A numerical study on the effect of ventilation on fire development in a medium-sized residential room

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A Numerical Study on the Effect of Ventilation on Fire Development in a Medium-Sized Residential Room

IRC-RR-241

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February 12, 2008

PREFACE

This report presents the results of numerical simulations of fire development in a medium-size residential room. The objective of this preliminary study was to evaluate the effect of various sizes and configurations of ventilation openings on fire development and thereby assist in the design of fire experiments for The Characterization of Fires in Multi-Suite Residential Dwellings (CFMRD) consortium project.

The CFMRD project is a four-year collaborative undertaking with industry, provincial governments and city authorities that was initiated by NRC-IRC in 2006 to study fires in low-rise multi-suite residential dwellings of light-frame construction. The main objectives of the project are to: a) address the lack of realistic characterized fire types, known as design fires, which are required to aid the development of methods for achieving performance-based solutions to fire problems, and b) further the understanding of how fires in residential buildings sometimes cause fatalities and substantial property losses, as revealed by fire statistics.

The CFMRD project focuses on fires in dwellings, such as apartments, semi-detached houses, duplex houses, townhouses or row houses, secondary suites and residential care facilities as these fires have a potentially greater impact on adjacent suites.

The main tasks/deliverables of the project are:

1. To conduct fire experiments to characterize fires originating in various living spaces within multi-suite dwellings.
2. To conduct numerical simulations of various fire scenarios in order to interpolate and extend the data beyond that obtained in the experimental studies.
3. To produce a set of realistic design fires for multi-suite dwellings from the experimental data.
4. To develop an analytical method that can be used to calculate design fires for multi-suite dwellings.

The research approach employed by the project utilizes literature reviews, surveys to determine typical configurations and combustibles, computer simulations and fire experiments. A well-instrumented test facility, equipped with a heat release calorimeter, will be used to conduct meduim- and full-scale fire experiments in order to determine the combustion characteristics of typical household furnishings found in living spaces that have a high incidence of fires, individually in a single room and collectively in realistically furnished and well-instrumented simulated residential rooms. Numerical modeling of fire development, using suitable fire models, will be conducted at various stages to assist in the design and instrumentation of the full-scale fire experiments as well as to study the effect of various parameters, such as the ventilation conditions, geometry, and fire load density on the development of the fire.

Characterization of Fires in Multi-Suite Residential Dwellings (CFMRD)

NRC-IRC gratefully acknowledges the financial and technical support of the Project Consortium, which consists of representatives from the following participating organizations:

- Canadian Automatic Sprinkler Association
- Canadian Concrete Masonry Producers Association
- Canadian Council of Furniture Manufacturers
- The Canadian Wood Council
- City of Calgary
- FPInnovations - Forintek Division
- Gypsum Association
- Masonry Worx
- Ontario Ministry of Municipal Affairs and Housing
- Régie du Bâtiment du Québec
- Canadian Codes Center

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A Numerical Study on the Effect of Ventilation on Fire Development in a Medium-Sized Residential Room

By

Hamed H. Saber, Ahmed Kashef, Alex Bwalya, Gary Lougheed, and Mohamed Sultan

ABSTRACT

Establishing proper design fire scenarios is a challenging task and an essential component for conducting fire safety design of different buildings. A design fire scenario is a qualitative description of a fire with time identifying key events that characterize the fire (ignition, growth, fully-developed, and decay stages of fire). In addition, it describes the ventilation conditions that will impact the course of a fire. A number of fire ventilation scenarios were investigated in order to identify the proper ventilation scheme for conducting design fire tests in a compartment of a size 4.2 m long, 3.8 m wide, and 2.4 m high. The work was part of the process of designing fire experiments in a project concerning the characteristics of fires in various rooms in low-rise residential dwellings of light-frame construction. The fuel package that was used in all scenarios consisted of a mock-up sofa and two wood cribs underneath it. The mock-up sofa was constructed entirely out of flexible polyurethane foam. The two wood cribs provided additional fuel load to sustain a fully developed fire for long period. The selection of this fuel package is supported by fire statistics that many fatal residential fires begin with an item of upholstered furniture.

This report presents the numerical predictions for different ventilation scenarios. The ventilation schemes in these scenarios were provided by using a window, door, or both with different sizes.

The Computational Fluid Dynamics (CFD) technique was used to conduct the numerical investigation for the study. The Fire Dynamics Simulator (FDS) version 5 was used to conduct the numerical simulations. Unlike the previous versions of FDS, the new combustion model in the FDS version 5 accounts for both mixing of fuel and oxygen without burning and the CO production (incomplete combustion). This is an important feature for the proper modelling of under-ventilated compartment fire.

The CFD results showed that ventilation scenario SC8 had resulted in the highest maximum Heat Release Rate (HRR) (7,450 kW) while SC9 had the lowest one (4,760 kW). In ventilation scenario SC9, the polyurethane sofa took the longest period to be burned completely (283 s). For SC2, the sofa was completely burned in 158 s. The ventilation scenario SC1 resulted in the largest total mass loss of the fuel package (79.1 kg) while SC2 produced the lowest total mass loss of 68.0 kg.

The CFD fire simulations conducted in this study will assist in the design and instrumentation of medium and large-scale fire tests to be conducted in the NRC's lab facility in order to evaluate various fire scenarios. In a later stage of this project, the CFD model will be used to conduct parametric studies to determine the effect of various parameters, such as the ventilation conditions, geometry, and fire load on the fire development. This information will be used to evaluate the impact of a fire on the life safety and the damage to property.

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1. Introduction

Selecting proper fire scenarios is an important initial step for conducting fire safety design and analysis of buildings. A fire scenario describes the course of a fire with time identifying key events and features that characterize the fire such as ignition, growth, fully-developed and decay phases of fire. Fire load characteristics, room geometry and ventilation conditions will impact the course of the fire.

This report documents a series of Computational Fluid Dynamics (CFD) numerical simulations that were conducted in order to study the effect of ventilation on fire dynamics in a room of a size of 4.2 m long, 3.8 m wide and 2.4 m high. A fuel package consisting of a mock-up sofa constructed with exposed polyurethane foam, the dominant combustible constituent of upholstered furniture, and two wood cribs was selected (Figure 1-1). The mock-up sofa was ignited first and the wood cribs provided the remaining fire load to sustain a fully developed fire for a desired period of time. The details of the fuel package and its characteristics are available in [1] and [2]. This fire scenario is supported by fire statistics that indicate that many fatal residential fires begin with an item of upholstered furniture.

Nine CFD simulations with different fire ventilation scenarios were investigated in order to identify the proper ventilation scheme for conducting design fire tests in the room. The size of the room was selected based on the survey results of combustible contents and floor areas in multi-family dwellings [3]. All scenarios in this study were simulated using the Fire Dynamic Simulator (FDS) version 5, which is a CFD model developed by National Institute of Standards and Technology (NIST) and adequately described in publications [4 and 5]. FDS version 5 has numerous improvements over the previous versions of FDS, including an enhanced combustion model that improves modeling of under-ventilated fire scenarios. A further description of the FDS model and the improvements in version 5 is summarized in Appendix A.

Based on this study, design fire tests will be conducted in NRC's lab facility in order to evaluate various fire scenarios. This report presents the CFD results for different ventilation scenarios. The same fire load was used in all simulations. The ventilation schemes were based on using a window, door, or both (see Table 2-1). Different sizes of windows and doors were investigated. In the next phase of this project, after identifying the proper ventilation scheme and conducting tests, the numerical results will be compared with the experimental results. After verifying the CFD simulation, a parametric analysis will be performed to investigate the effect of different parameters of interest (e.g. fire size, fire location, geometry, …etc). In the next section, the ventilation scenarios are described.

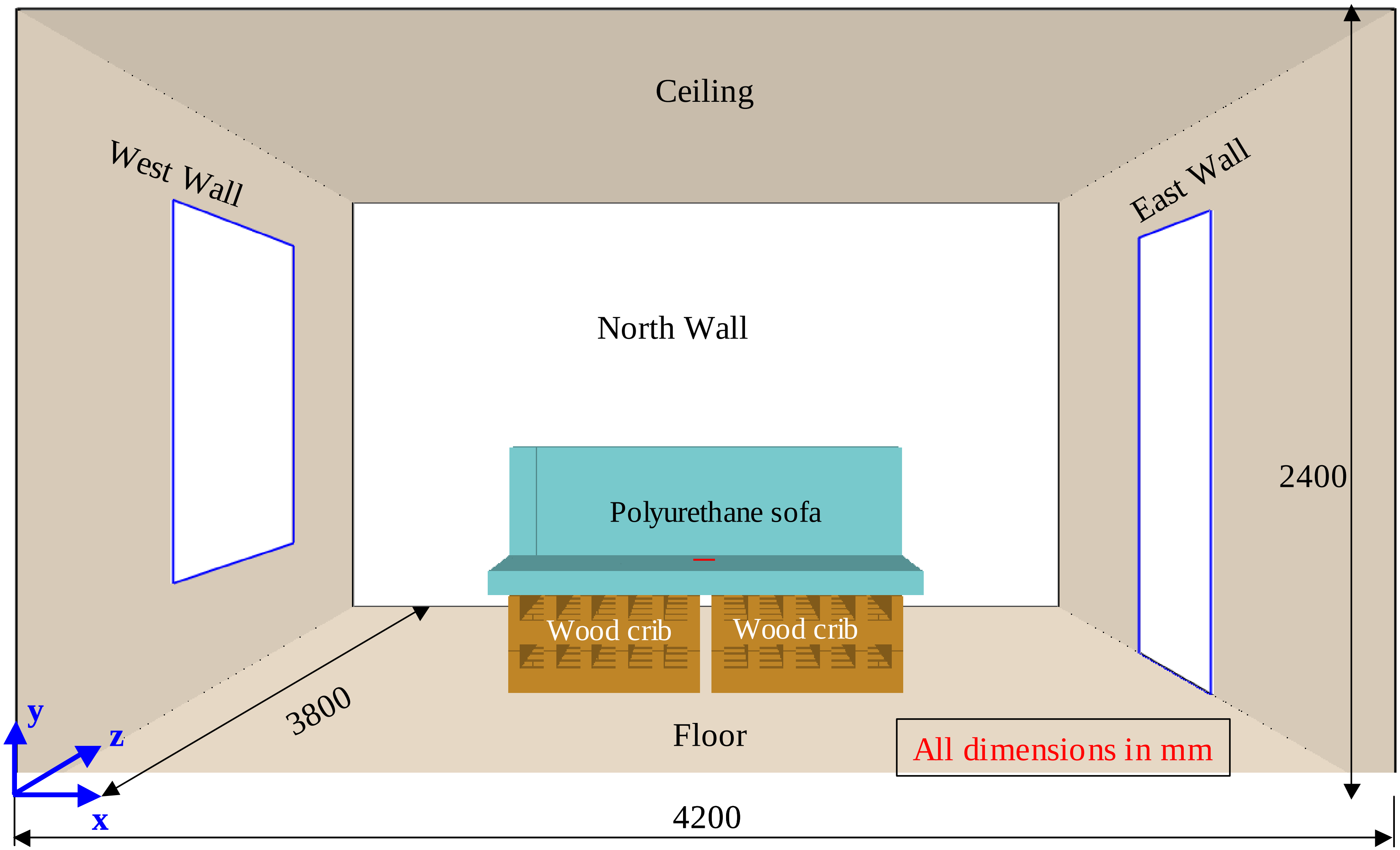


Figure 1-1 Room size and fire load

2. Ventilation Parameters and Fire Loads

Figure 2-1 shows the fire load and ventilation openings used for each simulation. Table 2-1 lists the ventilation settings for each scenario. The polyurethane sofa constructed of two blocks of flexible polyurethane foam (with a density of 30 kg/m^3). As shown in Figure 2-2, the dimensions of the first block was 1.83 m long x 0.61 m wide and 0.10 m thick, and that for the second block is 1.83 m long x 0.60 m wide and 0.15 m thick. The 0.15 m thick foam block was used for the backrest and the 0.10 m thick foam block for the seat cushion. A 0.10 m square burner was located on the top of the seat cushion at its center. The burner Heat Release Rate Per Unit Area (HRRPUA) was 304 kW/m^2 (~ 3.0 kW). The burner was ignited for a period of 30 s. This period was found to be enough to initiate and sustain the fire in all ventilation scenarios.

Two wood cribs were used and placed underneath the polyurethane sofa. The wood cribs were made of spruce lumber pieces, each piece measuring 50 mm x 100 mm x 800 m. The pieces were evenly spaced in rows of six and stacked to a height of 40 cm (Figure 2-3). It was assumed that wood cribs consist of 70% cellulose, 20% lignin and 10% water by mass. Table 2-2 lists the masses of the polyurethane sofa and the wood cribs used in all scenarios. A distance of 50 mm separated the two wood cribs (Figure 2-4). The fire load (polyurethane sofa and two wood cribs) was oriented in the east-west direction in all ventilation scenarios.

In ventilation scenario SC1 through scenario SC8, the fire load was placed at the center of the room. In scenario SC9, however, the fire load was placed in the northeast corner of the room. It was located 100 mm from both the east and north walls (Figure 2-1 and Table 2-1).

Table 2-1 Ventilation conditions for the nine scenarios

Ventilation Scenario	Window Size (m)		Door Size (m)		Window Location		Door Location		Fire Load Location
	Width	Height	Width	Height	Side	Center (x,y,z) (m)	Side	Center (x,y,z) (m)	
SC1	1.5	1.5	Closed		West	(0,1.9,1.25)	Closed		Center of room
SC2	1.5	1.5	0.9	2.0	West	(0,1.9,1.25)	East	(4.2,1.9,1.0)	Center of room
SC3	2.0	1.5	Closed		West	(0,1.9,1.25)	Closed		Center of room
SC4	1.0	1.0	0.9	2.0	West	(0,1.9,1.5)	East	(4.2,1.9,1.0)	Center of room
SC5	Closed		0.9	2.0	Closed		East	(4.2,1.9,1.0)	Center of room
SC6	Closed		1.5	2.0	Closed		East	(4.2,1.9,1.0)	Center of room
SC7	1.0	1.5	0.9	2.0	East	(4.2,2.85,1.25)	East	(4.2,0.95,1.0)	Center of room
SC8	1.0	1.0	0.9	2.0	East	(4.2,2.85,1.5)	East	(4.2,0.95,1.0)	Center of room
SC9	2.0	1.5	Closed		West	(0,1.9,1.25)	Closed		Corner of room*

* Fire load was located 100 mm from the east and north walls

Table 2-2 Mass of fire load used in all ventilation scenarios

Ventilation scenario	Polyurethane sofa mass (kg)	Number of wood cribs	Wood moisture content (%w)	Total wood mass (kg)
SC1 through SC9	8.3	2	10	86.7

Figure 2-1 Ventilation parameters for the nine scenarios

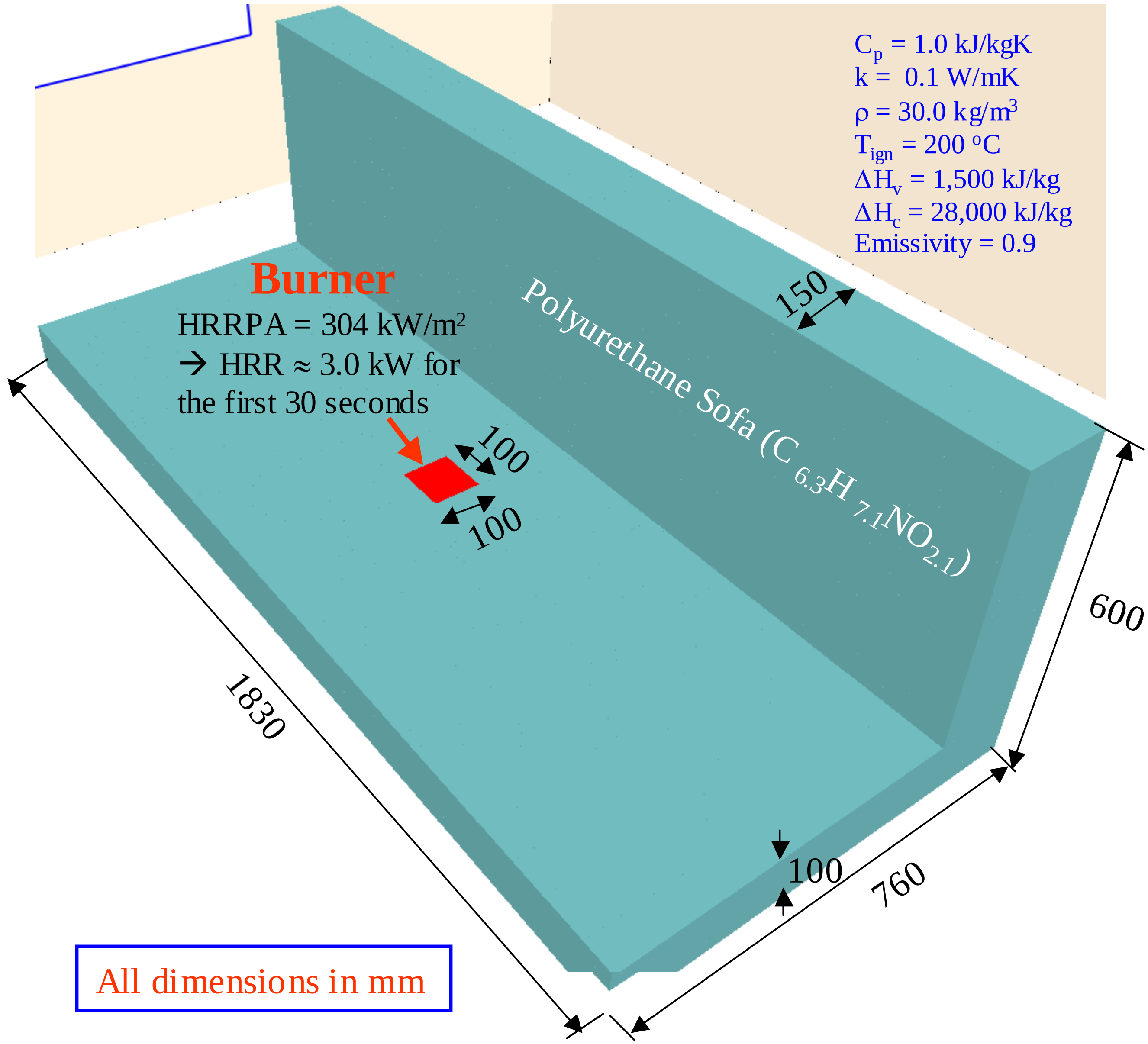


Figure 2-2 Sofa dimensions and thermal properties

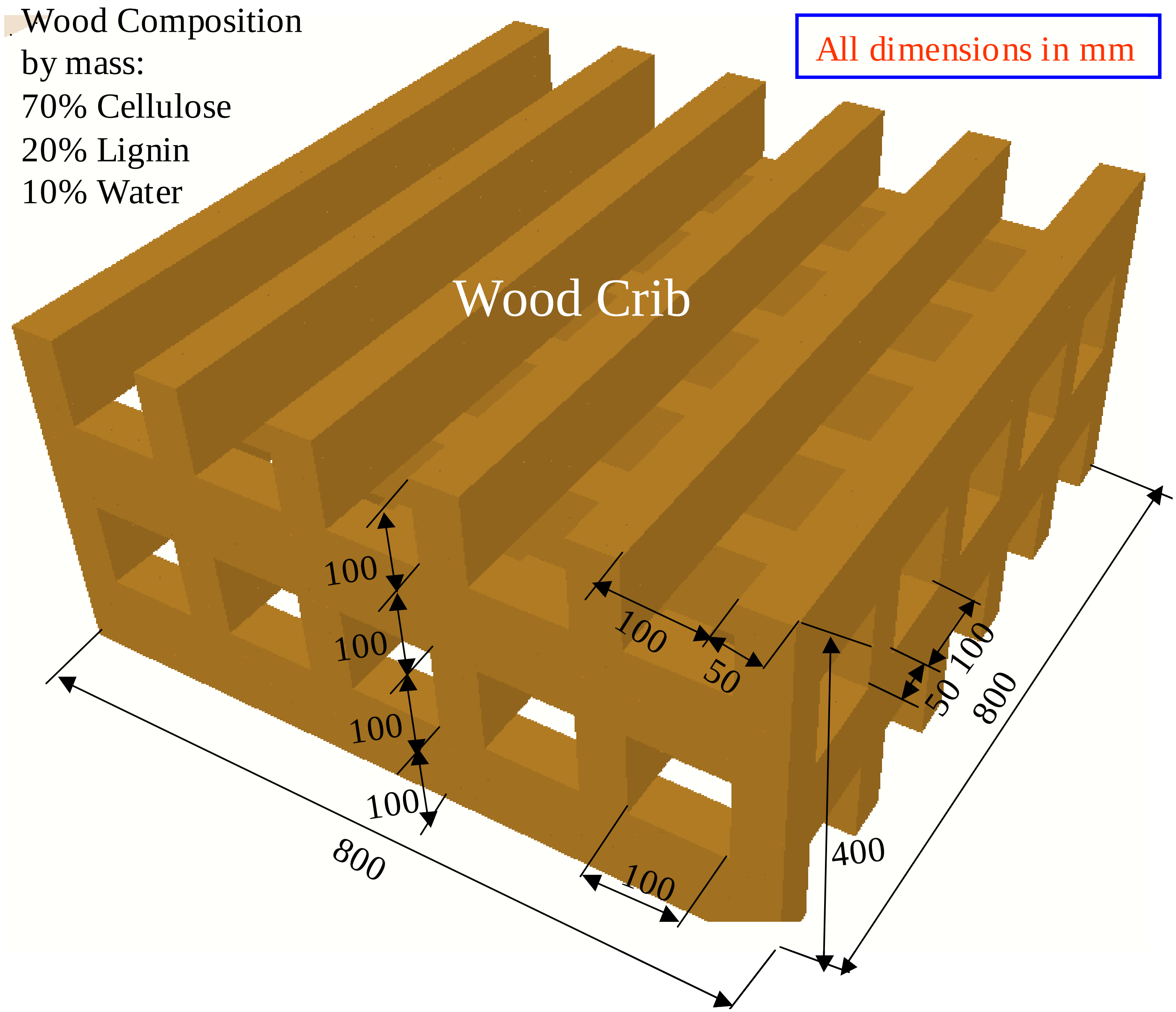


Figure 2-3 The Geometric arrangement of the wood crib

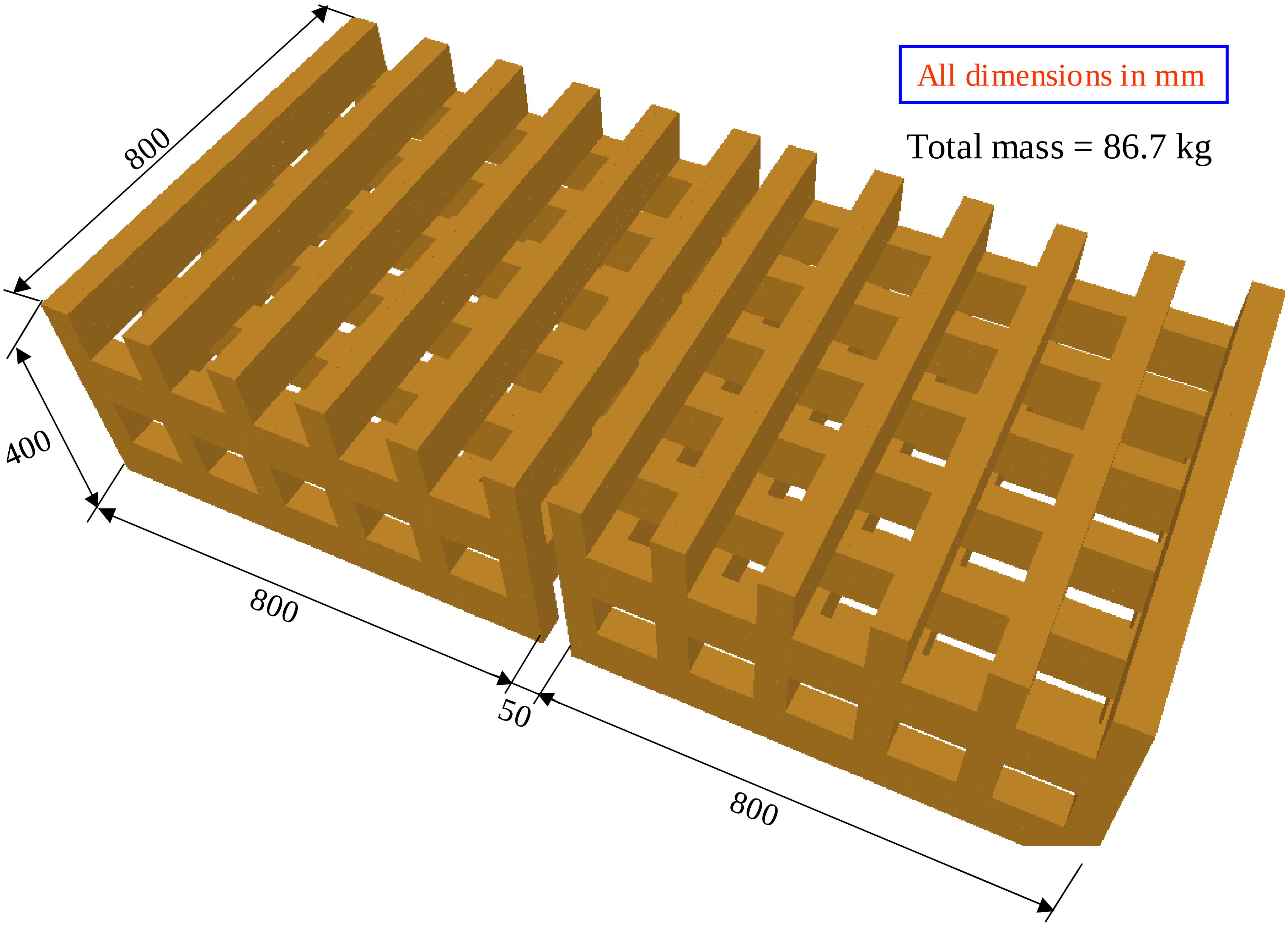


Figure 2-4 Arrangements of the two wood cribs

Cellulose:

Specific Heat, C_p = 2.3 kJ/kgK

Density, ρ = 400 kg/m^3

Emissivity = 1.0

Char:

Specific Heat, C_p = 1.1 kJ/kgK

Density, ρ = 440 kg/m^3

Emissivity = 1.0

Lignin:

Thermal conductivity, k = 0.1 W/mK

Specific Heat, C_p = 1.1 kJ/kgK

Density, ρ = 550 kg/m^3

Emissivity = 1.0

Water:

Thermal conductivity, k = 0.6 W/mK

Specific Heat, C_p = 4.19 kJ/kgK

Density, ρ = 1000 kg/m^3

Emissivity = 1.0

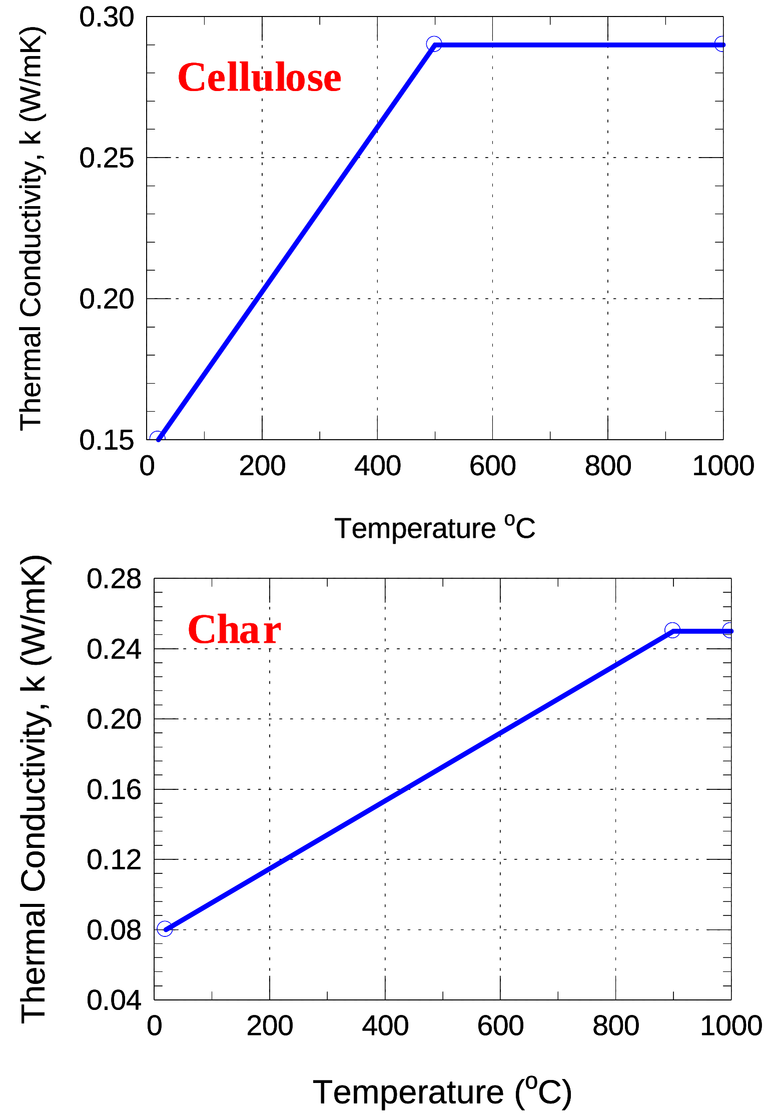


Figure 2-5 Thermal properties of the wood crib species

3. CFD Simulation Using FDS

The FDS is a CFD model developed to idealize fire-driven fluid flow. The model numerically solves a form of the Navier-Stokes equations appropriate for low-speed, thermally driven flow, with an emphasis on smoke and heat transport from fires. The partial differential equations for conservation of mass, momentum, and energy are discretized using the finite difference method, and the solution is updated in time on a three-dimensional, rectilinear grid. Thermal radiation is computed using a finite volume technique on the same grid as the flow solver. Lagrangian particles are used to simulate smoke movement and sprinkler discharge. FDS computes the temperature, density, pressure, velocity, and chemical composition within each numerical grid cell at each discrete time step. Additionally, FDS computes the temperature, heat flux, mass loss rate, and various other quantities at solid surfaces.

Version 5.0 of FDS [4-5] was used to simulate the nine ventilation scenarios listed in Table 2-1 in a room of a size of 4200 x 3800 x 2400 mm (Figure 1-1). Grids or meshes were developed in which the volume within the room was divided into hundreds of thousands of control volumes or cells. In each cell, the governing equations (momentum, energy, and diffusion equations) are simultaneously solved for the velocities, temperatures and mass fractions as a function of time. Only one mesh (stretched in x- and y-directions, and uniform in z-direction) was designed for each ventilation scenario. The total number of cells was 720,000. As shown in Figure 3-1, the mesh was refined in the regions where large temporal and/or spatial gradients of key flow quantities were anticipated (e.g. in the vicinity of the fire, door and window). Additionally, in order to capture the steep change of the key quantities with time, the time step, Δt was selected according:

$$\Delta t = \min[(\Delta x, \Delta y, \Delta z)^2 / \alpha], \qquad (3\text{-}1)$$

where α is the thermal diffusivity [$\alpha = k/(\rho C_p)$], and Δx, Δy, Δz are the cell size in x-, y- and z-directions, respectively. Note that, the local Heat Release Rate (HRR) was calculated from the local oxygen consumption rate at the flame surface. Therefore, a fine mesh is necessary where the flame exists in order to capture the profile of the flame surface (see Figure 3-2), and hence accurately predict the HRR. The CPU time using the NRC-IRC cluster machine for each scenario was ~14 – 21 days.

The walls, floor and ceiling of the room were assumed inert and thermally insulated (adiabatic) for all scenarios. This resulting in the thermal feedback to the surfaces of the fire load becomes high. As a result, it is expected that the predicted HRRs and the temperatures in the compartment for all scenarios will be higher than the case of allowing for the heat losses from the boundaries. Therefore, treating the boundaries of the compartment as thermally insulated would represent the most sever case.

In all scenarios, the windows and doors lead to the exterior (i.e. open to the outside). Ventilation vents were introduced to mimic the actual doors and windows. The wind can affect the flow field within the room, and hence the HRR.

The effect of the wind on the HRR strongly depends on both wind speed and its direction. In all scenarios, the effect of the wind was neglected. However, this effect will be taken into account in the next phase of this project.

The total local pressure (dynamic + static + gravitational pressure) in the room with and without fire is equal to the atmospheric pressure. To satisfy this condition, the boundary conditions at the windows and doors were treated as open vents. Upon initiating the fire, the flow field inside the room was modified such that the total local pressure in the room was equal to the atmospheric pressure. Subsequently, the mass flow rates at the doors and windows were calculated. These values were different depending on the ventilation scenario.

The nine fire simulations were conducted for a certain period of time. The CFD simulation in each scenario was terminated after the combustion of fire load had stopped. As will be shown later, the combustion of the fire load was stopped at different periods of time for these ventilation scenarios.

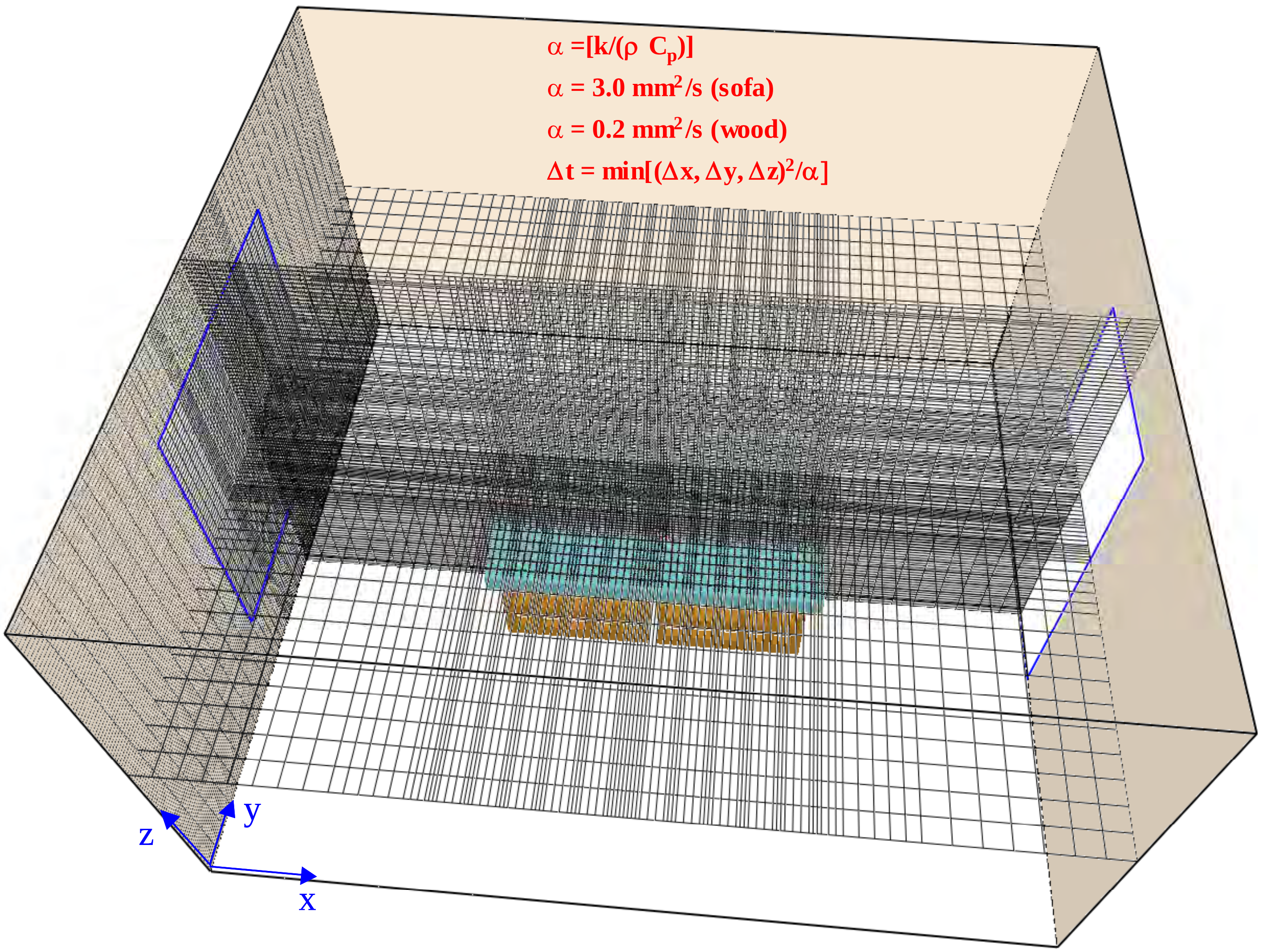


Figure 3-1 Stretched mesh in the x- and y-directions to capture the important phenomena.

