# PERFORMANCE EVALUATION ON NATURAL SMOKE VENTING SYSTEM IN A LARGE CARGO HALL

W.K. Chow and S.S Han
Research Centre for Fire Engineering, Department of Building Services Engineering
Area of Strength: Fire Safety Engineering, The Hong Kong Polytechnic University
Hong Kong, China

Y. Gao and S.S Li
Department of Building Engineering, Harbin Engineering University, Harbin, Heilongjiang, China

## ABSTRACT

Performance of the natural smoke venting systems (known as static smoke exhaust systems) in a large cargo hall in Hong Kong will be evaluated by Computational Fluid Dynamics. Elevation of the smoke layer interface is demonstrated to be kept above an agreed height. Numerical simulations on the smoke exhaust were carried out with a 5 MW fire at two levels. The simulation tool selected was the Fire Dynamics Simulator (FDS) developed at the Building and Fire Research Laboratory, National Institute of Standards and Technology in USA.

Wind action is another factor affecting the efficiency of the natural smoke venting systems. Effect of wind is simulated by imposing incident air flow with speeds varying up to 20 $ms^{-1}$. Adverse effects might be resulted when strong wind is blowing towards a tall vertical surface adjacent to the large cargo hall. Smoke might be pushed downwards under some conditions leading to negative wind pressure coefficients on the leeward side. Performance of an adjacent wall next to the hall was also studied.

## INTRODUCTION

A big cargo hall is constructed in Hong Kong. It is a single compartment of length 160 m, width 18 m and height 46 m. The floor area is 2,880 $m^2$ and space volume of 132,480 $m^3$. Space volume of this hall exceeds the maximum limit of 28,000 $m^3$ allowed in the prescriptive code [1] on fire service installations (FSI code). Smoke exhaust systems have to be installed for providing fire safety, especially in buildings with large spaces such as an atrium.

Basically, there are dynamic smoke exhaust systems and static smoke exhaust systems (in fact natural smoke venting systems) as specified in the local code [1]. Dynamic smoke exhaust systems were commonly used in the past, but not static smoke exhaust systems. However, there are more proposals recently on installing static smoke exhaust system due to many reasons. For example, low exhaust rate of dynamic smoke exhaust systems might not be so effective in removing smoke. There might be no space for installing the fan and air ductworks. The natural vent can be integrated with daylighting design.

In this particular project, fire engineering approach [2] was adapted in designing fire safety provisions. A static smoke exhaust system with natural vents (natural smoke venting systems) was finally decided to give an acceptable safety level in fire. The performance of the natural smoke venting system [3] depends on factors affecting the flow rates through the ceiling vent. Smoke layer temperature and interface height under different fire sizes should be investigated for better understanding the smoke exhaust system. Further, wind effect [4] should be investigated carefully in fire hazard assessment.

Possible fire scenarios were identified based on the combustibles stored with the heat release rate estimated. Computational Fluid Dynamics (CFD) was applied to study smoke filling and exhaust in hazard assessment. The software Fire Dynamics Simulator (FDS) developed at the Building and Fire

Research Laboratory, National Institute of Standards and Technology[5] was selected as the CFD tool to study the performance of the natural smoke venting system and the effects of wind. The numerical works on smoke exhaust will be reported in this paper.

## NATURAL SMOKE VENTING SYSTEM

Natural smoke venting systems or known as static smoke exhaust systems in Hong Kong[1] are now proposed in many new projects. Natural vents[3] such as vertical vent at the sidewall or horizontal ceiling vent at the roof are installed Driving forces for natural vents are stack effect, buoyancy[6] and wind action[4,7]. Stack pressure is low for places with a small difference between indoor and outdoor temperatures. Stack effect might be significant in highrise buildings, but only in lift shafts or staircases with a large height to length (or width) ratio. In halls with a large cross-sectional area, the stack pressure might be overridden by pressure difference due to other air flow paths. An example is the open atrium with direct air flow path to shopping levels. There is concern on having reverse stack in pulling smoke down under some conditions.

Buoyancy[6,8] is the key driving force of smoke exhaust in both static and dynamic systems. Bigger the fire size, stronger the buoyancy and hence the higher the exhaust rate of a static smoke exhaust system[3,8,9]. If smoke is hot enough to give sufficient buoyancy, a static smoke extraction system is more effective in removing smoke from a hall. There are numerous studies on vent flow induced by buoyancy reported in the literature. Estimation on the vent size based on buoyancy was reviewed[8].

For a tall hall located in the core of a building, horizontal ceiling vents are commonly designed as it is easier to get roof space. A pressure difference is required to be maintained across a vent to push fluid from the high pressure side to the low pressure regions. For a fire in this cargo hall, buoyancy induced by the fire is the key driving force.

