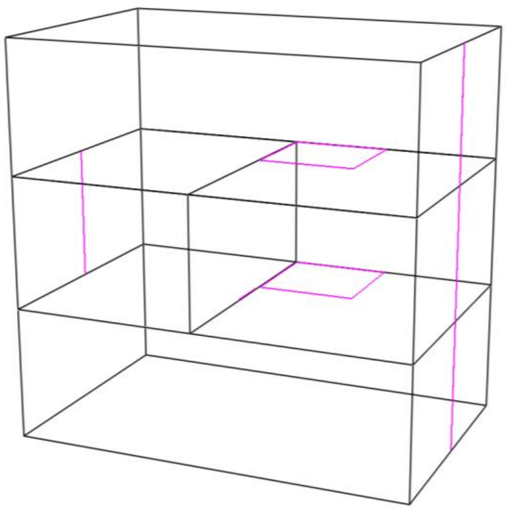

Figure 6 - 3D-view CFAST model

4.2.5 Fire

According to EN 1991-1-2 the t^2-squared curve should be used, given by equation 12, to model the fire growth. The average heat release rate of dwellings is 250kW/m². The fire will develop towards this value with a medium fire growth rate, which means that α is 0.01172 kW/s². It is assumed that the fire area develops similar as the heat release rate of the fire, equation 13, and is limited by the floor area of the fire compartment ($A_{fire,max}$).

$$HRR(t) = \alpha \cdot t^2 \qquad (12)$$

$$A_{fire} = A_{fire,max} \cdot \frac{HRR(t)}{HRR_{max}} \qquad (13)$$

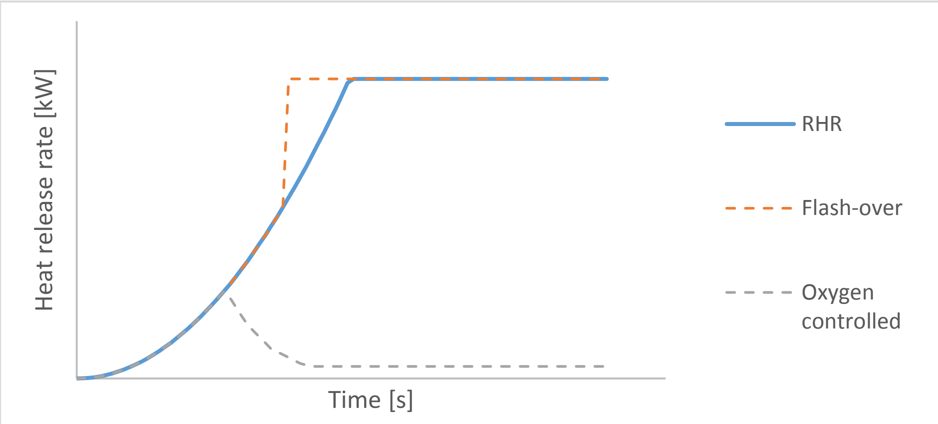

Figure 7 - Heat release rate according to t^2-curve, after flash-over and oxygen controlled

In the next paragraph several scenarios will be explained that will be simulated. One of those scenarios contains a different fire curve. Instead of the t^2-squared curve a more realistic fire will be applied whereby several objects ignite after each other ("traveling fire"). The objects that will be used are a sofa, curtains, upholstered chair and a television-set. The fire first ignites in the sofa and after 30 seconds the curtains ignite followed by the chair and television set after 60 and 90 seconds.

4.3 Scenarios

To determine sensitivity for certain parameters different scenarios will be simulated, defined in table 9. To examine the volume of the fire compartment the fire will be simulated in two different compartments. First simulations will be performed for a relatively 'large' compartment, namely compartment 1 (ground floor). Thereafter a 'smaller' compartment will be simulated, namely compartment 3 (bedroom 1st floor). For both compartments different fire growth rates (medium, fast and slow) will be simulated to study the influence of the fire load. Since the t-squared curve may be exorbitant for dwellings also a 'traveling fire' will be simulated whereby several objects will ignite in sequence. To be able to compare results with a traditional dwelling, which is not airtight, also a traditional dwelling will be simulated with larger cracks. The volume flow of this dwelling is based on the basic requirements regarding airtightness. According to the Dutch building code the maximum $q_{v,10}$-value is 1.0 dm³/s. It is assumed that for a traditional dwelling the flow exponent will be close to 0.5 and therefore a flow exponent of 0.55 is maintained for this scenario, which results in a surface area of total openings of 315 cm² for the first simulation.

All scenarios, except for the traditional dwelling, will be simulated 2 times, one time without the additional opening of the mechanical ventilation system and the second time with the extra opening.

Table 9 - Simulated scenarios

Scenario	Airtightness	Fire compartment	Fire growth rate
1	Case 2	1	Medium
2	Case 2	1	Fast
3	Case 2	1	Slow
4	Case 2	3	Medium
5	Case 2	3	Fast
6	Case 2	3	Slow
7	Case 2	1	"Traveling fire"
8	Traditional dwelling	1	Medium

4.4 Model modification

In figure 8 the first simulation results for the described CFAST-model are shown. However for all compartments a significant underestimation of air flowing to the outside can be seen at higher pressures. The solid lines in figure 8 show the volume flow based on the performed airtightness measurements and are further extrapolated according to equation 3. The dashed lines show the simulated volume flow towards outside. As predicted in paragraph 4.1.1 there is an underestimation between both lines caused by a difference in flow exponent, n.

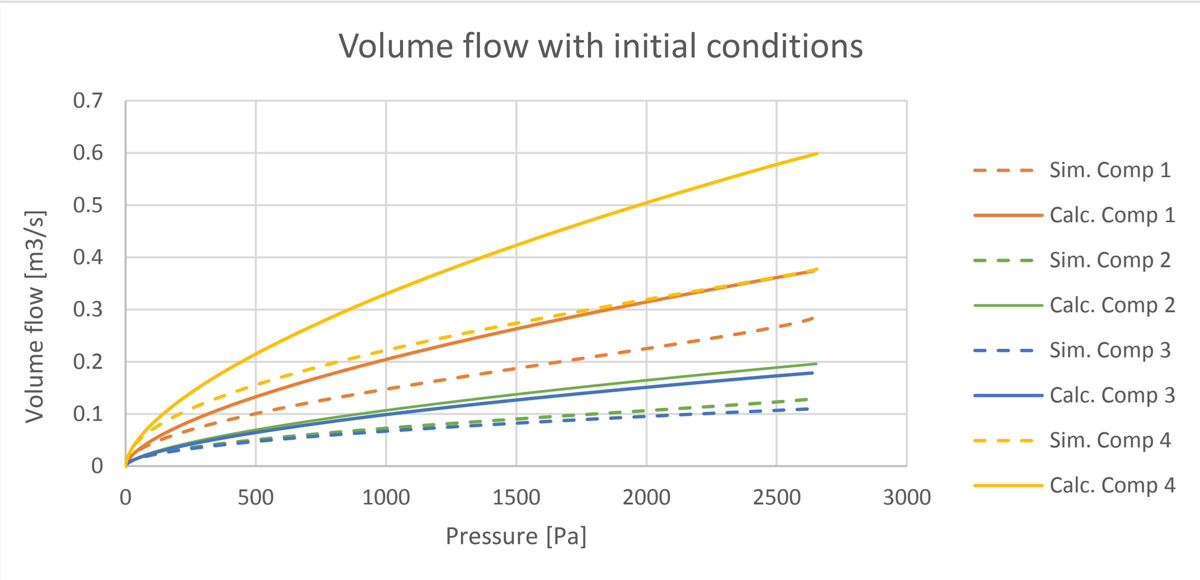

Figure 8 - Volume flow with constant openings as calculated

In order to reduce this difference a method is developed whereby the surface of the opening is adjusted in time based on the pressure difference. By slightly widening the opening the air flow increases and the difference between the measured and simulated air flow is reduced. Adjusting the opening at multiple points makes it possible to approach the line defined by equation 3 and the measurements. In figure 9 an example can be seen of this process. For lower pressures the interval is smaller since the slope of the power function declines more than for high pressure intervals.

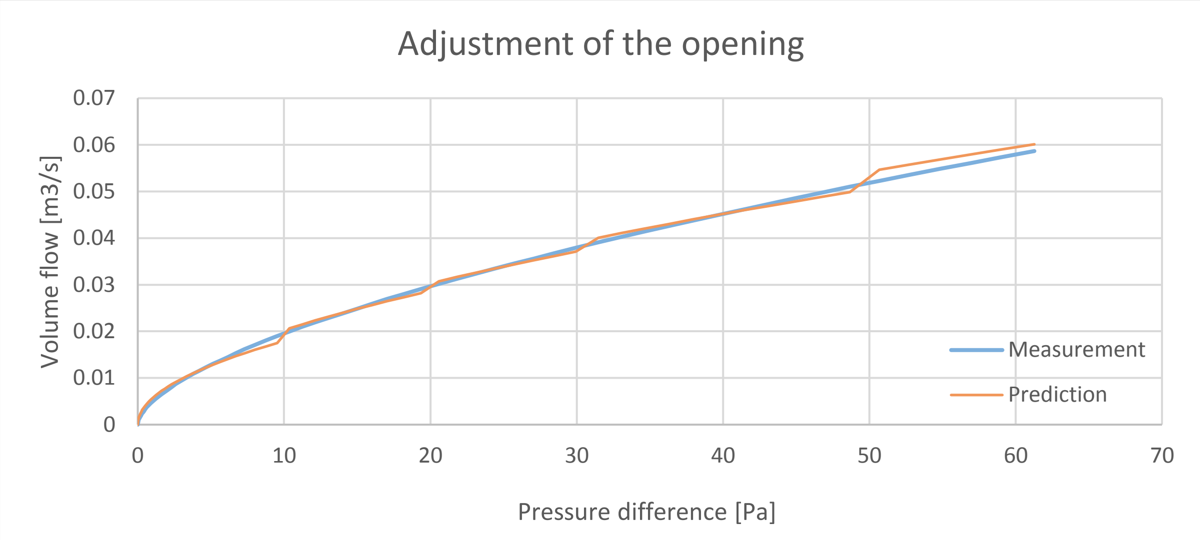

Figure 9 - Prediction of the volume flow by changing the opening for small pressure intervals

To determine the time intervals and corresponding fractions of the openings a spreadsheet has been compiled. All output data of CFAST simulations is saved in several .csv files. These files can be imported into the spreadsheet. The spreadsheet contains two sheets for every compartment, namely a general sheet and a background sheet. The pressure in the concerned compartment is loaded into the background sheet for every second and calculates the corresponding air flow according to equation 3 based on the measurements. Since CFAST returns the air flow in kilograms per second the air density and air temperature are required to compare the simulated air flow with the measured are flow. The background sheet uses the imported .csv files to establish these parameters. Thereafter the background sheet determines for all pressure intervals the corresponding time intervals, the average compartment temperature and the average air density, which will be used later on to determine the surface of the openings.

In the general sheet a default number is filled in for the air flow capacity, C. Since the flow exponent of equation 3 cannot be changed in CFAST the air flow capacity has to increase in order to increase the air flow. This can be achieved by enlarging the opening, according to equation 11. By finding the "optimal" value of C for every pressure interval the air flow can be modified to approach the measured function. A non-linear regression analysis is required for all pressure intervals to find the most accurate value of C. In the background sheet the air flow is calculated according to equation 3, hereby n is 0.5 and C is used from the general sheet for the corresponding interval. The calculated value will be compared with the measured function values. This result in an error value for every second in a certain pressure interval. The sum of squares of errors can be found in the general sheet. With the solver function the minimum value for the sum of squares can be found by modifying C.

In order to accelerate this process a macro have been added, which executes the solver function for all pressure intervals at once. This way all the required values of C are determined and can be used to find the corresponding surface of the openings. Determination of these surfaces is now relatively easy with equation 11 and the already determined average density.

Since the input for changing openings in CFAST is expressed in a fraction of the maximum value all surface are divided by the maximum surface. This results in a list of fractions between 0 and 1 with a corresponding start time, in seconds. This list can be copied into CFAST as shown in figure 10. The opening is spread out over the height of the compartment, which makes the width of the opening very small. The maximum width of the opening can also be read out of the spreadsheet if the appropriate height has been set. The model has now been set to run the next simulation, which will be more closely to the measured function.