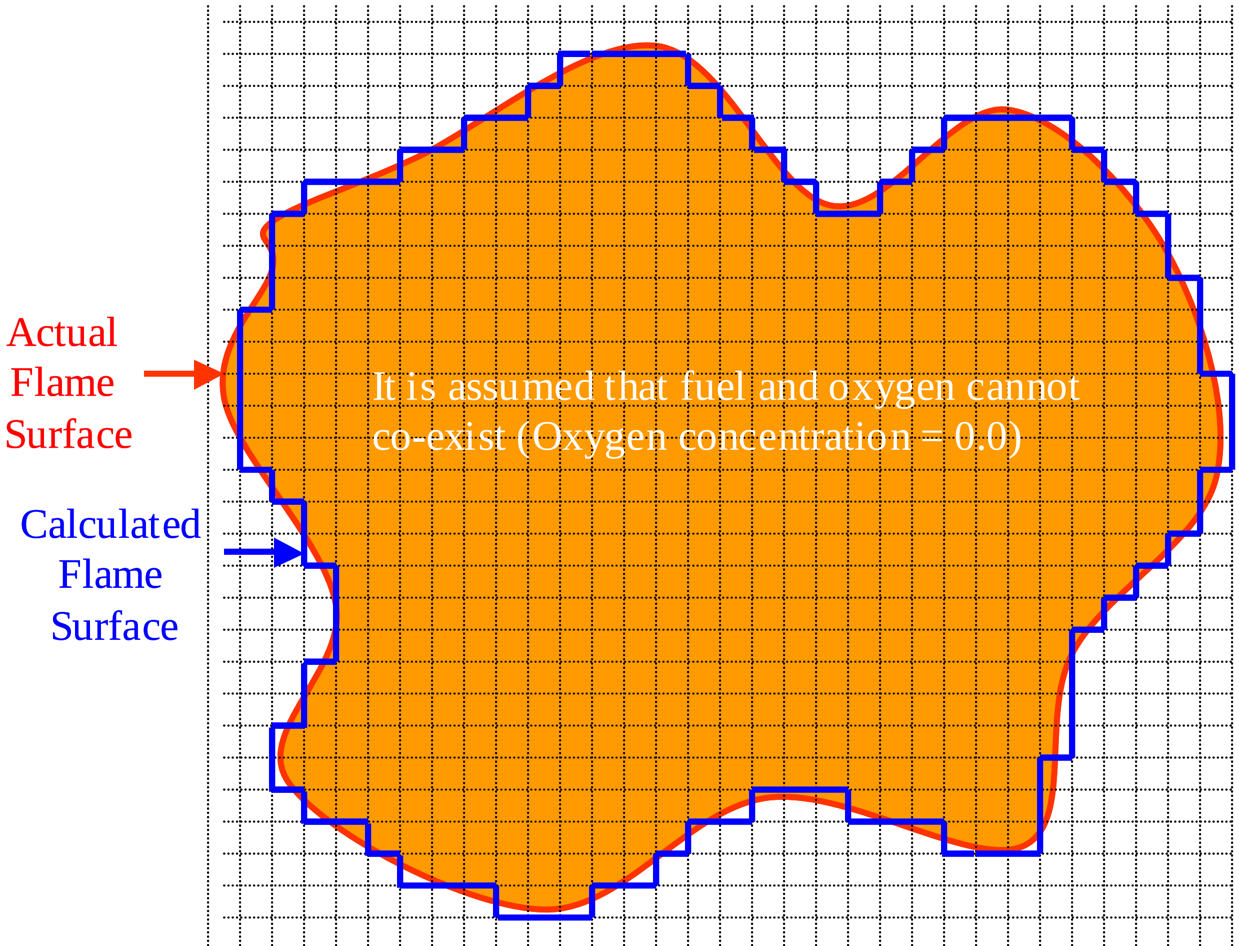


Figure 3-2 A schematic of the calculated flame cross-section for a given mesh and the actual flame surface

4. Results and Discussions

In this section, the results of simulations for the different ventilation scenarios are presented and discussed.

Before conducting the CFD simulations for the ventilation scenarios, preliminary numerical tests and debugging were carried out. One of these tests (Test Case I) was conducted using two wood cribs only as shown in Figure 2-4. The wood cribs were located at the center of the room and ventilation scenario SC5 (Figure 4-1) was used. Different mesh sizes were used in order to obtain the optimum mesh size. The following were the main observations from this numerical test:

- Placing a burner with a thermal power of ~ 3 kW on the top of the wood cribs for 30 s was not capable of initiating and sustaining the fire with the wood cribs.
- The time period of a burner placed on the top of the wood cribs was extended to 120 s. In this case, the wood started to ignite. However, ~15 s later, the fire was extinguished.
- Placing a burner between the two wood cribs for a time period of 120 s was capable of initiating and sustaining the fire. In this case, most of the wood was burned (see Figure 4-1).
- It was found that increasing the size of a stretched mesh (in x- and y-directions) beyond 100 x 75 x 96 has an insignificant effect on the results. Therefore, a stretched mesh of a size of 100 x 75 x 96 was used in all ventilation scenarios shown in Figure 2-1 and listed in Table 2-1.
- The calculated effective heat of combustion of the wood in Test Case I matches that in the literature for wood [7].

Recently, Babrauskas [7] obtained an empirical correlation for calculating the effective heat of combustion, ΔH_{eff}, of wood as a function of the Moisture Content (MC). This correlation was based on curve fitting the experimental data for different values of MC ranging from 0 – 170%, which is given as:

$$\Delta H_{eff} = 19.05 \left[\frac{100}{100 + MC} \right], \tag{4-1}$$

where, MC is defined as:

$$MC = \frac{M_{fresh} - M_{dry}}{M_{dry}} \, x \, 100 = \frac{Y_{water}}{1 - Y_{water}} \, x \, 100 \, . \tag{4-2}$$

In the above equation, M_{fresh} and M_{dry} are the mass of the fresh wood and dry wood, respectively. Also, Y_{water} is the mass fraction of the water in the wood, which was taken equal 0.1 in this study. Babrauskas' correlation agrees with most of the experimental data to within ± 25% [7]. From the calculated heat release rate shown in Figure 4-2 and the burn rate, an effective heat of combustion of 19.5 MJ/kg was predicted for the wood cribs in this numerical test. This effective heat of combustion is within 13% higher than that obtained from Babrauskas' correlation (17.2 MJ/kg).

Another numerical test (Test Case II) was conducted to burn the fire load that consists of a polyurethane sofa and two wood cribs underneath it in a fully open room (Figure 4-3). A stretched mesh in x- and y-directions of a size of 100 x 75 x 96 was used in this test. Since the polyurethane sofa was more volatile than the wood, placing a burner with a thermal power of ~ 3 kW on the top of the sofa at its center (Figure 4-3a) for only 30 s was more than enough to initiate and sustain the fire. In this test, the oxygen feeds the fire uniformly along the surface of the flame resulting in a vertical fire plume with minimum lateral fluctuations (see Figure 4-3b). The polyurethane sofa was completely burned after 312 s at which time (5.2 min); some of the wood cribs was burned (see Figure 4-3c).

The fire was completely extinguished after 638 s. At this time, a considerable amount of the wood cribs was lost (Figure 4-3d). The unburned amount of the wood was 19.6 kg (22.6 % by mass).

Since the flame was vertical in this test, the remaining mass in each of the two wood cribs was symmetric about the plane located at the middle distance between the two wood cribs. This symmetrical plane acted as a mirror between the two wood cribs. Additionally, the amount of net heat feedback to the wood surface was greater at the middle of the wood cribs than at its external boundaries. This was because the amount of heat loss by convection and radiation at the boundaries of the wood cribs were greater than that at the middle of the wood cribs. Some of this heat was utilized to decompose the solid fuel to gas fuel. As a result, more mass loss of the wood occurred at the middle than at the boundaries as shown in Figure 4-3d.

Figure 4-4 shows the temporal change of the Heat Release Rate (HRR) for Test Case II. The highest HRR (4,721 kW) was achieved at 225 s. The effective heat of combustion of the fire load (polyurethane sofa + wood cribs) was 17.8 MJ/kg. Since the polyurethane sofa was completely burned at 312 s, the HRR shown in Figure 4-4 and the burning rate for time > 312 s were used to calculate the effective heat of combustion of the wood. The predicted effective heat of combustion of wood was 18.5 MJ/kg, which was in a good agreement (within +7.6%) with that obtained using Babrauskas' correlation [7] (17.2 MJ/kg).

The good agreement between the predicted effective heat of combustion and that obtained from Babrauskas' correlation [7] for wood in both numerical tests (Test Cases I and II) confirmed the appropriateness of both the modified mixture fraction combustion model and pyrolysis model in FDS version 5.0. Based on the numerical results of Test Cases I and II, a stretched mesh in x- and y- directions of a size of 100 x 75 x 96 and burner of thermal power of ~ 3 kW for a period of 30 s were used to conduct the CFD simulations for the ventilation scenarios listed in Table 2-1 and Figure 2-1. The results of these simulations are presented and discussed next.

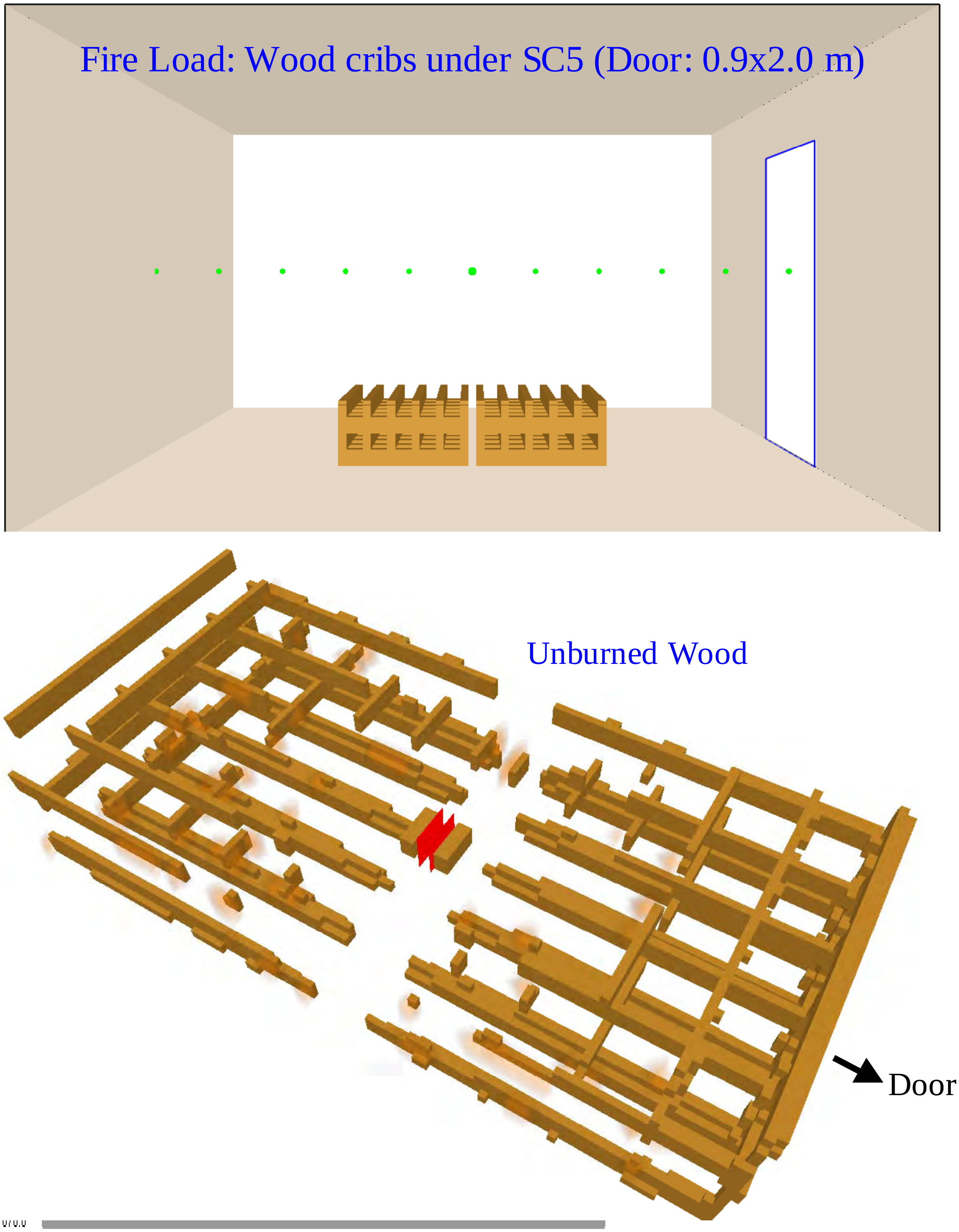


Figure 4-1 Test Case I for burning two wood cribs only under ventilation scenario 5 (SC5)

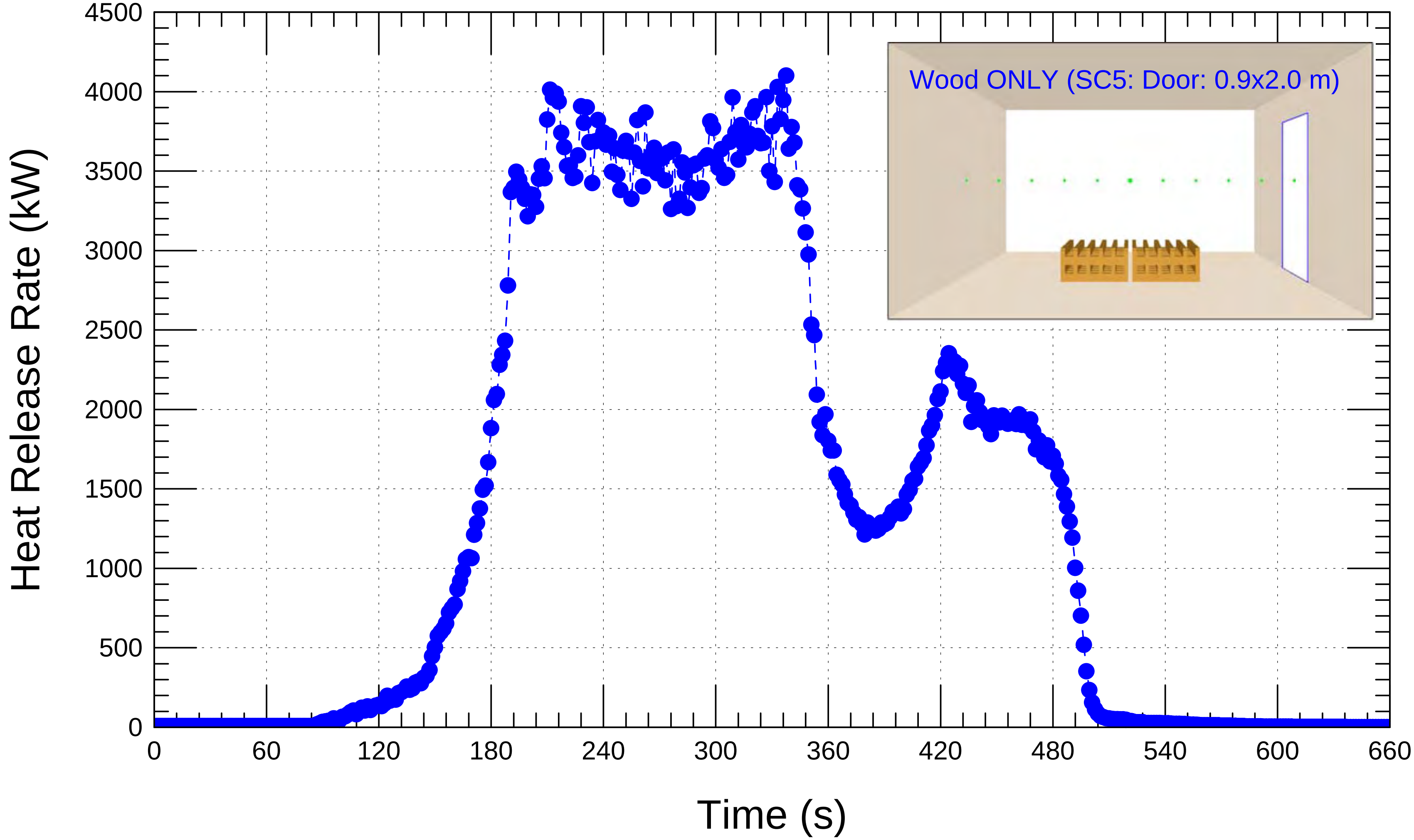
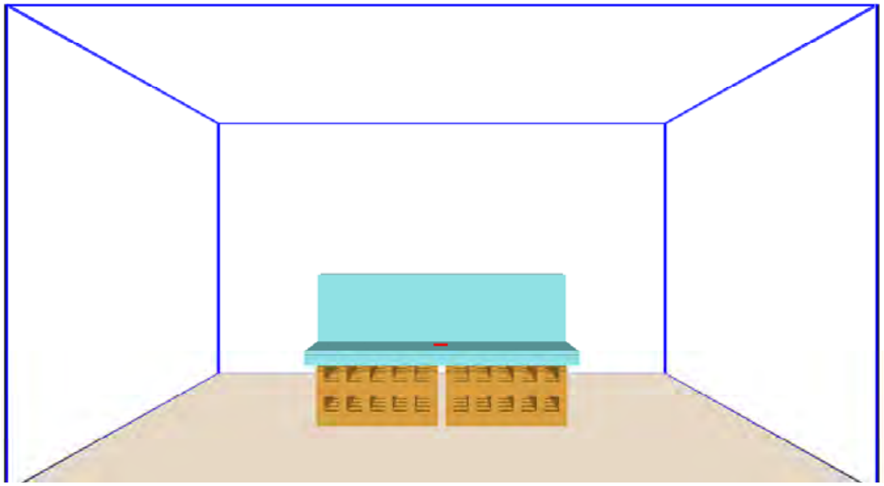
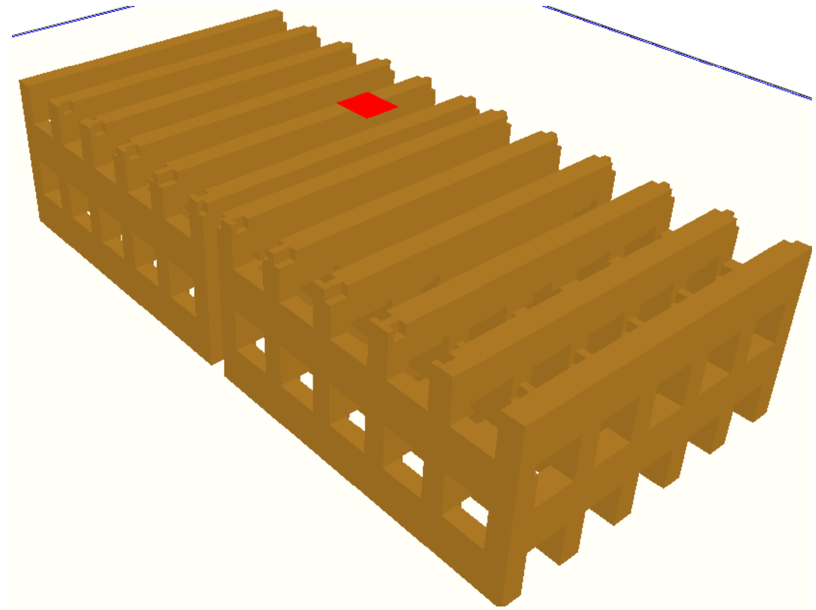


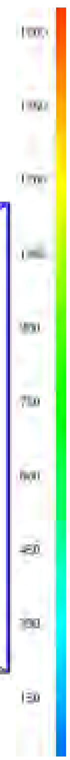
Figure 4-2 Heat Release Rate for two wood cribs under ventilation scenario SC5 (Test Case I).

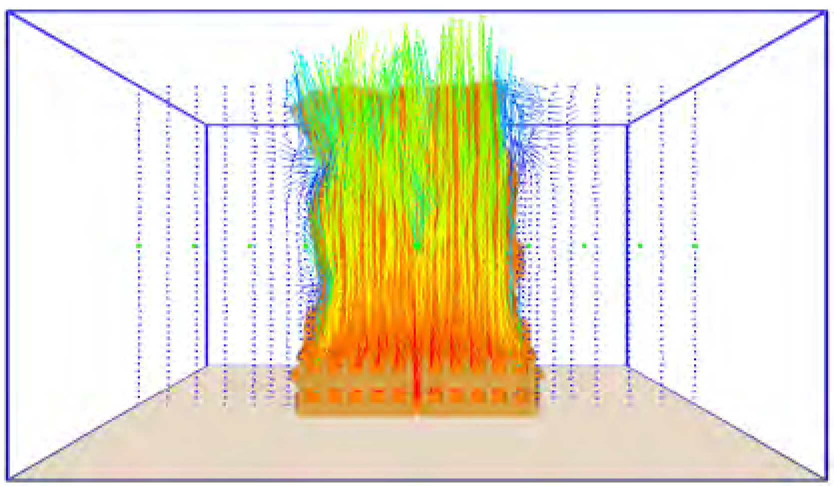


(a) Before initiating the burner (Time = 0)

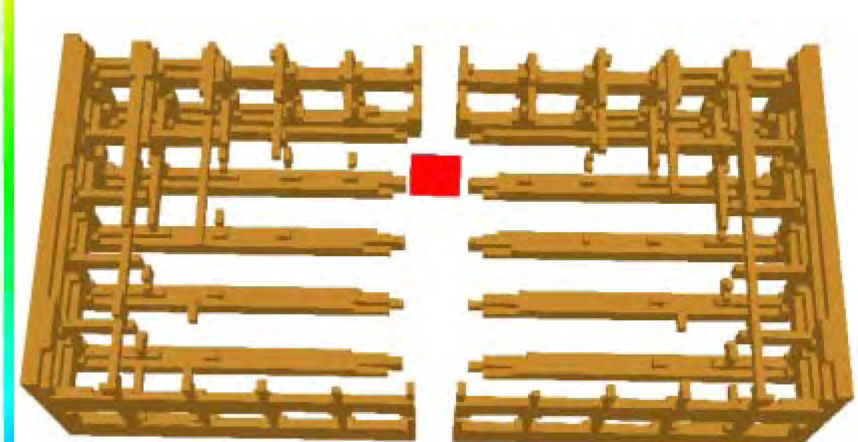


(c) Status of wood cribs when sofa was completely burned, Time = 312 s





(b) Fire when sofa was completely burned at Time = 312 s



(d) Status of wood cribs when fire was completely stopped

Figure 4-3 Test Case II for burning polyurethane sofa and two wood cribs in fully open room

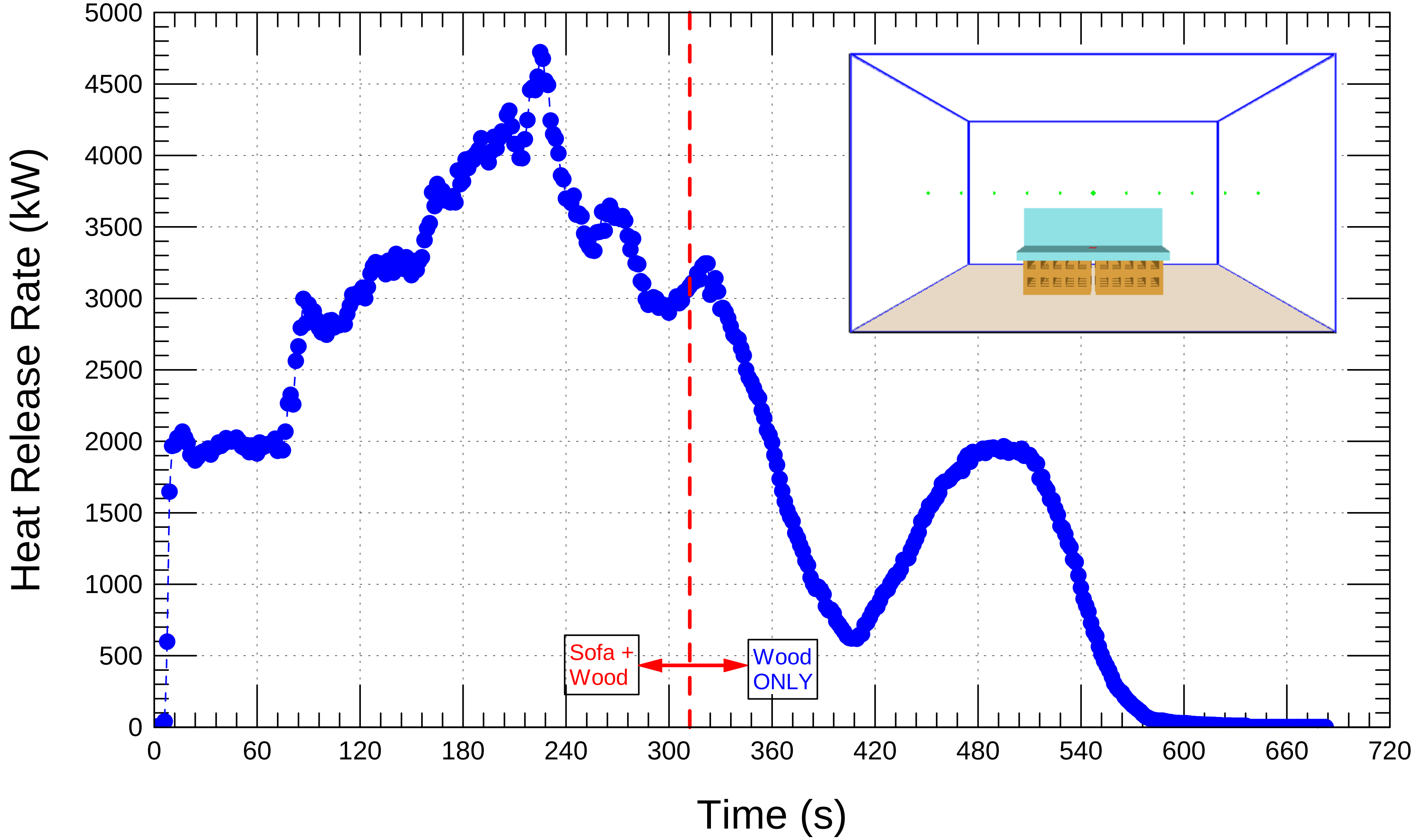


Figure 4-4 Heat release rate due to burning polyurethane sofa and two wood cribs in fully opened room (Test Case II)

Ventilation Scenario SC1

Figure 4-5 shows the status of the fire load before initiating the burner, when the polyurethane sofa was completely burned, and when the fire was completely extinguished for ventilation scenario SC1. In this scenario, the fire load (polyurethane sofa + two wood cribs) was located at the center of the room with a window of square exterior opening of a size of 1.5 m (Figure 2-1 and Table 2-1). The coordinate of the center of the window (in meters) was located at (x,y,z) = (0,1.9,1.25). The sofa was completely burned after 236 s (Figure 4-5b and c). At this time (236 s), a 50.6 kg (58% by mass) of the wood was lost. 15.9 kg (18% by mass) of the wood was left when the fire was completely extinguished (Figure 4-5d).

Figure 4-6 shows the temporal change of the HRR in scenario SC1. As shown in this figure, the HRR increased rapidly and reached its maximum value (6,092 kW) at 24 s. After 24 s, the HRR decreased rapidly until 37 s. In the period from 37 s to 236 s (sofa was completely burned), the HRR was more or less constant and its mean value was 3,850 kW. In this period, the HRR was due to burning both the polyurethane sofa and wood cribs. In the period from 236 s to 269 s, the HRR was approximately constant (its mean value equal 3,965 kW). After 269 s, the HRR decreased reaching a minimum value (479 kW) at 325 s. After that the HRR increased again, reaching another peak (2,347 kW) at 400 s. In the period from 400 s – 425 s, the HRR decreased from 2,347 kW to 2,211 kW. After 425 s, the HRR decreased rapidly to 1 kW at 600 s.

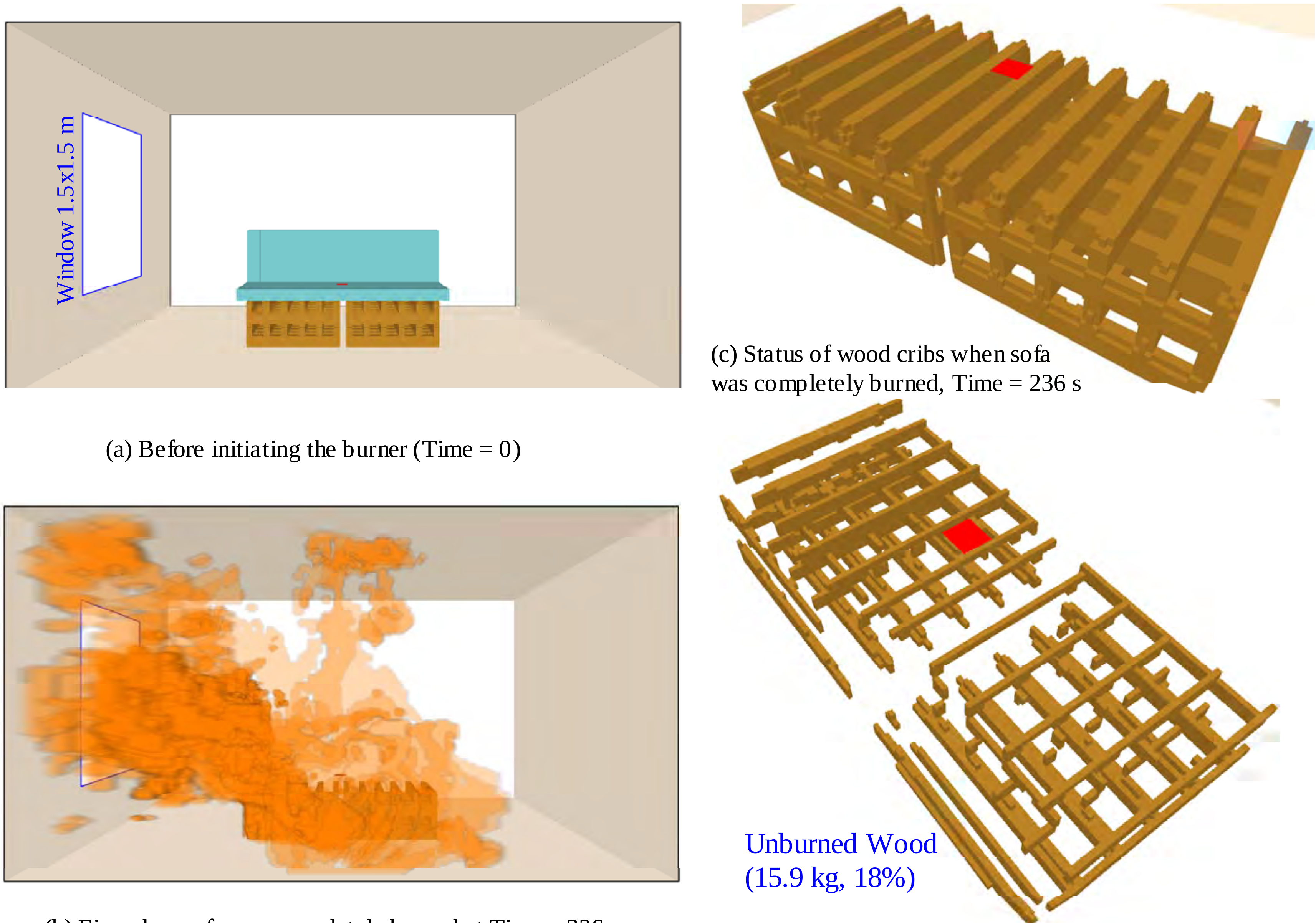
Sustaining the reaction requires two conditions: (a) sufficient energy (greater than or equal the heat of reaction) has to be absorbed or conducted through the solid fuel to evaporate/decompose the solid fuel to gas fuel, and (b) the surface temperature of the wood must be maintained well above its ignition temperature. In the late stages of burning the wood cribs (time > 425 s), both the lateral and longitudinal spacing between the wood cribs becomes wider due to the mass loss from the surfaces of the wood cribs (see Figure 4-5d), resulting in an enhancement of the heat transfer by convection on the wood surface. As a result, a considerable portion of the HRR is lost by convection decreasing the portion of the HRR conducted through the wood (portion of this heat is needed as a heat of reaction), and the surface temperature of the wood. Once the spacing between the wood cribs becomes wide enough in both conditions mentioned above for sustaining the reaction were not satisfied and, the wood reaction would stop as shown in Figure 4-5d.

Flow through vents plays an important role in the fire dynamics. This flow determines the amount of oxygen available for combustion to take place inside the compartment and also the heat loss by convection via the outgoing hot gases. The characteristic of this flow depends on the vent size and their locations as well as on the temperature and pressure imposed by natural wind or forced ventilation effects (e.g. fan(s)). In a compartment subjected to only natural convection conditions such as the ventilation scenarios in this study, vent flows through wall openings (windows and/or doors) were a result of buoyancy forces generated from the temperature or density difference between the two quiescent environments inside and outside the compartment. By considering an opening in the compartment wall, the outside cold ambient air flows into the compartment (inflow) as a result of the pressure difference. At the same time, hot gases flow out of the opening (outflow) to maintain the mass balance inside the compartment.

The inflow and outflow forms a countercurrent flow through the opening. Consequently, there will be a line of zero pressure difference in the opening at which the flow velocity equals zero. This is referred to as a neutral plane. Below the neutral plane, the differential pressure in the compartment is negative (compared to outside, $P_{inside} < P_{outside}$) with fresh air entering the compartment. Above the neutral plane, however, hot gases flowed out of the compartment due to positive differential pressure in the compartment ($P_{inside} > P_{outside}$).

Figure 4-7 and Figure 4-8 show the temperatures and the vectors of the velocity field at a longitudinal slice passing though the middle of the window (at y = 1.9 m) at different times. As shown in these figures, the combustion products and the hot gases travelled upward, and then exited the room through the upper part of the window. The cold fresh air enters the room through the lower part of the window. The mixing of the fresh air with the hot gases in the compartment induced eddies and vortices that produced a flicking/shaking fire flame (Figure 4-7). With such results, the locations of the neutral plane (at which the velocity equal ~ zero) oscillated with time between ~1/3 to 1/2 of the height of the window from the floor (Figure 4-8a-d).

In scenario SC1, the total energy released due to burning of 79.1 kg of the fire load (70.9 kg wood and 8.3 kg polyurethane sofa) was 1,317 MJ. Additionally, the effective heat of combustion in this scenario was 16.6 MJ/kg. Fire load densities of 83 MJ/m^2 and 248 MJ/m^2 were predicted assuming the fire spread over the entire floor area and 1/3 of the floor area, respectively.