Normally, wind action will give a more negative pressure above the vent to remove more smoke. But the wind-induced action should be demonstrated not to give adverse effects in pulling smoke down, especially when there are adjacent taller buildings[10,11]. This point will be studied by CFD simulations and reported in this paper.

## THE CARGO HALL

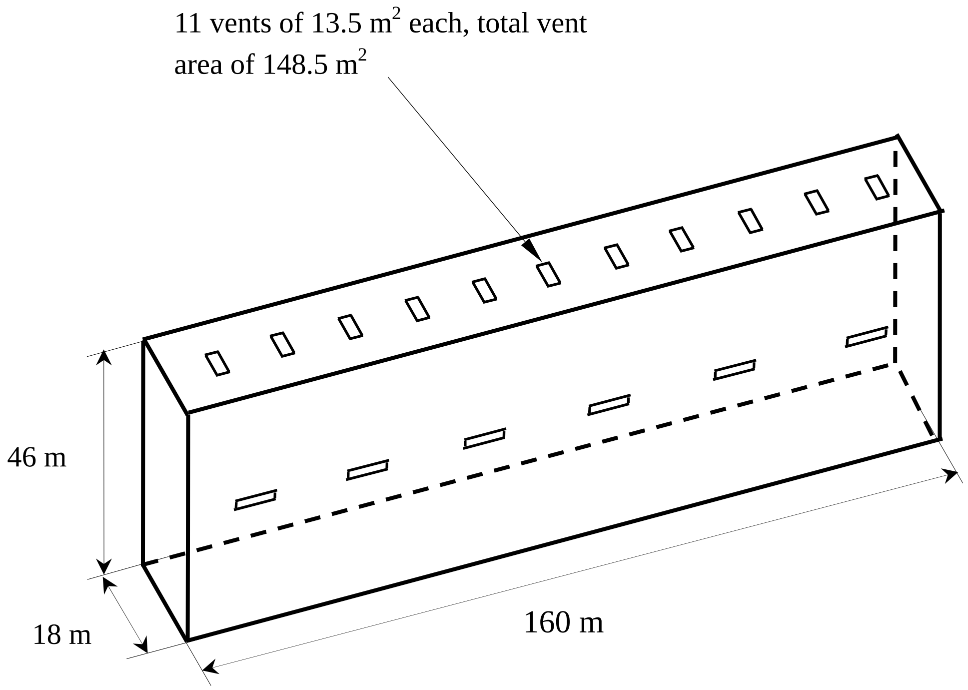
The architectural feature of the hall and locations of smoke vents are shown in Fig. 1. There are 11 roof vents, each of area 13.5 $m^2$; and six inlet vents, each of 13.5 $m^2$ on the side-wall as in Fig. 1a. The total smoke vent area is 148.5 $m^2$ at the roof and 81 $m^2$ on the wall.

An NFPA fast $t^2$-fire[3] with cut-off value of 5 MW was used. Two scenarios with the fire at two levels were considered:

- Scenario 1: Low-level fire at the lowest level of stored goods.
  A fire at low level would generate more smoke due to bigger air entrainment rate to the tall clear height. Buoyancy of smoke has to be justified.

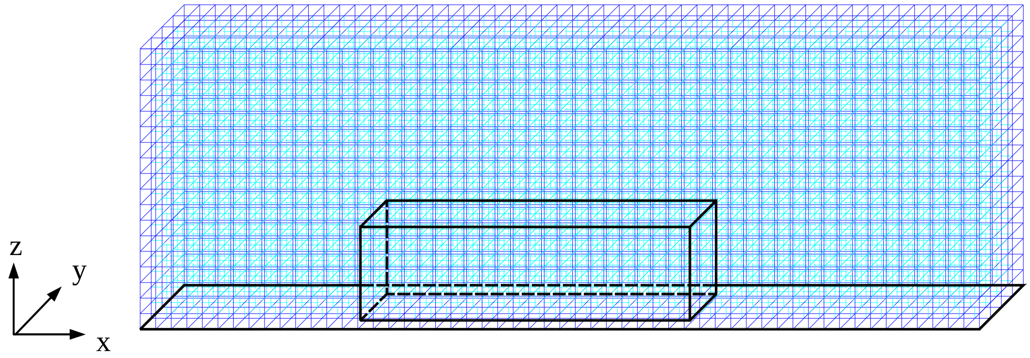
- Scenario 2: High-level fire in the penultimate level of stored goods at height 28.5 m.
  A high level fire will give higher air temperature near to the ceiling.

Geometries of the two fire scenarios are shown in Fig. 1c. Cartesian coordinate system (x, y, z) was used with geometry of the grid system shown in Fig. 1b.