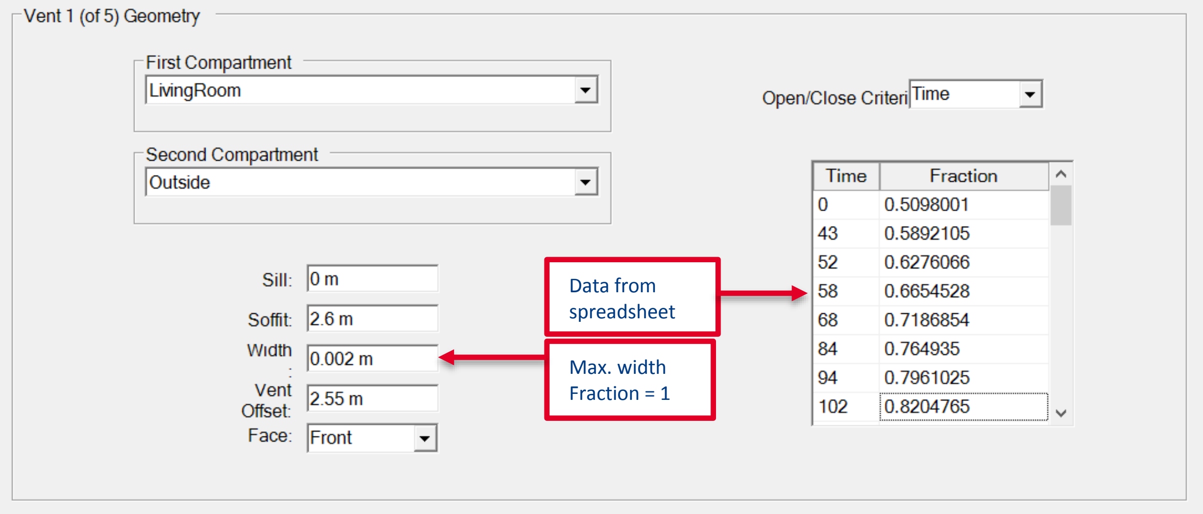

Figure 10 - Changing the opened fraction of openings in CFAST

Figure 11 shows the results of the simulation after the first attempt of changing the openings in time. In contrast to the previous simulation the results show an overestimation of the air flow, but this time the deviation is already much smaller. The overestimation can be explained by the slightly different fire behaviour that occurs due to the larger openings. Due to a larger air flow the temperature and pressure will increase slower, resulting in slightly overestimated air flow. By refreshing the output data of CFAST in the spreadsheet the macro can be run again and a new list of time intervals and fractions will be compiled. Again this list can be copied into CFAST along with the new maximum width. Thereafter a third simulation can be made, resulting in figure 12.

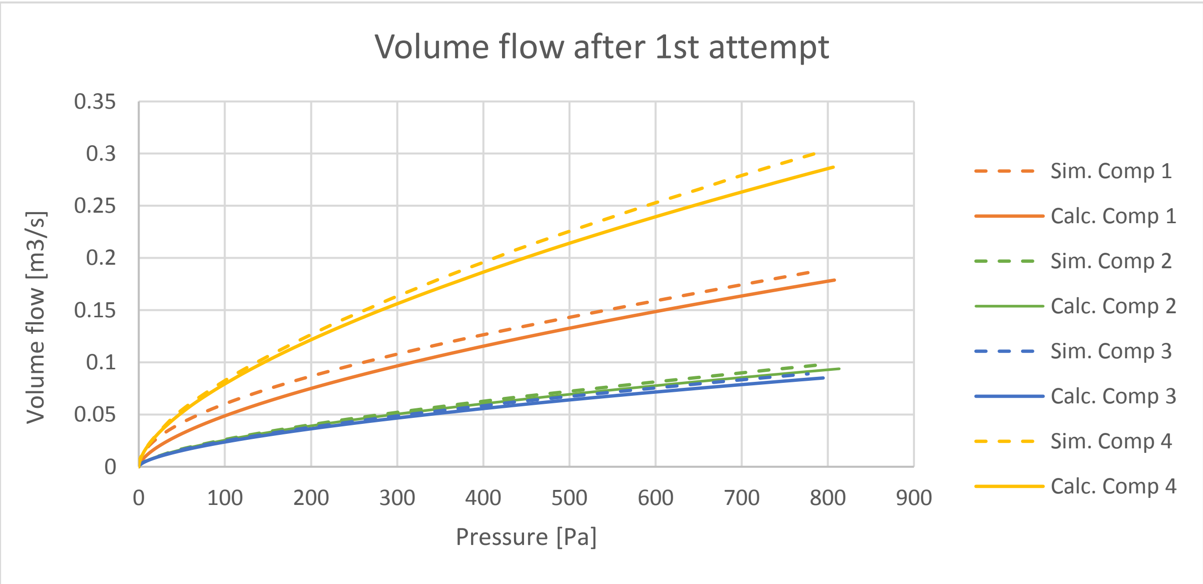

Figure 11 - Volume flow with variable openings, after 1st attempt

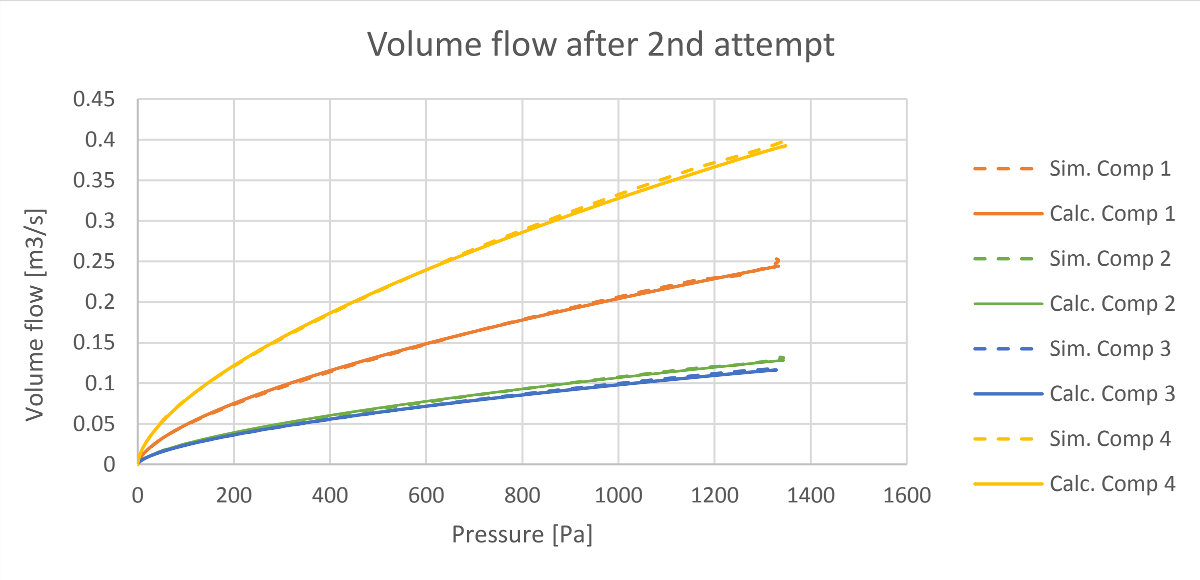

Figure 12 - Volume flow with variable openings, after 2nd attempt

After the second attempt the volume flow simulated by the CFAST model is almost similar than the volume flow according to the measurements. With this result fire behaviour in airtight compartments can be studied, provided that the volume flow through cracks shows similar behaviour for higher pressures, which is assumed in this study.

Stepwise determination CFAST input the openings

1. Calculate the equivalent surface area of the openings as described in paragraph 4.2.1
2. Divide the surface area of openings over the compartments.
3. Spread the surface area per compartment over the height of the certain compartment.
4. Fill in the height and width of the openings in CFAST.
5. Run the first simulation (if all input is filled in).
6. Import the .csv files into the spreadsheet.
7. Run the macro for all compartments, by pressing CTRL+r.
8. Export the list of time intervals and corresponding fractions to CFAST, along with the maximum width.
9. Run the second simulation.
10. Import the .csv files into the spreadsheet.
11. Run the macro again for all compartments, by pressing CTRL+r.
12. Export the new list of time intervals and corresponding fractions to CFAST, along with the maximum width.
13. Run the third simulation.
14. Import the .csv files into to analyze the results.

Conditions for using the spreadsheet

In order to successfully use the spreadsheet some conditions have to be satisfied, which are described below.

- The number of the opening towards outside has to match the number of the compartment. So opening number 1 in CFAST is the opening towards outside from compartment 1. Openings between compartments will start from the number of compartments + 1. So if there are 4 compartments and there is an opening between compartment 1 and 2 the number of this opening will be 5 and so on.
- The spreadsheet output interval in CFAST has to be set to 1 second.
- Parameters C and n obtained from the measurements have to be filled in.
- The height of the compartments has to be filled in to determine the width of the slit.
- In the general sheet(s) the correct range of cells has to be set to determine the maximum surface area. If not all surfaces are selected it is possible to obtain fraction values larger than 1. On the other hand if cells are selected for pressures that do not occur an error will appear and the fractions will not be calculated.
- In the data sheet(s) the correct range of cells has to be set. The spreadsheet is designed for increasing pressures, once the maximum pressure is reached also the maximum opening is reached. When the pressure starts decreasing there will be two different moments in time whereby the pressure is in a certain interval. However temperatures can be different in those moments. Since the spreadsheet cannot see the difference between increasing and decreasing pressures all values will be taken for determining the average temperature and density, which will lead to inaccurate results. Therefore it is important to select a range of cells which ends after the maximum pressure is reached.
- To obtain complete graphs appropriate ranges have to be set.

5. Results

5.1 Assessment evacuation time

In table 10, 11 and 12 an overview is given of the most important simulation results regarding evacuation through the front door. In paragraph 3.5 a threshold was given to assess evacuation possibilities during a fire. To assure safe evacuation of building occupants the pressure in compartment 1 may not exceed 30 Pascal in the first three minutes after ignition. The results in table 10 show that for all simulated scenarios the threshold is exceeded. Even for the dwelling designed according the minimum requirements of the Dutch building code.

Table 10 - Overview results

	With ventilation openings			Without ventilation openings		
Scenario	Max. pressure [Pa]	Max. pressure after [s]	Pressure[1] >30Pa [s]	Max. pressure [Pa]	Max. pressure after [s]	Pressure[1] >30Pa [s]
1	1348	275	55	1631	279	58
2	3730	186	32	4098	187	30
3	469	420	127	606	424	116
4	634	179	59	736	180	54
5	1649	119	29	1895	120	28
6	211	268	121	260	270	107
7	4708	214	33	5238	214	27
8	-	-	-	247	261	114

Table 11 - Conditions in each compartment after 3 minutes, ventilation openings included

		Compartment 1				Compartment 2					Compartment 3				Compartment 4			
No.	🔥	LLT	ULT	HGT	PRS	LLT	ULT	HGT	PRS	🔥	LLT	ULT	HGT	PRS	LLT	ULT	HGT	PRS
1	x	32.8	74.6	0.38	679	20.9	46.9	1.18	683		20.5	20.5	2.48	676	20.6	33.4	1.66	685
2	x	73.8	236	0.03	3691	23.9	127	0.69	3703		22.4	22.5	2.16	3650	22.9	67.3	0.98	3708
3	x	22.5	39.7	1.05	82	20.2	31.0	1.79	83		20.1	20.1	2.58	83	20.1	24.2	2.25	83
4		20.4	20.0	2.60	495	20.5	42.0	1.56	495	x	48.8	184	0.00	633	20.4	30.7	2.23	496
5		19.9	20.0	1.89	< 0	20.2	39.1	1.89	< 0	x	56.1	219	0.00	< 0	20.0	35.4	1.55	< 0
6		20.1	20.0	2.60	91	20.1	22.3	2.37	91	x	27.4	62.7	0.18	115	20.1	20.0	2.60	91
7	x	53.0	162	0.06	2887	23.3	85.0	0.89	2896		22.0	22.1	2.29	2850	22.3	47.9	1.16	2899

Table 12 - Conditions in each compartment after 3 minutes, ventilation openings not included

		Compartment 1				Compartment 2					Compartment 3				Compartment 4			
No.	🔥	LLT	ULT	HGT	PRS	LLT	ULT	HGT	PRS	🔥	LLT	ULT	HGT	PRS	LLT	ULT	HGT	PRS
1	x	32.6	78.9	0.42	806	21	49.0	1.18	810		20.6	20.7	2.48	802	20.7	34.9	1.64	811
2	x	74.4	235	0.03	4051	24.1	127	0.68	4063		22.7	22.7	2.16	4009	23.1	67.2	0.97	4068
3	x	22.5	39.9	1.08	105	20.2	31.1	1.78	106		20.1	20.1	2.58	106	20.1	24.3	2.23	106
4		20.4	20.0	2.60	601	20.6	42.0	1.54	601	x	50.7	184	0.00	735	20.4	30.7	2.17	601
5		19.4	39.9	2.38	< 0	19.8	55.6	1.14	< 0	x	60.2	383	0.00	< 0	19.5	43.3	1.44	< 0
6		20.1	20.0	2.60	119	20.1	22.3	2.37	119	x	27.4	62.7	0.18	143	20.1	20.0	2.60	119
7	x	53.2	161	0.06	3270	23.6	84.8	0.85	3279		22.3	22.4	2.29	3233	22.6	48.0	1.14	3282
8	x	33.4	78.2	0.25	128	20.4	46.8	1.25	134		20.1	20.1	2.49	127	20.2	33.0	1.85	136

LLT = Lower Layer Temperature [°C]
HGT = Height lower layer [m]
PRS = Pressure [Pa]
ULT = Upper Layer Temperature
🔥 = Fire in compartment
Failure by toxic smoke layer
Failure by gas temperatures
Failure by both conditions

[1] Pressure in compartment 1, in this compartment exits are located.

