A CFD-based Study about Smoke Distribution in Presence of a Mechanical Ventilation System in a Passive House

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Abstract

Passive houses are subject to ambitious energy standards. To achieve these standards the transmission heat loss of the building envelope has to be significantly lower than in conventional houses. A mechanical ventilation system with heat recovery lowers the heating demand of the house. Furthermore passive houses have high requirements concerning the air-tightness of the building, to prevent cooling or warming of the room air by infiltration of outside air through the building envelope. It is not yet clear how these energy-efficient strengthening of the building envelope effects the growth of a possible fire. In the present study, CFD-based numerical simulations were carried out to examine the influence of the mechanical ventilation system during fires. A family home with ground floor and first floor according to the passive building standards was selected as representative for modern suburban housing. ANSYS CFX was used to compute the fire dynamics. The results of the simulations were compared to a window ventilated fire.

Keywords: Passive house fire; Computational Fluid Dynamics, ventilation condition, Fractional Effective Dose, pressure rise

Introduction

The number of energy efficient buildings increases steadily, because energy-efficient erection and renovation of buildings are supported by the German Federal Government by low-interest loans or subsidies. Table 1 gives an overview of the projects supported for energy-efficient renovation and energy-efficient new building of flats.

Table 1. Number of financially supported building projects in Germany [1].

	Financial support 2010	Financial support 2011	Financial support 2012	Financial support 2013
renovation	344,000	181,000	242,000	276,000
new building	840,00	81,000	115,000	129,000

An energy-efficient building differs from a conventional building by:

- better heat insulation of the building cover
- mechanical ventilation system
- low ventilation rate
- higher requirements concerning the air-tightness
- higher requirements for the glazing.

This entails that also the course of a possible fire may change due to:

- lower loss of heat to the surroundings due to the improved heat insulation
- later failure of the multi-layer window glass due to its higher mechanical resistance
- impeded access of fresh air due to improved air-tightness of the building
- changes in the smoke migration due to the controlled airflow.

The mentioned effects on the fire course have not yet been described completely. In a previous study it was observed that an overpressure originated from the fire in the building and that windows shattered later than compared to fires in “conventional” buildings [2]. Further it remains to examine if a complete or incomplete combustion occurs because the type of combustion causes significantly different compositions of components of fire smoke.

In the present study, CFD-based numerical simulations were carried out for fire scenarios in a passive family home to examine the influence of the mechanical ventilation system on the evolution of the fire and the migration of smoke.

Numerical Setup

The simulations were undertaken with the computational fluid dynamics software ANSYS CFX 14.5 and R14.5. ANSYS CFX uses the finite volume method for discretisation. The general transport equation in differential form is given with Equation 1 [3].

$$\frac{\partial}{\partial t}(\varrho\phi) + \frac{\partial}{\partial x_i}(\varrho u_i \phi) = \frac{\partial}{\partial x_i}\left(\Gamma_i \frac{\partial \phi}{\partial x_i}\right) + S_\phi \qquad \text{(Eq. 1)}$$

The general equation for conservative of mass [3] and conservative of energy [3] are given in Equation 2 and 3 in differential form:

$$\frac{\partial \varrho}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho u_j\right) = 0 \qquad \text{(Eq. 2)}$$

$$\frac{\partial h}{\partial t} + \frac{\partial}{\partial x_i}(u_i h) = \frac{\partial}{\partial x_i}\left(k\frac{\partial T}{\partial x_i}\right) + S_h \qquad \text{(Eq. 3)}$$

Equation 4 shows the conservation equation of momentum.

$$\frac{\partial}{\partial t}(\varrho u) + \frac{\partial}{\partial x_i}(\rho u_i u) = \frac{\partial}{\partial x_i}\left(\mu\frac{\partial u}{\partial x_i}\right) - \frac{\partial p}{\partial x}\partial + f_x \qquad \text{(Eq. 4)}$$

In the present study a family home with ground floor and first floor was selected as representative for suburban housing. According to the passive building standards a fresh air and an exhaust air fan are present. Living rooms, bedrooms and study are configured as fresh air zones while the kitchen, the utility room and the bathrooms are connected to the extraction system. Room doors are equipped with overflow orifices to allow air exchange.