(a) Before initiating the burner (Time = 0)

(b) Fire when sofa was completely burned at Time = 236 s

(c) Status of wood cribs when sofa was completely burned, Time = 236 s

(d) Status of wood cribs when fire was completely stopped

Figure 4-5 Burning polyurethane sofa and two wood cribs for ventilation scenario SC1 (window 1.5x1.5 m)

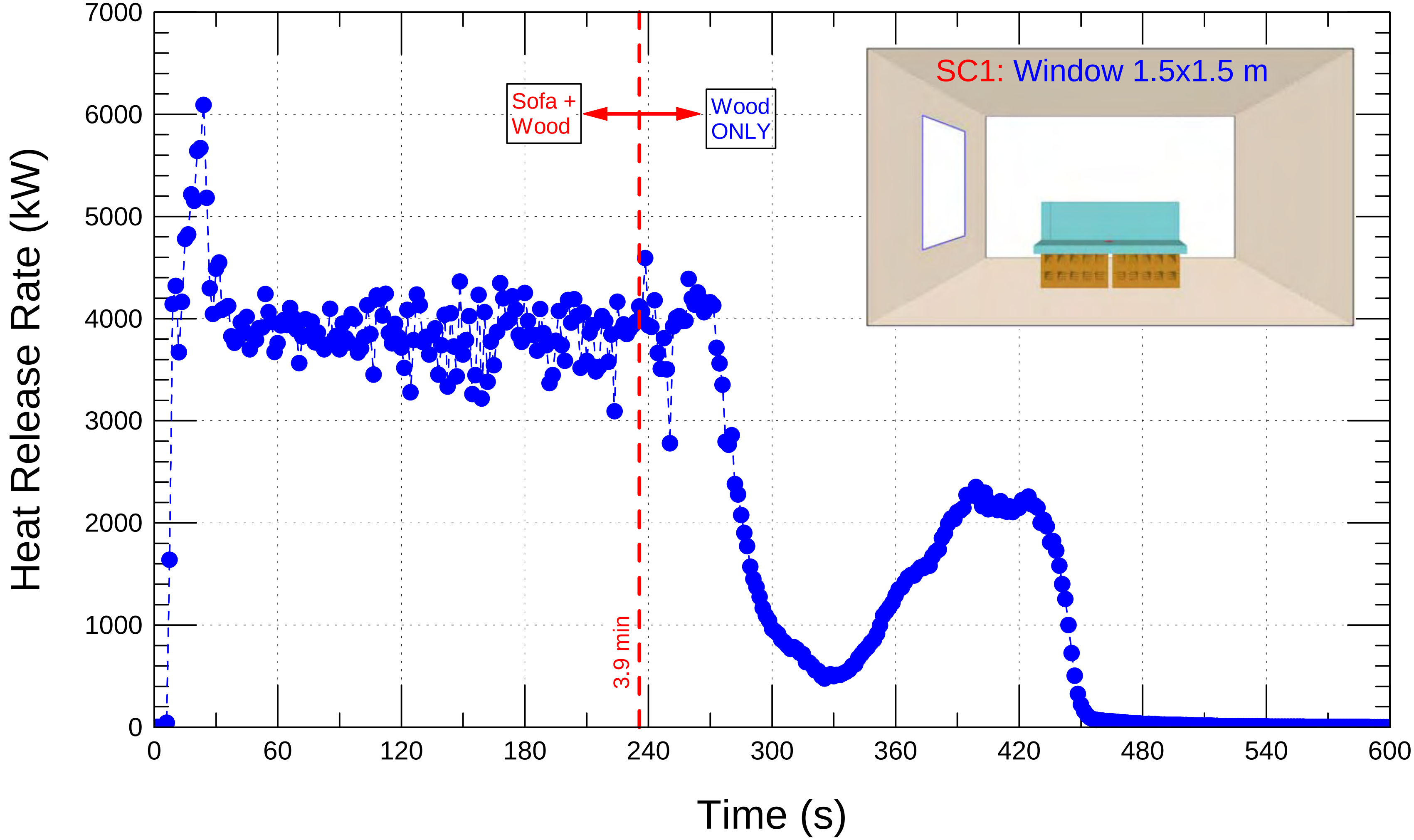
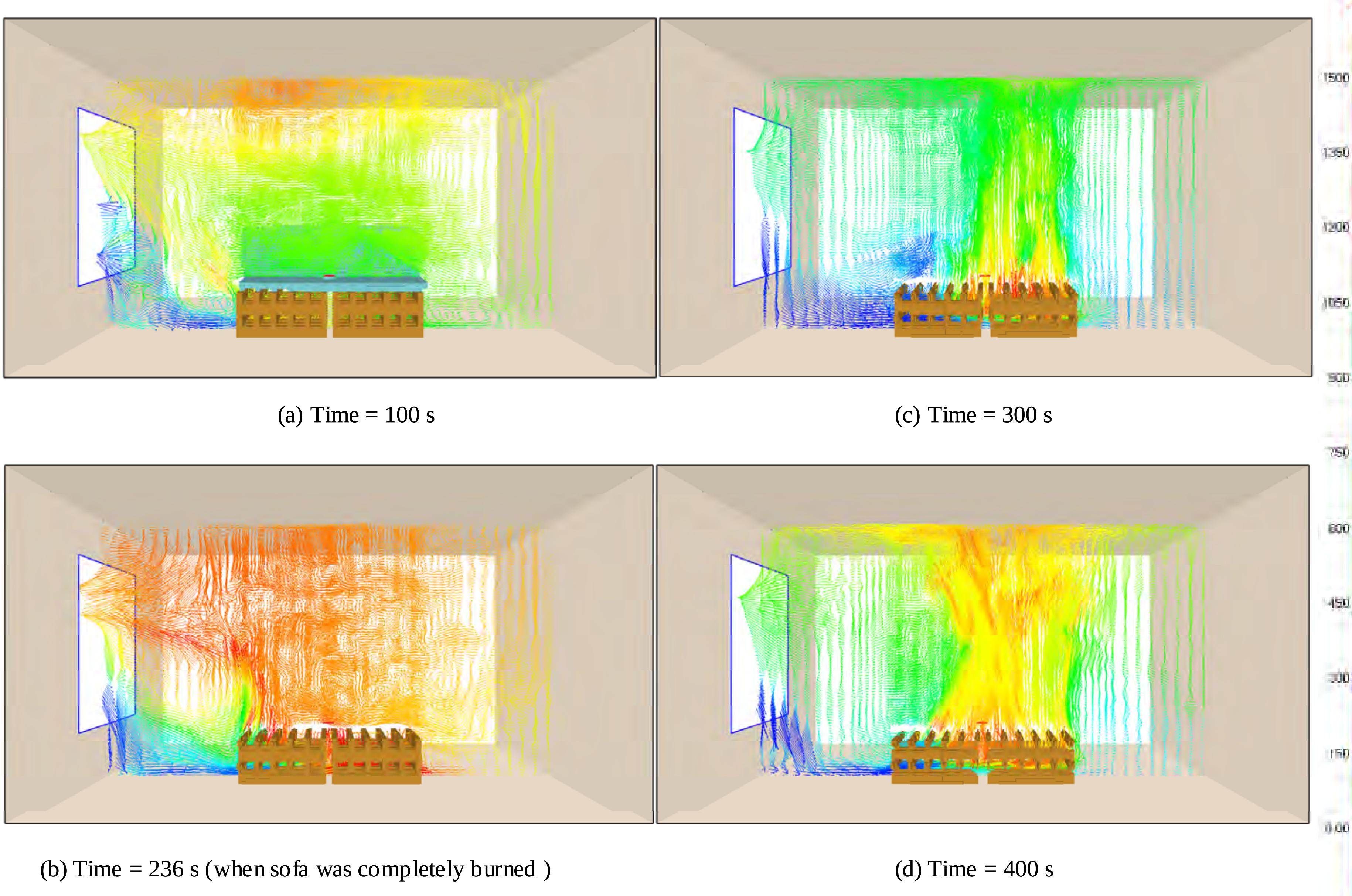


Figure 4-6 Heat Release Rate of ventilation scenario SC1 (window 1.5x1.5 m)



(a) Time = 100 s

(c) Time = 300 s

(b) Time = 236 s (when sofa was completely burned)

(d) Time = 400 s

Figure 4-7 Temperatures and vectors of the velocity field at a longitudinal slice passing through the middle of the window for SC1

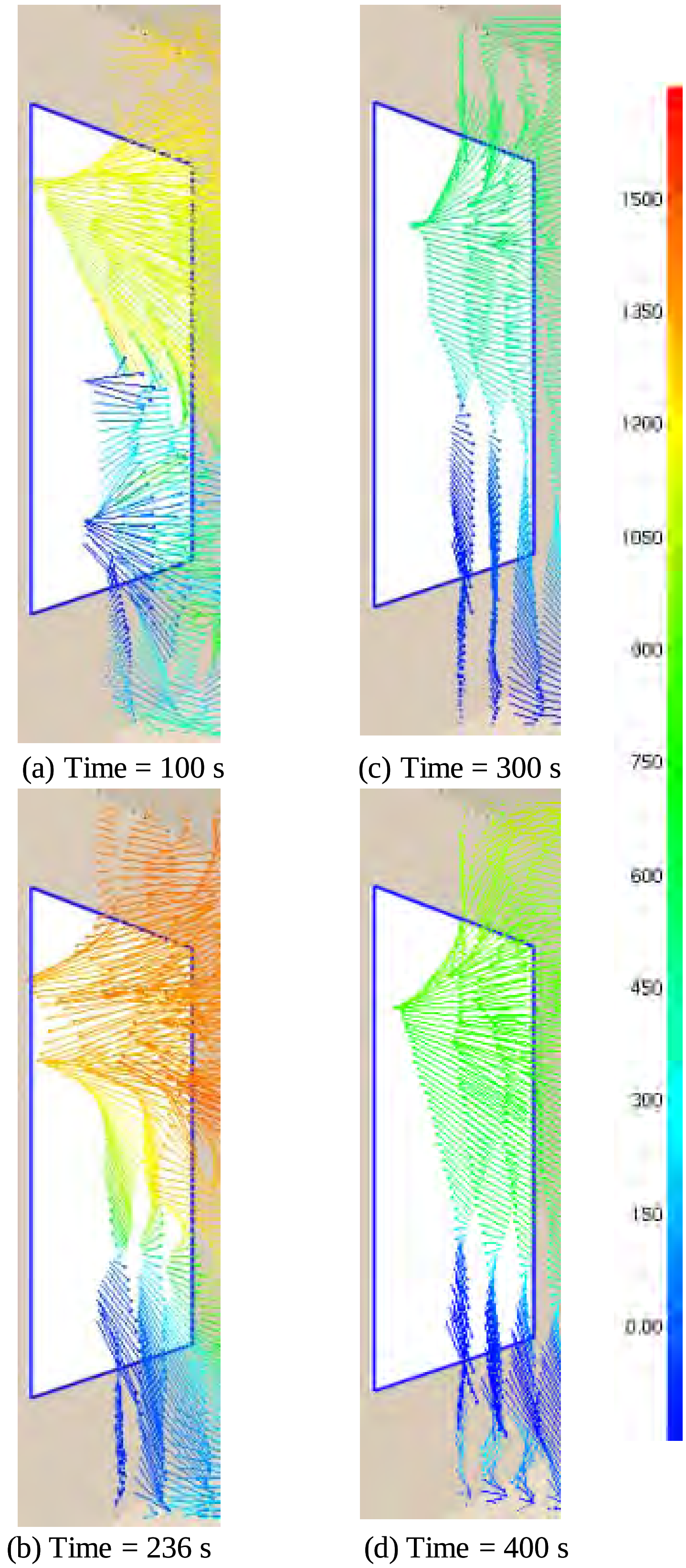


Figure 4-8 Temperatures and vectors of the velocity field at a longitudinal slice passing through the middle of the window for SC1

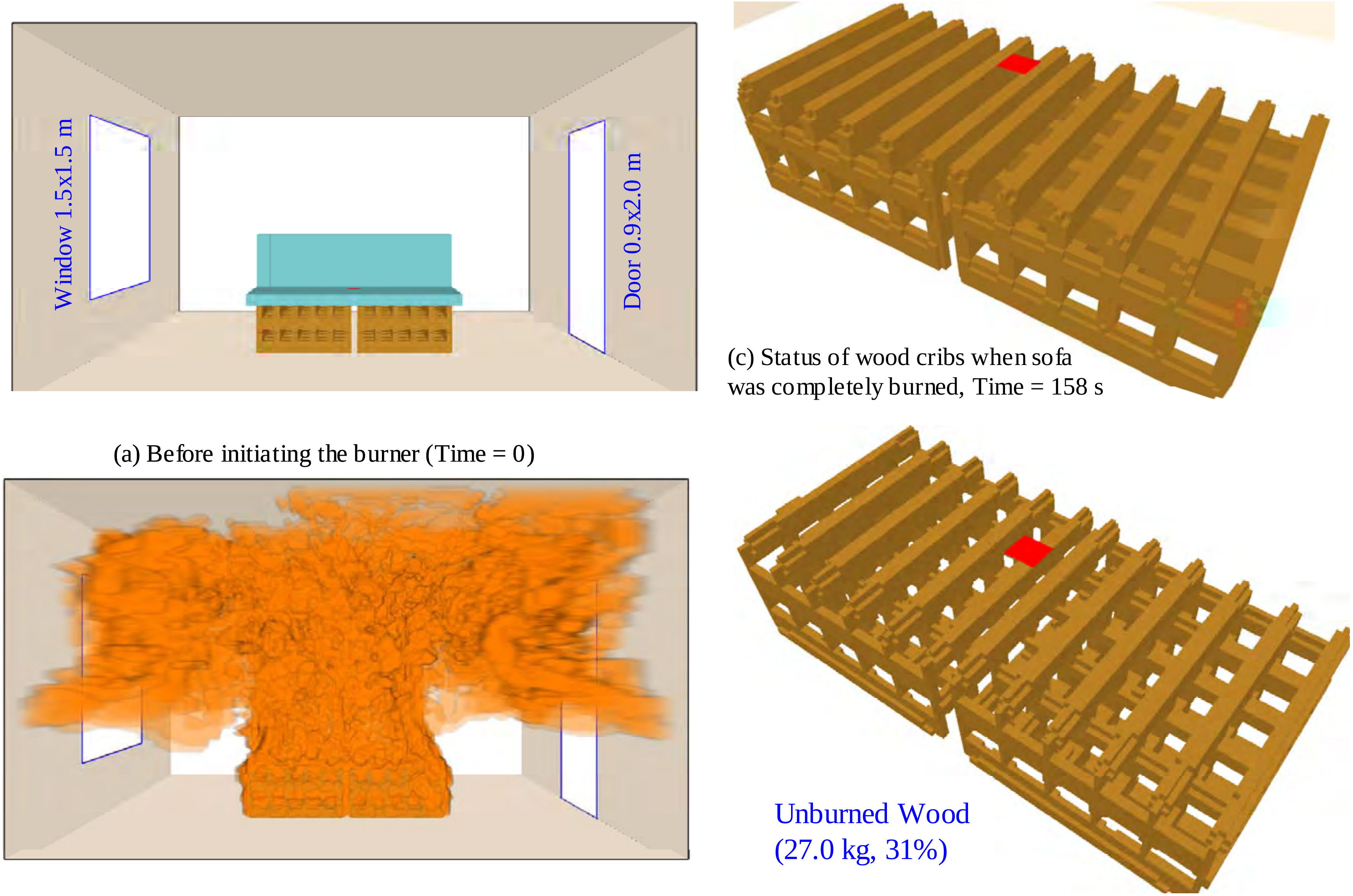
Ventilation Scenario SC2

Figure 4-9 shows the status of the fire load before initiating the burner, when the polyurethane sofa was completely burned, and when the fire was completely extinguished in ventilation scenario SC2. In this scenario, the fire load was located at the center of the room with a window of square exterior opening of a size of 1.5 m and a door of rectangular exterior opening of a size of 0.9 m wide by 2.0 m high (Figure 2-1 and Table 2-1). The coordinates (in meters) of the center of the window and the door were located at (0,1.9,1.25) and (4.2,1.9,1.0), respectively. The sofa was completely burned after 158 s (Figure 4-9b and c). At this time (158 s), 49.0 kg (57% by mass) of the wood was burned. At the end of simulation when the fire was completely extinguished, 27.0 kg (31% by mass) of the wood was left (Figure 4-9d).

The temporal change of the HRR is shown in Figure 4-10. As shown in this figure, in the first 23 s, the HRR increased rapidly and reached 5,877 kW. In the period from 23 s – 69 s, the HRR further increased but at a lower rate, reaching its first peak (7,292 kW) at 69 s. In the period from 69 s – 158 s, the HRR decreased reaching 4,961 kW at 158 s when the sofa was completely burned. After 158 s, the HRR slightly increased reaching a second peak (5,258 kW) at 168 s. Subsequently, the HRR decreased rapidly and eventually reached 1 kW at 300 s.

The thermal energy feedback from the flame to top of the fuel, as well as the radiation from the surrounding hot environment provides the energy required to vaporize the unburned solid fuel. The conservation of energy means that the energy going into a control volume will be equal to the energy going out, such that the heat released by the fire equals the sum of the heat loss from the convective gas flow, the radiative losses via the openings, the convective and radiative heat loss to the enclosing boundaries, the heat feedback vaporizing the excess fuel, and the heat stored in the gas volume. As a result, the size of the openings and their location play an important role in the thermal feedback and hence on the fire development. In the early stages of the burning, because of a high oxygen concentration with the large exterior openings in this ventilation scenario (1.5 m x 1.5 m window and 0.9 m x 2.0 m door), the maximum HRR was high (7,292 kW). In the late stages of burning with the wood cribs (time > 168 s), however, the good mixing by the inflow from both the window and the door resulted in significant heat losses reducing the thermal energy feedback to the bulk fuel and the fuel surface temperature. As a result, the fire lasted for the shortest period (~ 300 s) compared to other ventilation scenarios as will be shown later.

Figure 4-11 and Figure 4-12 show the temperatures and the vectors of the velocity field at a longitudinal slice passing though the middle of the window and the door (at y = 1.9 m) at different times. As shown in these figures, the combustion products and the hot gases exited the room through the upper portion of the window and the door. The cold fresh air enters the room through the lower portion of the window and the door. The location of the neutral plane in both the window and the door changed with time. The location of the neutral plane varied between ~1/3 to 1/2 of the height of the window from the floor. For the door, however, this location was between ~1/2 and 2/3 of the height from the floor (Figure 4-12a-d). The total energy released due to burning 68.0 kg of the fire load (57.9 kg wood and 8.3 kg polyurethane sofa) was 1,169 MJ. The predicted effective heat of combustion for this scenario was 17.2 MJ/kg. Fire load densities of 73 MJ/m^2 and 220 MJ/m^2 were predicted by assuming the fire spread over the entire floor area and 1/3 of the floor area, respectively.



(a) Before initiating the burner (Time = 0)

(b) Fire when sofa was completely burned at Time = 158 s

(c) Status of wood cribs when sofa was completely burned, Time = 158 s

(d) Status of wood cribs when fire was completely stopped

Figure 4-9 Burning polyurethane sofa and two wood cribs for ventilation scenario SC2 (window 1.5 x 1.5 m and door 0.9 x 2.0 m)

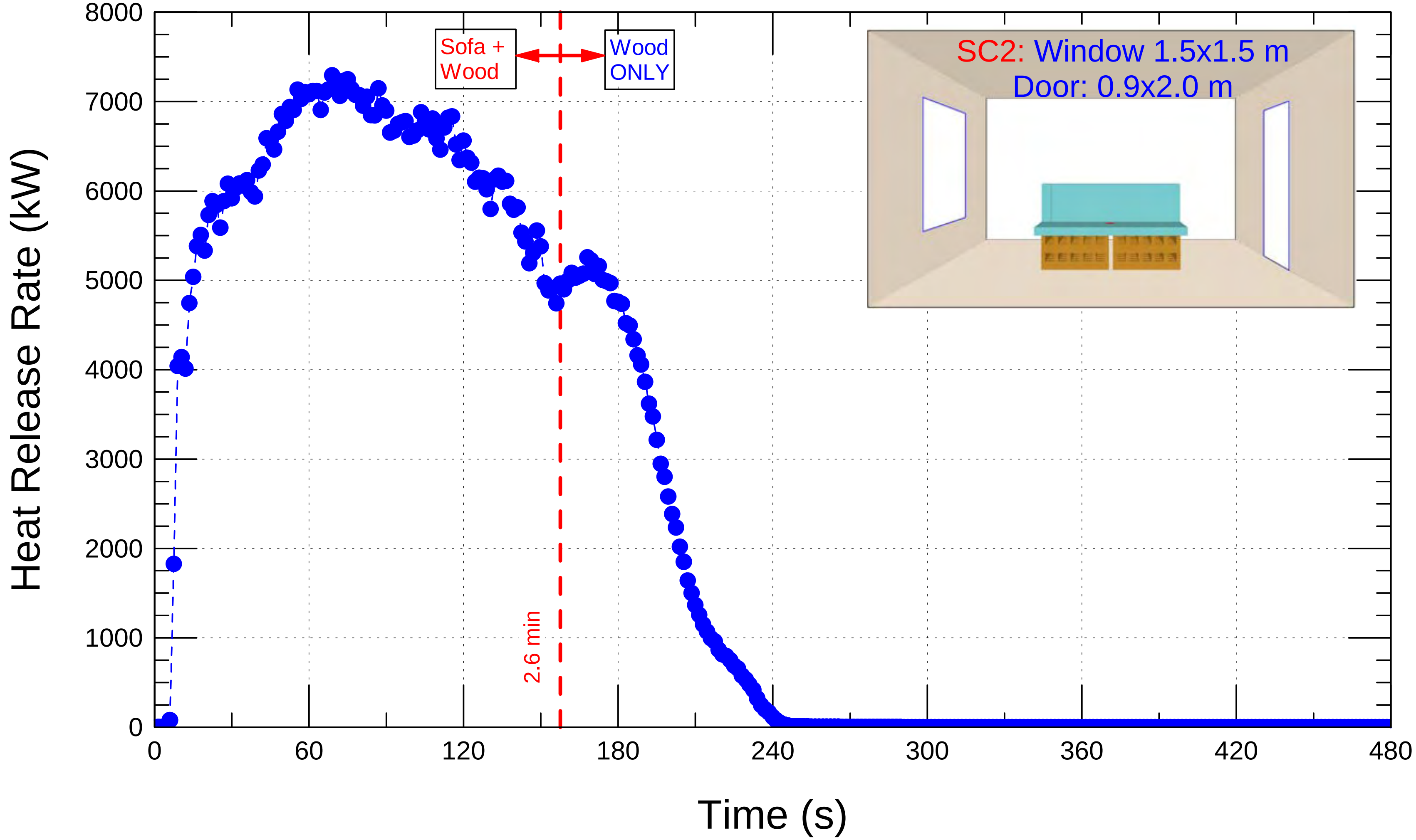
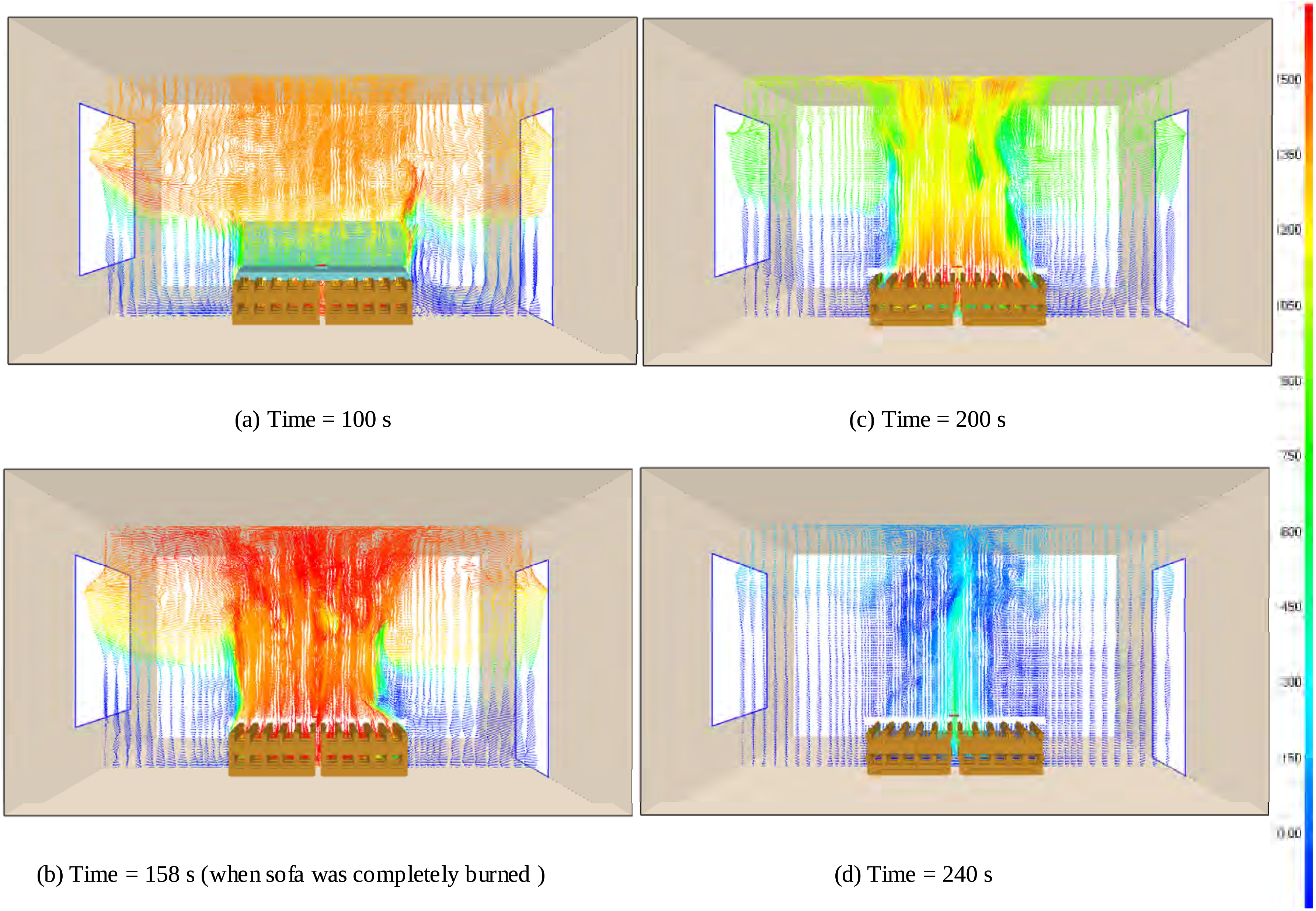


Figure 4-10 Heat Release Rate of ventilation scenario SC2 (window 1.5 x 1.5 m and door 0.9 x 2.0 m)



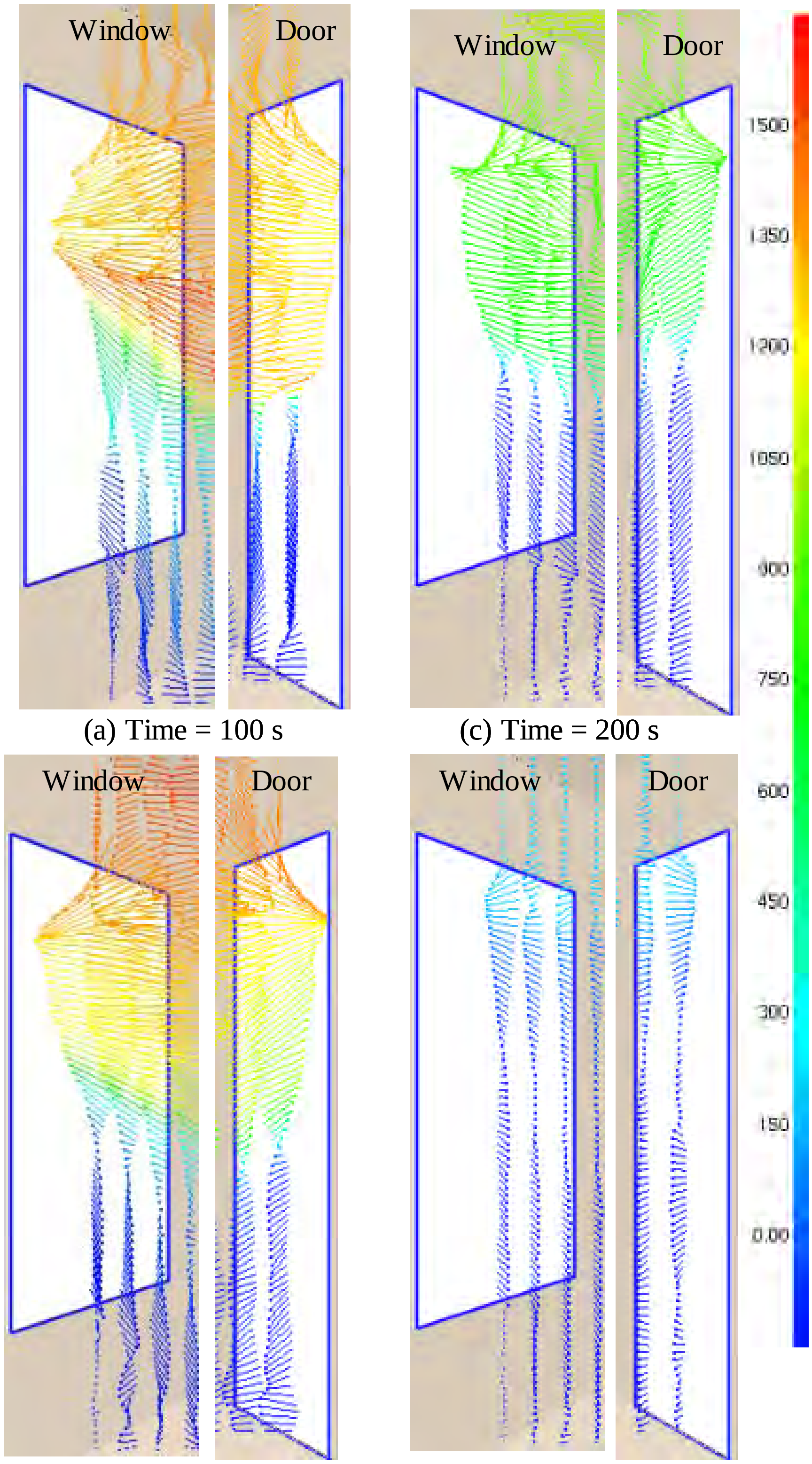
(a) Time = 100 s

(c) Time = 200 s

(b) Time = 158 s (when sofa was completely burned)

(d) Time = 240 s

Figure 4-11 Temperatures and vectors of the velocity field at a slice passing through the middle of the window and door for SC2



(a) Time = 100 s

(c) Time = 200 s

(b) Time = 158 s

(d) Time = 240 s

Figure 4-12 Temperatures and vectors of the velocity field at a longitudinal slice passing through the middle of the window and door for SC2

Ventilation Scenario SC3

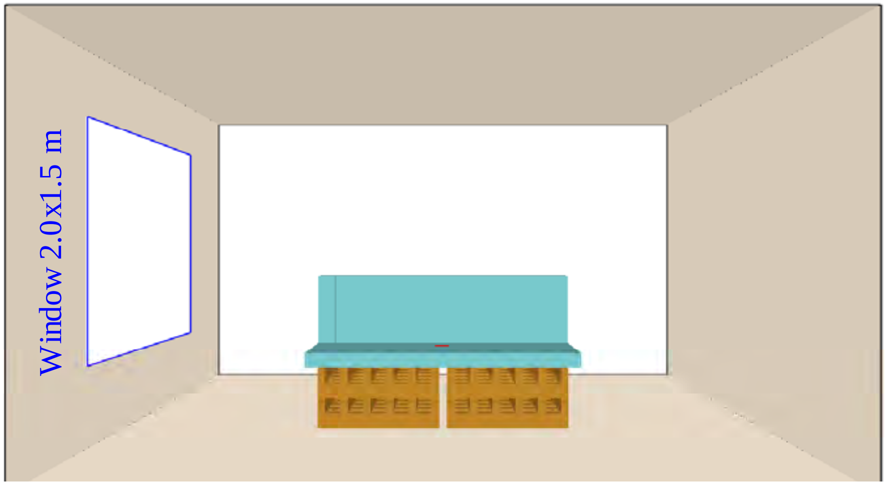
In the ventilation scenario SC3, the fire load was located at the center of the room with a large window of a rectangular exterior opening of 2.0 m wide by 1.5 m high (Figure 2-1 and Table 2-1). The coordinate (in meters) of the center of the window was located at (0,1.9,1.25). As shown in Figure 4-13b and c, the sofa was completely burned after 192 s. At this time, the amount of mass loss from the wood was 49.6 kg (57% by mass). When the fire was completely extinguished, 16.8 kg (19% by mass) of the wood was left (Figure 4-13d).

Figure 4-14 shows the temporal change of the HRR. As shown in this figure, in the first 39 s, the HRR increased rapidly and reached its first peak of 6,940 kW. Between 39 s – 60 s, the HRR decreased gradually, and reached a value of ~5,200 kW at 60 s.

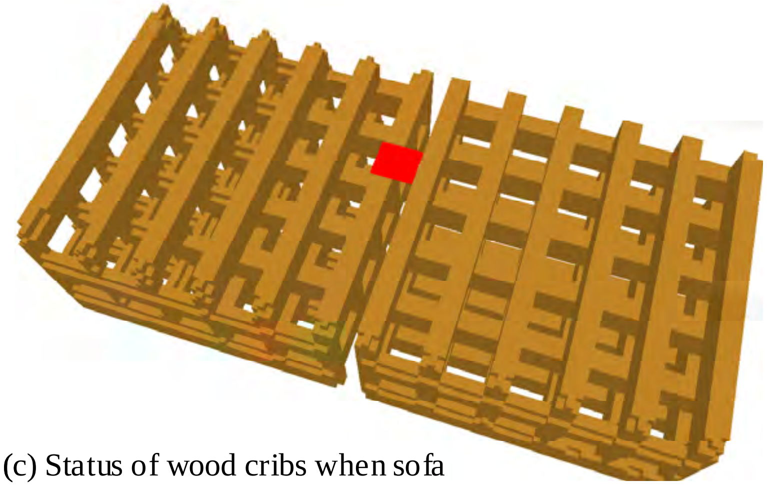
During the period of burning the polyurethane sofa and wood simultaneously, and in the period of early stage of burning wood only, the size of the flame was large (flame filled most of the compartment) due to not only burning the polyurethane sofa and the wood cribs simultaneously, but also because the polyurethane sofa was volatile and easily evaporated into gas fuel. Having only one exterior opening with a flame of a large size resulted in a good mixing between the inflow (entering the compartment through the opening) and the combustion products inside the compartment. This kind of mixing generates vortices and eddies (see Figure 4-15a and b) and causes non-uniform oxygen concentration in the vicinity of the flame sheet. As a result, a wavy or flicking flame was produced. Since the HRR was calculated from the local rate consumption of the oxygen at the flame surface, the HRR becomes larger when the flame surface existed in a domain of higher oxygen concentration than that when the flame surface existed in a domain of lower oxygen concentration. In other words, the HRR fluctuates up and down with time; see for example the HRR in Figure 4-6 and Figure 4-14 for ventilation scenarios SC1 and SC3, respectively, where there was only one exterior opening in the wall of the room. This was not the case with two exterior openings with approximately the same size and facing each other such as scenario SC2, or the Test Case II (fire load was burned in a fully open environment) where the flame was approximately vertical. In these cases the HRR does not fluctuate with time (see Figure 4-9b and Figure 4-10 for SC2, and Figure 4-3b and Figure 4-4 for Test Case II).

Between 60 s – 200 s, which was the period of burning of both the polyurethane sofa and wood cribs simultaneously, and the early stage of burning wood only, the mean HRR was 5,081 kW. After 200 s, the HRR decreased rapidly reaching its minimum value (581 kW) at 279 s. Because of the back effect, the HRR increased gradually again with a second peak (2,799 kW) at 358 s. After the second peak, the HRR decreased gradually in the period from 358 s – 373 s, and then decreased rapidly until the reaction was completely stopped (at 545 s). The HRR did not fluctuate in the late stages of burning wood only. In this period, the flame size was small, and the generated vortices and eddies due to the mixing between the inflow and combustion products were not strong enough to produce flicker flame (see Figure 4-15c and d). This was the case for all ventilation scenarios investigated in this study.