5.1.1 Pressure peak

The simulations where ventilation openings were considered show little differences with the simulations where ventilation openings were neglected. Due to the ventilation openings the pressure peak is reduced, but in an early stage of the fire development the pressure increase looks similar, as showed in figure 13 for scenario 1. The pressure is only plotted until the maximum is reached, because the adjustments of the openings cannot be made for decreasing pressures.

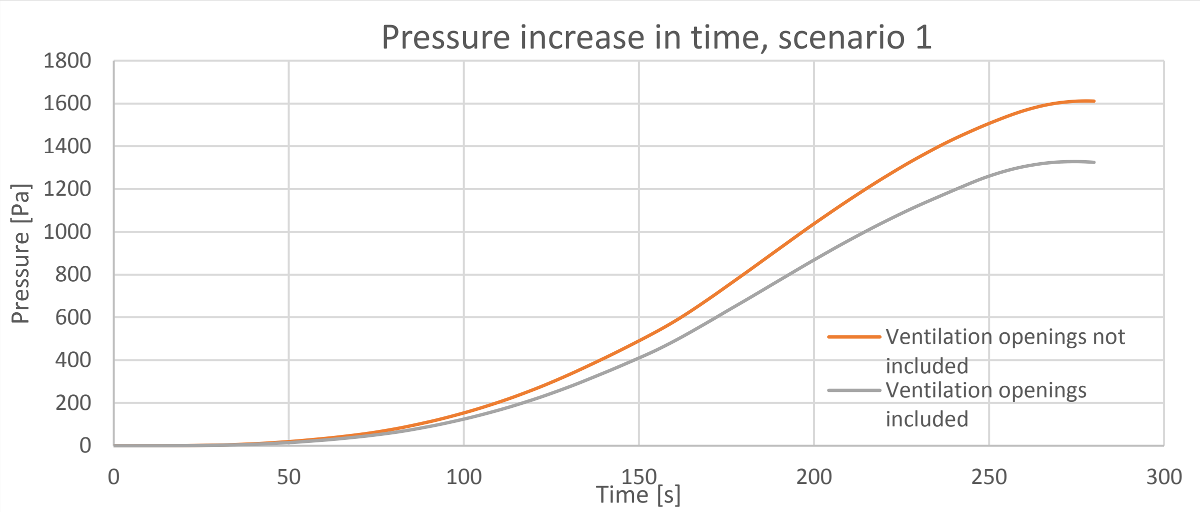

Figure 13 - Pressure increase in time, till maximum pressure is reached

After 269 seconds the oxygen level in the fire compartment drops below 15% and the fire becomes ventilation controlled (scenario 1). This explains that the pressure peak is already reached although the fire is not yet fully developed. Due to the reduced oxygen level the heat release rate drops rapidly, which also decreases the over pressure rapidly. High pressures occurred only for a few minutes and will be restored to normal levels by the time the fire brigade arrives.

5.1.2 Pressure difference between compartments

Since some connections between compartments were relatively small it was expected that there would be pressure differences between these compartments. However, figure 14 shows a similar pressure increase for all compartments when the fire is located in compartment 1. This compartment has a large open connection with compartment 2, and compartment 2 has this same connection with compartment 4. Compartment 2 and 3 are connected by a 2 cm high slit under a closed door. The results indicate that this slit of 2cm is large enough to have an equal pressure increase in all compartments and that the dwelling also could have been modelled as one compartment.

In figure 15 can be seen that when a fire started in a compartment with a small connection to its surrounding compartment(s) the pressure increase is different from other compartments. In this case the slit under the door is too small to have an equal pressure increase. However, this difference in pressure increase does not prevent exceedance of the threshold for save evacuation.

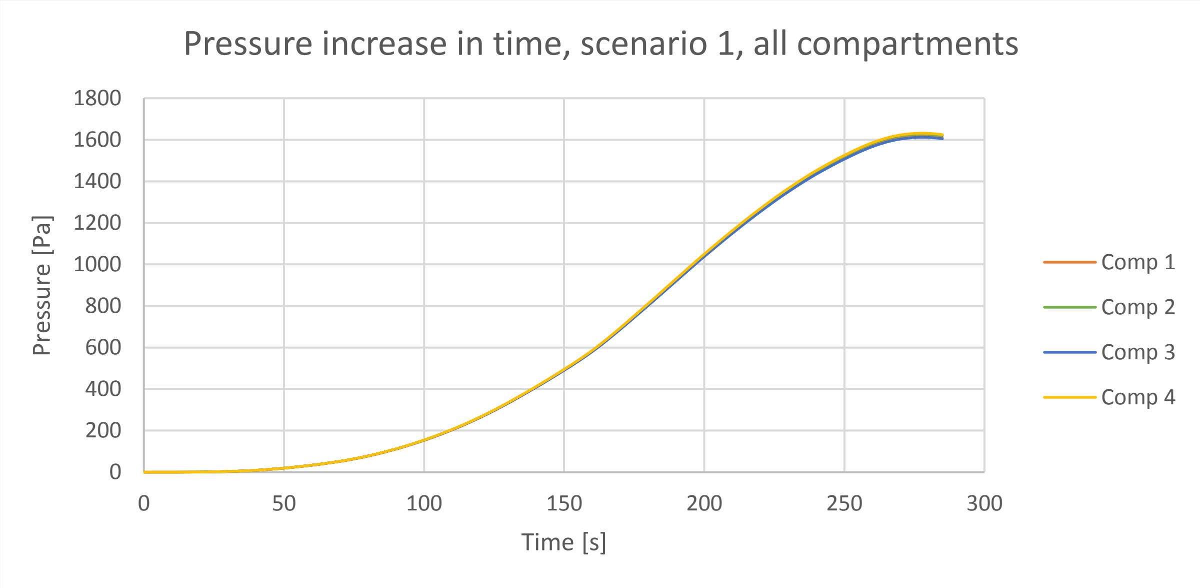

Figure 14 - Pressure increase in different compartments, scenario 1

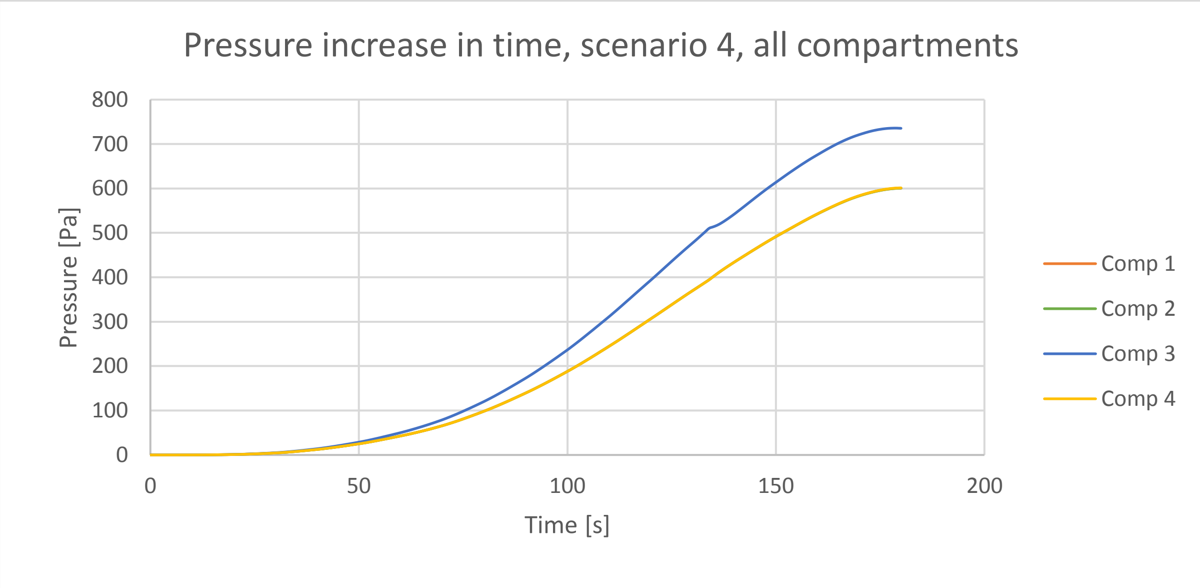

Figure 15 - Pressure increase in different compartments, scenario 4

Although the threshold for pressure is exceeded the conditions in compartment 1, 2 and 4 are survivable due to the closed door. When building occupants are located in one of these compartments they are able to reach the front door within 3 minutes. At that moment the pressure will be too high to open the door, but the hot smoke layer will not form a problem for at least 10 minutes, provided that the door of the fire room is kept closed. After 5 à 6 minutes the pressure has dropped and the door can be opened. This is only applicable if the fire is located at the first floor or higher and doors remain closed.

5.1.3 Consequences fire growth rate

The pressure increase is showed in figure 16 and 17 for different fire growth rates. In absolute numbers the fast growth rate shows the largest reduction of the pressure peak when ventilation openings are considered in the simulations. However, this is only an 8.9% reduction, where 17.4% can be reduced for a medium growth rate and 22.6% for a slow growth rate. This indicates that for rapidly developing fires the influence of the mechanical ventilation system is negligible. Although slower growth rates show better results figure 17 clearly indicates that in the first two minutes the pressure increase is almost equal for simulations with and without mechanical ventilation openings included. For all three growth rates consideration of the mechanical ventilation openings cannot prevent exceedance of the threshold (30 Pascal) within roughly two minutes.

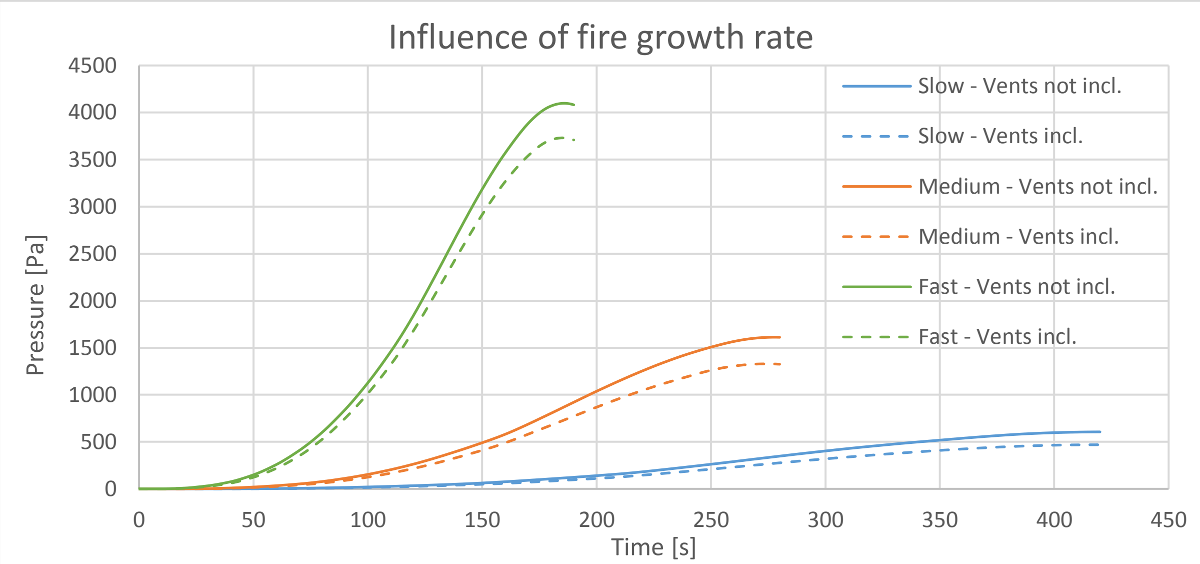

Figure 16 - Pressure increase in time for different fire growth rates, fire is located in compartment 1