Because of the numerous inclined surfaces and the adaptive meshing, a tetrahedral (unstructured) mesh was chosen. Figure 1 shows the computational domain with the tetrahedral mesh on the surfaces for (a) mechanical ventilation and (b) window ventilation. In regions where high flow gradients were expected the mesh was locally refined. This relates in particular to the areas in front of the exhaust and supply valves as well as the areas in front and behind the overflow orifice for the simulations with mechanical ventilation system. For the window ventilated fire the mesh density for the volume around the window openings and the overflow orifice were increased.

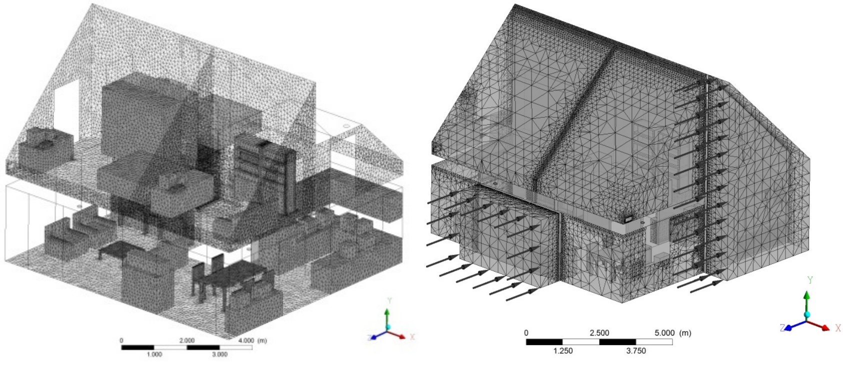

Fig. 1. Computational domain with tetrahedral mesh (a) mechanical ventilation system; (b) window ventilation.

A grid-independent solution of the differential equation system underlying the calculation algorithm resulted for 675,976 nodes with a maximum grid step width of 11 cm (simulations with mechanical ventilation system).

It is beyond the scope of the present paper to explain details of turbulent reactive flow modeling. Information can be obtained from [3] or from the ANSYS User Guide [4]. The model settings used for the simulations reported here are summarized in Table 2.

Table 2. Settings of simulation.

Fluid Models	**Set-up**
Heat transfer	Thermal Energy
Turbulence	k-ε Model
Combustion	Eddy Dissipation (EDM)
Thermal Radiation	P 1

Ventilation conditions and boundaries

In the simulations the following two different types of ventilation conditions were examined:

- mechanical ventilation system with a combined exhaust und supply system and
- a window ventilation.

The combined ventilation system generates a characteristic directed air flow. The airflow from a supply room to an exhaust room is controlled by the pressure difference across the supply to exhaust areas.

Figure 2 shows the geometry of the house with boundary condition (a) mechanical ventilation and (b) window ventilation.

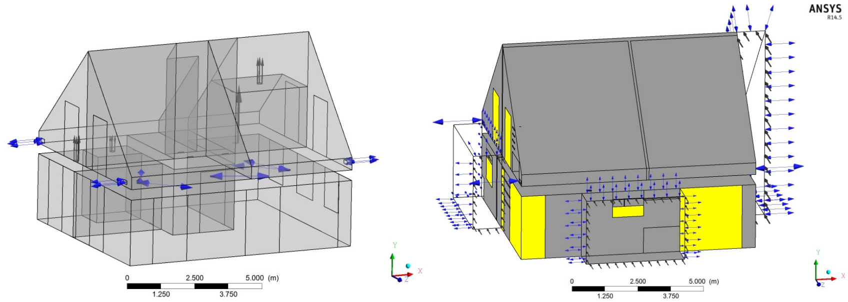

Fig. 2. Geometry of the house and boundary conditions (a) mechanical ventilation system; (b) window ventilation.

The black arrows in Figure 2 (a) symbolize the exhaust air valves. The black arrows in Fig. 2 (b) symbolize the wind side. Blue colored arrows mark in Fig. 2 (a) the supply air valves and in Fig. 2 (b) the openings to the environment. In Table 3 information is given about boundary conditions and settings.