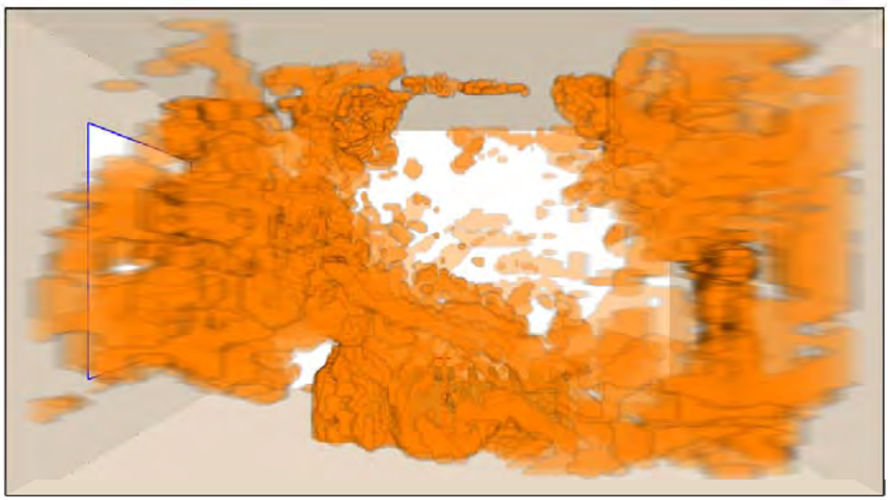
Figure 4-15 and Figure 4-16 show the temperatures and the vectors of the velocity field at a longitudinal slice passing though the middle of the window (at y = 1.9 m) at different times for scenario SC3. As shown in these figures, the location of the neutral plane in the window changed with time. The neutral plane lay between ~1/4 to 1/3 of the height of the window from the floor. The total energy released due to burning 78.2 kg of the fire load (69.9 kg wood and 8.3 kg polyurethane sofa) was 1,398 MJ. The effective heat of combustion in this scenario was 17.9 MJ/kg. Fire load densities of 88 MJ/m^2 and 263 MJ/m^2 were predicted by assuming the fire spreads over the entire floor area and 1/3 of the floor area, respectively.



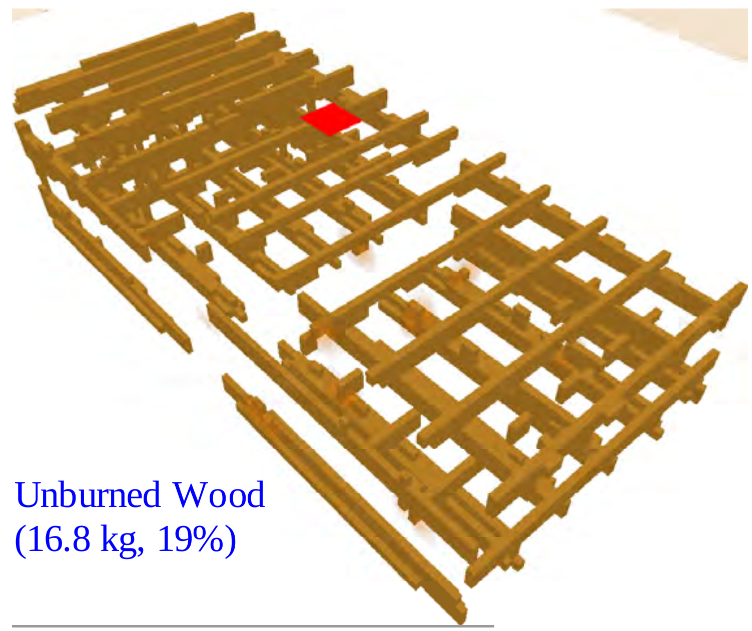
(a) Before initiating the burner (Time = 0)



(c) Status of wood cribs when sofa was completely burned, Time = 192 s



(b) Fire when sofa was completely burned at Time = 192



(d) Status of wood cribs when fire was completely stopped

Figure 4-13 Burning polyurethane sofa and two wood cribs for ventilation scenario SC3 (window 2.0 x 1.5 m)

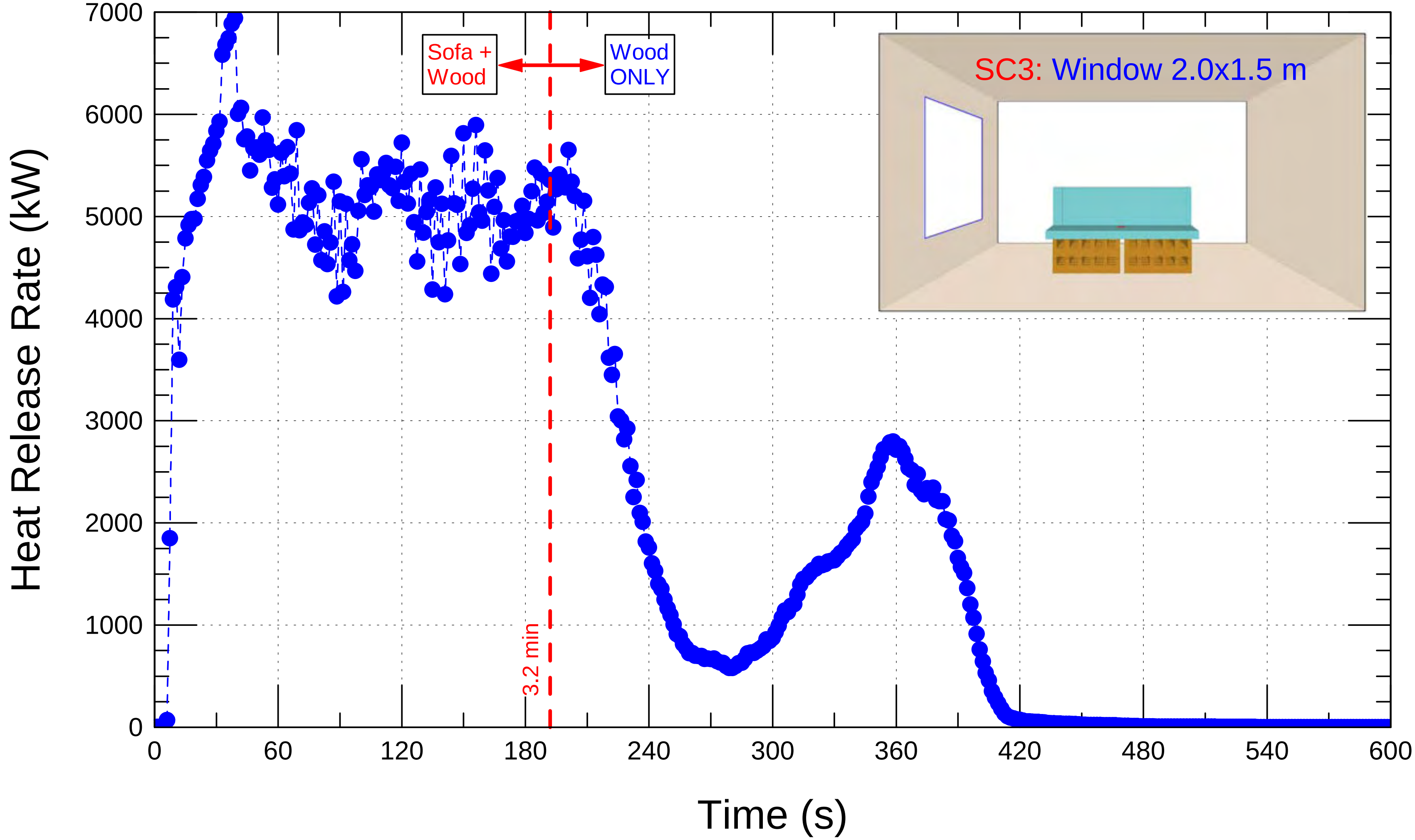
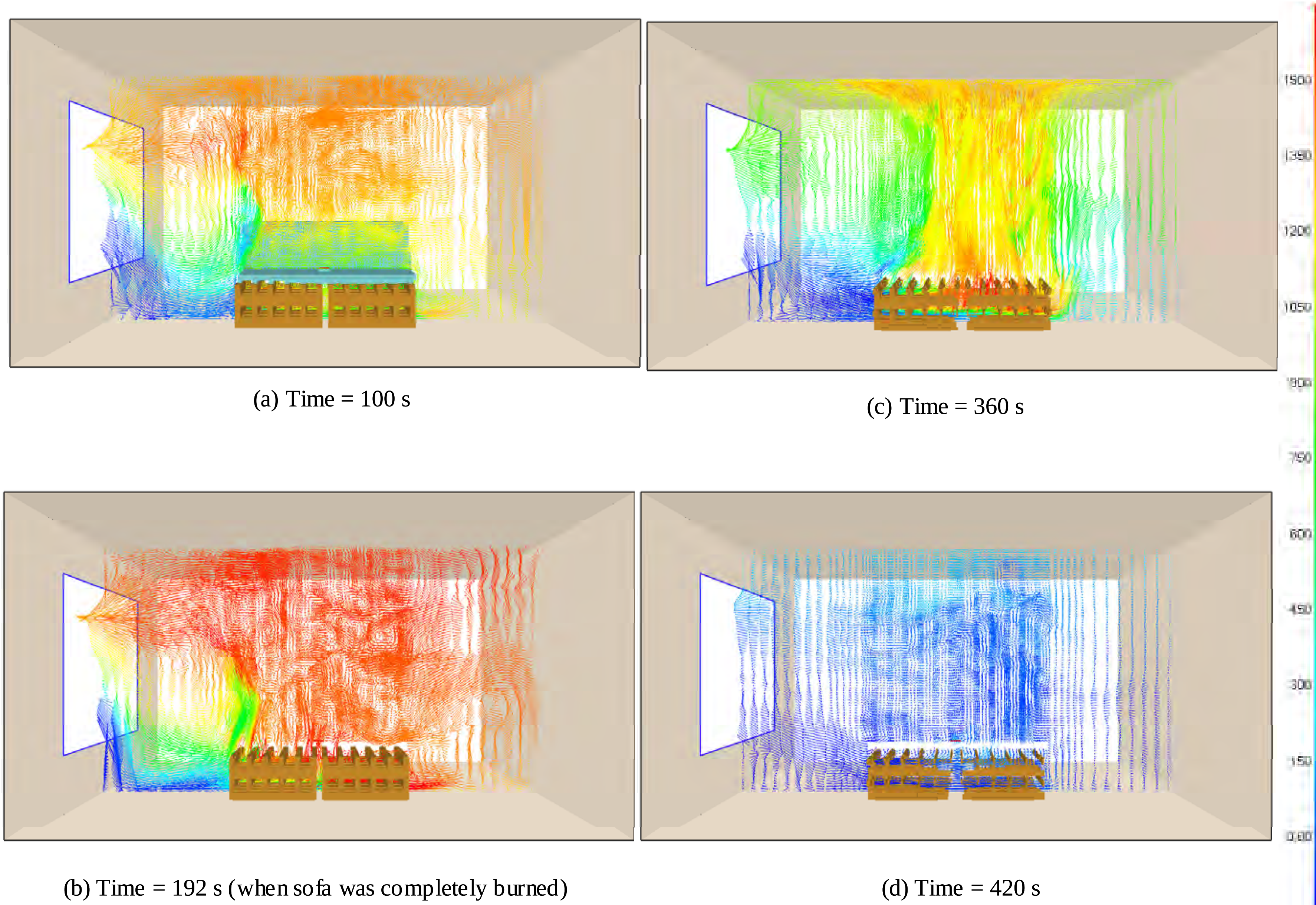


Figure 4-14 Heat Release Rate of ventilation scenario SC3 (window 2.0 x 1.5 m)



(a) Time = 100 s

(c) Time = 360 s

(b) Time = 192 s (when sofa was completely burned)

(d) Time = 420 s

Figure 4-15 Temperatures and vectors of the velocity field at a longitudinal slice passing through the middle of the window for SC3

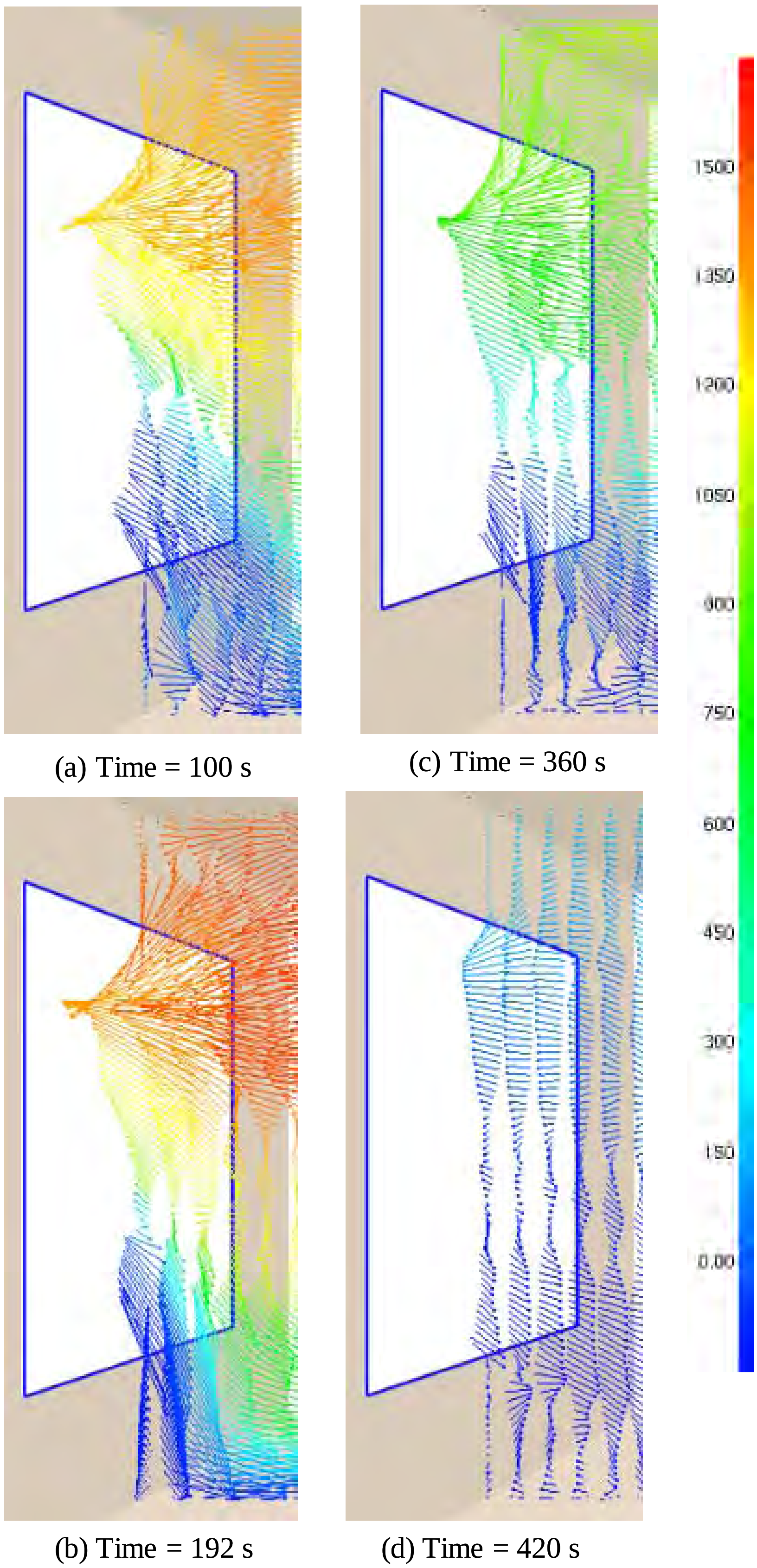


Figure 4-16 Temperatures and vectors of the velocity field at a longitudinal slice passing through the middle of the window for SC3

Ventilation Scenario SC4

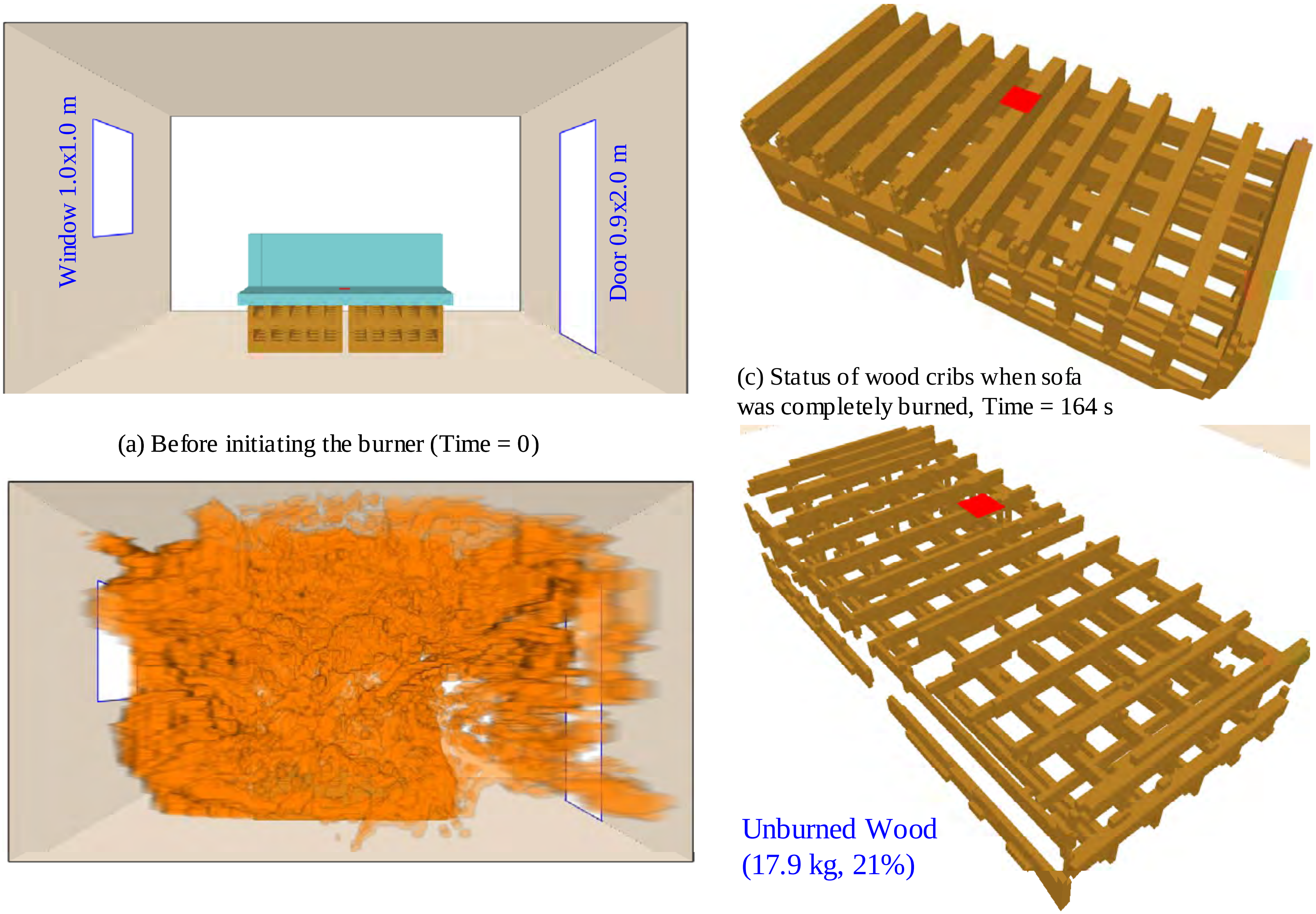
Figure 4-17 shows the status of the fire load in ventilation scenario SC4 at 0 s, when the polyurethane sofa was completely burned, and when the fire was completely extinguished. In this scenario, the fire load was located at the center of the room with two rectangular exterior openings: a small window of a size of 1.0 m wide by 1.0 m high and a door of a size of 0.9 m wide and 2.0 m high. The coordinates (in meters) of the center of the window and the door were (0, 1.9, 1.5) and (4.2, 1.9, 1.0), respectively (see Figure 2-1 and Table 2-1). As shown in Figure 4-17b and c, the sofa was completely burned after 164 s. At this time, the amount of mass loss from the wood cribs was 48.3 kg (56% by mass). At the end of the simulation and the fire completely extinguished, the amount of the unburned wood was 17.9 kg (21% by mass) (Figure 4-17d).

Figure 4-18 shows the temporal change of the HRR. In the first 30 s, the HRR increased rapidly and reached a first peak at 6,816 kW. Three seconds later, the HRR decreased to 5,517 kW. Between 33 s – 164 s, the HRR decreased gradually with time, and reached a value of 4,713 kW at 164 s (the polyurethane sofa was completely burned). Despite having two exterior openings facing each other, the HRR fluctuated during the period where both the polyurethane sofa and the wood cribs were burning simultaneously. This was because the size of one of the openings (window) was much smaller than that of the other opening (door). As such, the generated vortices and eddies due to the mixing of the inflow from the door and the combustion products produced a flickering flame in SC4 (see Figure 4-17b, and Figure 4-19a and b). This was not the case in scenario SC2 that had two exterior openings facing each other but with approximately the same size (see the previous subsection for more details).

After the polyurethane sofa was completely burned (time >164 s), the HRR decreased gradually from 4,713 kW to 4,218 kW at 192 s. Consequently, the HRR decreased rapidly with time reaching a minimum value (1,442 kW) at 238 s. At time > 238 s, the HRR increased gradually and reached a second peak (2,591 kW) at 309 s. After the second peak was been reached (Figure 4-18), the HRR decreased rapidly again until the reaction was completely stopped at 435 s.

The temperatures and the vectors of the velocity field at a longitudinal slice passing though the middle of both the window and the door (at y = 1.9 m) at different times were shown in Figure 4-19 and Figure 4-20. These figures clearly show that the small window (1.0 m x 1.0 m) acted as a chimney for the combustion products. The upper half of the door acted as a chimney while the inflow of the cold fresh air entered the compartment through the lower half of the door. As such, a neutral plane did not exist in the window. For the door, the location of the neutral plane did not change (Figure 4-20) and was at ~1/2 of the door height.

The total burned mass in this ventilation scenario was 77.1 kg (68.8 kg wood and 8.3 kg polyurethane sofa). The total energy released due to burning this mass was 1,304 MJ. Also, the effective heat of combustion in this scenario was 16.9 MJ/kg. Fire load densities of 82 MJ/m^2 and 245 MJ/m^2 were predicted by assuming the fire spread over the entire floor area and 1/3 of the floor area, respectively.



(a) Before initiating the burner (Time = 0)

(b) Fire when sofa was completely burned at Time = 164 s

(c) Status of wood cribs when sofa was completely burned, Time = 164 s

(d) Status of wood cribs when fire was completely stopped

Figure 4-17 Burning polyurethane sofa and two wood cribs for ventilation scenario SC4 (window 1.0 x 1.0 m, Door 0.9 x 2.0 m)

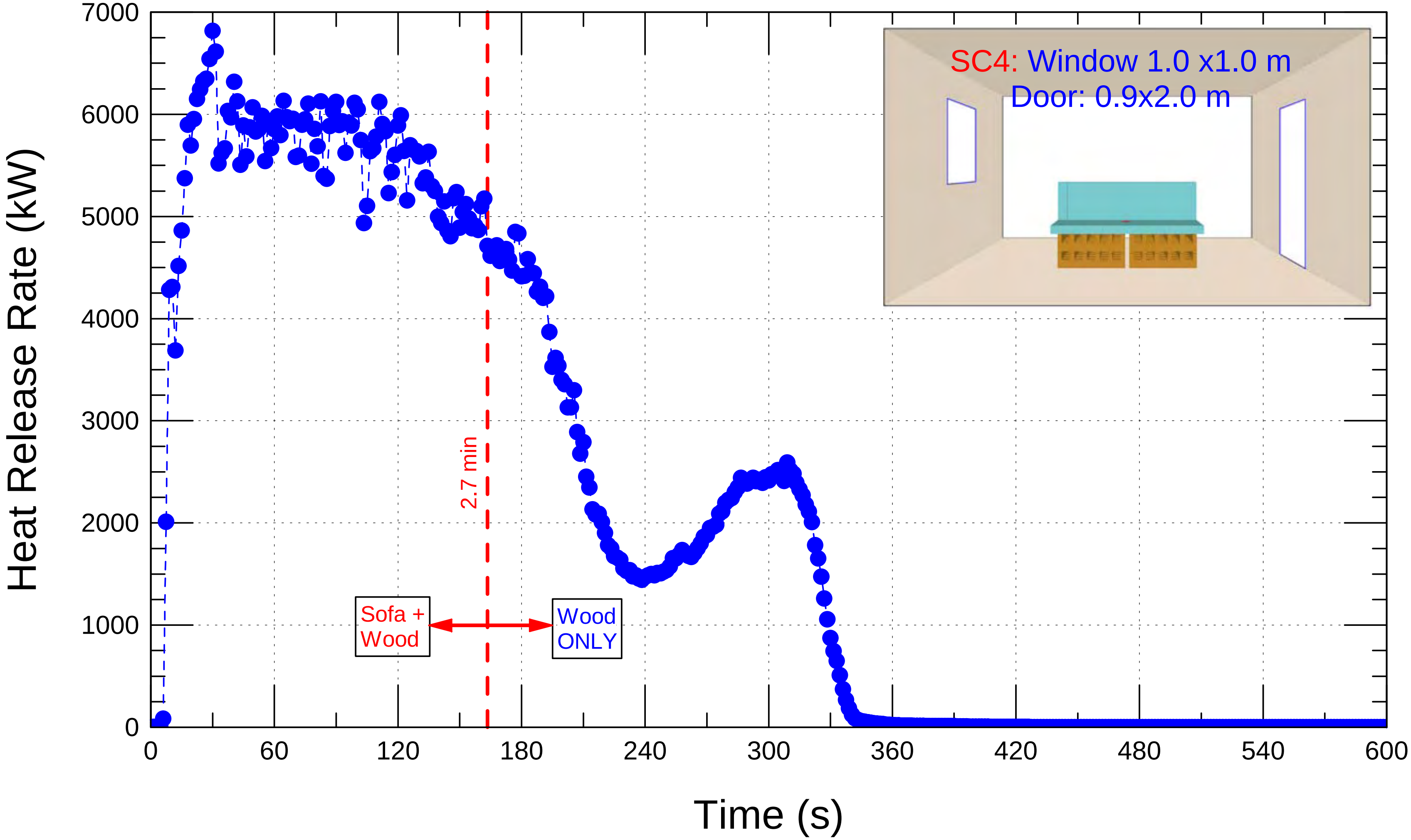
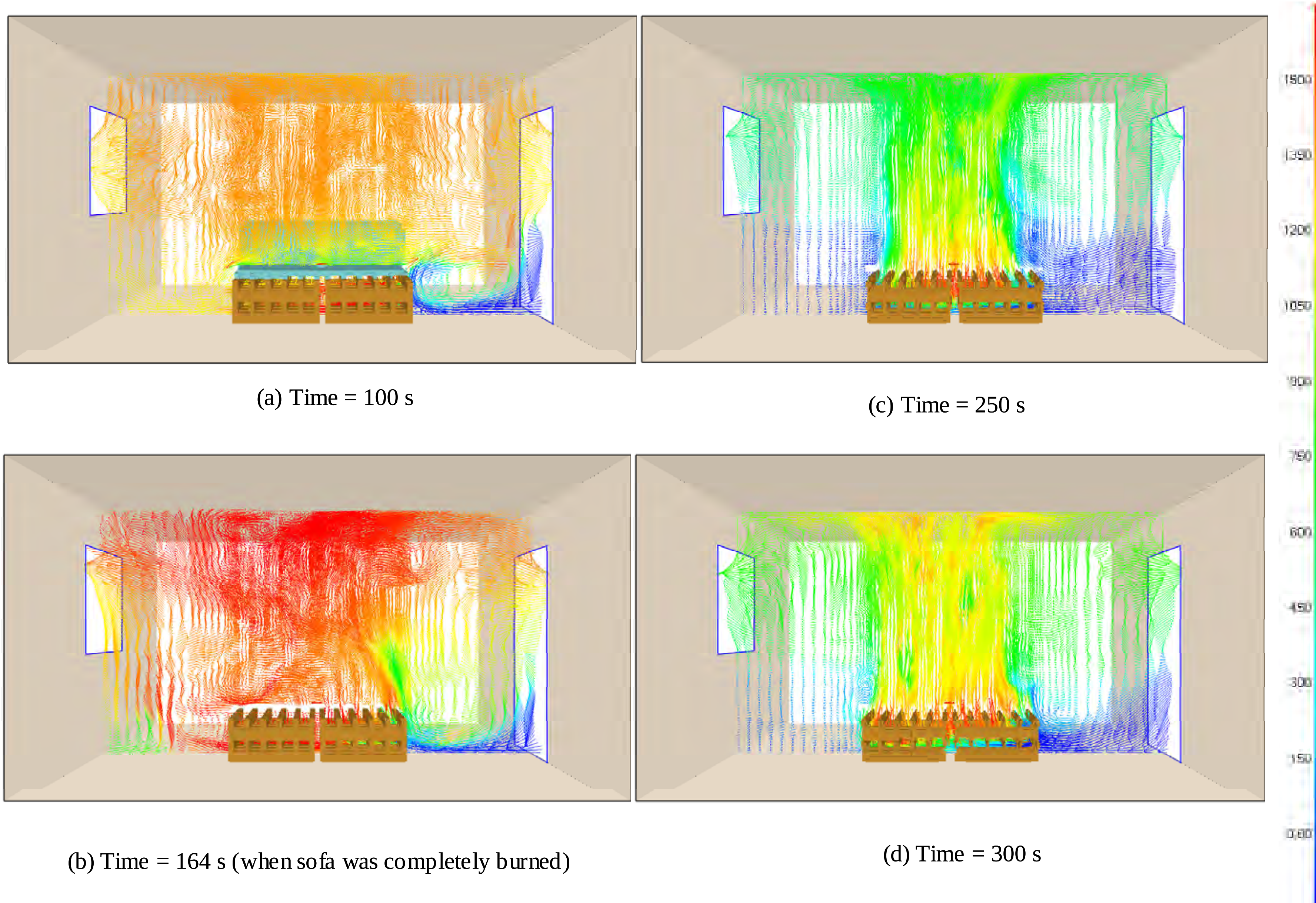


Figure 4-18 Heat Release Rate of ventilation scenario SC4 (window 1.0 x 1.0 m, Door 0.9 x 2.0 m)



(a) Time = 100 s

(c) Time = 250 s

(b) Time = 164 s (when sofa was completely burned)

(d) Time = 300 s

Figure 4-19 Temperatures and vectors of the velocity field at a longitudinal slice passing through the middle of the window and the door for SC4

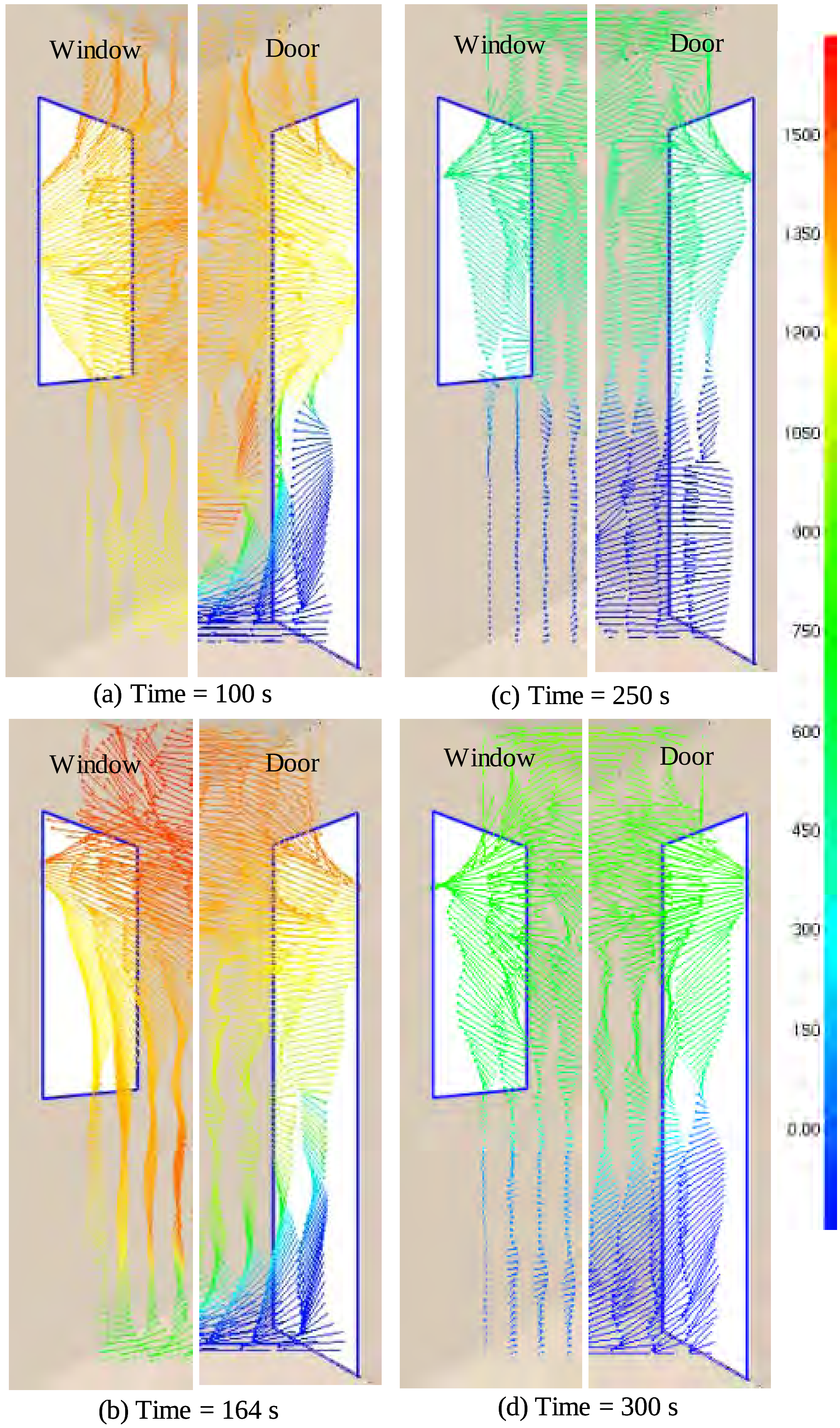


Figure 4-20 Temperatures and vectors of the velocity field at a longitudinal slice passing through the middle of the window and door for SC4

Ventilation Scenario SC5

Figure 4-21 shows the status of the fire load in ventilation scenario SC5 at 0 s, when the polyurethane sofa was completely burned, and when the fire was completely extinguished. In this scenario, the fire load was located at the center of the room with a door of a rectangular exterior opening of a size of 0.9 m wide and 2.0 m high. The coordinate (in meters) of the center of the door was (4.2,1.9,1.0) (see Figure 2-1 and Table 2-1). As shown in Figure 4-21b and c, the sofa was completely burned after 249 s. At this time, the burned mass from the wood was 52.4 kg (60% by mass). At the end of simulation when the fire was completely extinguished, the unburned mass of the wood was 18.3 kg (21% by mass) (Figure 4-21d).

Figure 4-22 shows the temporal change of the HRR for scenario SC5. The first HRR peak (4,983 kW) was at only 15 s from initiating the fire. Within 12 s after reaching the first peak (from 15 s to 27 s), the HRR decreased rapidly with time from 4,983 kW to 3,460 kW. As explained earlier, the HRR fluctuated with the single exterior opening that causes a flickering flame (see Figure 4-21b and Figure 4-23a, b and c). The mean HRR in the period where both the polyurethane sofa and wood cribs were burning simultaneously was 3,622 kW. After the polyurethane sofa was completely burned, the HRR (249 s to 289 s) continued to fluctuate and its mean value was 3,724 kW. Subsequently, it decreased rapidly with time reaching a minimum value (1,521 kW) at 319 s. For time > 319 s, the HRR increased gradually and reached a second peak (1,961 kW) at 351 s (Figure 4-22), then decreased with different rates (i.e. different slopes, dHRR/dt) until the reaction was completely stopped (at 536 s).

Figure 4-23 and Figure 4-24 show the temperatures and the vectors of the velocity field at a longitudinal slice passing though the middle of the door (at y = 1.9 m) at different times. As shown in these figures, the location of the neutral plane in the door did not vary much in ventilation scenario SC5. It was located at the lower ~1/3 of the door height. The total energy released due to burning 76.7 kg of the fire load (68.4 kg wood and 8.3 kg polyurethane sofa) was 1,219 MJ. In this scenario, the effective heat of combustion was 15.9 MJ/kg. Fire load densities of 76 MJ/m^2 and 229 MJ/m^2 were predicted by assuming the fire spread over the entire floor area and 1/3 of the floor area, respectively.