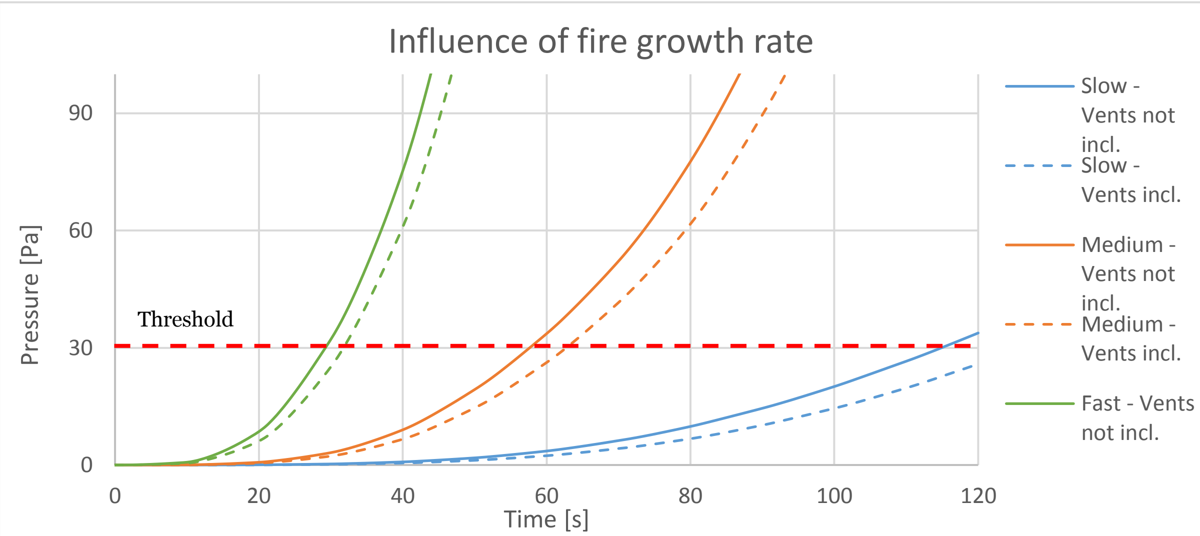

Figure 17 - Pressure increase in first two minutes for different fire growth rates, fire is located in compartment 1

5.2 Application of a pressure release valve

To extend the available safe evacuation time the minimum size and influence of a pressure release valve has been studied. To assure safe evacuation of building occupants the pressure in compartment 1 has to be kept below 30 Pascal. A pressure release valve is placed next to the front door in compartment 1 and opens when the pressure difference with the outside environment reached 30Pa. It is assumed the valve will maintain open once it has been opened. And only scenarios with a medium fire growth rate have been studied.

In paragraph 3.5 the required evacuation time has been determined, namely 3 minutes. In other words the pressure has to be kept below 30 Pascal by the valve in the first 3 minutes. In figure 18 the pressure increase can be seen with application of a pressure release valve. Hereby the fire is located in compartment 1 and a valve of 20x25cm is applied in compartment 1. After approximate 60 seconds the pressure reaches 30 Pascal and the valve is opened. This causes an immediate pressure drop, hereafter the pressure starts increasing slowly. During the evacuation time (first 3 minutes) the pressure in compartment 1 is lower than 30 Pascal, which makes it possible for building occupants to open the front door and escape. Exceedance of the threshold after 3 minutes is acceptable, because by the time the fire brigade arrives the pressure has already dropped due to a lack of oxygen.

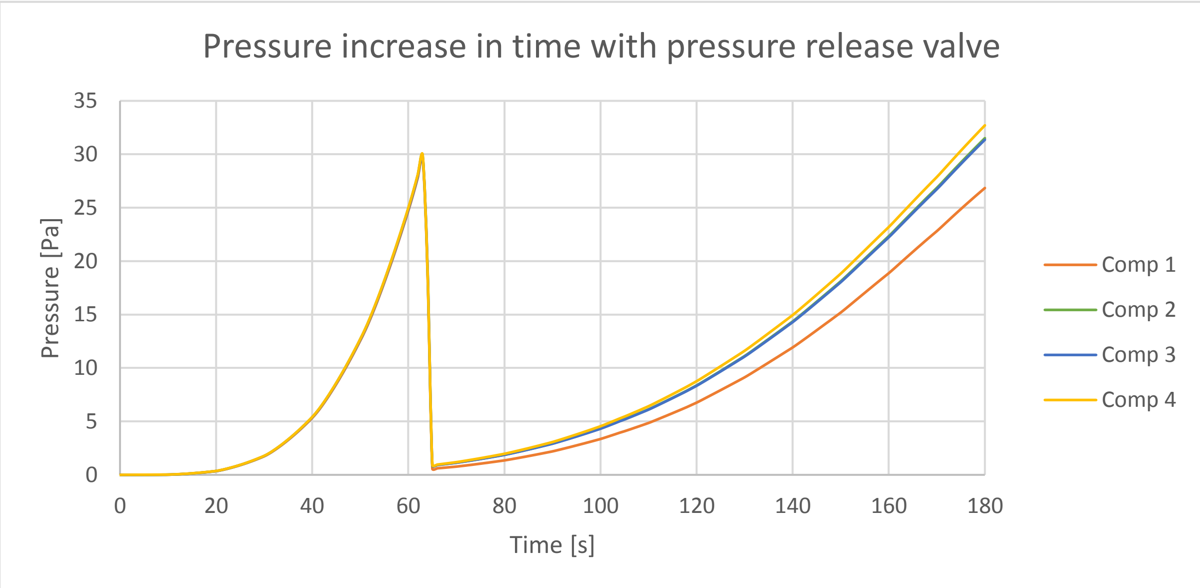

Figure 18 - Pressure increase in time, 20x25cm pressure release valve, fire located in compartment 1

Several valve sizes, positions and numbers have been studied. The results of this study show that a minimum cross sectional area of 0.05m² is required to prevent exceedance of the threshold in compartment 1. Placing two valves, one in compartment 1 and the other in compartment 4, still requires the same total cross sectional area. This can be explained by the relatively large connections between compartments 1, 2 and 4. When it is assumed the fire is located in compartment 3 the valve can be smaller. Due to the closed door between compartment 2 and 3 the pressure in compartment 3 is higher than in other compartments. In figure 19 can be seen that the pressure increases rapidly again in compartment 3 after the valve is opened, while in other compartments the pressure is maximum 30 Pascal.

Since fire ignition in other compartments then compartment 3 cannot be ruled out and open/closed doors cannot be predicted a valve size of 0.05m² will still be required.

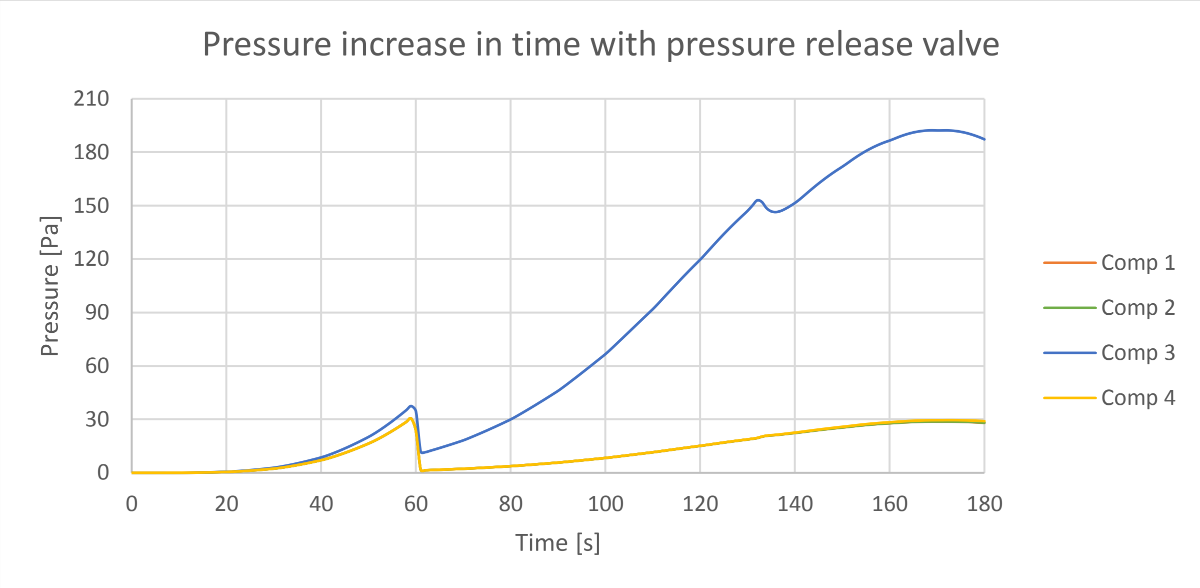

Figure 19 - Pressure increase in time, 15x25cm pressure release valve, fire located in compartment 3

6. Conclusion

In earlier performed studies toward fire development in modern airtight dwellings has been concluded that pressure built-up in an early stage of the fire may cause circumstances whereby building occupants are unable to escape safely from the building. However, in these studies the potential openings of the balanced mechanical ventilation system were neglected. In this study simulations has been made with mechanical ventilation openings, in order to determine its influence on the fast pressure increase in airtight dwellings.

From the performed simulations can be concluded that, despite the fire growth rate and location of the fire, the pressure increase in airtight dwellings is too high in the first three minutes to assure safe evacuation of building occupants. The mechanical ventilation system has only an influence on the pressure peak, which can be reduced with a few hundreds of Pascal, depending on the fire scenario. However, the threshold for safe escape of 30 Pascal is reached after approximately the same time, for simulations with and without mechanical ventilation openings. The extension of available evacuation time is only a few seconds and results in an available evacuation time of 0.5 - 2 minutes, depending on the fire scenario. The influence of the mechanical ventilation system is too small to assure safe evacuation of occupants within 3 minutes after ignition, this means that the stated hypothesis can be rejected.

The total balanced mechanical ventilation system has a resistance in such a way that the equivalent surface opening is reduced to a small fraction of the actual opening through the building envelope. Consequence of this reduction is a minimum impact of the mechanical ventilation system on the fire behaviour and safety of building occupants.

Due to the minimum influence of the mechanical ventilation system consequence for the fire service do not differ from results of earlier studies. By the time the fire services arrive the pressure has already dropped and the fire became oxygen controlled. Therefore it is still possible that creating openings by the fire services cause a smoke gas explosion or backdraft.

To extend available evacuation time a pressure release valve near the front door is a suitable solution. Opening the valve when a pressure difference of 30 Pascal is reached extends the available evacuation time to 3 minutes, if a medium fire growth rate has been applied. For the performed case the valve has a relatively large size of 20x25cm, which makes it from other perspectives a less desired solution.

From this study can be concluded that conclusions from earlier studies can be upheld. Modern airtight buildings maintain a potential danger for building occupants due to high pressures which make it more difficult to escape. Smoke gas explosion or backdraft are still potential risks for fire services.

7. Perspective view on research

7.1 Reliability

Due to absence of field experiments it is difficult to validate the results of the simulations. Different factors that are not modelled can influence the results. Soot particles may constipate air filters in the ventilation system unit, which results in higher pressures. Also the changing behaviour of cracks are not considered. At higher temperature it is possible that cracks widen and the pressure increase will be reduced. Since it is expected that both mentioned situations do not occur in the first minutes of the fire its influence can be neglected for circumstances during evacuation.

Ducts that form connections between rooms are not modelled. These connections contribute to spreading of smoke and through the entire dwelling and may possibly level out pressure differences between rooms. The little quantity of smoke that is distributed through the ducts increases the temperature and smoke layer height in other compartments, but this small impact can be neglected since the pressure is the determining factor for occupant safety.

7.2 Dwelling type

The performed simulations are based on airtightness measurements. The results of these measurements indicate that the airtightness class of the dwelling is “good”. This means that for passive houses the pressure increase can even be higher. But also for less airtight dwellings has been proved that pressure increase cause problems for evacuation of occupants. This indicates that the problem may occur for all modern build dwellings.

7.3 Limitations & improvements

The currently developed model has some limitations. These limitations are not crucial for the results, but improvement of these limitations can be interesting for other studies.

At the moment “standard” pressure intervals are used in the spreadsheet. The possibility of user-defined intervals offer the modeller to solve problems were smaller pressure intervals are required.

Also it is not possible to model fluctuating pressure differences with the spreadsheet. For this study this is less relevant since only the pressure increase in the beginning is relevant. Extension of the spreadsheet with fluctuating pressure intervals can be an added value for other studies.