For the simulations with mechanical ventilation system the required supply and exhaust air volume flows were calculated according to [5]. The required volumes flows are summarized in Table 4. During the simulation with mechanical ventilation system all windows were closed. In the doors between the rooms were overflow orifices. To ensure that the overflow area is similar between the simulations with different ventilation types, the overflow orifices were considered in the window ventilated simulations, too. In the window ventilated fire example the windows in the bathrooms, the utility room, the kitchen and in a bedroom remained open.

Table 3. Boundary conditions and settings for inlets, outlets and openings.

Boundary Type	**Set-up**
Inlet (window ventilation)	
Flow Regime	Subsonic
MassandMomentum	CartesianVelocity Components
Turbulence	Medium Intensity
Heat Transfer	Statictemperature
Thermal Radiation	LocalTemperature
Component Details	O_2 (0.232)
Opening (mechanicalventilationsystem)	
Flow Regime	Subsonic
MassandMomentum	Average StaticPressure
Relative Pressure	0 Pa
Opening (windowventilation)	
Flow Regime	Subsonic
Mass an Momentum	Pressureand Dirn
Relative Pressure	0 Pa

Table 4. Supply and exhaust air flow for mechanical ventilation system.

Room	Supply air flow	Room	Exhaust air flow
Living Area	69 m^3/h	**Kitchen**	53 m^3/h
Sleeping Room 1	31 m^3/h	**Utility Room**	28 m^3/h
Sleeping Room 2	31 m^3/h	**Bathroom Ground floor**	28 m^3/h
Study	31 m^3/h	**Bathroom First floor**	53 m^3/h
Σ	162 m^3/h		162 m^3/h

All walls were set up as “no slip” walls with the wall roughness smooth and an outside temperature of 10 °C. For the heat transfer through the building envelope to the environment a heat transfer coefficient was chosen (see Table 5). The heat transfer coefficients were based on 20 passive houses which were built up in reality [6].

Table 5. Heat transfer coefficients for different parts

Part	Heat transfer coefficient
Roof	0.24 W/m^2K
Window	0.65 W/m^2K
Outer Wall	0.09 W/m^2K

Fire scenario and fuel load

For both simulations, the fire was supposed to start in the utility room with a fuel load of 531 MJ/m^2. Compared to maximum values from literature [7] it is a small value for fire load. It was presumed, that there were no high risk items (like upholstered furniture) with a high energy density in the utility room. The fuel consisted of plastics like PE, PP, PVC, PUR and cellulose as well as wood. The chemical reactions representing the combustion process are presented in [8]. In the simulations the burning materials were built up as a solid with a solid fluid interface through the surrounding air. On the fluid side of the interface a continuity and energy source was implemented to generate a time dependent and material specific fire spread. A validation of the fire spread and chemical reactions is published in [9].

Comparison of a fire in the utility room with mechanical ventilation and window ventilation conditions

Figure 3 shows the temperature-vs.-time curve for a location 1.8 m above the floor surface in the hot gas layer. As it can be seen in Figure 3 the evolution of the temperature with time was computed to be similar in the first 180 s for both ventilation conditions. After 180s the temperature in the window ventilated fire remained nearly constant with values of 105 °C. Temperature in the fire with mechanical ventilation system increased slowly until 300 s and reached a value of 150 °C. After that a flashover occurred and the temperature in the upper layer of hot gases increased rapidly up to 990 °C. A flashover is by definition from the International Standard Organization the rapid transition to a state of total surface involvement in a fire of combustible material within an enclosure [10].

As it is shown in Figure 4 the amount of CO increased simultaneously after the maximum temperature was reached up to 11.000 ppm in the fire with mechanical ventilation system. Under window-ventilated conditions the CO concentration reached values up to 300 ppm and the pressure difference between the utility room and the adjacent corridor was around 4 Pascal (see Figure 5). For the first 120 s during the fire with mechanical ventilation system the pressure difference between the utility room and the adjacent corridor is less than 1 Pascal. 120 s after ignition of the fire, the pressure in the utility room increased up to approximately 3 Pascal, while the pressure in the corridor reached values up to -0.3 Pascal.