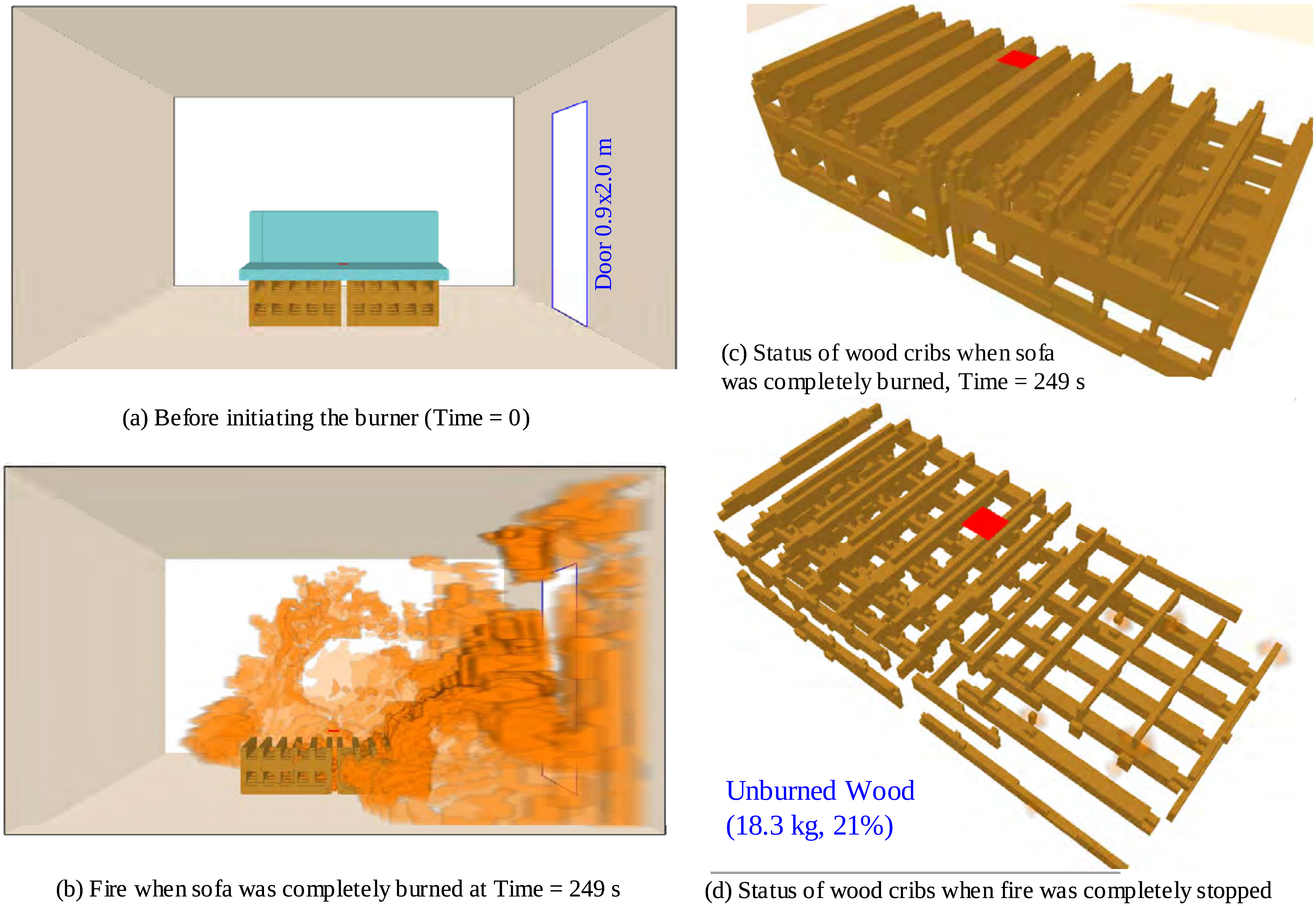


Figure 4-21 Burning polyurethane sofa and two wood cribs for ventilation scenario SC5 (Door 0.9 x 2.0 m)

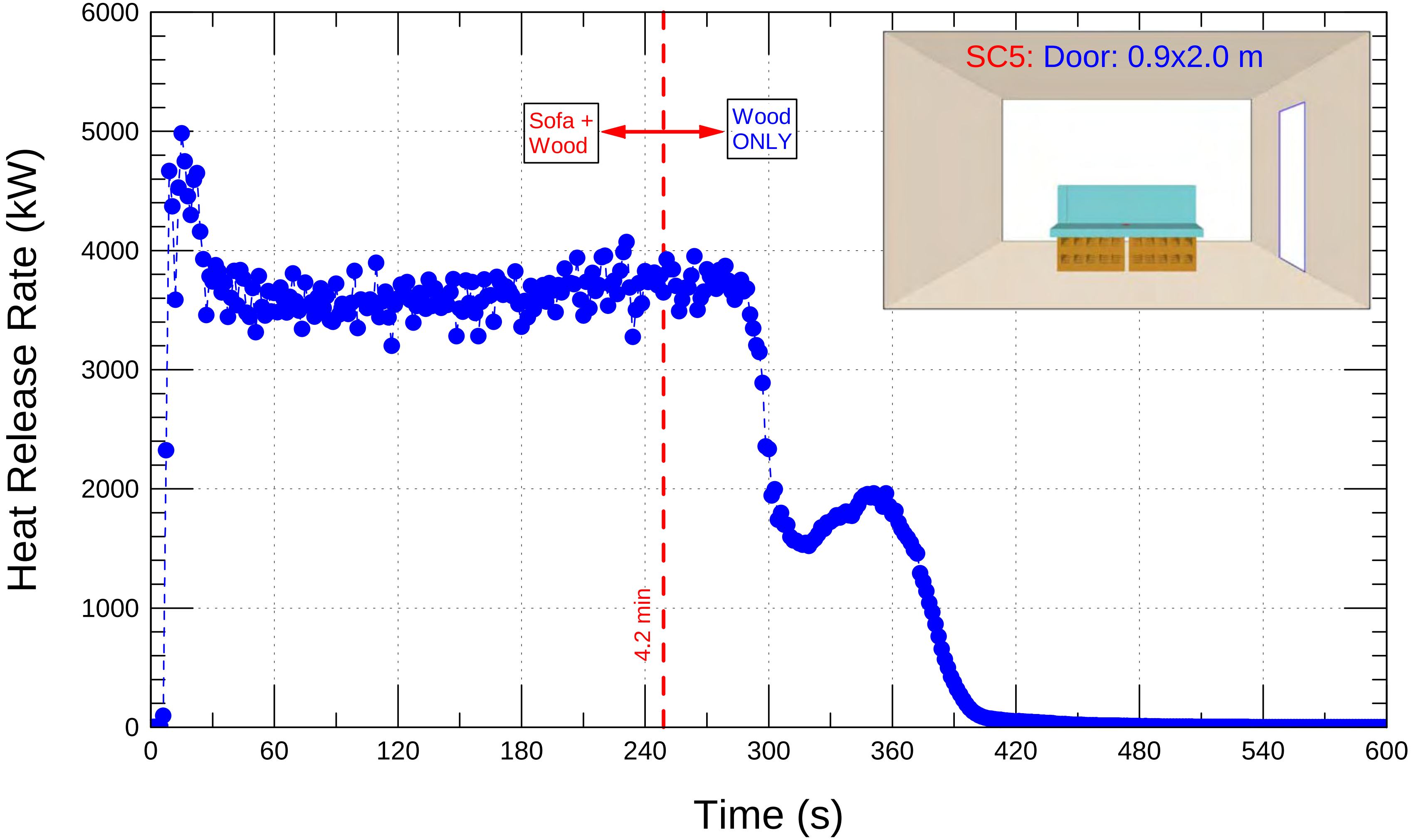
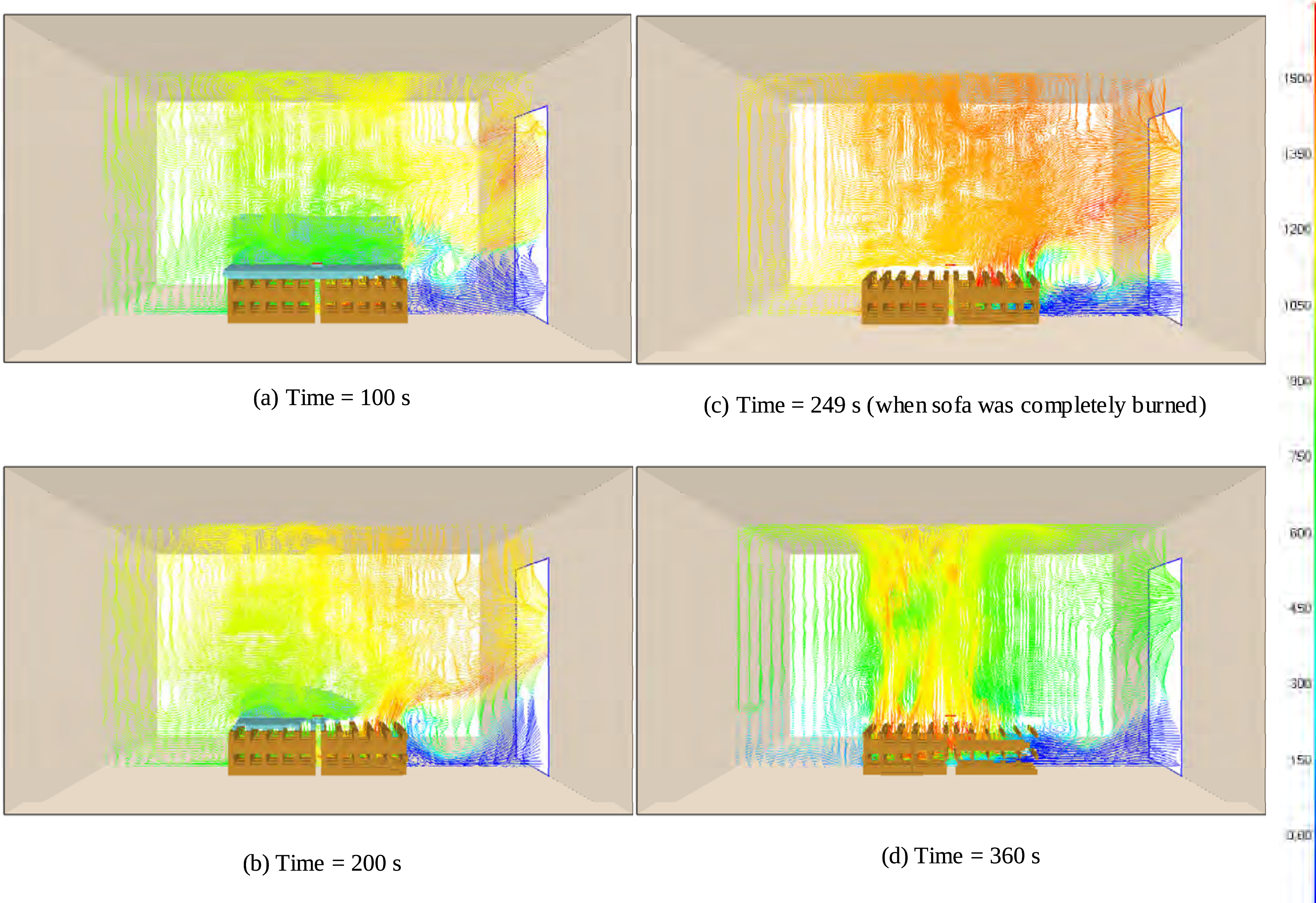


Figure 4-22 Heat Release Rate of ventilation scenario SC5 (Door 0.9 x 2.0 m)



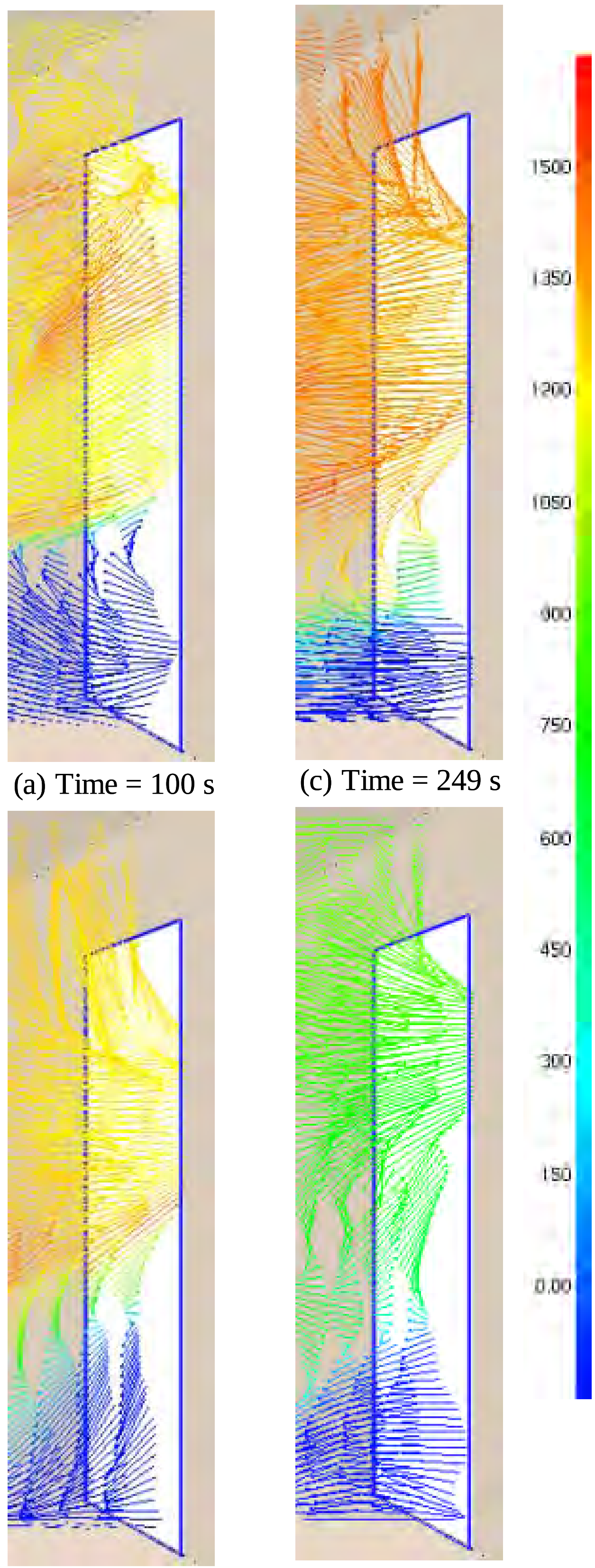
(a) Time = 100 s

(c) Time = 249 s (when sofa was completely burned)

(b) Time = 200 s

(d) Time = 360 s

Figure 4-23 Temperatures and vectors of the velocity field at a longitudinal slice passing through the middle of the door for SC5



(a) Time = 100 s (c) Time = 249 s

(b) Time = 200 s (d) Time = 360 s

Figure 4-24 Temperatures and vectors of the velocity field at a longitudinal slice passing through the middle of the door for SC5

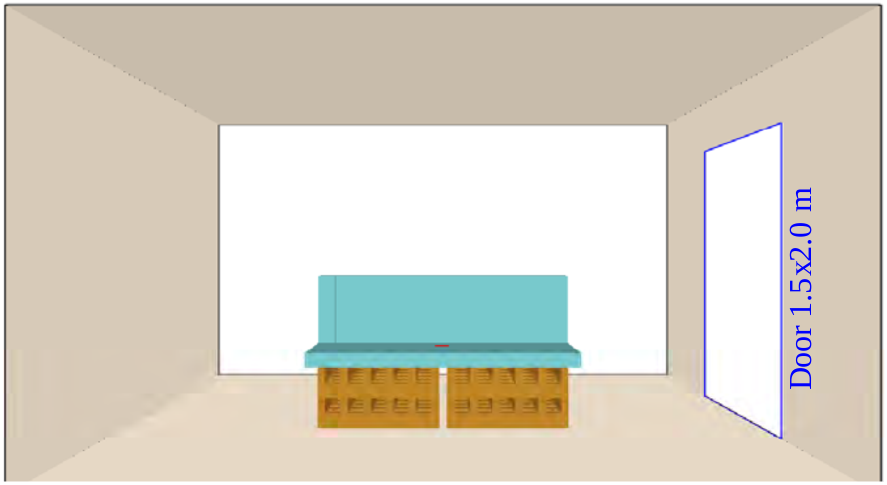
Ventilation Scenario SC6

The ventilation scenario SC6 was similar to scenario SC5 except for having a wider door of a rectangular exterior opening of a size of 1.5 m wide and 2.0 m high in the former compared to 0.9 m wide and 2.0 m high in the latter. The coordinate (in meters) of the center of the door in both scenarios was (4.2, 1.9, 1.0) (see Figure 2-1 and Table 2-1). Figure 4-25 shows the status of the fire load in SC6 at 0 s, when the polyurethane sofa was completely burned, and when the fire was completely extinguished. It took a shorter time for the polyurethane sofa to be completely burned in SC6 (167 s) (Figure 4-25b and c) compared to that in SC5 with a small door (249 s, Figure 4-21b and c). When the sofa was completely burned, the mass loss from the wood in SC6 (47.1 kg, 54% by mass) was smaller than that in SC5 (52.4 kg, 60% by mass). The larger exterior opening in SC6 (door size of 1.5 m x 2.0 m) causes more heat losses (by convection and radiation) than in SC5 (door size of 0.9 m x 2.0 m). As such, the net heat feedback in SC6 was lower than that in SC5. For this reason, it took a shorter time to completely extinguish the fire in SC6 (346 s) than that in SC5 (536 s). At these times, the unburned mass of the wood was 25.6 kg (29% by mass) in SC6 (Figure 4-25d) compared to 18.3 kg (21% by mass) in SC5 (Figure 4-21d).

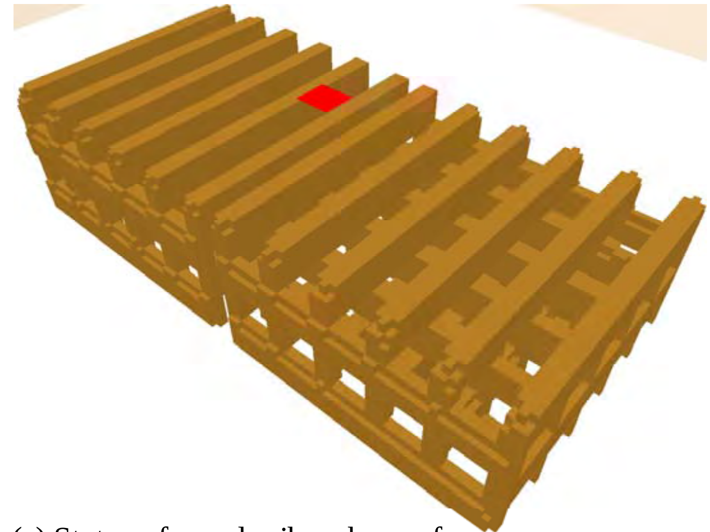
The temporal change of the HRR for scenario SC6 is shown in Figure 4-26. As shown in this figure, in the first 30 s, the HRR increased rapidly, after that it increased further but at a lower rate and reached a first peak (7,069 kW) at 85 s. In the period from 130 s to 167 s, the HRR decreased rapidly from 6,400 kW at 130 s to a minimum value (4,156 kW) at 167 s (sofa was completely burned). For time > 167 s, the HRR slightly increased again and reached a second peak (4,513 kW) at 180 s. In the period from 180 s to 200 s, the HRR was more or less constant (Figure 4-26). For time > 200 s, the HRR decreased with time with different rates (i.e. different slopes at different times) until the reaction was completely stopped (at 346 s).

Similar to ventilation scenarios SC1 (Figure 4-6), SC3 (Figure 4-14) and SC5 (Figure 4-22), after a few seconds of initiating the fire (~30 s) and during the period of burning both the polyurethane sofa and wood simultaneously, and the period of early stage of burning the wood only, the HRR fluctuated with time in SC6 (Figure 4-26) due to having only one exterior opening as explained earlier. Because of the larger opening in SC6, the back effect in this scenario was smaller than that in SC5 due to more heat losses in the former than in the latter. As such, the HRR increased 357 kW in 13 s from its minimum value (4,156 KW at 167 s) to its second peak (4,513 kW at 180 s) compared to 440 kW in 32 s from its minimum value (1,521 KW at 319 s) to its second peak (1,961 kW at 351 s) in SC5. Conversely, the maximum HRR in SC6 (7,069 kW) was significantly higher than that in SC5 (4,983 kW) due to having more oxygen available for combustion to take place in the former than in the latter.

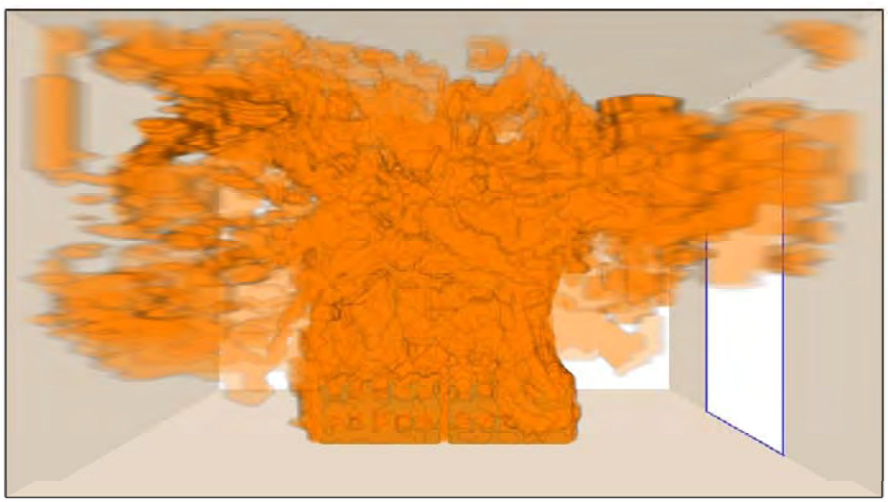
Figure 4-27 and Figure 4-28 show the temperature and the vectors of the velocity field at a longitudinal slice passing though the middle of the door (at y = 1.9 m) at different times in scenario SC6. As shown in these figures, the locations of the neutral plane in the door changed with time. It was located between ~1/5 to ~5/9 of the height of the door from the floor (Figure 4-28a-d). In this scenario, the total energy released due to burning 69.5 kg of the fire load (61.2 kg wood and 8.3 kg polyurethane sofa) was 1,198 MJ. The total energy released in SC6 was about the same as in SC5 (1,219 MJ), although the total mass loss in the former (69.5 kg) was 7.2 kg smaller than that in the latter (76.7 kg). Having a larger exterior opening in SC6 than in SC5 resulted in higher oxygen concentration inside the compartment in SC6 than in SC5. Accordingly, the amount of CO production in the former was smaller (due to converting most of the CO to CO_2) than in the latter. As a result, the effective heat of combustion in SC6 (17.2 MJ/kg) was greater than in SC5 (15.9 MJ/kg). Fire load densities of 75 MJ/m^2 and 225 MJ/m^2 in SC6 were predicted by assuming the fire spread over the entire floor area and 1/3 of the floor area, respectively.



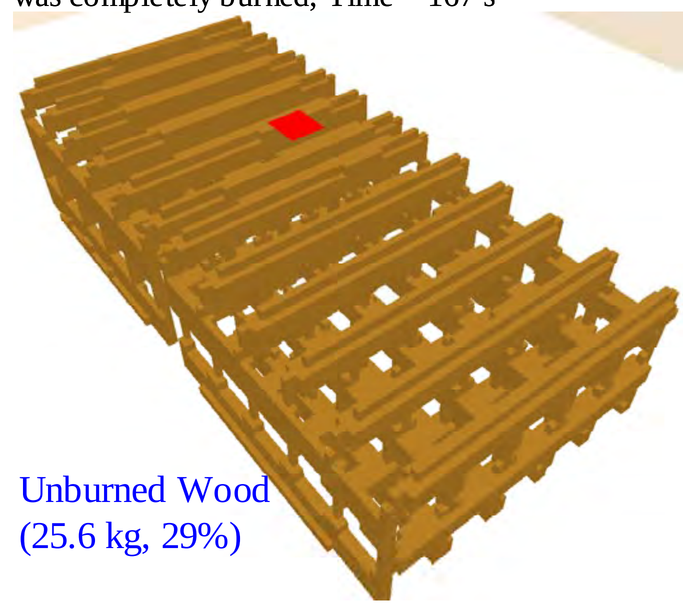
(a) Before initiating the burner (Time = 0)



(c) Status of wood cribs when sofa was completely burned, Time = 167 s



(b) Fire when sofa was completely burned at Time = 167 s



(d) Status of wood cribs when fire was completely stopped

Figure 4-25 Burning polyurethane sofa and two wood cribs for ventilation scenario SC6 (Door 0.9 x 2.0 m)

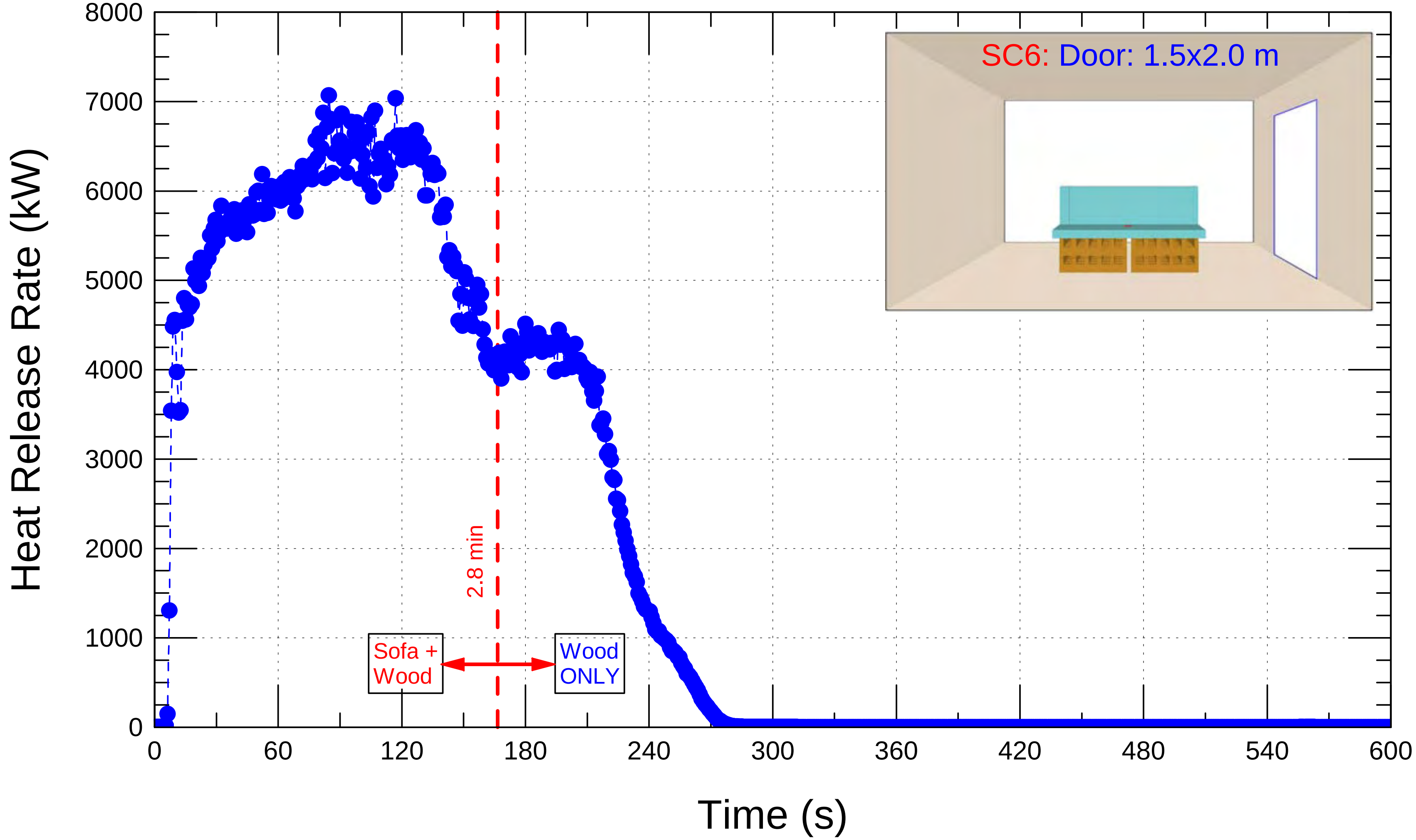
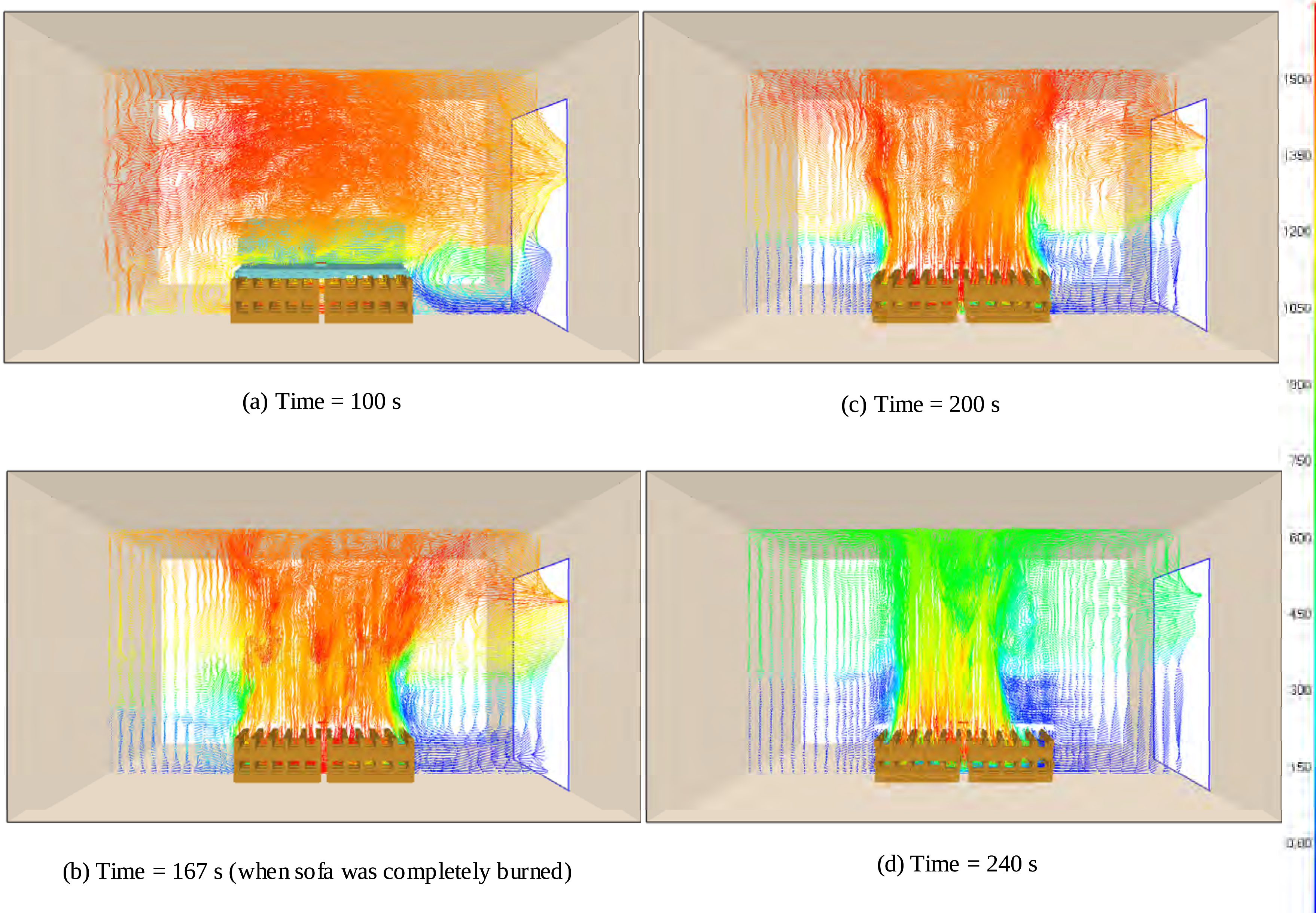


Figure 4-26 Heat Release Rate of ventilation scenario SC6 (Door 0.9 x 2.0 m)



(a) Time = 100 s

(c) Time = 200 s

(b) Time = 167 s (when sofa was completely burned)

(d) Time = 240 s

Figure 4-27 Temperatures and vectors of the velocity field at a longitudinal slice passing through the middle of the door for SC6

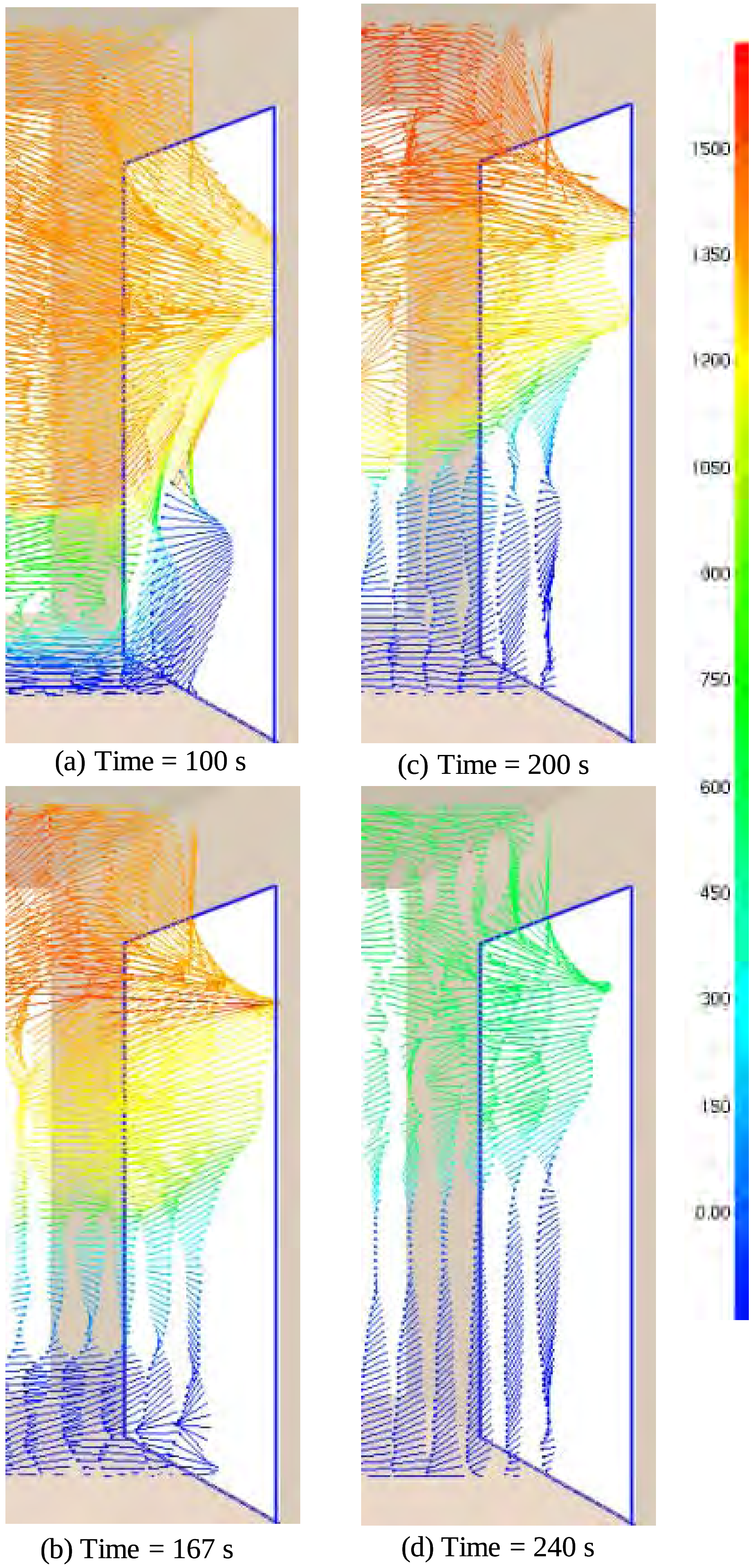


Figure 4-28 Temperatures and vectors of the velocity field at a longitudinal slice passing through the middle of the door for SC6

Ventilation Scenarios SC7 and SC8

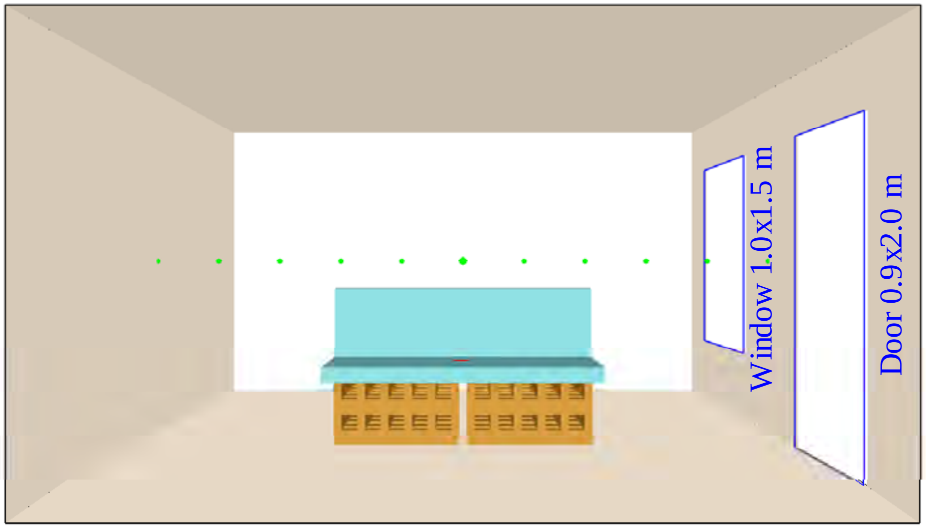
In this subsection, the CFD results of ventilation scenarios SC7 and SC8 are discussed. These two scenarios used a door and a window located on the same wall (3.8 m side) and the fire load (polyurethane sofa + two wood cribs) was located at the center of the room. Both scenarios had a door of a rectangular exterior opening of a size of 0.9 m wide and 2.0 m high and the coordinate of its center (in meter) was (4.2,0.95,1.0) (see Figure 2-1 and Table 2-1). To investigate the effect of the window size on the fire performance, two different sizes were used. Scenario SC7 had a window of a rectangular exterior opening of a size of 1.0 m wide and 1.5 m high and the coordinate of its center was (4.2,2.85,1.25). While, SC8 had a smaller window of a square exterior opening of a size of 1.0 m and the coordinate of its center was (4.2,2.85,1.5).