8. References

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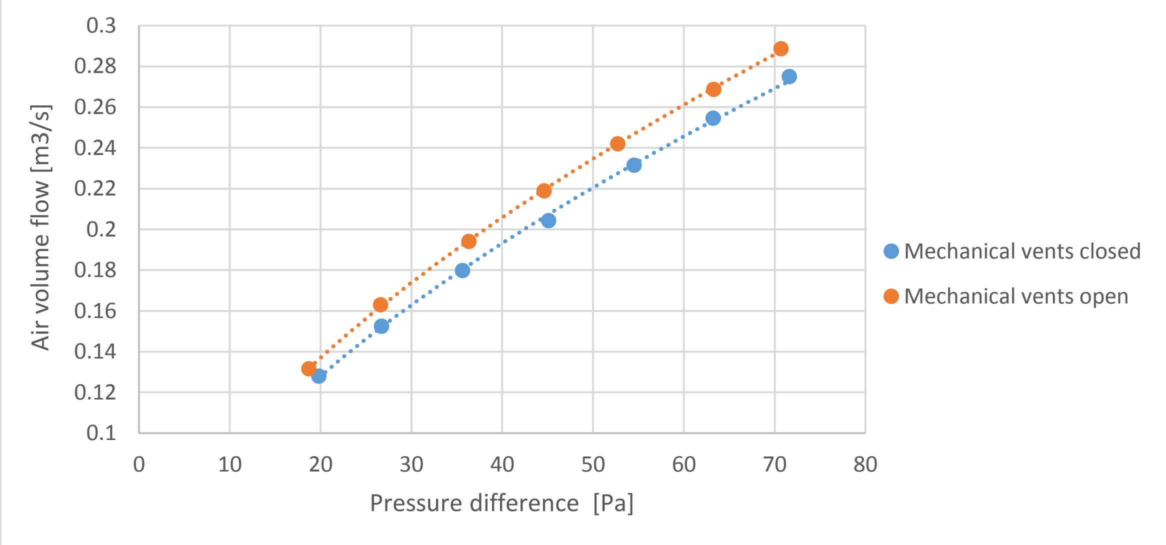
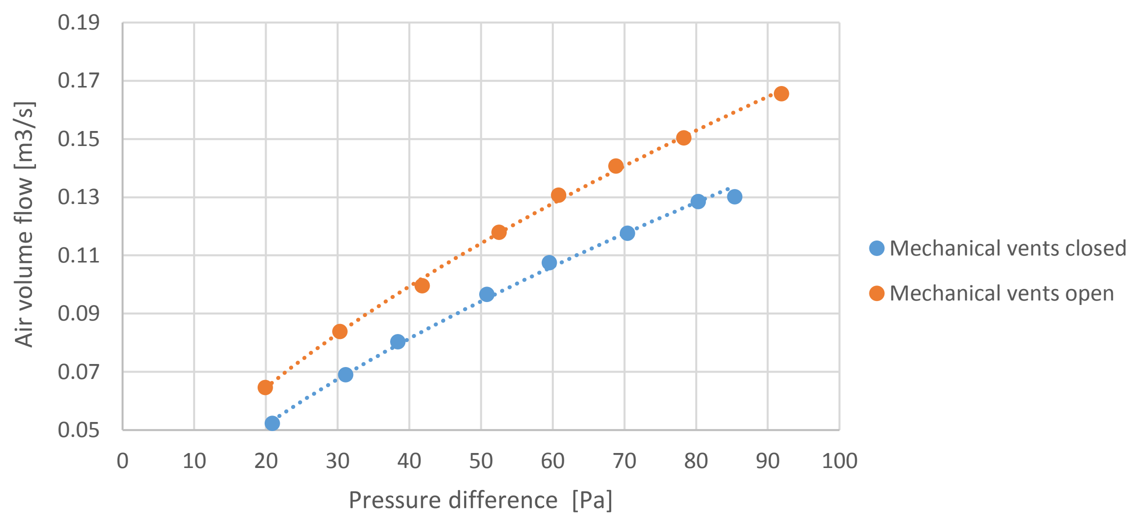
9. Attachments

9.1 Results Airtightness measurements and analysis

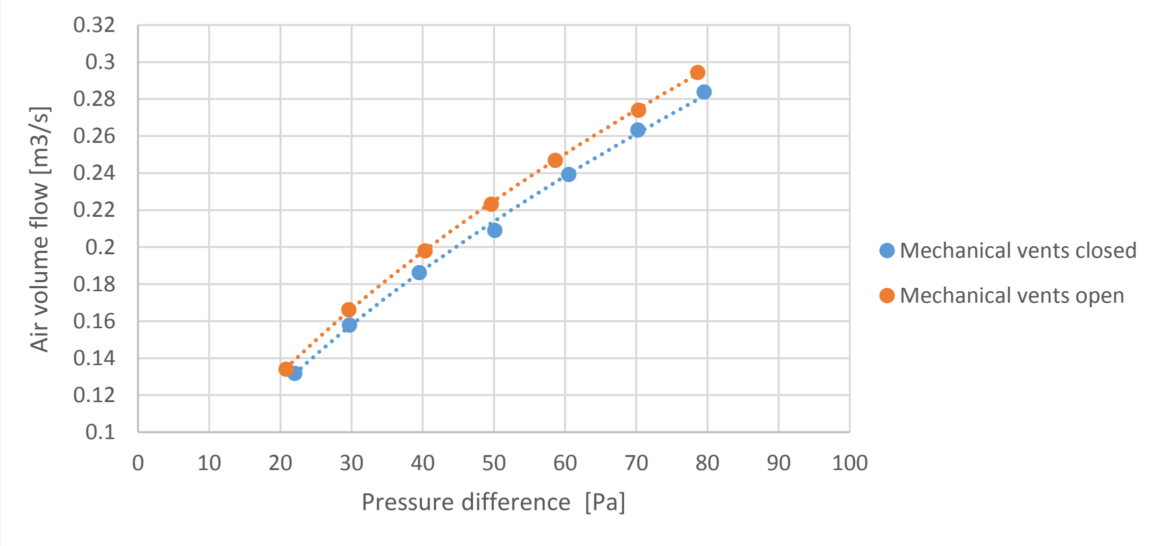
Project	Dwelling Epe	
User surface area [m²]	124	
Building volume [m³]	322.4	
Date measurements	November 24th, 2016	
Inside temperature	20	
Outside temperature	4	
	Mech. vents closed	Mech. vents open
$Q_{v,10}$ [dm³/s]	84.9	91.1
$Q_{v,10}$ [dm³/s.m²]	0.685	0.735
Flow exponent [-]	0.593	0.587
Air permeability coefficient (C) [m³/s]	0.0236	0.0217
Equivalent surface area [cm²]	157.9	157.9 + 26.1
Equivalent surface area [cm²/m²]	1.27	1.27 + 0.21
Q_{vents} [dm³/s] =	0.0019*√(ΔP)	



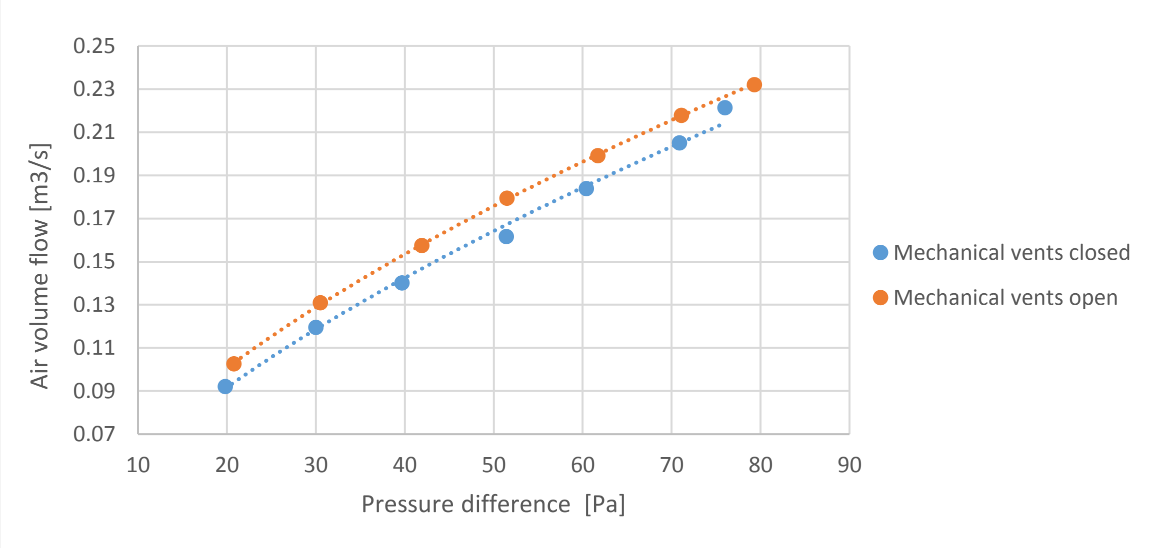
Project	Dwelling Lieverley	
User surface area [m^2]	121.9	
Building volume [m^3]	320	
Date measurements	August 3rd 2016	
Inside temperature	17	
Outside temperature	17	
	Mech. vents closed	Mech. vents open
$Q_{v,10}$ [dm^3/s]	34	47.8
$Q_{v,10}$ [dm^3/s.m^2]	0.279	0.392
Flow exponent [-]	0.654	0.622
Air permeability coefficient (C) [m^3/s]	0.0073	0.01
Equivalent surface area [cm^2]	51.1	51.1 + 36.9
Equivalent surface area [cm^2/m^2]	0.42	0.42 + 0.3
Q_{vents} [dm^3/s] =	0.0028*√(ΔP)	



Project	Dwelling Rhenen nr. 150	
User surface area [m²]	119	
Building volume [m³]	309.4	
Date measurements	June 6th, 2016	
Inside temperature	20	
Outside temperature	25	
	Mech. vents closed	Mech. vents open
$Q_{v,10}$ [dm³/s]	82.3	87
$Q_{v,10}$ [dm³/s.m²]	0.692	0.731
Flow exponent [-]	0.593	0.587
Air permeability coefficient (C) [m³/s]	0.021	0.0226
Equivalent surface area [cm²]	153	153 + 21.2
Equivalent surface area [cm²/m²]	1.29	1.29 + 0.18
Q_{vents} [dm³/s] =	0.0016*√(ΔP)	

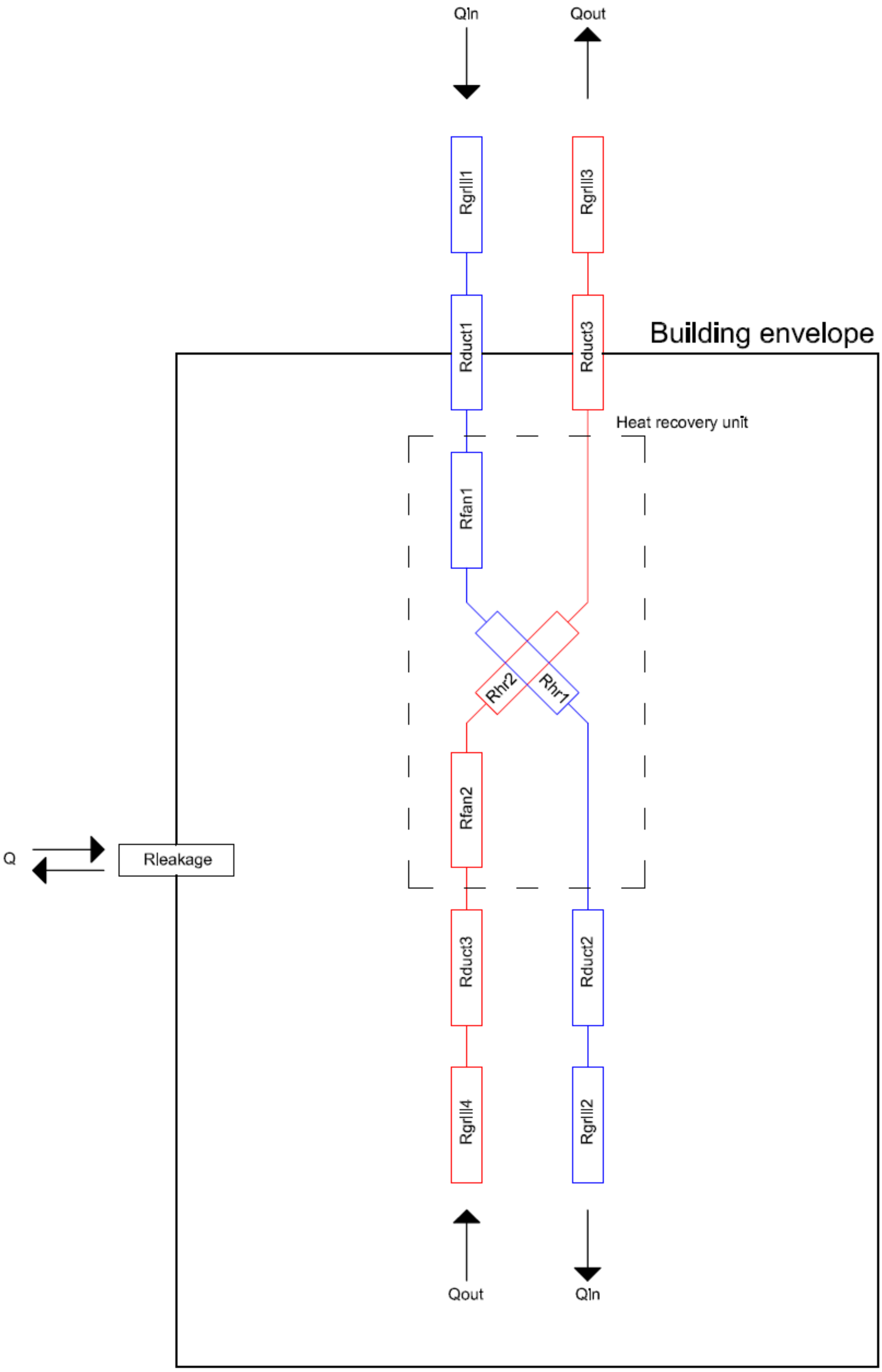


Project	Dwelling Rhenen nr. 157	
User surface area [m²]	125.9	
Building volume [m³]	327.3	
Date measurements	June 6th, 2016	
Inside temperature	20	
Outside temperature	25	
	Mech. vents closed	**Mech. vents open**
$Q_{v,10}$ [dm³/s]	0.465	65.2
$Q_{v,10}$ [dm³/s.m²]	58.5	0.518
Flow exponent [-]	0.636	0.608
Air permeability coefficient (C) [m³/s]	0.0137	0.0163
Equivalent surface area [cm²]	96.4	96.4 + 19.4
Equivalent surface area [cm²/m²]	0.77	0.77 + 0.15
Q_{vents} [dm³/s] =	0.0015*√(ΔP)	