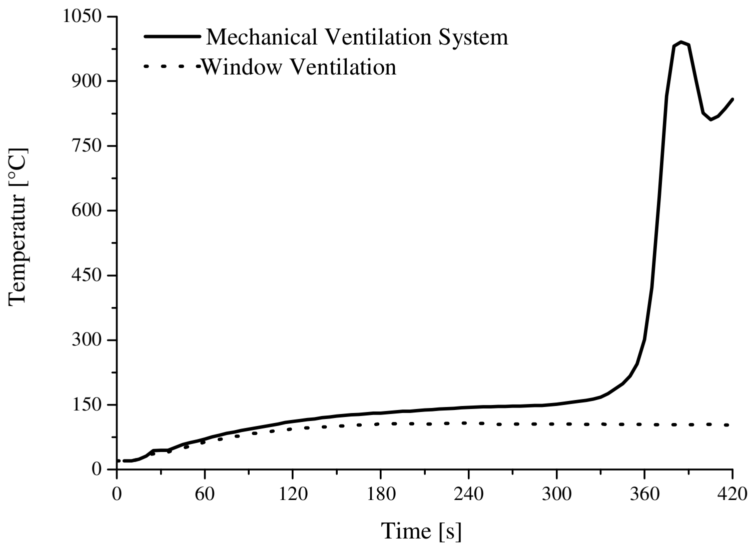

Fig. 3 Temperature vs. time in the utility room,1.8 m above floor surface.

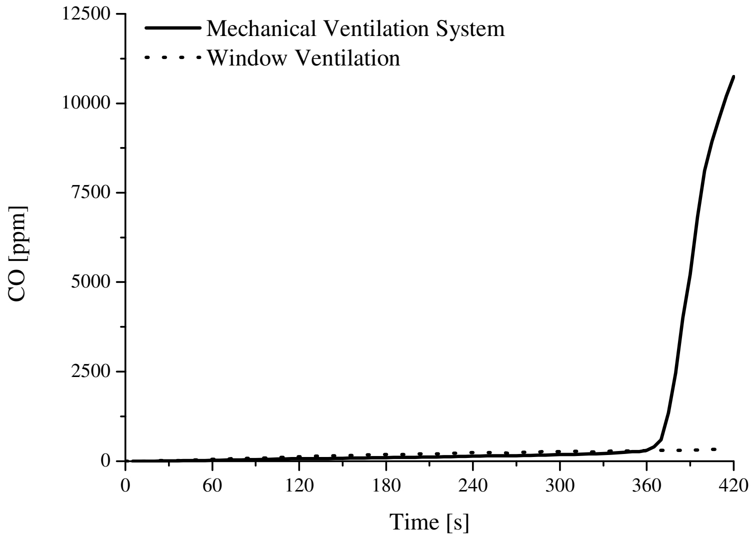

Fig. 4 CO Concentration vs. time in the utility room, 1.8m above floor surface

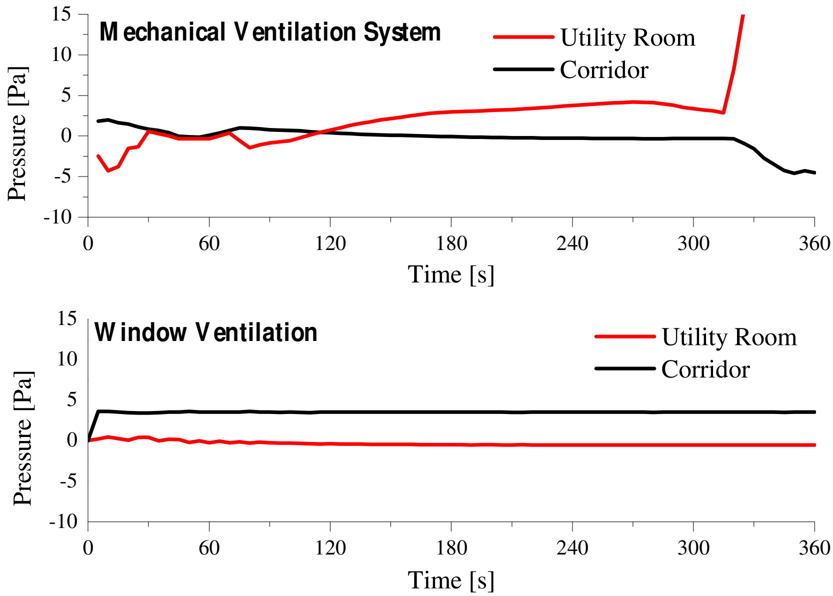

Fig. 5 Pressure vs. time curves for different ventilation conditions.