Figure 4-29 and Figure 4-34 show the status of the fire load at 0 s, when the polyurethane sofa was completely burned, and when the fire was completely extinguished for scenarios SC7 and SC8, respectively. It took a shorter time for the polyurethane sofa to be completely burned in SC7 with the larger window (176 s) (Figure 4-29b and c) than in SC8 with a smaller window (186 s, Figure 4-34b and c). At the time the sofa was completely burned, the mass loss from the wood cribs in SC8 (48.4 kg, 56% by mass) was 1.2 kg (2% by mass) greater than that in SC7 (47.2 kg, 54% by mass). Because of the larger window in SC7 (1.0 m x 1.5 m) than in SC8 (1.0 m x 1.0 m), more heat was lost (by convection and radiation) in the former than that in the latter. As a result, the net heat feedback in SC7 was lower than in SC8. Therefore, it took a shorter time to completely extinguish the fire in SC7 (550 s) than in SC8 (580 s). At these times, the remaining wood mass was 17.1 kg (20% by mass), and 17.4 kg (20% by mass) in SC7 (Figure 4-29d) and SC8 (Figure 4-34d), respectively.

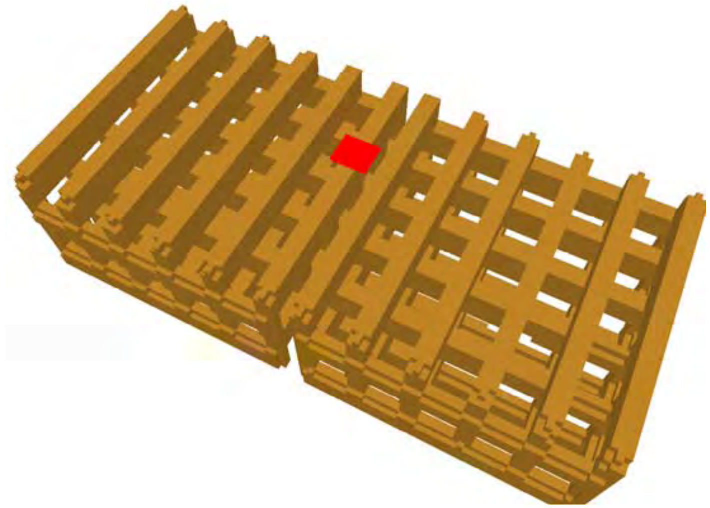
Figure 4-30 and Figure 4-35 show the temporal changed of the HRR for scenarios SC7 and SC8, respectively. As shown in these figures, in the first ~15 s, the HRR increased rapidly, after that it increased further but with a lower rate reaching a first peak (7,348 kW) at 58 s in SC7 and (7,450 kW) at 36 s in SC8. In both scenarios, after reaching the first peak of the HRR, and in the period of burning both a polyurethane sofa and wood simultaneously and in the early stage of burning wood only, flickering large flame sizes were produced due to having the exterior openings of the door and window in these scenarios on the same side of the room as explained earlier. As such, the HRR fluctuated during these periods (see Figure 4-30 and Figure 4-35). Additionally, in these periods (from 58 s to ~200 s in SC7, and from 36 s to ~200 s in SC8), the HRR decreased slowly in SC7 (Figure 4-30), and was more or less constant in SC8 (Figure 4-35). In the period from 200 s to 240 s, the HRR decreased rapidly in both scenarios. At time >240 s, the HRR decreased further but with a lower rate until a minimum value (826 kW in SC7 and 707 kW in SC8) was reached at ~277 s. After 277 s, the HRR increased again and reached a second peak (2,524 kW in SC7 and 2,487 kW in SC8) at 339 s and 346 s in SC7 and SC8, respectively. After the second peak was reached, the HRR decreased again with time with different rates until the reaction was completely stopped (at 550 s in SC7 and at 580 s in SC8).

Figure 4-31 through Figure 4-33, and Figure 4-36 through Figure 4-38 show the temperature and the vectors of the velocity field at longitudinal slices passing though the middle of the door (at y = 0.95 m) and the middle of the window (at y = 2.85 m) at different times in scenarios SC7, and SC8, respectively. In scenario SC7, the locations of the neutral plane in the door changed with time. The neutral plane lays between ~1/4 and 1/2 of the height of the door from the floor (Figure 4-33a-d). In scenario SC8, however, the location of the neutral plane in the door did not change with time and lay at ~ 1/2 of the height of the door (Figure 4-38a-d). Additionally, the window in SC7 provided some fresh air into the compartment (inflow) with the neutral plane at ~1/4 of its height from the floor (Figure 4-33a-d). In scenario SC8, however, the window acted as a chimney at all times (Figure 4-38a-d).

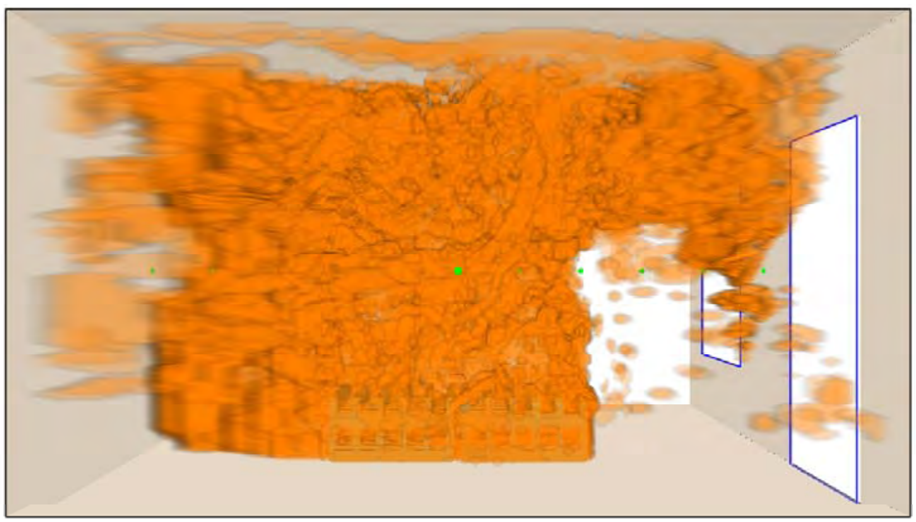
The total energy released due to burning 77.9 kg of the fire load (69.6 kg wood and 8.3 kg polyurethane sofa) was 1,515 MJ in scenario SC7. In SC8, the total mass loss was 77.6 kg (69.3 kg wood and 8.3 kg polyurethane sofa), which produced a total energy of 1,470 MJ. Having a larger exterior opening for the window in scenario SC7 than that in SC8 resulted in a higher oxygen concentration inside the compartment in the former than that in the latter, and hence a lower amount of CO was produced in the SC7 than in SC8. As such, the effective heat of combustion in SC7 (19.4 MJ/kg) was greater than in SC8 (18.9 MJ/kg).



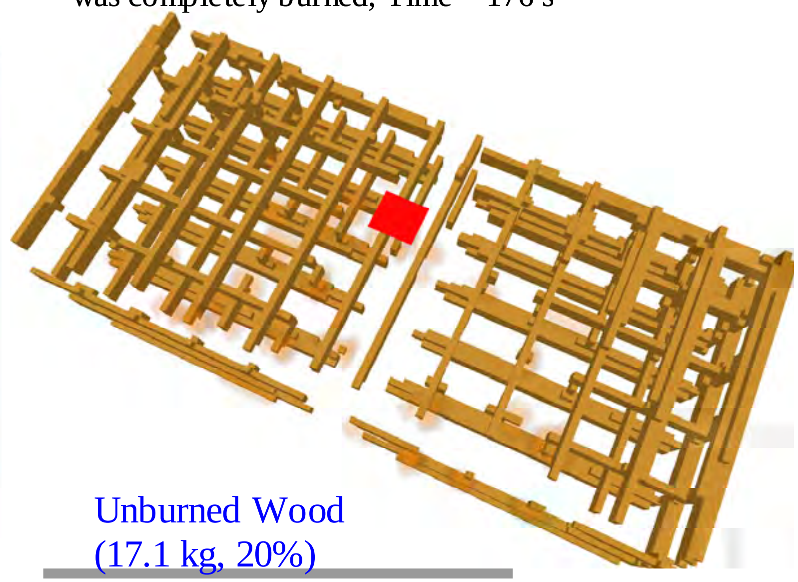
(a) Before initiating the burner (Time = 0)



(c) Status of wood cribs when sofa was completely burned, Time = 176 s



(b) Fire when sofa was completely burned at Time = 176 s



(d) Status of wood cribs when fire was completely stopped

Figure 4-29 Burning polyurethane sofa and two wood cribs for ventilation scenario SC7 (Window 1.0 x 1.5 m, Door 0.9 x 2.0 m)

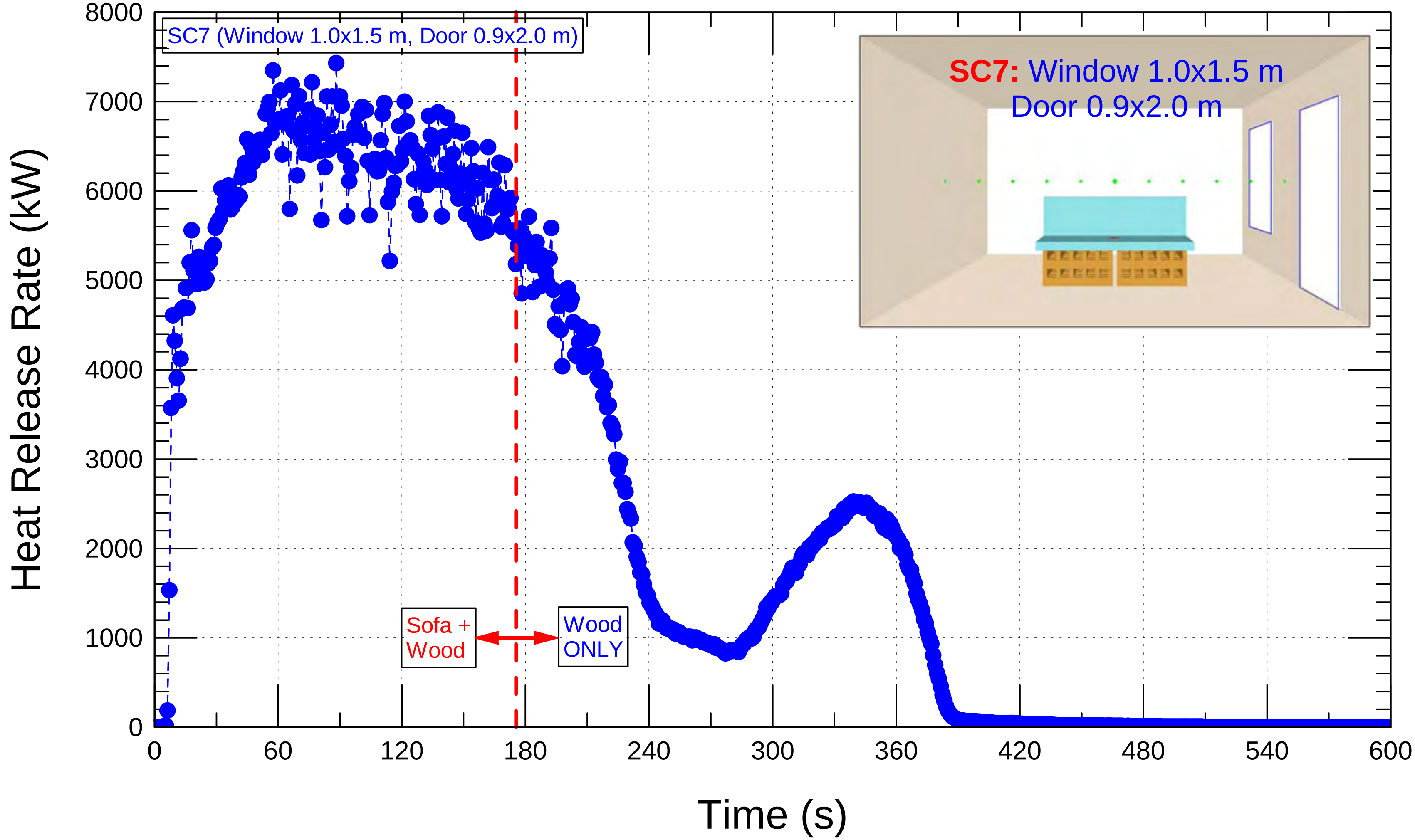
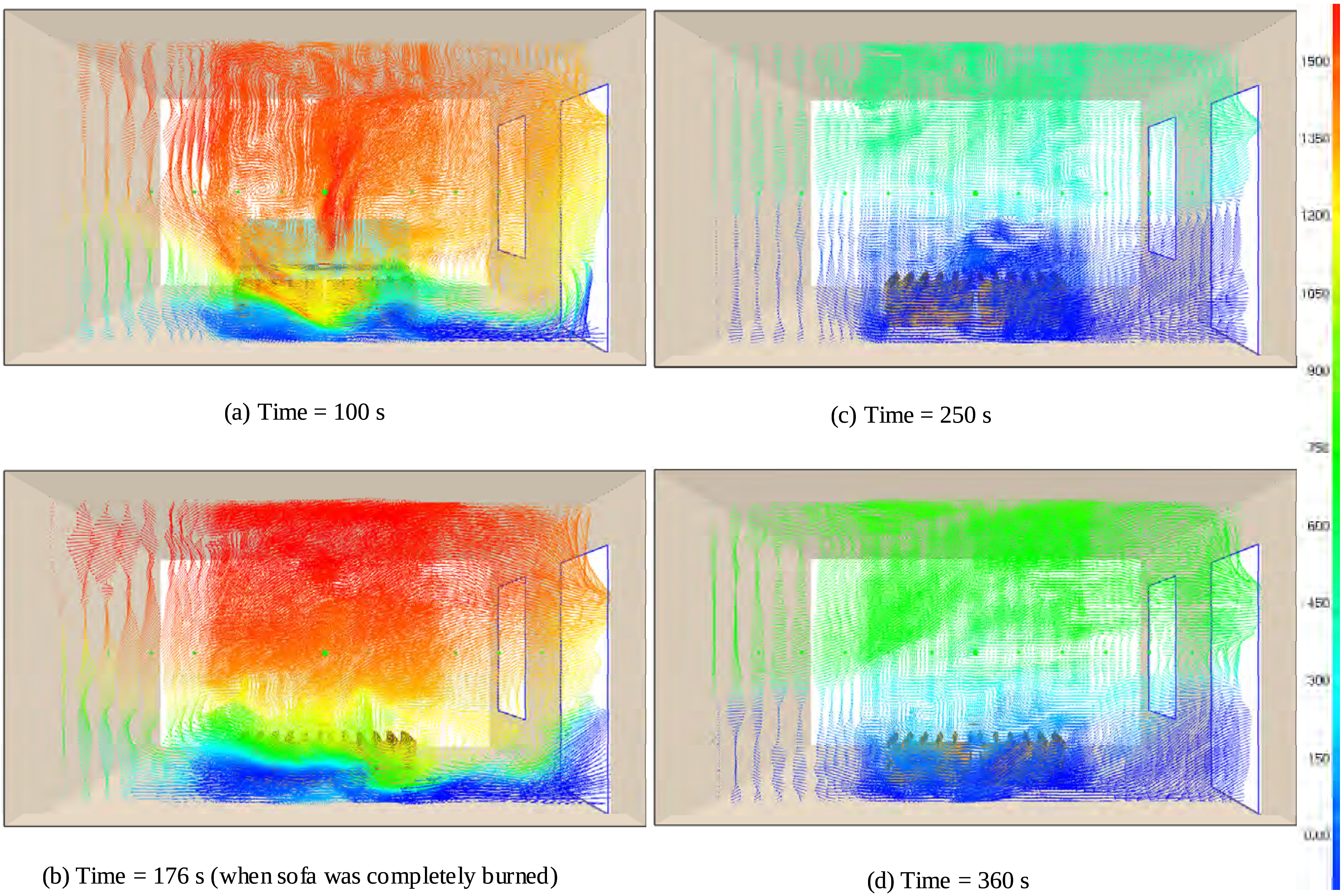


Figure 4-30 Heat Release Rate of ventilation scenario SC7 (Window 1.0 x 1.5 m and Door 0.9 x 2.0 m)



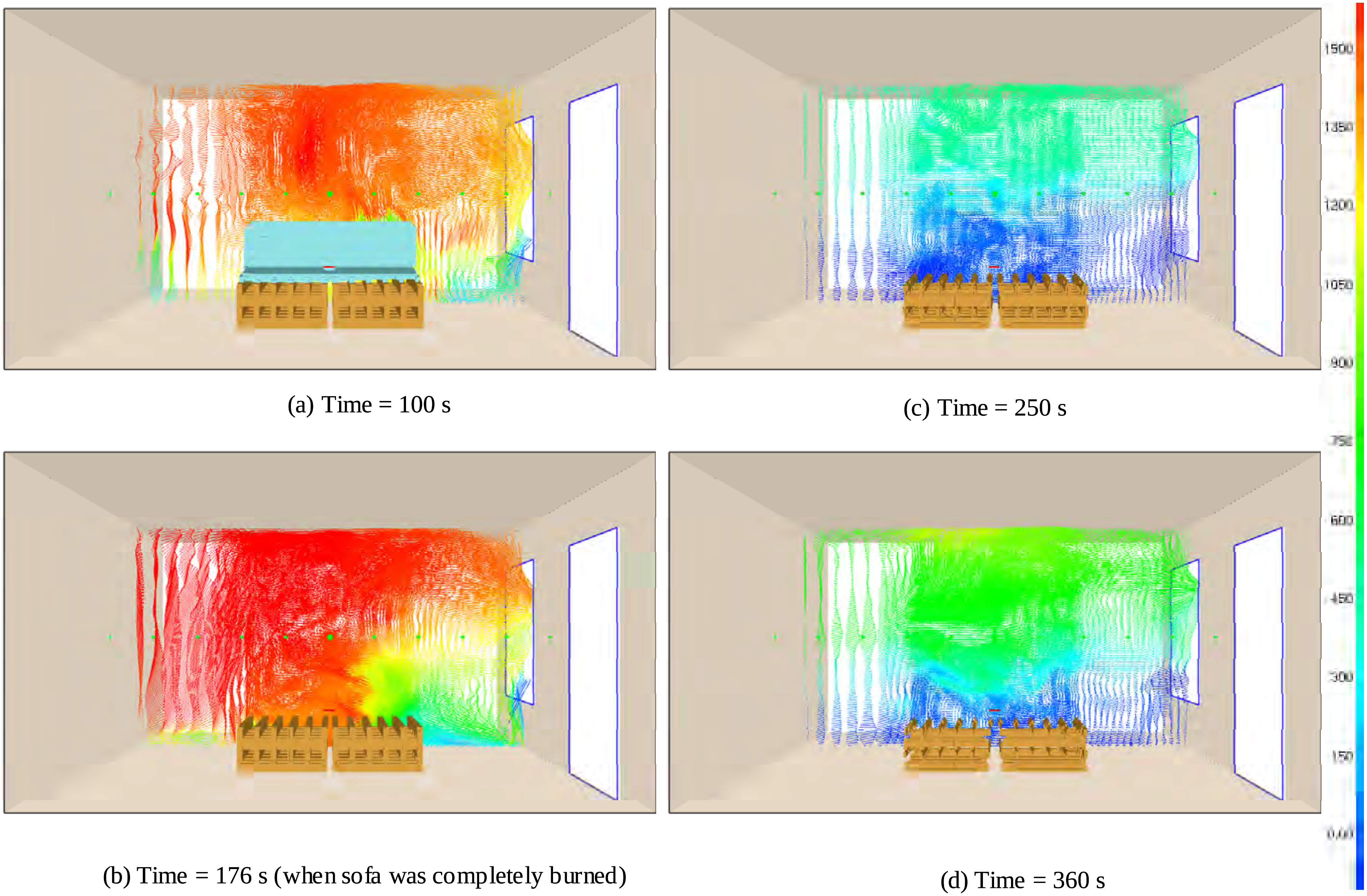
(a) Time = 100 s

(c) Time = 250 s

(b) Time = 176 s (when sofa was completely burned)

(d) Time = 360 s

Figure 4-31 Temperatures and vectors of the velocity field at a longitudinal slice passing through the middle of the door for SC7



(a) Time = 100 s

(c) Time = 250 s

(b) Time = 176 s (when sofa was completely burned)

(d) Time = 360 s

Figure 4-32 Temperatures and vectors of the velocity field at a longitudinal slice passing through the middle of the window for SC7

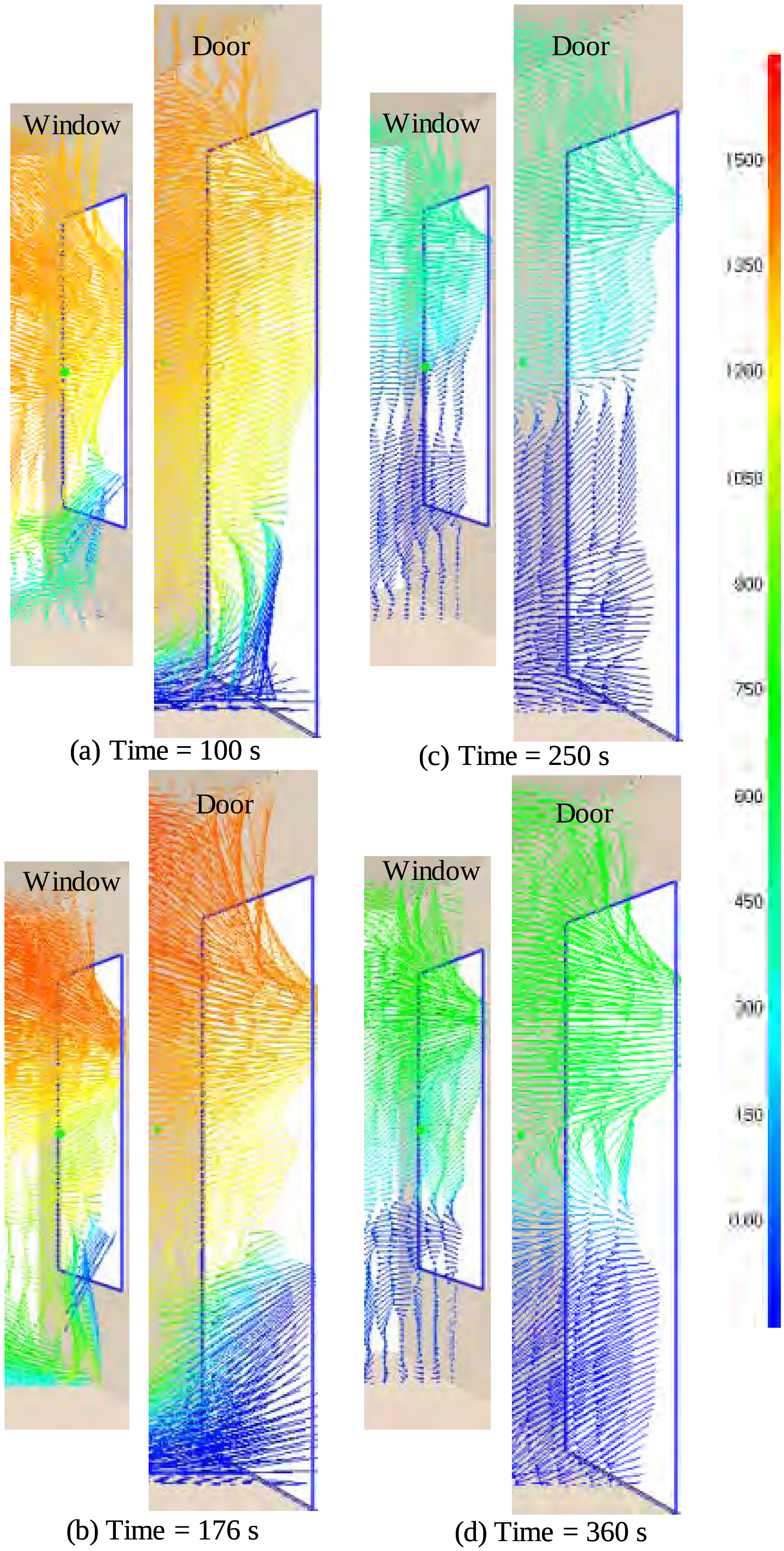
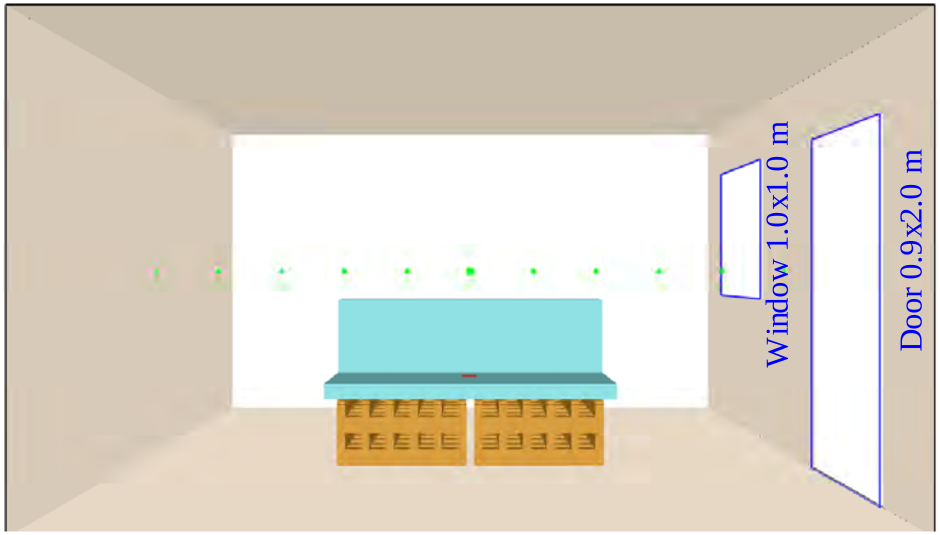
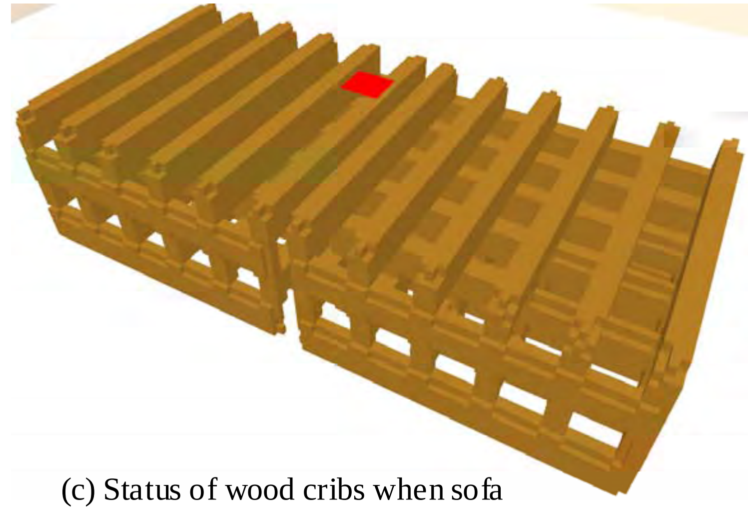


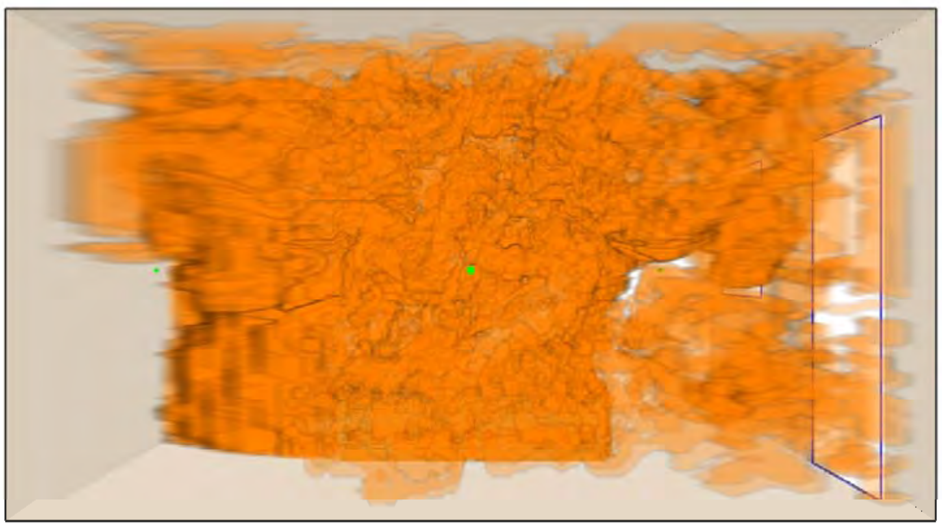
Figure 4-33 Temperatures and vectors of the velocity field at a longitudinal slice passing through the middle of the window and the door for SC7



(a) Before initiating the burner (Time = 0)



(c) Status of wood cribs when sofa was completely burned, Time = 186 s



(b) Fire when sofa was completely burned at Time = 186 s

(d) Status of wood cribs when fire was completely stopped

Figure 4-34 Burning polyurethane sofa and two wood cribs for ventilation scenario SC8 (Window 1.0 x 1.0 m, Door 0.9 x 2.0 m)

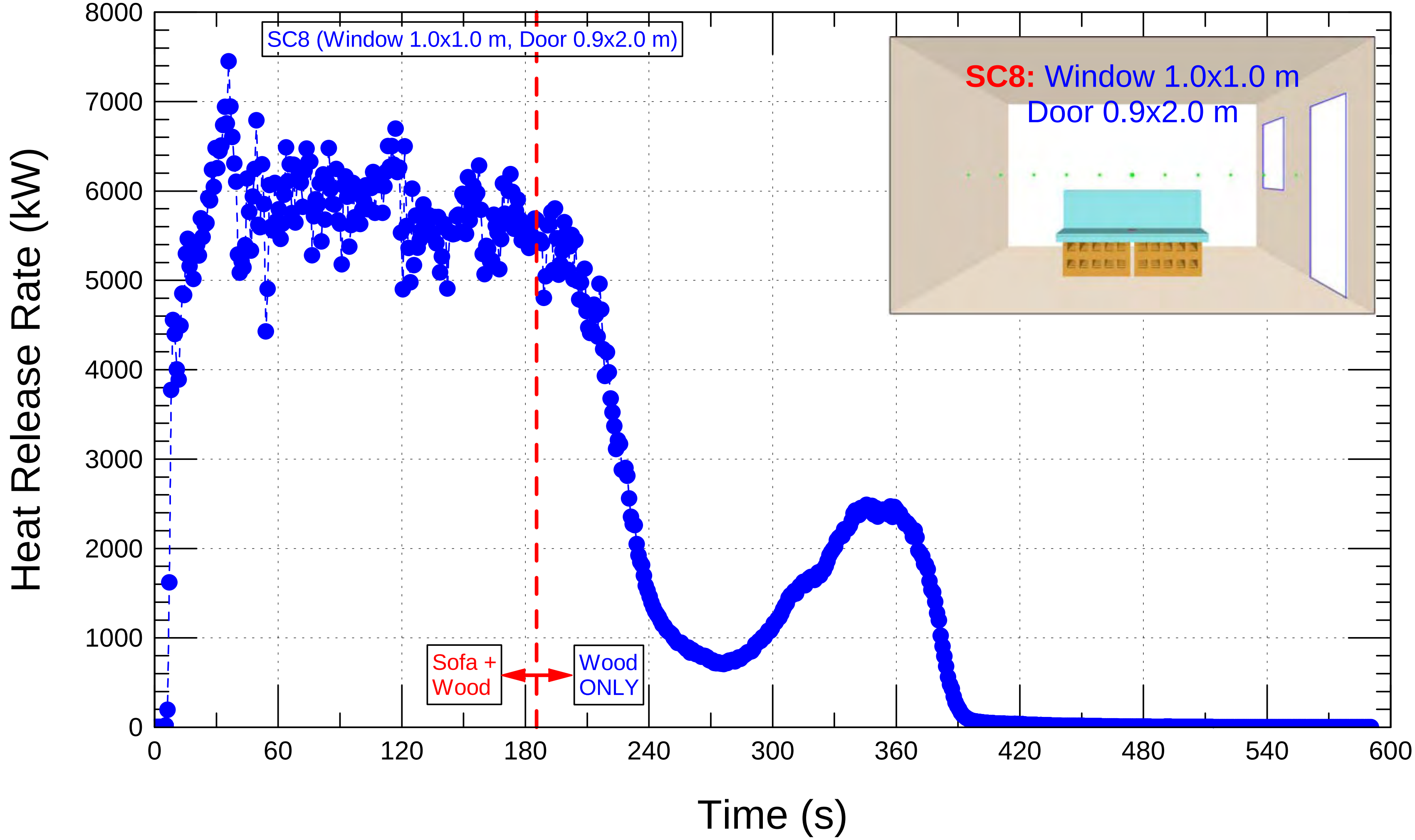


Figure 4-35 Heat Release Rate of ventilation scenario SC8 (Window 1.0 x 1.5 m and Door 0.9 x 2.0 m)