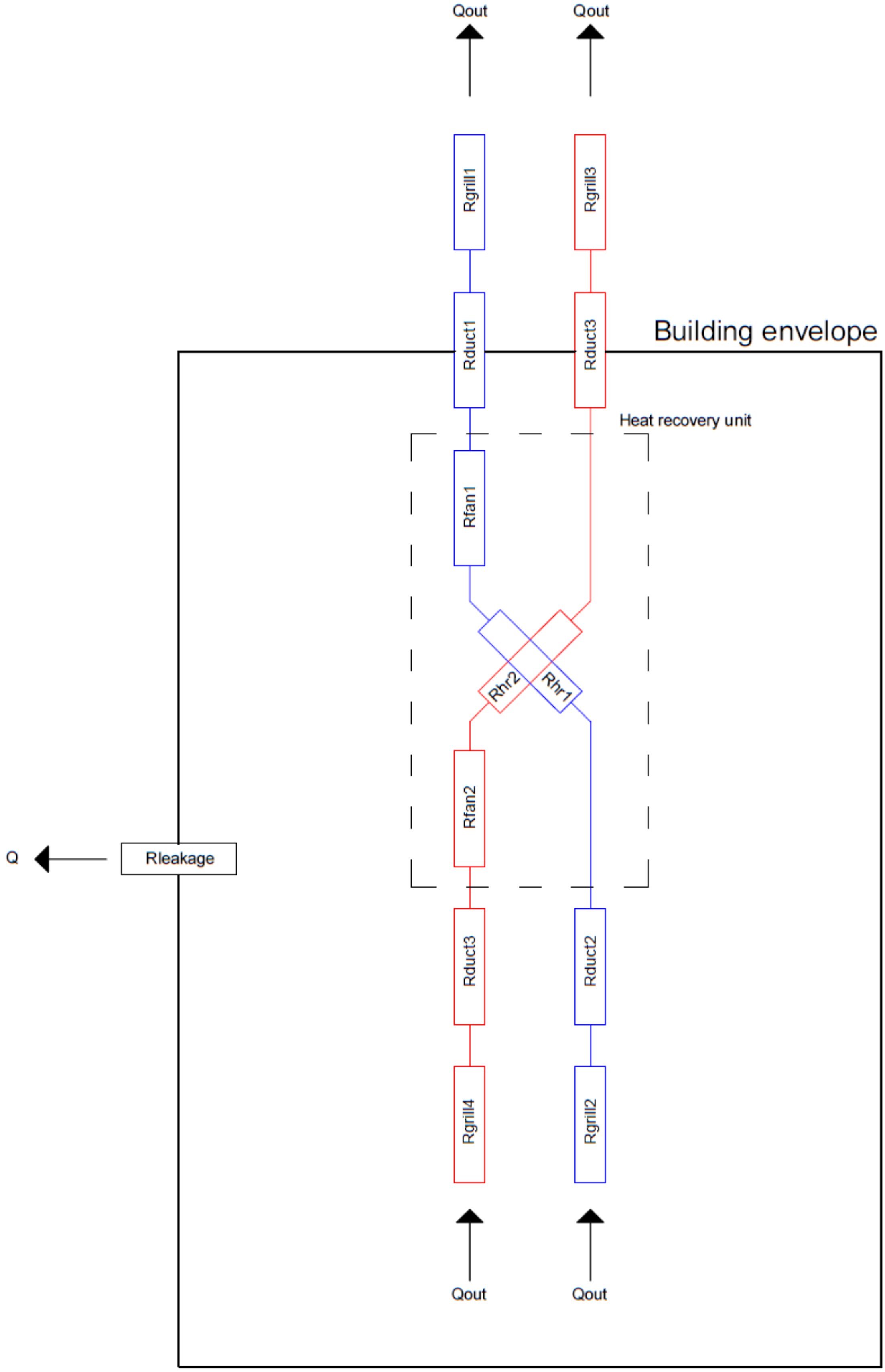


9.2 Air flow schemes with resistances

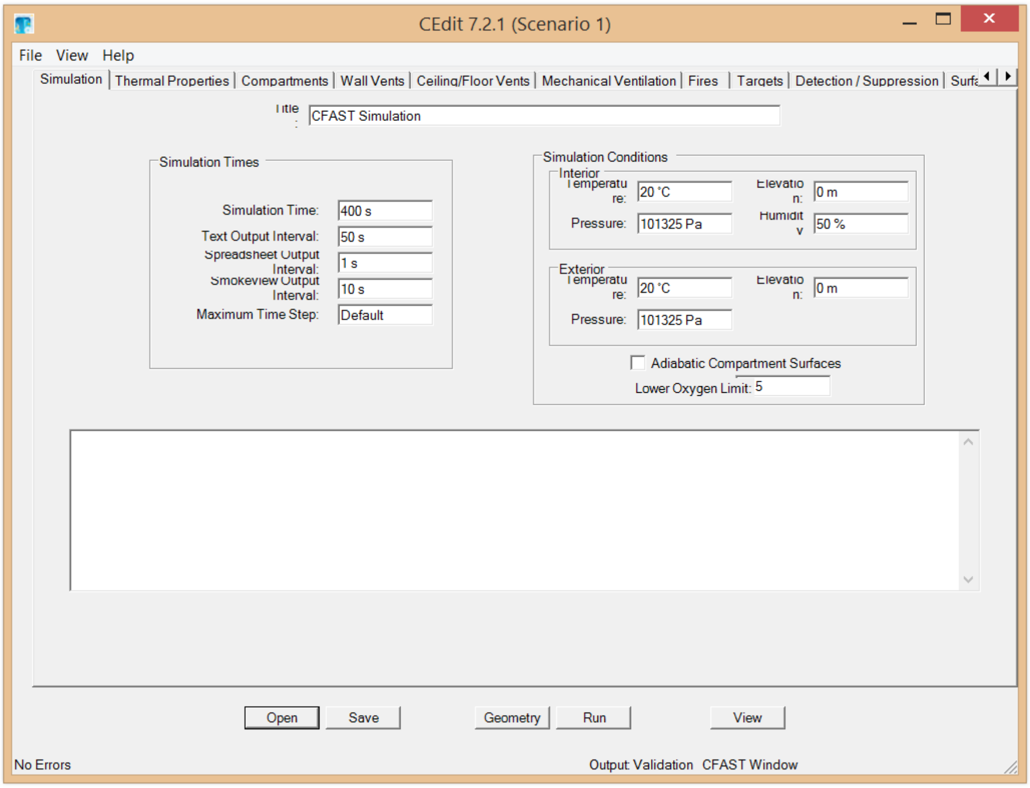
Normal situation

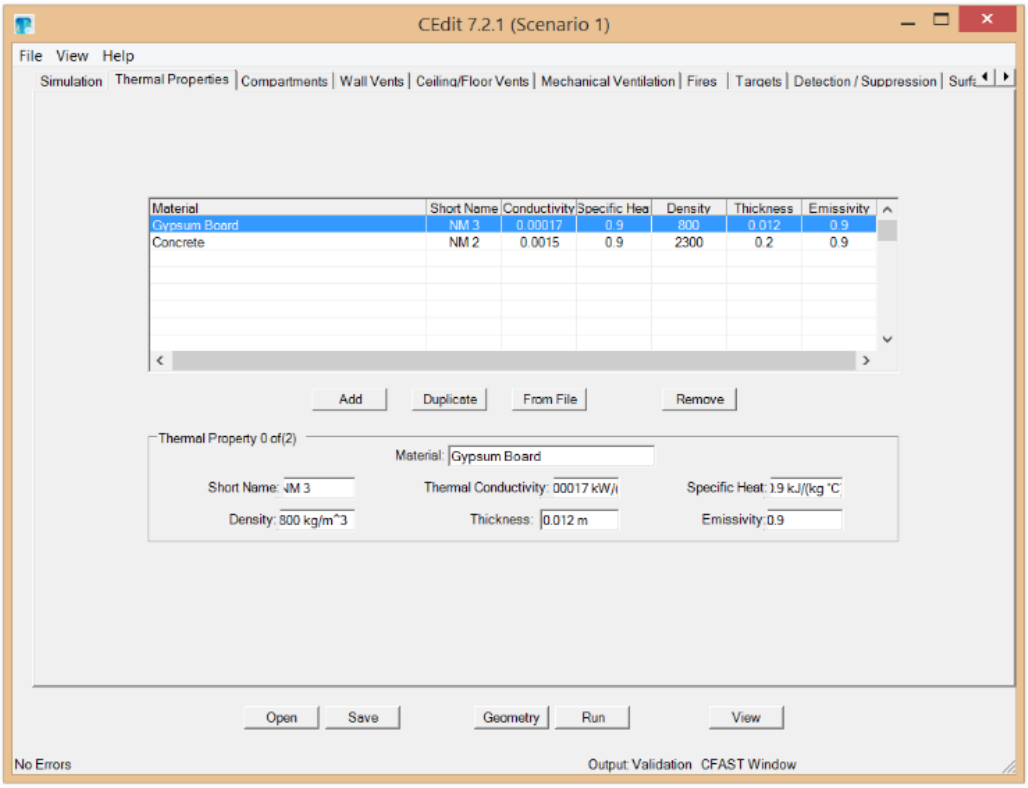


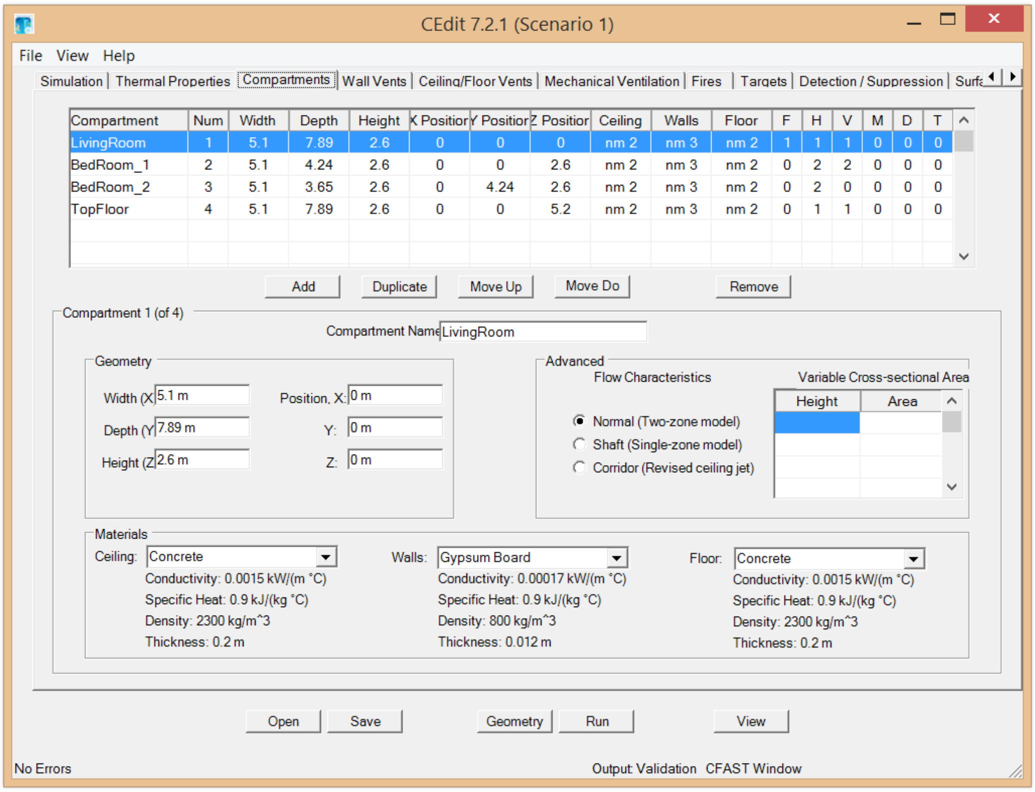
Overpressure (development stage of fire)