For predicting toxic hazards the Fractional effective dose model (FED) was implemented into ANSYS CFX by user functions [8, 11, 12]. If FED reaches a value of 0.3 11.4 % of the population lose their capability to escape.

During the fire growth phase (up to 300 s after ignition) the FED didnot vary substantially between the mechanical ventilated fire and the window ventilated fire. As shown in Figure 6 the FED reached a value of 0.3 after 400 s in the fire with mechanical ventilation system. For the example with window ventilation an FED of 0.3 could not be observed.

Window Ventilation Mechanical Ventilation System

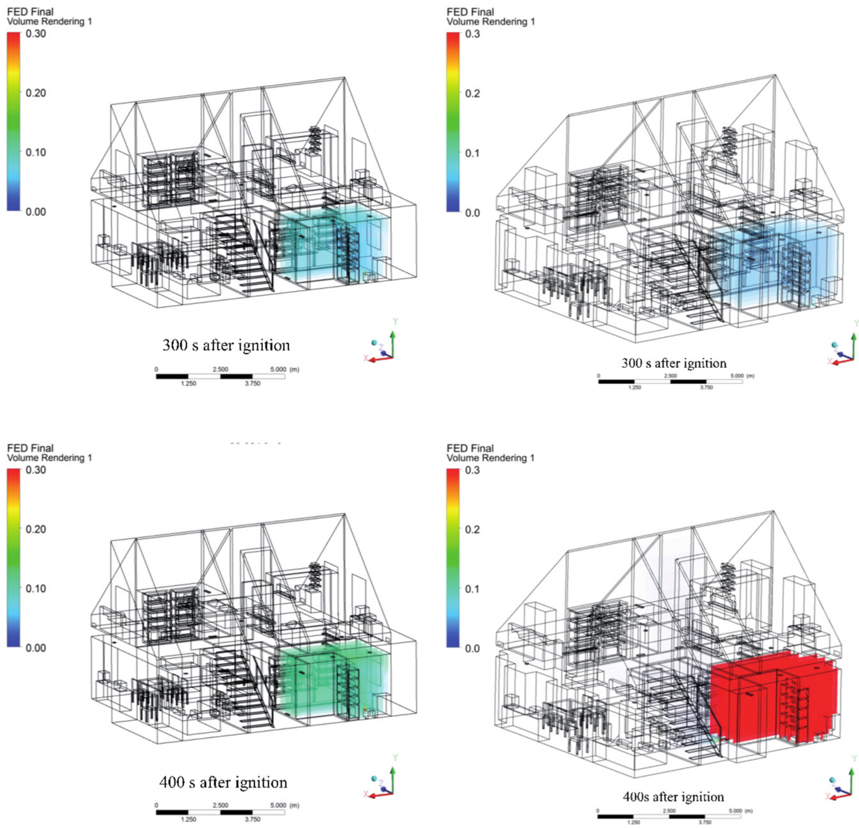

Fig. 6 Iso-volume with a FED value less or equal to 0.3 for a window ventilated fire on the left side and for a dwelling with mechanical ventilation system on the right side.

Conclusions

Numerical simulations for a window ventilated fire and a fire in a passive house with combined exhaust and supply ventilation system were undertaken. It has been shown, that the increase in temperature and CO concentration during the growth period of the fire was similar for both ventilation conditions. In a later stage of a fire drastic differences occurred.

In the fire with mechanical ventilation system 300 s after ignition the temperature increased up to values of 990°C. FED values of 0.3 were reached after 400 s and the CO concentration was much larger than that in the fire with window ventilation. The course of the pressure during time was different between the two ventilation types, too. In the fire with mechanical ventilation system the pressure in the room of fire origin exceeds the pressure in the adjacent corridor after 120 s.

This means that hot und toxic gases could penetrate into the corridor. In further investigations the influence of the pressure rise should be examined. At this time the relation of the pressure rise to the fire growth and to the rapid temperature increase cannot be estimated. A large scale fire test in a passive house is required to validate the numerical results. Furthermore a study with numerical simulations should be done, to figure out, what can prevent a ventilation controlled fire.

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