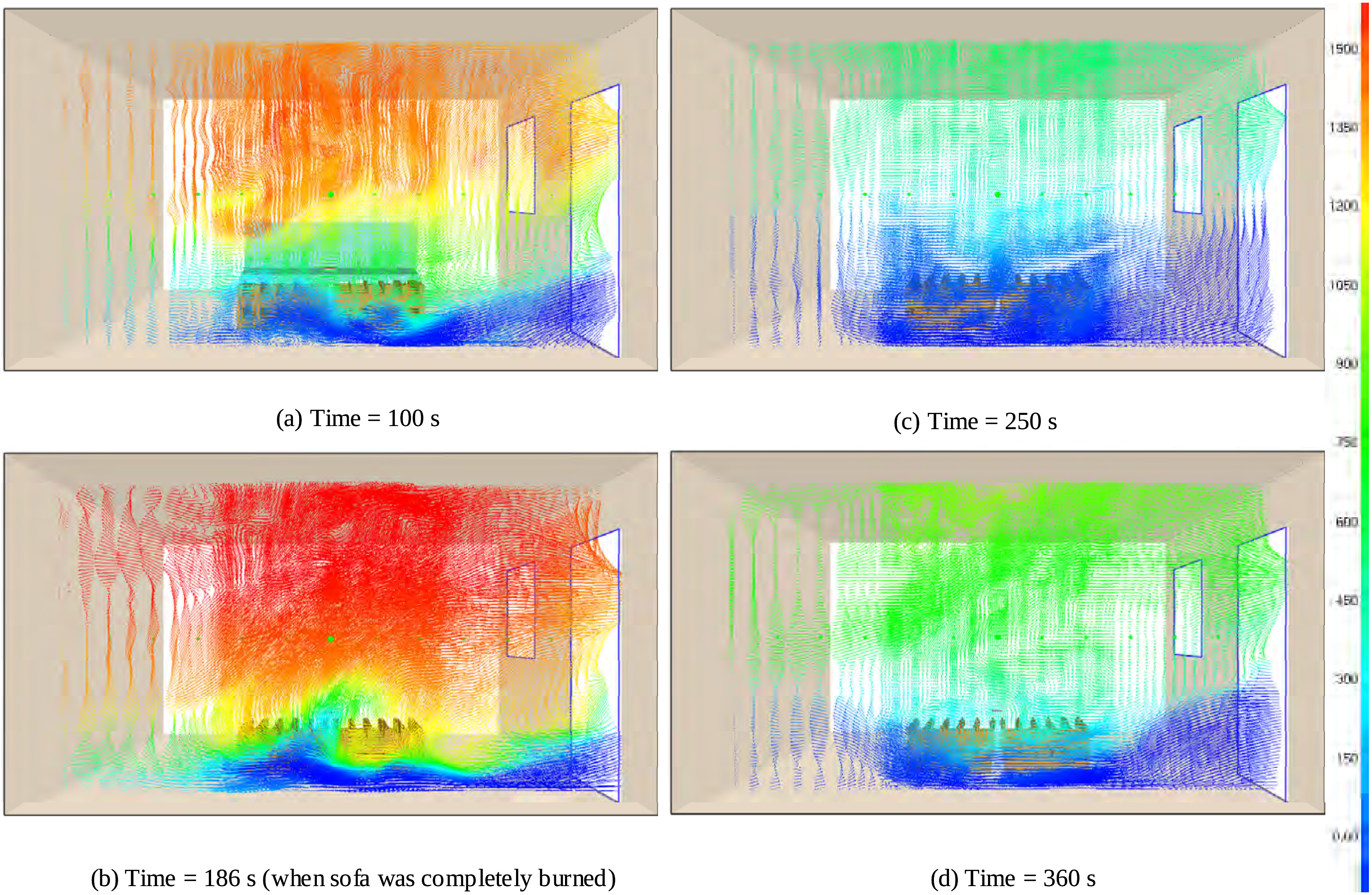
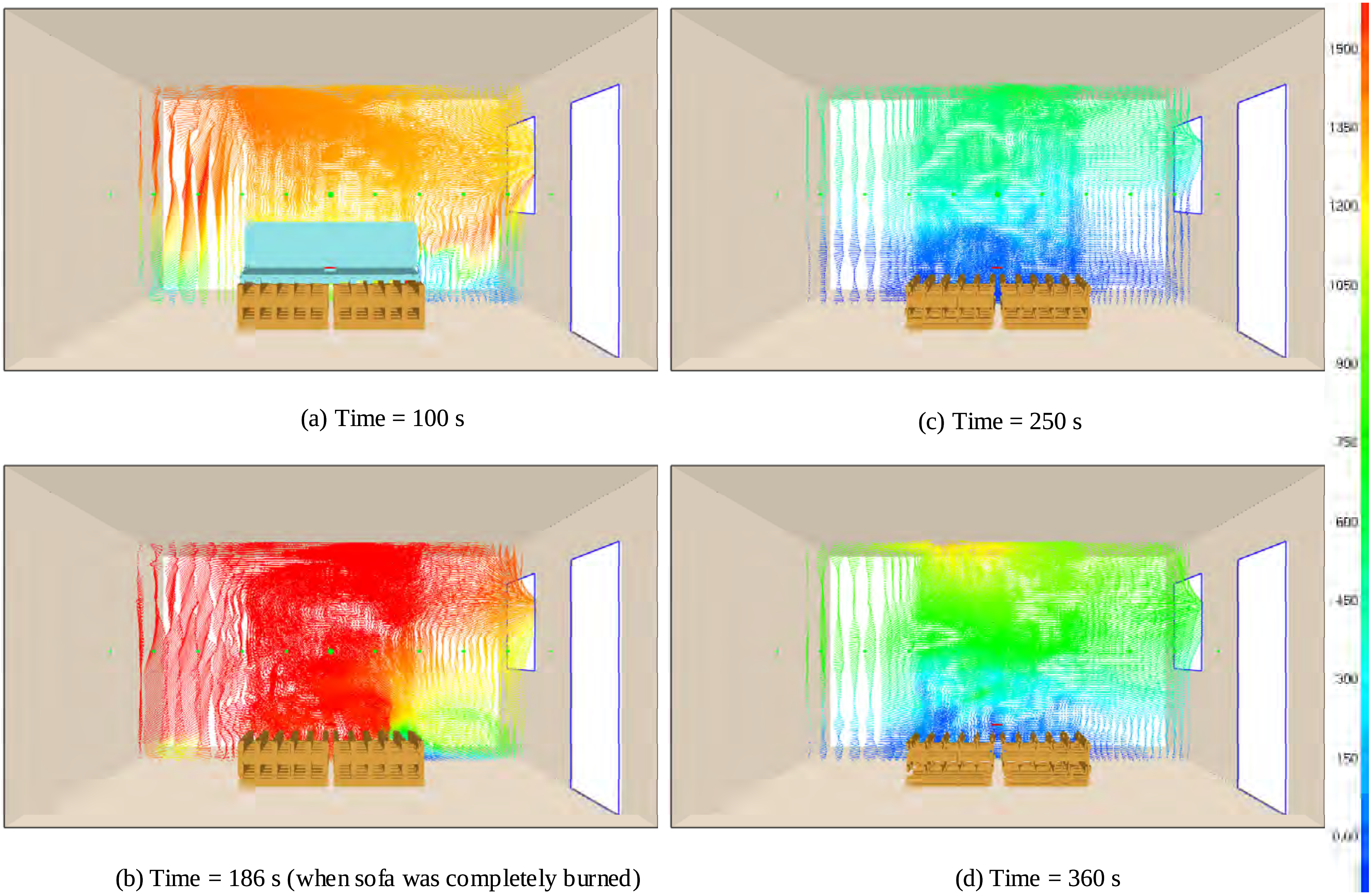


Figure 4-36 Temperatures and vectors of the velocity field at a longitudinal slice passing through the middle of the door for SC8



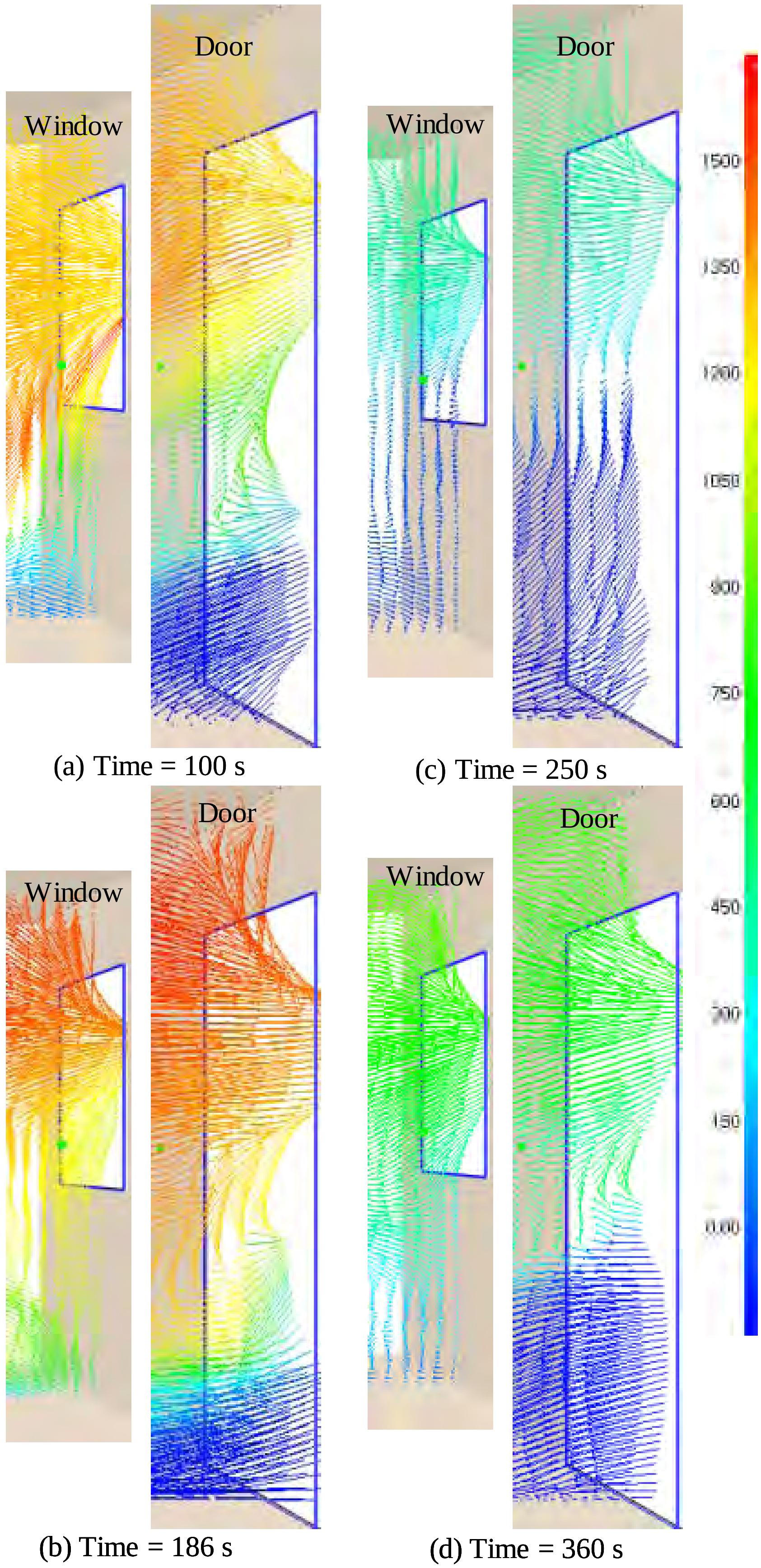
(a) Time = 100 s

(c) Time = 250 s

(b) Time = 186 s (when sofa was completely burned)

(d) Time = 360 s

Figure 4-37 Temperatures and vectors of the velocity field at a longitudinal slice passing through the middle of the window for SC8



(a) Time = 100 s

(c) Time = 250 s

(b) Time = 186 s

(d) Time = 360 s

Figure 4-38 Temperatures and vectors of the velocity field at a longitudinal slice passing through the middle of the window and the door for SC8

Ventilation Scenario SC9

The ventilation scenario SC9 was similar to scenario SC3 except for having the fire load (polyurethane sofa + two wood cribs) located at one of the corners of the room as shown in Figure 4-39 in the former and at the center of the room in the latter. A window of a rectangular exterior opening of a size of 2.0 m wide and 1.5 m high was used in these two scenarios. The coordinate (in meters) of the center of the window was (0.0,1.9,1.25) (see Figure 2-1 and Table 2-1). In SC9, the leakage in the room was represented by a square exterior opening of a size of 0.2 m and the coordinate of its center was (4.2,3.3,0.2) (see Figure 4-39).

Figure 4-40 shows the status of the fire load in scenario SC9 at 0 s, when the polyurethane sofa was completely burned, and when the fire was completely extinguished. It took a long period of time for the polyurethane sofa to be completely burned in SC9 (283 s) (Figure 4-40b and c) compared to all other ventilation scenarios used in this study. When the sofa was completely burned, the mass loss from the wood cribs in SC9 (53.4 kg, 62% by mass) was the highest of all scenarios. Additionally, it took a long period of time to completely extinguish the fire in SC9 (645 s). At this time, the unburned mass of the wood was 17.2 kg (20% by mass) (Figure 4-40d).

Figure 4-41 shows the temporal change of the HRR for scenario SC9. As shown in this figure, in the first 10 s, the HRR increased rapidly reaching a value of 4,756 kW, then decreased to a value of ~4,000 kW at ~11 s. After 11 s until the sofa was completely burned (at 283 s), the HRR was more or less constant with some fluctuations. In this period, the mean HRR was ~4,200 kW. The first peak of the HRR (4,760 kW) occurred at 282 s. After the sofa was completely burned, the HRR decreased with time with different rates until a minimum value was reached (592 kW) at 374 s. For time > 374 s, the HRR gradually increased again and reached a second peak (1,742 kW) at 445 s. For time > 445 s, the HRR decreased with time with different rates until the reaction was completely stopped (at 645 s).

Figure 4-42 through Figure 4-44 show the temperature and the vectors of the velocity field at two longitudinal slices passing though the middle of the window (at y = 1.9 m), and the middle of the leakage opening (at y = 3.3 m) at different times for scenario SC9. As shown in these figures, fresh air entered the compartment through the exterior leakage opening at all times (Figure 4-44a-d). The locations of the neutral plane in the window did not vary. It was located at ~1/2 of the height of the window (Figure 4-44a-d). In this scenario, the total energy released due to burning 77.8 kg of the fire load (69.5 kg wood and 8.3 kg polyurethane sofa) was 1,511 MJ. The effective heat of combustion in SC9 was 19.4 MJ/kg. In summary, placing the fire load in the corner of the room resulted in low HRR and a long period for the combustion to take place.

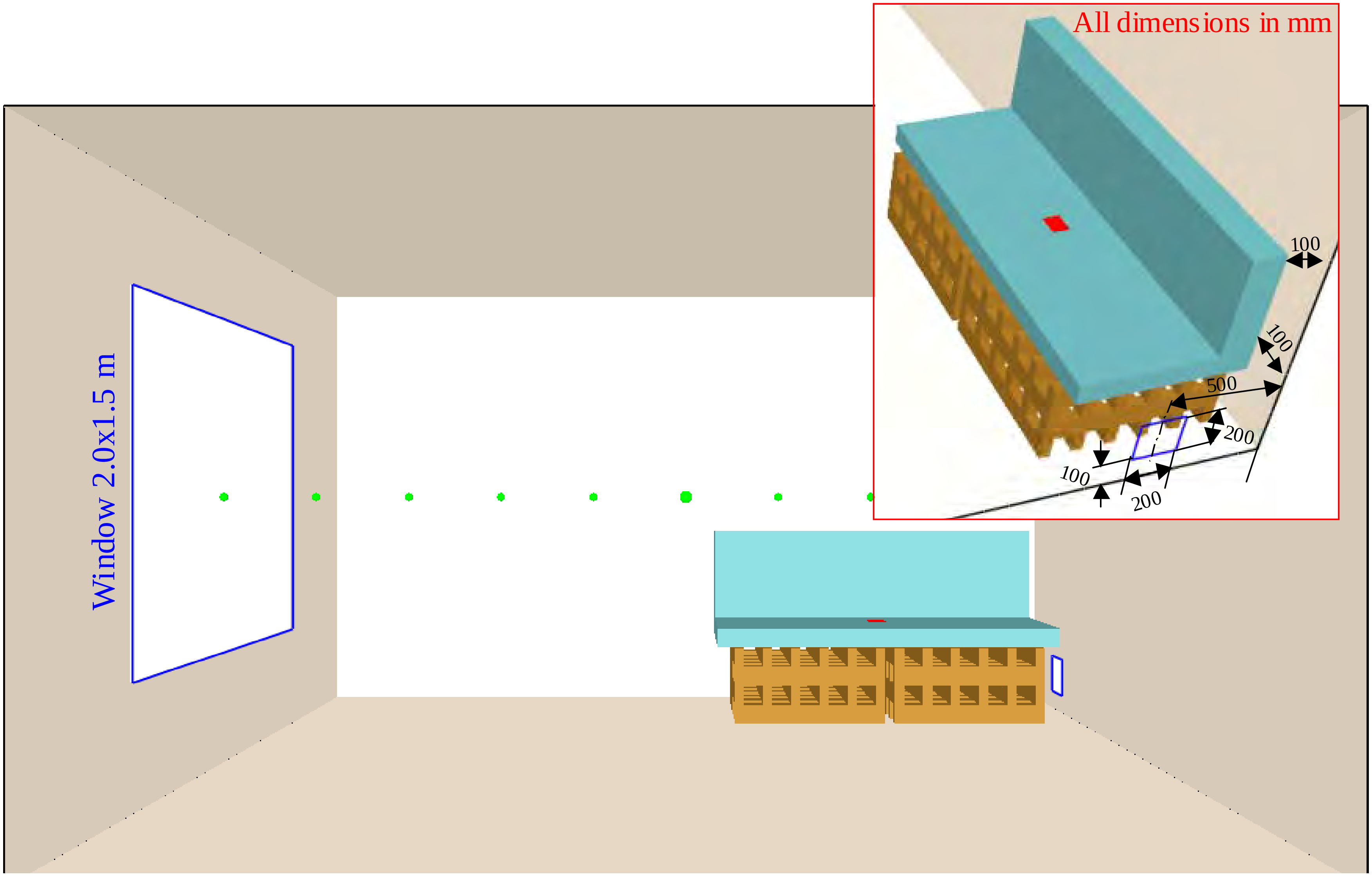
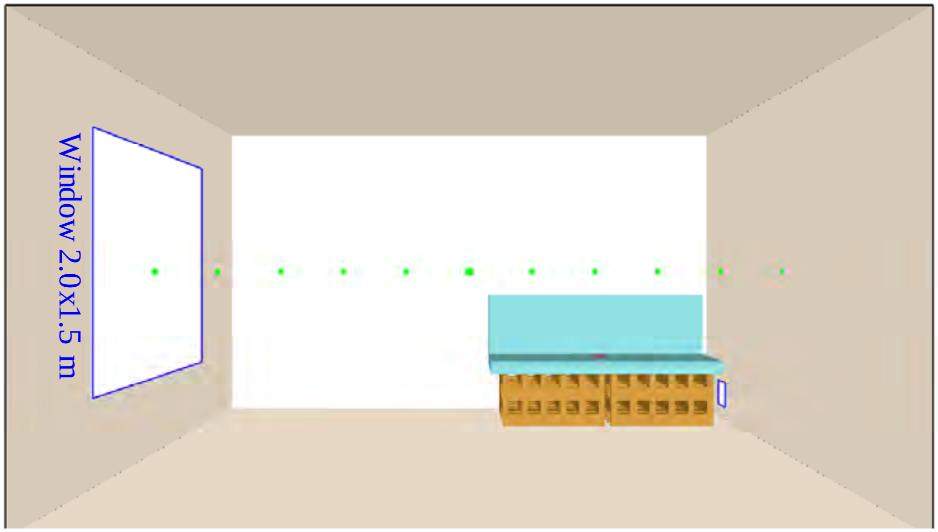
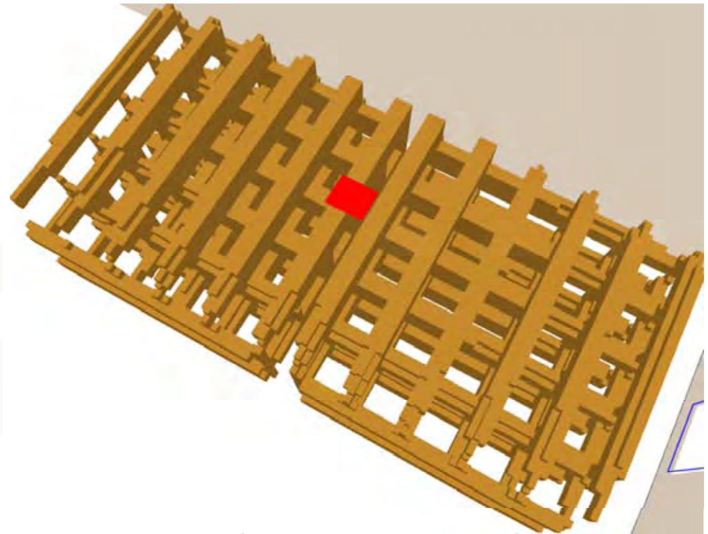


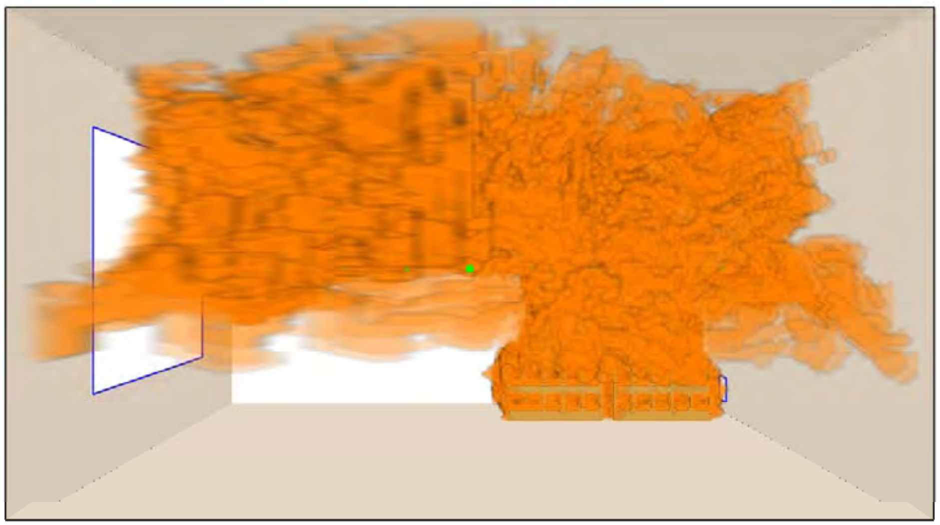
Figure 4-39 Polyurethane sofa and two wood cribs located at the corner of the room for ventilation scenario SC9 (Window 2.0x1.5 m)



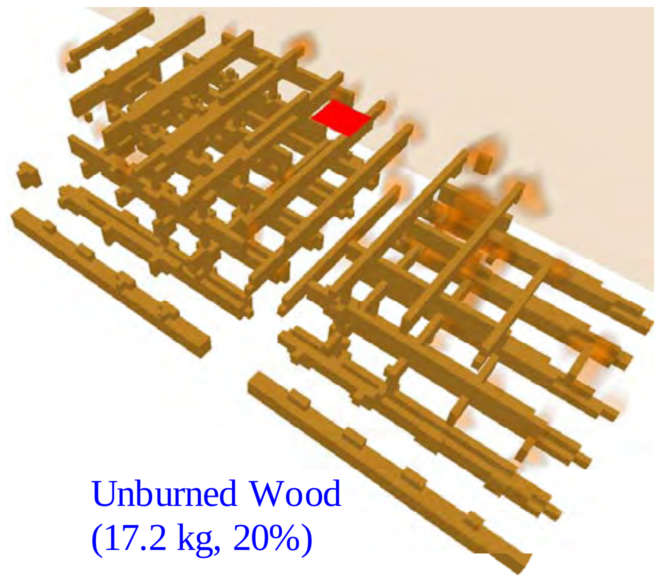
(a) Before initiating the burner (Time = 0)



(c) Status of wood cribs when sofa was completely burned, Time = 283 s



(b) Fire when sofa was completely burned at Time = 283 s



(d) Status of wood cribs when fire was completely stopped

Figure 4-40 Burning polyurethane sofa and two wood cribs for ventilation scenario SC9 (Window 2.0 x 1.5 m)

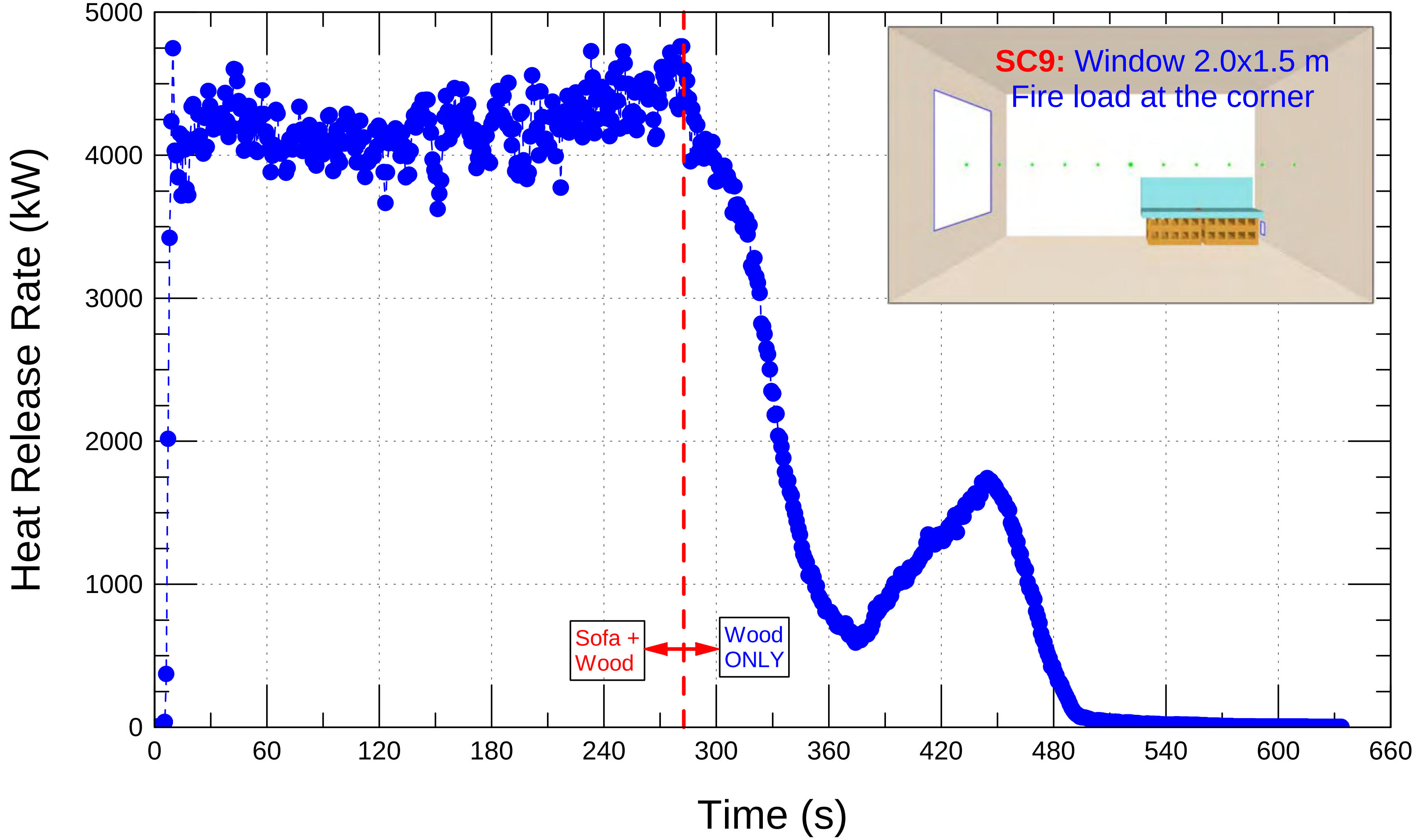
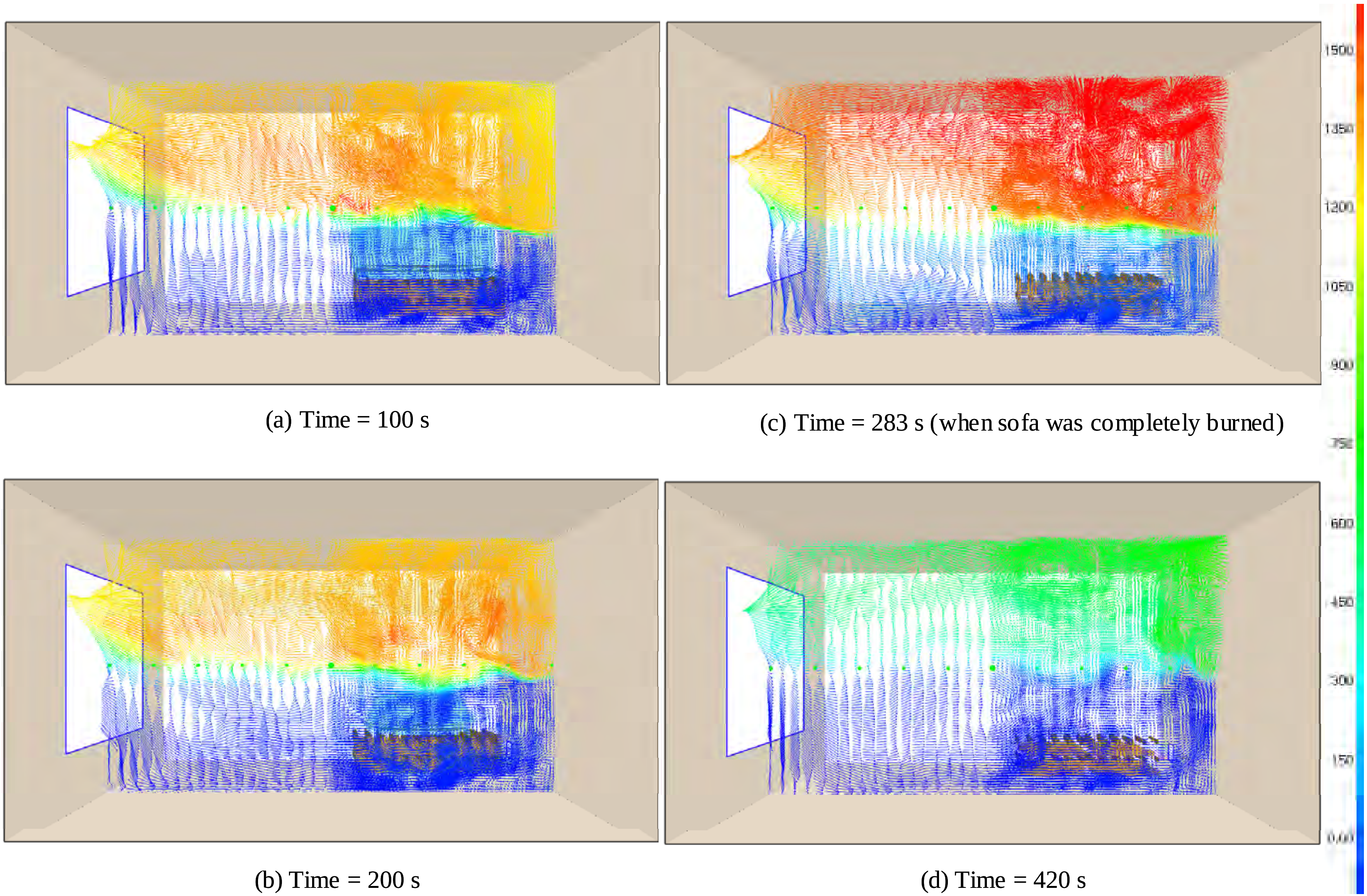


Figure 4-41 Heat Release Rate of ventilation scenario SC9 (Window 2.0 x 1.5 m)



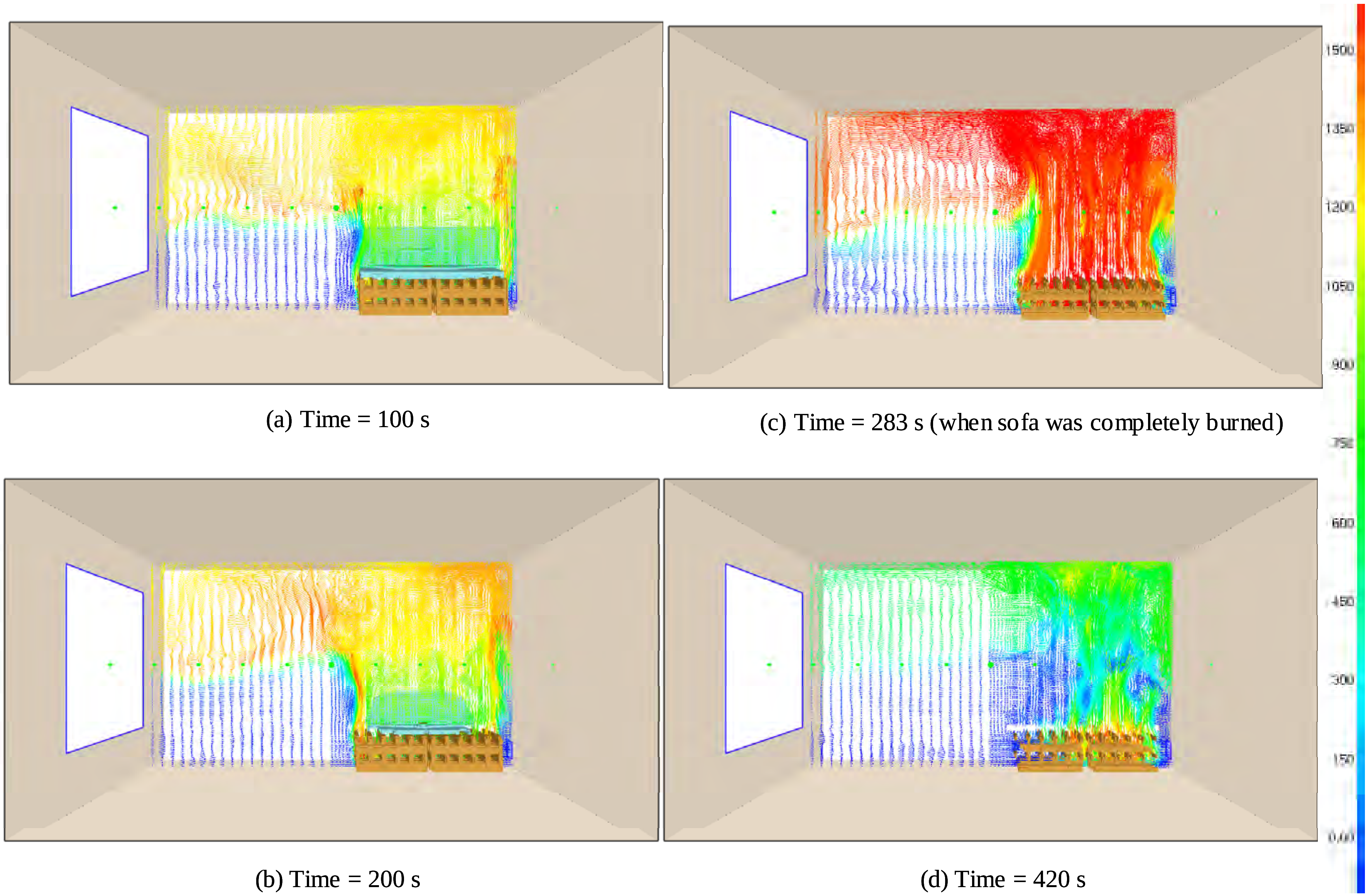
(a) Time = 100 s

(c) Time = 283 s (when sofa was completely burned)

(b) Time = 200 s

(d) Time = 420 s

Figure 4-42 Temperatures and vectors of the velocity field at a longitudinal slice passing through the middle of the window for SC9



(a) Time = 100 s

(c) Time = 283 s (when sofa was completely burned)

(b) Time = 200 s

(d) Time = 420 s

Figure 4-43 Temperatures and vectors of the velocity field at a longitudinal slice passing through the middle of the leakage opening for SC9

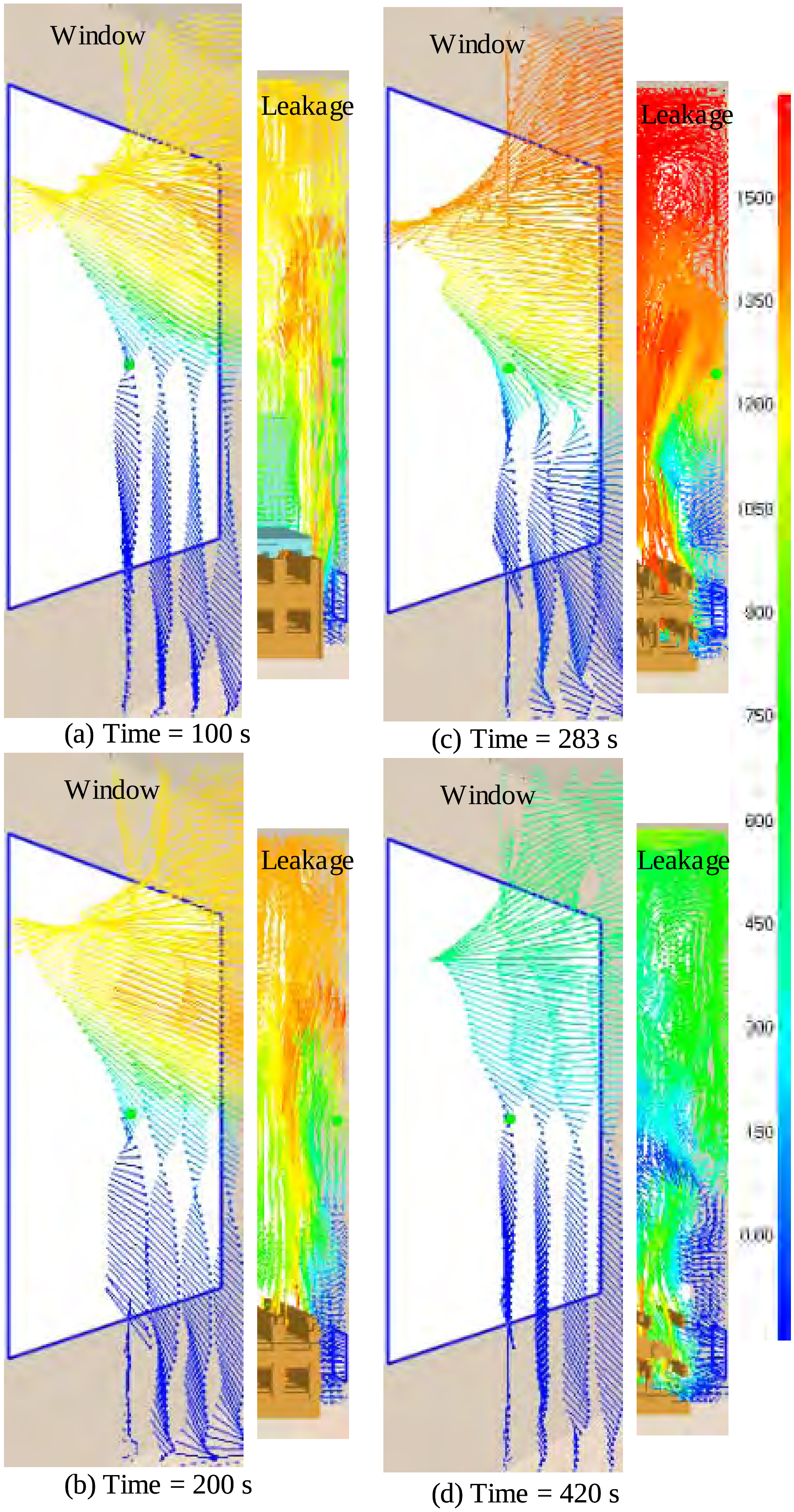


Figure 4-44 Temperatures and vectors of the velocity field at a longitudinal slice passing through the middle of the window and leakage opening for SC9

5. Summary and Conclusion

Nine ventilation scenarios were investigated in order to identify the proper ventilation scheme for conducting design fire tests in a room of a size of 4.2 m length x 3.8 m width x 2.4 m height. The fire load used in all scenarios consisted of a polyurethane sofa and two wood cribs underneath it. The total mass of the polyurethane sofa and two wood cribs were 8.3 kg and 86.7 kg, respectively. The mass fraction of water in the wood was assumed to be 0.1.