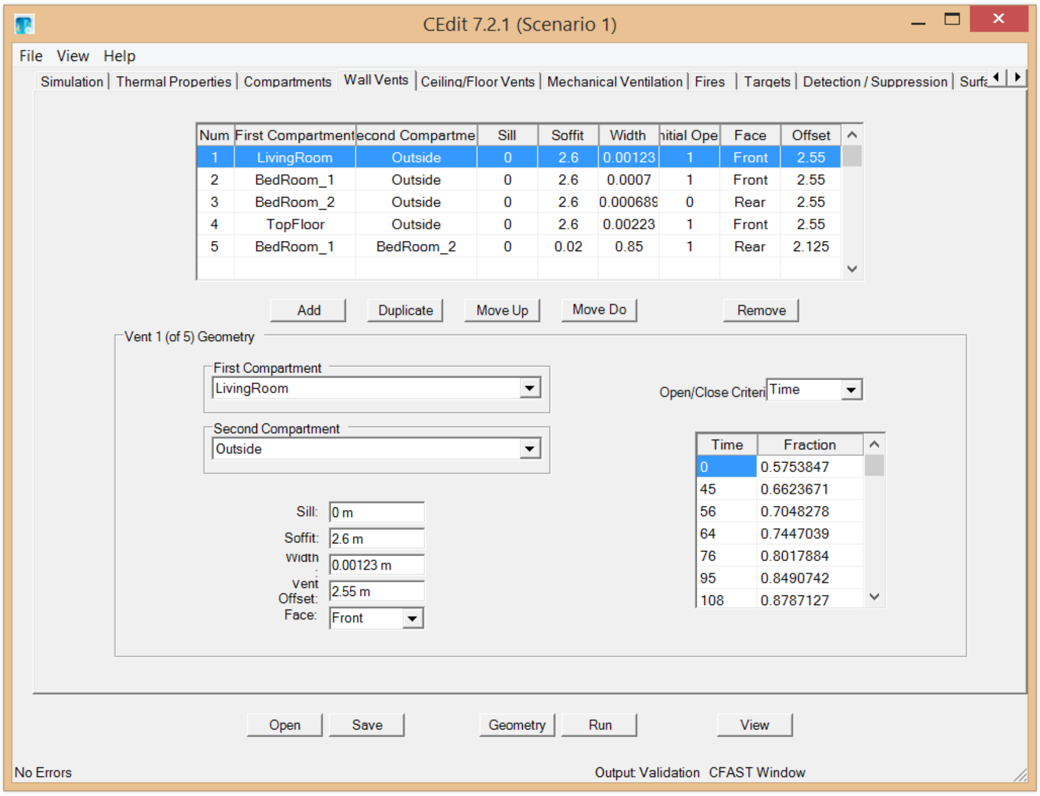


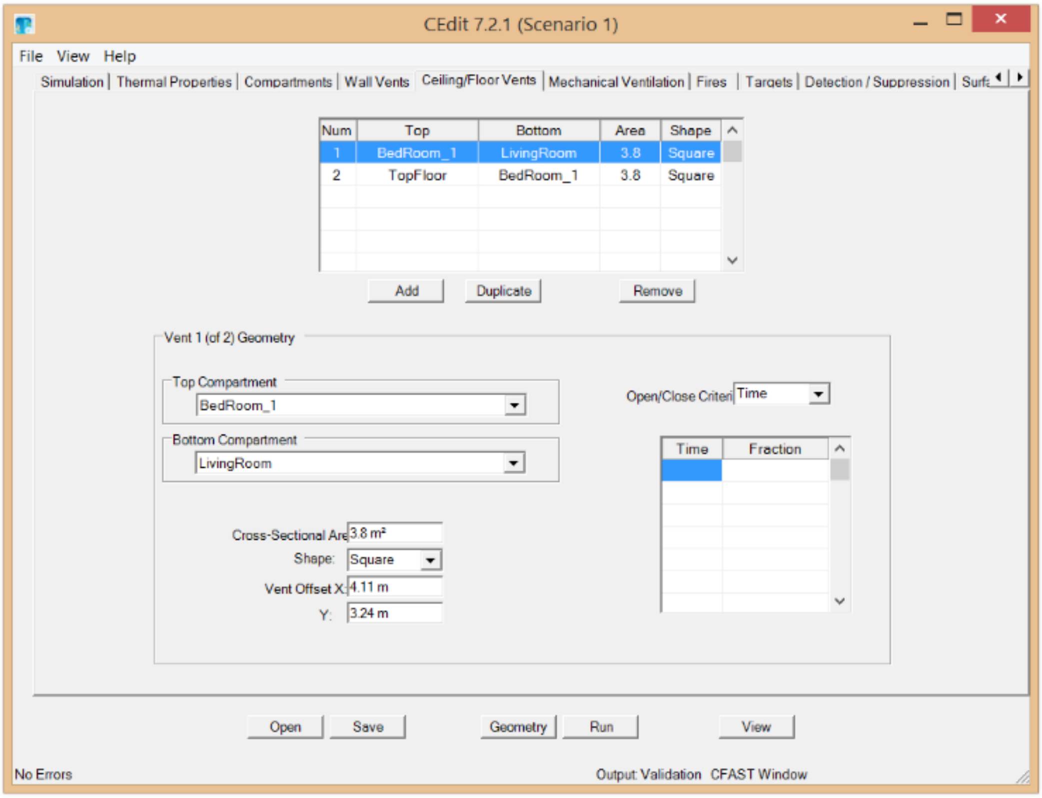
9.3 Input CFAST

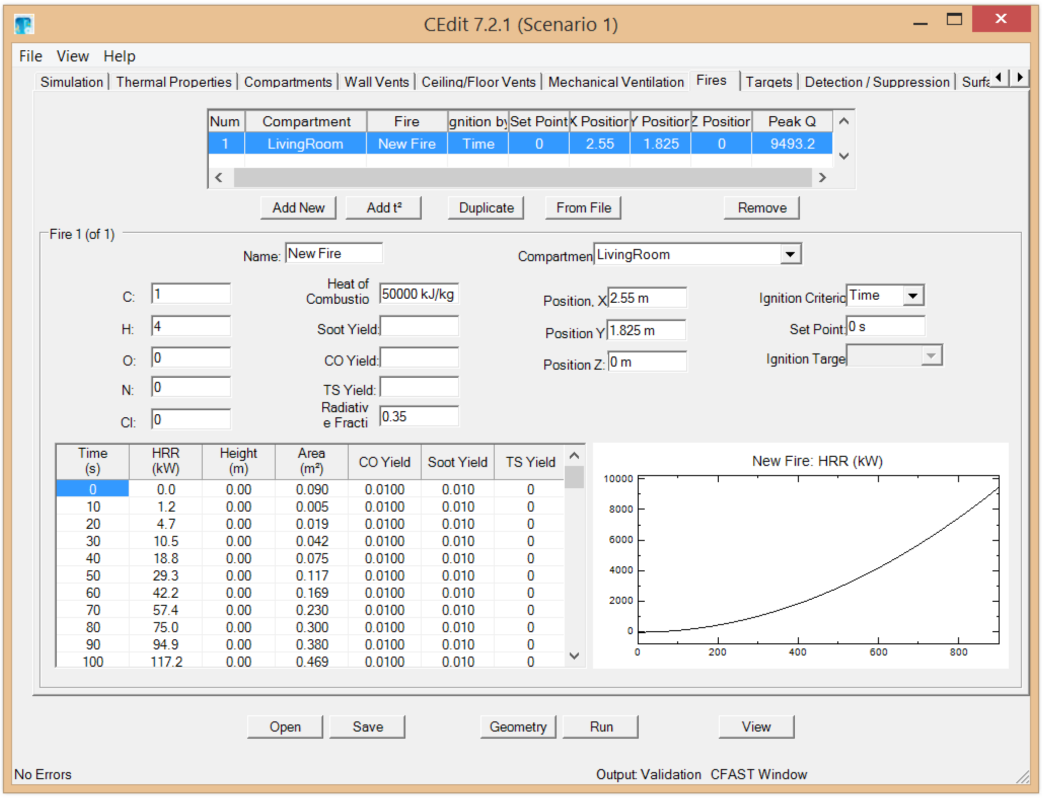


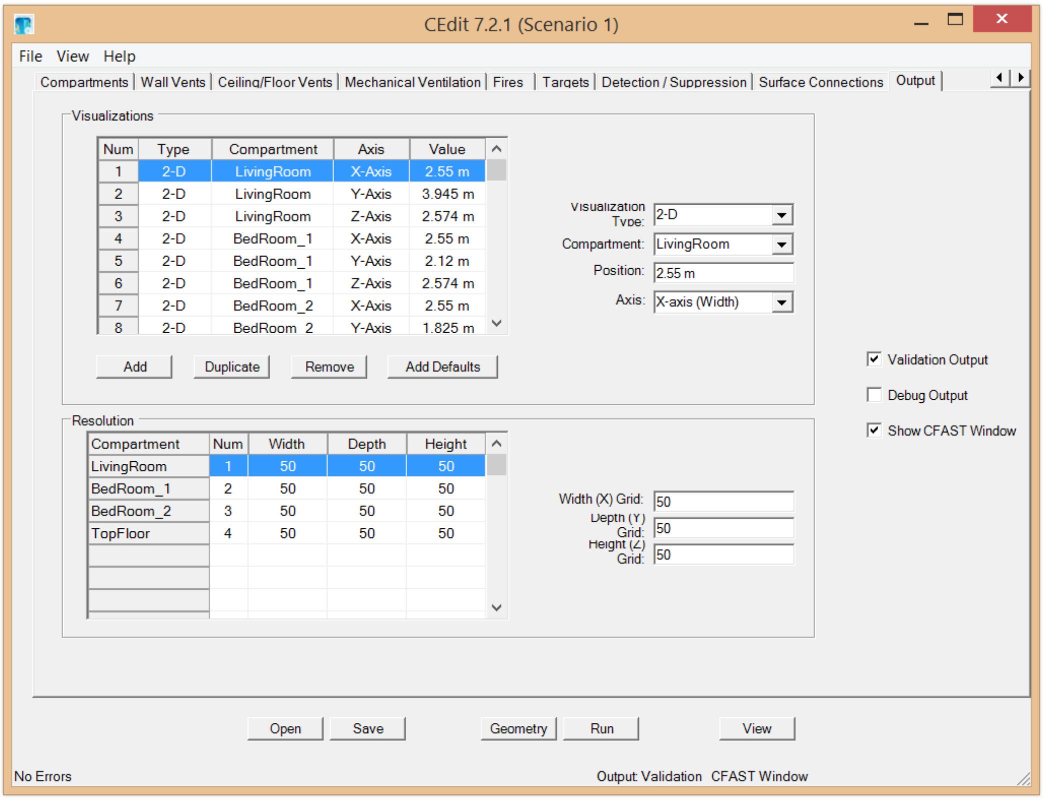



CEdit 7.2.1 (Scenario 1)
File View Help
Simulation | Thermal Properties | Compartments | Wall Vents | Ceiling/Floor Vents | Mechanical Ventilation | Fires | Targets | Detection / Suppression | Surfa
Compartment | Num | Width | Depth | Height | X Position | Y Position | Z Position | Ceiling | Walls | Floor | F | H | V | M | D | T
LivingRoom | 1 | 5.1 | 7.89 | 2.6 | 0 | 0 | 0 | nm 2 | nm 3 | nm 2 | 1 | 1 | 1 | 0 | 0 | 0
BedRoom_1 | 2 | 5.1 | 4.24 | 2.6 | 0 | 0 | 2.6 | nm 2 | nm 3 | nm 2 | 0 | 2 | 2 | 0 | 0 | 0
BedRoom_2 | 3 | 5.1 | 3.65 | 2.6 | 0 | 4.24 | 2.6 | nm 2 | nm 3 | nm 2 | 0 | 2 | 0 | 0 | 0 | 0
TopFloor | 4 | 5.1 | 7.89 | 2.6 | 0 | 0 | 5.2 | nm 2 | nm 3 | nm 2 | 0 | 1 | 1 | 0 | 0 | 0
Add Duplicate Move Up Move Do Remove
Compartment 1 (of 4)
Compartment Name LivingRoom
Geometry
Width (X 5.1 m
Depth (Y 7.89 m
Height (Z 2.6 m
Position, X: 0 m
Y: 0 m
Z: 0 m
Advanced
Flow Characteristics
Normal (Two-zone model)
Shaft (Single-zone model)
Corridor (Revised ceiling jet)
Variable Cross-sectional Area
Height Area
Materials
Ceiling: Concrete
Conductivity: 0.0015 kW/(m °C)
Specific Heat: 0.9 kJ/(kg °C)
Density: 2300 kg/m^3
Thickness: 0.2 m
Walls: Gypsum Board
Conductivity: 0.00017 kW/(m °C)
Specific Heat: 0.9 kJ/(kg °C)
Density: 800 kg/m^3
Thickness: 0.012 m
Floor: Concrete
Conductivity: 0.0015 kW/(m °C)
Specific Heat: 0.9 kJ/(kg °C)
Density: 2300 kg/m^3
Thickness: 0.2 m
Open Save Geometry Run View
No Errors
Output Validation CFAST Window