In scenarios SC1 through SC8, the fire load was located at the center of the room. In scenario SC9, however, the fire load was located in one of the corners of the room. The ventilation schemes in all scenarios were based on using exterior square/rectangular openings to represent rough window and door openings, or both with different sizes.

A 0.10 m by 0.10 m burner was located on the top of the seat cushion at its center. The burner was ignited for a period of 30 s with a Heat Release Rate Per Unit Area of 304 kW/m^2 (~ 3.0 kW). This period was found to be enough for initiating and sustaining the fire in the nine ventilation scenarios.

FDS version 5 was used to conduct the simulations. Unlike the previous versions of FDS, the new combustion model in the FDS version 5 accounts for both mixing of fuel and oxygen without burning and CO production. This is an important feature for modelling under-ventilated compartments such as the different ventilation scenarios used in this study. Before conducting the CFD simulations for all scenarios, many numerical tests and debugging were carried out in order to (a) find out the optimum mesh size, and (b) test the validity of the new combustion model in FDS version 5. It was found that increasing the size of a stretched mesh (in x- and y- directions) beyond 100 x 75 x 96 had insignificant effect on the results. Therefore, a stretched mesh of a size of 100 x 75 x 96 was used for all ventilation scenarios. Furthermore, it was found that the predicted effective heat of combustion of wood was in good agreement with that obtained using Babrauskas' correlation [7]. This good agreement confirmed the soundness of both the modified mixture fraction combustion model and pyrolysis model in FDS version 5.0.

After the first few seconds from initiating the fire (~20 – 30 s) especially during the period of burning the polyurethane sofa and wood cribs simultaneously, and in the period of the early stage of burning wood only, the observed size of the flame using the Smokeview was large. Having only one exterior opening or two openings facing each other of different sizes with a flame of large size resulted in a good mixing between the inflow (entering the compartment through the opening(s)) and the combustion products inside the compartment. This mixing generated vortices and eddies that cause non-uniform oxygen concentration in the vicinity of the flame sheet. As such result, a flickering flame was produced. A high HRR was predicted when the flame surface happened to exist in a domain of higher oxygen concentration and vice versa. Consequently, the HRR fluctuated during these periods. This was the case for all ventilation scenarios but SC2. In SC2, there were two exterior openings with approximately equal size in the walls and facing each other where the flame was approximately vertical; consequently, the HRR did not fluctuate with time.

In the late stages of burning wood only, the flame size was small, and the generated vortices and eddies due to the mixing between the inflow and combustion products were not strong enough to produce a flickering flame. As a result, the HRR did not fluctuate in this period. This was the case for all ventilation scenarios investigated in this study. In all scenarios, after the HRR decreased and reached its minimum value, it increased again due to the net heat feedback reaching a second peak. The values of both the HRR and the time for the second peak depended on the ventilation scenario.

Comparisons of the CFD results for all ventilation scenarios are summarized in Table 5-1 through Table 5-3, and Figure 5-1 through Figure 5-3. The maximum HRRs and burning rates in all scenarios are compared in Table 5-1. Figure 5-1 compares the temporal change of the HRRs in all scenarios. Comparisons of the status of the fire load for all scenarios when the polyurethane sofa was completely burned, and when the fire was extinguished (HRR ~1 kW) are shown in Figure 5-2 and Figure 5-3, respectively. Note that the snapshots of the wood cribs in Figure 5-2 and Figure 5-3 do not exactly reflect the amount of mass loss from the wood. This is because Smokeview plots all cells in which fuels were not completely burned. In other words, if a fuel in a cell was partially burned, that whole cell will appear in the plot. Finally, the total mass losses, total energy releases and the effective heat of combustions for all scenarios are compared in Table 5-3. As shown in these tables and figures, the following observations can be made from the CFD results of nine ventilation scenarios:

- Ventilation scenario SC8 (fire load located at the center of the room) has the highest maximum HRR (7,450 kW) at 36 s from initiating the fire. This scenario employed two exterior openings located in the same wall (3.8 m side), namely: (a) a door of a size of 0.9 m wide and 2.0 m high and the coordinate of its center (in meter) was (4.2,0.95,1.0), and (b) a square window of a size of 1.0 m and the coordinate of its center was (4.2, 2.85, 1.5).
- Ventilation scenario SC9 (fire load located at one of the corners of the room) has the lowest maximum HRR (4,760 kW) at 282 s from initiating the fire. This scenario used a window of a rectangular exterior opening of a size of 2.0 m wide and 1.5 m high and the coordinate of its center was located at (0.0, 1.9, 1.25). Additionally, the leakage in the room was represented by a square exterior opening of a size of 0.2 m and the coordinate of its center was (4.2,3.3,0.2).
- The sofa took the longest period to be completely burned in SC9 (283 s).
- The polyurethane sofa took the shortest period to be completely burned in SC2 (158 s). In this scenario, the fire load was located at the center of the room. This scenario used two exterior openings facing each other, namely: (a) a square window of a size of 1.5 m and the coordinate of its center was (0,1.9,1.25), and (b) a rectangular door of a size of 0.9 m wide by 2.0 m high and the coordinate of its center was (4.2,1.9,1.0).
- Ventilation scenario SC1 (fire load was located at the center of the room) has the highest total mass loss (79.1 kg) (70.9 kg wood and 8.3 kg polyurethane sofa). Only 15.9 kg (18% by mass) of the wood was left when the fire was completely extinguished. This scenario used a window of square exterior opening of a size 1.5 m. The coordinate of the center of the window was (0, 1.9, 1.25).
- Ventilation scenario SC2 had the lowest total mass loss (68.0 kg) (59.7 kg wood and 8.3 kg polyurethane sofa). At the end of simulation when the fire was completely extinguished, 27.0 kg (31% by mass) of the wood was left in this scenario.

Table 5-1 Comparison of the maximum HRR and burning rate for all scenarios

Ventilation Scenario	Maximum Heat Release Rate and its Time		Maximum Burn Rate and its Time	
	kW	s	kg/s	s
SC1	6,092	24.0	0.405	58.5
SC2	7,292	69.0	0.517	66.0
SC3	6,940	39.0	0.508	112.5
SC4	6,816	30.0	0.531	58.5
SC5	4,983	15.0	0.347	72.0
SC6	7,069	84.5	0.495	87.0
SC7	7,431	88.2	0.513	56.7
SC8	7,450	36.0	0.495	54.0
SC9	4,760	281.7	0.324	186.2

Table 5-2 Comparison of the time and burned mass when sofa completely burned

Ventilation Scenario	Time at which the sofa was completely burned, t* (s)	Burned mass of the wood cribs at t* (kg)	Total burned mass at t* (kg)	Percentage of Wood Cribs Burned at t* (%w)
SC1	236	50.6	58.9	58
SC2	158	49.0	57.3	57
SC3	192	49.6	57.9	57
SC4	166	48.3	56.6	56
SC5	249	52.4	60.7	60
SC6	167	47.1	55.4	54
SC7	176	47.2	55.5	54
SC8	186	48.4	56.7	56
SC9	283	53.4	61.7	62

Table 5-3 Comparison of the total mass losses, total energy release and the effective heat of combustion

Ventilation Scenario	Total burned mass of the wood cribs (kg)	Total burned mass (sofa + wood cribs) (kg)	Total remaining mass of the wood cribs (kg)	Percentage of total remaining mass of the wood cribs (%w)	Total Energy released (MJ)	Effective Heat of Combustion (MJ/kg)
SC1	70.9	79.1	15.9	18	1,317	16.6
SC2	59.7	68.0	27.0	31	1,169	17.2
SC3	69.9	78.2	16.8	19	1,398	17.9
SC4	68.8	77.1	17.9	21	1,304	16.9
SC5	68.4	76.7	18.3	21	1,219	15.9
SC6	61.2	69.5	25.6	29	1,198	17.2
SC7	69.6	77.9	17.1	20	1,515	19.4
SC8	69.3	77.6	17.4	20	1470	18.9
SC9	69.5	77.8	17.2	20	1,511	19.4

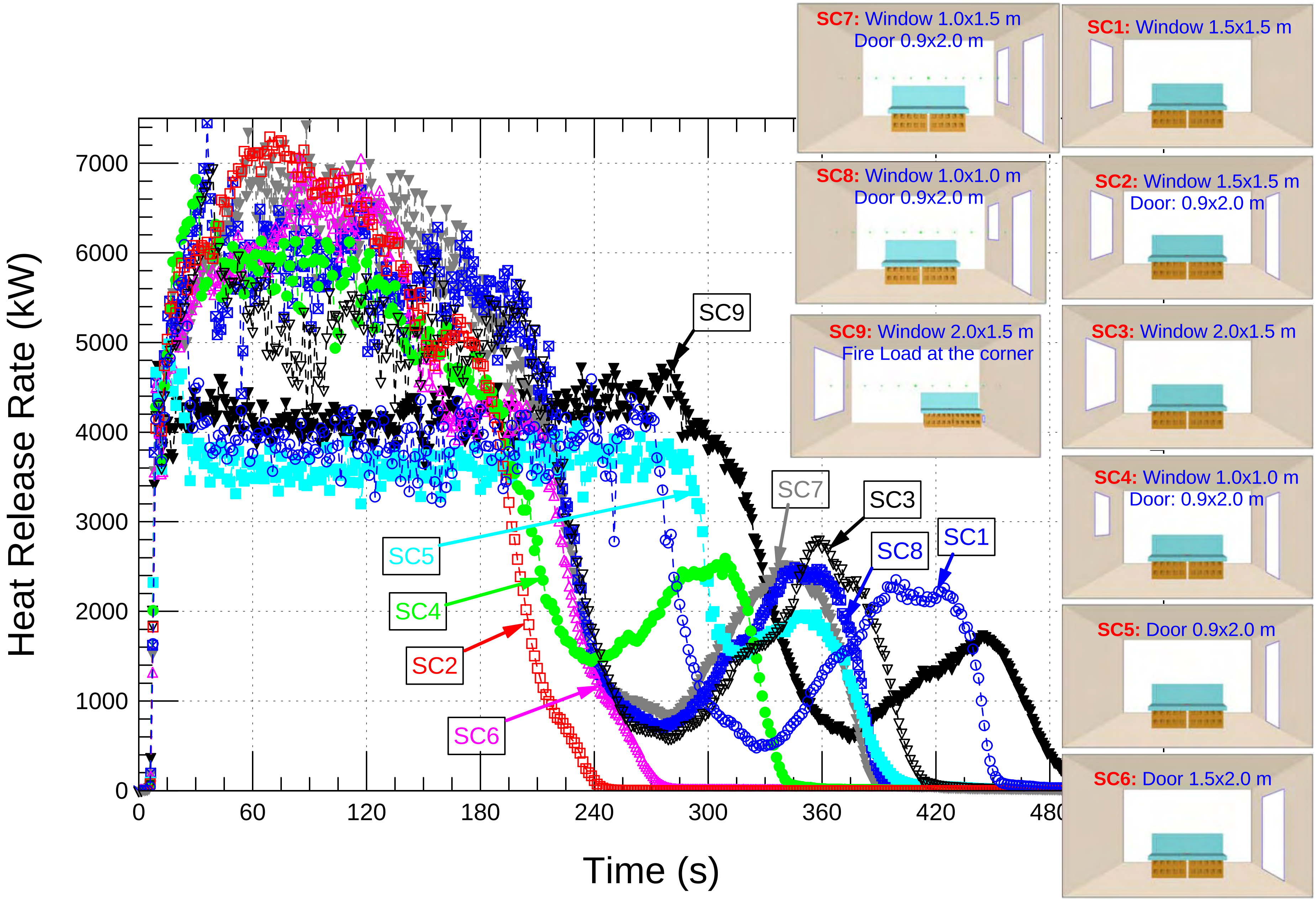


Figure 5-1 Comparison of the HRR of all ventilation scenarios.

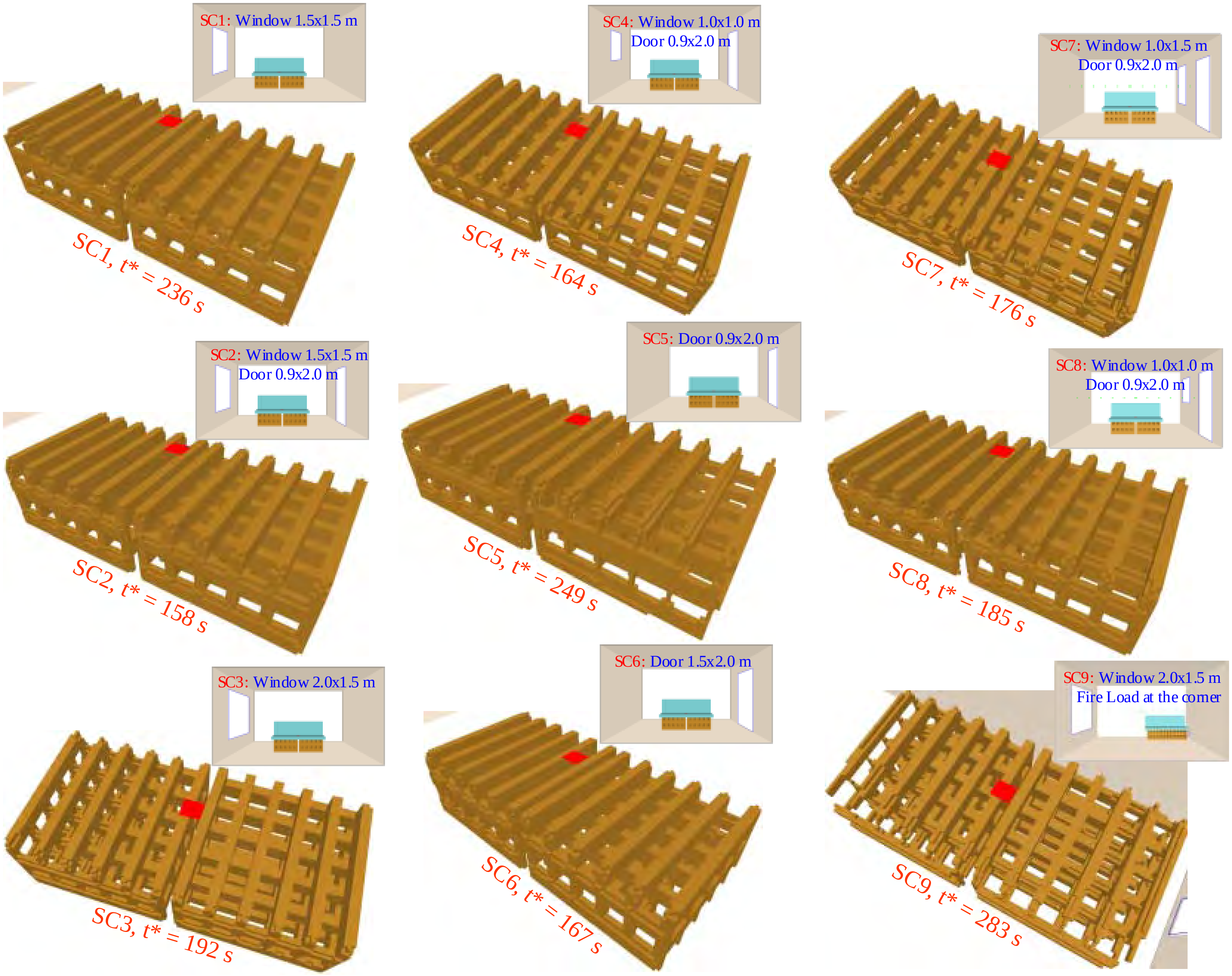


Figure 5-2 Status of the wood cribs and the time, t*, at which the sofa completely burned

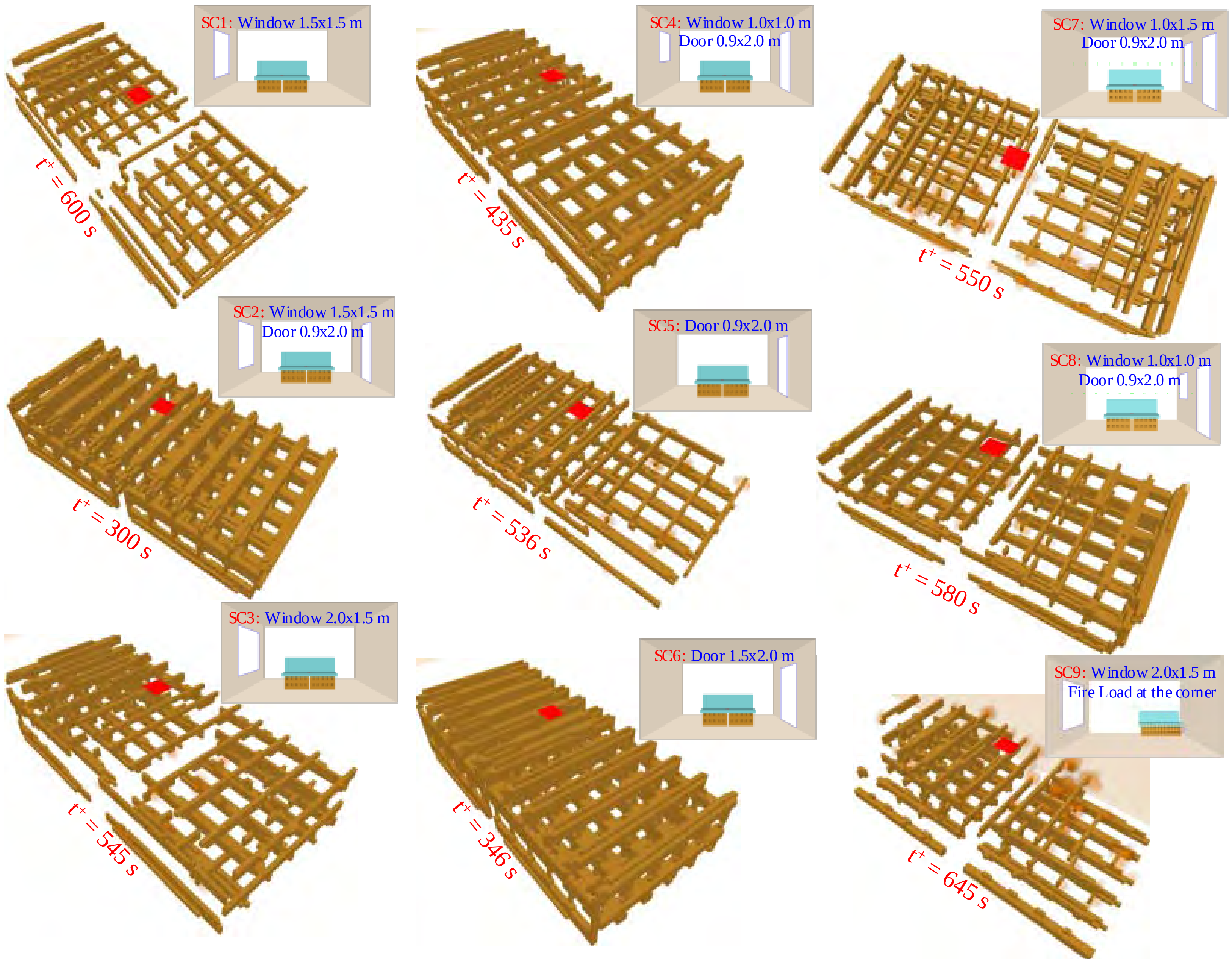


Figure 5-3 Status of the wood cribs and the time t^+ at which the HRR = 1 kW

6. References

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7. Appendix A – Combustion Model in FDS Version 5

A significant change has been made in the combustion model in FDS version 5. This section summarizes the new features in the combustion model that were used in the current CFD simulations for different ventilation scenarios. Figure 7-1 shows the process of burning the fire load (polyurethane sofa + wood cribs). The first step is basically the conversion of the solid fuel to gas fuel. For the polyurethane sofa, the conversion solid fuel to gas fuel consumes energy (heat of vaporization, ΔH_v = 1,500 kJ/kg). For the wood cribs, however, the modified pyrolysis model was used in the conversion of solid fuel to gas fuel. In this process the wood fuel undergoes several reactions as briefly summarized below.

Modified Pyrolysis Model

The pyrolysis model represents different reactive processes such as evaporation, charring and internal heating. This model considers that the solid fuels can undergo simultaneous reactions. Each material component may undergo several competing reactions, and each of these reactions may produce some other solid component (residue, char in our case), gaseous fuel, and/or water vapor. The wood cribs (70% cellulose, 20% lignin and 10% water by mass) underwent the following reactions:

Reaction 1:
Cellulose (solid) → Active Cellulose (solid) with heat of reaction (ΔH_v) = 0
Reaction 2:
Active Cellulose (solid) → Char (35% by mass) + Fuel (gas) (65% by mass), with ΔH_v = 418 kJ/kg
Reaction 3:
Active Cellulose (solid) → Fuel (gas), with ΔH_v = 418 kJ/kg
Reaction 4:
Water (liquid) → Water (vapor), with ΔH_v = 2260 kJ/kg

The reaction rates are functions of local mass concentration and temperature, and calculated as a combination of Arrhenius and power functions. For example, the reaction rate, r_{ij} of the *i*th material component undergoing its *j*th reaction is given as:

$$r_{ij} = \left(\frac{\rho_{s,i}}{\rho_{s0}}\right)^{n_{s,ij}} A_{ij} e^{\left(-\frac{E_{ij}}{RT_s}\right)} \max\left[0, \left(T_s - T_{ign,ij}\right)\right]^{n_{t,ij}} \text{, where} \qquad (7\text{-}1)$$

$\rho_{s,i}$ = current density of material component *i*th

ρ_{s0} = initial density of material layer that consists of different material components

A_{ij} = per-exponential factor (1/s)

E_{ij} = Activation Energy (kJ/kmole)

R = universal Gas Constant (kJ/kmole K)

T_s = surface temperature
$T_{ign,ij}$ = ignition temperature
$n_{t,ij}$ = temperature exponent
$n_{s,ij}$ = mass fraction exponent

One of the new features in the FDS version 5 is that the pyrolysis rate can depend on the surface temperature of the fuel (see the above equation). Additionally, when the fuel surface temperature is quite below its ignition temperature, the reaction would not happen (r_{ij} = 0). This is the case of some fuels whose reactions are temperature controlled. For wood cribs, the pyrolysis rate is independent of the surface temperature ($n_{t,ij}$ = 0) and equals zero when the surface temperature is less than the ignition temperature. The heat of reaction, activation energy and the pre-exponential factor of the above four reactions are given in Table 7-1.

Table 7-1 Pre-exponential factors and activation energies for wood reactions [5]

Reaction	**Heat of Reaction, ΔH_v (kJ/kg)**	**Pre-exponential Factor, A (1/s)**	**Activation Energy, E (kJ/kmole)**
1	0	2.800×10^{19}	2.424×10^{5}
2	418	1.300×10^{10}	1.505×10^{5}
3	418	3.230×10^{14}	1.965×10^{5}
4	2260	1.000×10^{20}	1.620×10^{5}

There are two ways of defining a fire: the first is to specify a Heat Release Rate Per Unit Area (HRRPUA). The other is to specify the heat of reaction along with other thermal parameters. In this case, the Burning Rate (BR) or the Heat Release Rate (HRR) of the fuel depends on the net heat feedback to the surface of the fuel.

The thermal parameters are listed in Figure 2-2 and Figure 2-5 for a polyurethane sofa and the wood cribs, respectively. In both cases, once the solid fuels of both the polyurethane sofa and the wood cribs have been converted to gas fuels as explained above, the modified Mixture Fraction Combustion Model (MFCM) is used as briefly explained below.

Modified Mixture Fraction Combustion Model

In the previous versions of FDS, it was assumed that fuel and oxygen react instantaneously upon mixing (i.e. mixed is burned). However, for fire scenarios where it cannot be assumed that fuel and oxygen react completely upon mixing (for example in under-ventilated compartments), this assumption no longer holds. One of the new features in the FDS version 5 is to account for mixing of fuel and oxygen without burning. Both the oxygen concentration and the temperature of gases in the vicinity of the flame sheet plays an important rule in whether burning can or cannot happen upon mixing of fuel and oxygen. Figure 7-2 shows the values of temperature and oxygen concentration for which burning can and cannot take place.

In the previous versions of FDS, it was assumed that combustion occurs with constant yield for CO (Y_{CO}), and soot (Y_{Soot}) that are based on post-flame measurements. In other words, CO and Soot are created at the flame and transported with the combustion products with no further reaction. This is a reasonable assumption if the purpose of the simulation is to assess the impact of the fire in the large space. However, in under-ventilated fires, CO and soot are produced at higher rates, and exist within the fuel-rich flame envelope at higher concentrations than would otherwise be predicted with a single set of fixed yields that are based on post-flame measurements. Another new feature in the FDS version 5 is the ability to account for the CO production and its eventual oxidation at the flame envelope or within a hot upper layer.

In order to account for both mixing of fuel and oxygen without burning and CO production, the modified mixture fraction combustion model in FDS version 5 considers the following three gas reactions (see Figure 7-1):

<u>Reaction 1</u>: (null reaction in the no burn region shown in Figure 7-2)
Fuel (gas) + O_2 → Fuel (gas) + O_2
<u>Reaction 2</u>: (incomplete reaction, burn region shown in Figure 7-2)
Fuel (gas) + O_2 → CO + other Products
<u>Reaction 3</u>: (complete reaction, burn region shown in Figure 7-2)
Fuel (gas) + O_2 → CO_2 + other Products

This process is called the three parameters mixture fraction combustion model. Three parameters were (Figure 7-1):

1. Progress parameter C_F. This parameter is the extent to which the gas fuel reacts with oxygen under the incomplete reaction (reaction 2) and complete reaction (reaction 3). The value of this parameter is in the range from 0 to 1. A zero value of C_F means no combustion at all (reaction 1, see no burn region in Figure 7-2). While a value of C_F = 1 means that all fuel reacts under reactions 2 and 3 (burn region in Figure 7-2).

2. Progress parameter C. This parameter is the extent to which gas mixture is composed of both incomplete reaction (reaction 2) and complete reaction (reaction 3). The value of this parameter is in the range from 0 to 1. A zero value of this parameter means that only incomplete reaction (reaction 2) takes place, while a value of C = 1 means that only complete reaction (reaction 3) takes place.

3. Progress parameter C_{CO}. This parameter is the extent to which CO has been converted to CO_2. Similar to C_F and C, the value of C_{CO} is in the range of 0 to 1. A zero value of C_{CO} means that no CO_2 is formed as a result of CO conversion. A value of C_{CO} = 1 means that the produced CO from reaction 2 has been completely converted to CO_2.

In summary, using the modified combustion model in FDS version 5 allows for the investigation of different fire ventilation scenarios for a room.

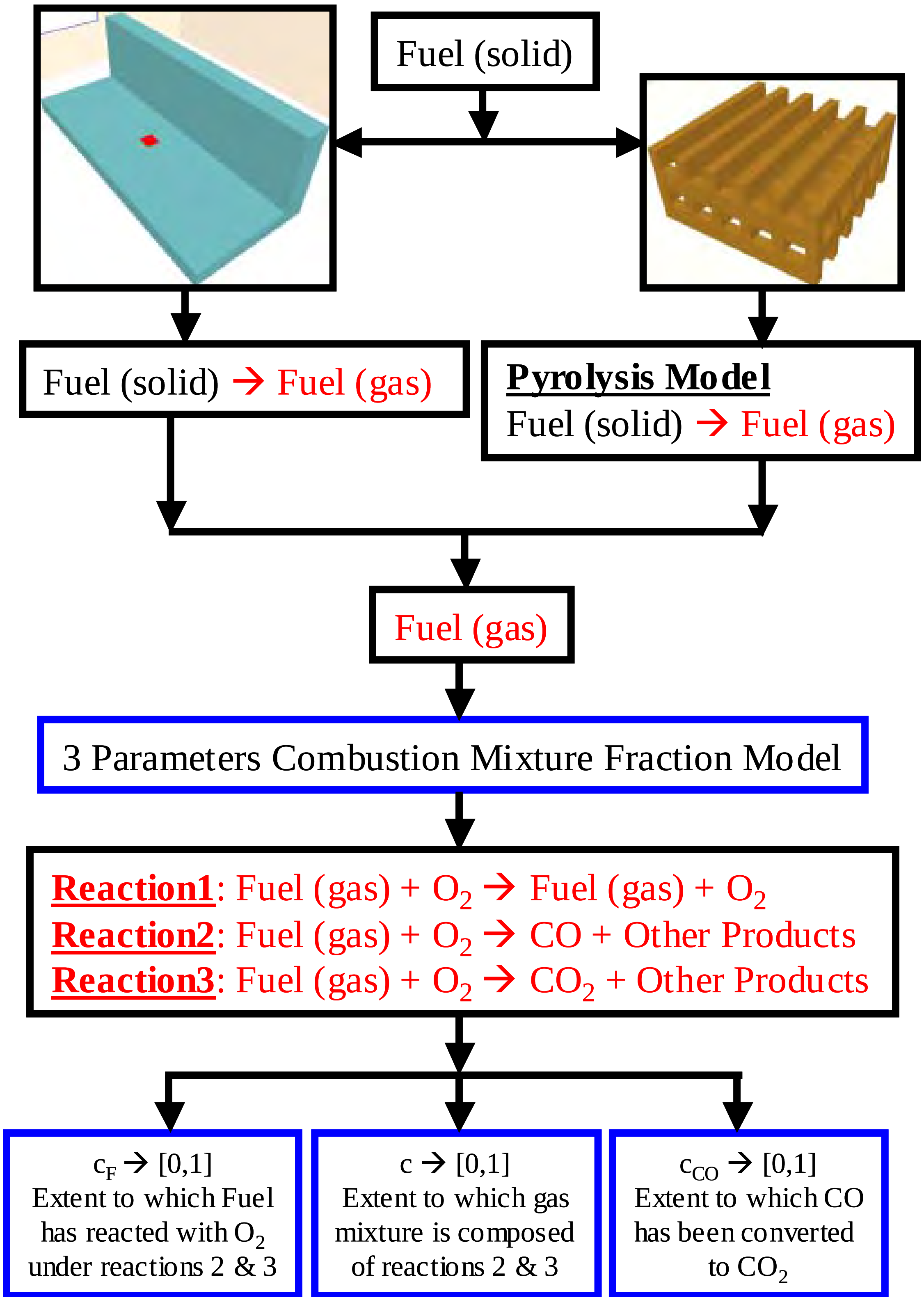

Figure 7-1 Procedure of burning polyurethane sofa and wood cribs in the FDS

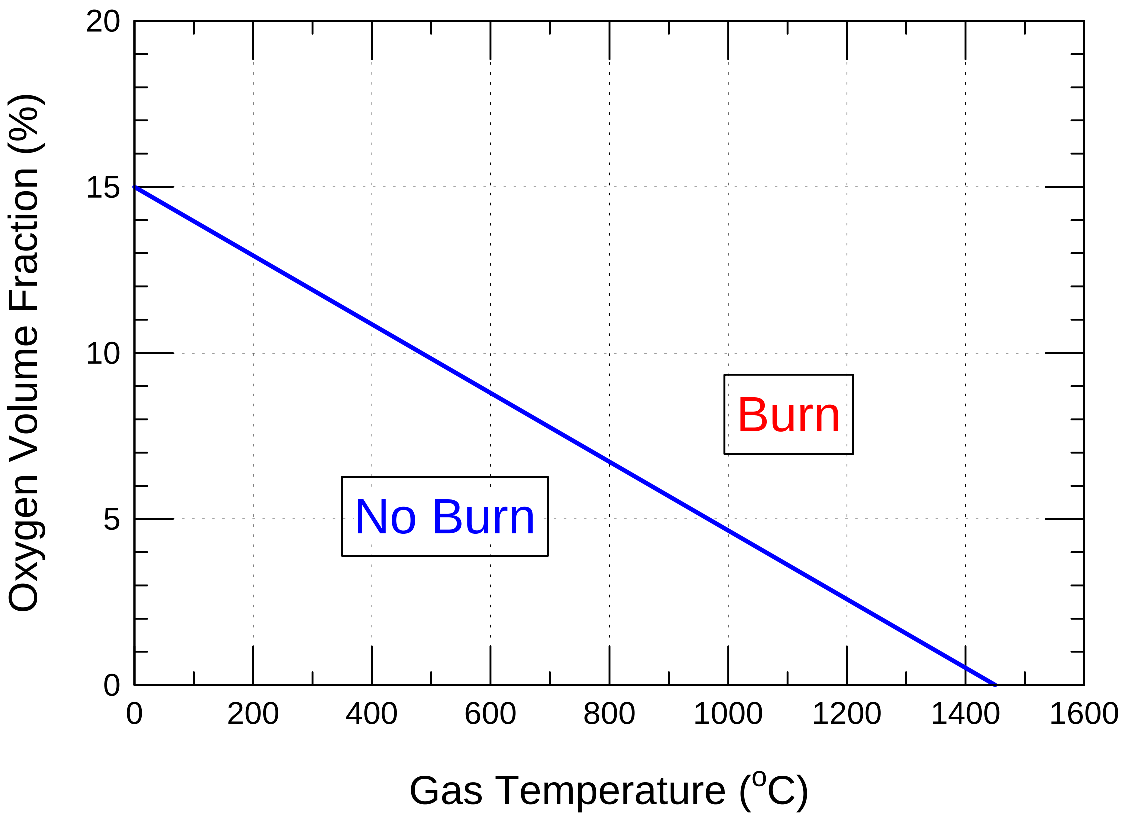

Figure 7-2 Oxygen-temperature phase space showing where combustion is allowed and not allowed to take place [4].