CEdit 7.2.1 (Scenario 1)
File View Help
Simulation | Thermal Properties | Compartments | Wall Vents | Ceiling/Floor Vents | Mechanical Ventilation | Fires | Targets | Detection / Suppression | Surfa
Num | First Compartment | Second Compartment | Sill | Soffit | Width | Initial Open | Face | Offset
1 | LivingRoom | Outside | 0 | 2.6 | 0.00123 | 1 | Front | 2.55
2 | BedRoom_1 | Outside | 0 | 2.6 | 0.0007 | 1 | Front | 2.55
3 | BedRoom_2 | Outside | 0 | 2.6 | 0.000689 | 0 | Rear | 2.55
4 | TopFloor | Outside | 0 | 2.6 | 0.00223 | 1 | Front | 2.55
5 | BedRoom_1 | BedRoom_2 | 0 | 0.02 | 0.85 | 1 | Rear | 2.125
Add Duplicate Move Up Move Do Remove
Vent 1 (of 5) Geometry
First Compartment
LivingRoom
Second Compartment
Outside
Open/Close Criteri Time
Time | Fraction
0 | 0.5753847
45 | 0.6623671
56 | 0.7048278
64 | 0.7447039
76 | 0.8017884
95 | 0.8490742
108 | 0.8787127
Sill: 0 m
Soffit: 2.6 m
Width 0.00123 m
Vent Offset: 2.55 m
Face: Front
Open Save Geometry Run View
No Errors
Output Validation CFAST Window


CEdit 7.2.1 (Scenario 1)
File View Help
Simulation | Thermal Properties | Compartments | Wall Vents | Ceiling/Floor Vents | Mechanical Ventilation | Fires | Targets | Detection / Suppression | Surfa
Num Top Bottom Area Shape
1 BedRoom_1 LivingRoom 3.8 Square
2 TopFloor BedRoom_1 3.8 Square
Add Duplicate Remove
Vent 1 (of 2) Geometry
Top Compartment
BedRoom_1
Bottom Compartment
LivingRoom
Open/Close Criteri Time
Time Fraction
Cross-Sectional Are 3.8 m²
Shape: Square
Vent Offset X: 4.11 m
Y: 3.24 m
Open Save Geometry Run View
No Errors
Output Validation CFAST Window


CEdit 7.2.1 (Scenario 1)
File View Help
Simulation | Thermal Properties | Compartments | Wall Vents | Ceiling/Floor Vents | Mechanical Ventilation | Fires | Targets | Detection / Suppression | Surfa
Num Compartment Fire gnition by Set Point X Position Y Position Z Position Peak Q
1 LivingRoom New Fire Time 0 2.55 1.825 0 9493.2
Add New Add t² Duplicate From File Remove
Fire 1 (of 1)
Name: New Fire
Compartmen LivingRoom
C: 1
H: 4
O: 0
N: 0
Cl: 0
Heat of Combustio 50000 kJ/kg
Soot Yield:
CO Yield:
TS Yield:
Radiativ e Fracti 0.35
Position X 2.55 m
Position Y 1.825 m
Position Z: 0 m
Ignition Criteria Time
Set Point 0 s
Ignition Targe
Time (s) HRR (kW) Height (m) Area (m²) CO Yield Soot Yield TS Yield
0 0.0 0.00 0.090 0.0100 0.010 0
10 1.2 0.00 0.005 0.0100 0.010 0
20 4.7 0.00 0.019 0.0100 0.010 0
30 10.5 0.00 0.042 0.0100 0.010 0
40 18.8 0.00 0.075 0.0100 0.010 0
50 29.3 0.00 0.117 0.0100 0.010 0
60 42.2 0.00 0.169 0.0100 0.010 0
70 57.4 0.00 0.230 0.0100 0.010 0
80 75.0 0.00 0.300 0.0100 0.010 0
90 94.9 0.00 0.380 0.0100 0.010 0
100 117.2 0.00 0.469 0.0100 0.010 0
New Fire: HRR (kW)
10000
8000
6000
4000
2000
0
0
200
400
600
800
Open Save Geometry Run View
No Errors
Output Validation CFAST Window

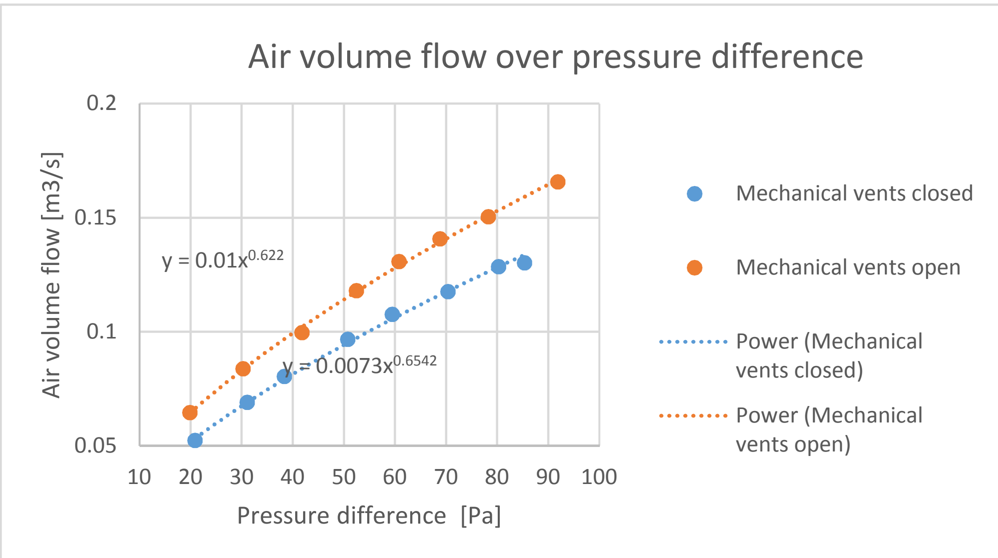

CEdit 7.2.1 (Scenario 1)
File View Help
Compartments | Wall Vents | Ceiling/Floor Vents | Mechanical Ventilation | Fires | Targets | Detection / Suppression | Surface Connections | Output
Visualizations
Num Type Compartment Axis Value
1 2-D LivingRoom X-Axis 2.55 m
2 2-D LivingRoom Y-Axis 3.945 m
3 2-D LivingRoom Z-Axis 2.574 m
4 2-D BedRoom_1 X-Axis 2.55 m
5 2-D BedRoom_1 Y-Axis 2.12 m
6 2-D BedRoom_1 Z-Axis 2.574 m
7 2-D BedRoom_2 X-Axis 2.55 m
8 2-D BedRoom_2 Y-Axis 1.825 m
Visualization Type: 2-D
Compartment: LivingRoom
Position: 2.55 m
Axis: X-axis (Width)
Add Duplicate Remove Add Defaults
Validation Output
Debug Output
Show CFAST Window
Resolution
Compartment Num Width Depth Height
LivingRoom 1 50 50 50
BedRoom_1 2 50 50 50
BedRoom_2 3 50 50 50
TopFloor 4 50 50 50
Width (X) Grid: 50
Depth (Y) Grid: 50
Height (Z) Grid: 50
Open Save Geometry Run View
No Errors
Output: Validation CFAST Window

9.4 Determination initial surface area mechanical ventilation openings

Name	Lieverley
Date measurement	August 3rd, 2016
User surface	121.9 m^2
Building volume	320 m^3
Temperature	17 °C

	Mechanical vents closed			
	Δ Pressure [Pa]	Air volume flow [dm3/s]	Air volume flow [m3/s]	Air volume flow [m3/h]
1	20.9	52.33	0.052333333	188.4
2	31.1	69.06	0.069055556	248.6
3	38.4	80.42	0.080416667	289.5
4	50.8	96.67	0.096666667	348
5	59.5	107.56	0.107555556	387.2
6	70.4	117.64	0.117638889	423.5
7	80.3	128.56	0.128555556	462.8
8	85.4	130.14	0.130138889	468.5
9				
10				

	Mechanical vents open			
	Δ Pressure [Pa]	Air volume flow [dm3/s]	Air volume flow [m3/s]	Air volume flow [m3/h]
1	19.9	64.64	0.064638889	232.7
2	30.3	83.83	0.083833333	301.8
3	41.8	99.61	0.099611111	358.6
4	52.5	117.94	0.117944444	424.6
5	60.8	130.72	0.130722222	470.6
6	68.8	140.69	0.140694444	506.5
7	78.3	150.44	0.150444444	541.6
8	91.9	165.61	0.165611111	596.2
9				
10				



Air volume flow entire building: $Q_v = C \cdot \Delta P^n$

Mechanical vents closed

C =	0.0073	*read from graph/trendline*
n =	0.6542	*read from graph/trendline*

Mechanical vents open

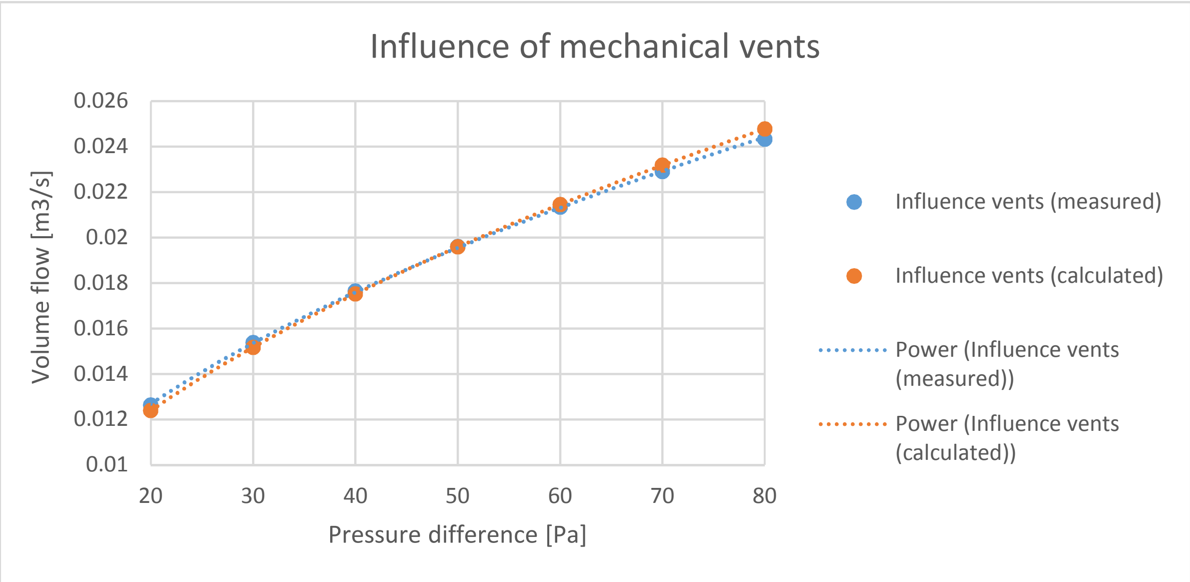
C =	0.01	*read from graph/trendline*
n =	0.622	*read from graph/trendline*

ΔP [Pa]	Air volume flow [m3/s]		ΔQv [m3/s]		$Q_v = C \cdot \sqrt{\Delta P}$
	Vents closed	Vents open			
20	0.05181514	0.0644526	0.012637		0.012388827
30	0.0675547	0.082941	0.015386		0.015173153
40	0.08154372	0.0991931	0.017649		0.017520448
50	0.09436024	0.1139618	0.019602		0.019588456
60	0.10631374	0.1276468	0.021333		0.021458078
70	0.11759423	0.1404918	0.022898		0.023177373
80	0.12832886	0.1526588	0.02433		0.024777655

Air volume flow vents only: $Q_v = C \cdot \sqrt{\Delta P}$

Determine C	0.00277023
Σ(ΔQv^2)	4.1838E-07

use goal seek to find Σ(ΔQv^2) as small as possible



$$C_{vent} = A \cdot \mu \cdot \sqrt{\frac{2}{\rho}}$$

A = cross section area [m^2]

Contraction coefficient $\mu = \dfrac{1}{1 + \sqrt{\zeta_i}}$

ζ_i	0.5

μ	0.586	
ρ	1.217	kg/m^3

A	0.00369	m^2	=	36.9	cm^2	=	0.30 cm^2/m^2

Vent (square)	a =	6.1	cm	2 Vents (square)	a =	4.3	cm
Vent (circular)	r =	3.4	cm	2 Vents (circular)	r =	2.4	cm