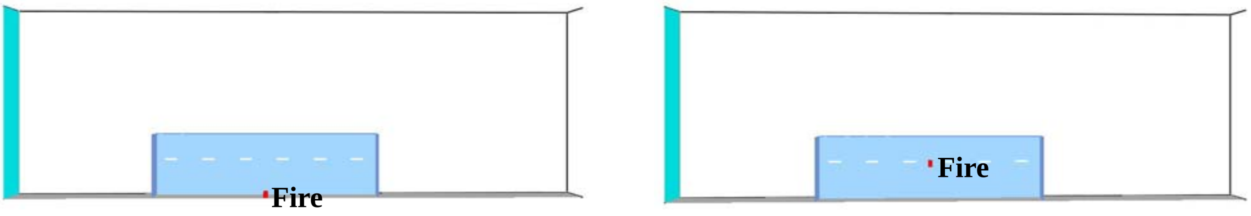


(a) Architectural layout

Grid (270×20×90)



(b) Grid system



Scenario 1

Scenario 2

(c) The two scenarios

**FIGURE 1.** The cargo hall

The grid systems used are:

- Grid system for the computing domain : 270 by 20 by 90 along the x-, y- and z-directions.
- Grid system in the hall : 106 by 12 by 30 along the x-, y- and z-directions.

To study wind effects, computing domains are extended outside. The geometry used was 270 by 20 by 90 grids along the x-, y- and z- directions.

Input environmental conditions are indoor temperature of 28 $^{o}$C and ambient temperature 30 $^{o}$C.

The wind speed V at height h is expressed by:

$$V = V_o \left( \frac{h}{H_o} \right)^n \quad [1]$$

$H_o$ is the ceiling height of 46 m and n is 0.3. Values of $V_o$ are taken to be 1 ms$^{-1}$, 5 ms$^{-1}$, 10 ms$^{-1}$ and 20 ms$^{-1}$ in the CFD simulations.

## ACCEPTANCE CRITERIA

The key criterion is to limit smoke spread in a fire. The smoke layer is agreed to be kept above 37 m from floor level, i.e. 80% of the ceiling height.

To illustrate the effect of smoke, visibility ($V_i$ in m) is commonly used[12] to describe light obscuration by smoke. $V_i$ is related to the light extinction coefficient K (in m$^{-1}$) of the smoke medium. K can be measured by attenuating a monochromatic light beam of intensity $I_o$ to I, while traveling through smoke of distance L by:

$$I = I_o e^{-KL} \quad [2]$$

K is given by the smoke density and mass specific extinction coefficient of the fuel. $V_i$ can then be expressed in terms of K by a non-dimensional constant C:

$$V_i = C/K \quad [3]$$

Value of C is 8 for a light emitting sign and 3 for a light reflecting sign. As values of K vary at different positions in the hall, $V_i$ would be varying as well.

The visibility level up to 80% of ceiling height (46 m), i.e. 37 m is agreed to be kept at 10 m. This is the acceptance criterion after a series of meetings with the Authority. Further, plotting the smoke particle development patterns will confirm that the smoke layer can be kept above a certain height.

## RESULTS

Similar to all CFD simulations, vast volume of data were generated. In this paper, only the predicted visibility contours of 10 m and smoke particles tracking diagrams will be presented. Such results on the two scenarios for low- and high-level fires for wind speeds up to 20 ms$^{-1}$ are shown from Figs. 2 to 5.

In view of Figs. 2 and 3 for low-level fire, all regions above 37 m or 80% of ceiling height in the hall have visibility over 10 m. In view of Figs. 4 and 5 on high-level fire, all regions above 37 m have visibility over 10 m.

It is observed that wind can give an upper ‘pull’ in taking smoke away. This is a good demonstration on the positive effect of wind when there are no adjacent buildings.

## EFFECT OF VERTICAL WALL

As pointed out years ago and confirmed by CFD recently [10,11], air recirculation might be induced by wind on the leeward side of the building if it is close to a vertical wall. This might give downward push of smoke across the ceiling vent. Such possibility will be simulated by placing a vertical wall on the right hand side of the cargo hall. Only the condition with high wind speed of 20 $ms^{-1}$ was evaluated.

Results on visibility and smoke development patterns of this scenario are plotted in Figs. 6 and 7.

It is observed from the figures that downward push on the smoke layer was induced by the strong wind speed when there was a wall adjacent to the hall. The visibility level in some parts of the hall was reduced.

## CONCLUSION

Efficiency of natural smoke venting systems in a large cargo hall was studied in this paper by the CFD package FDS [5]. Smoke layer was demonstrated to be kept above a specified height in the hall under a 5 MW fire. Wind-induced motion at the vent was also studied with wind speeds next to the vent up to 20 $ms^{-1}$ with turbulent flow induced by an adjacent vertical wall investigated.

The above CFD study would give a clear picture on smoke movement and control. This is more acceptable by the Authority in comparing with those designs using only empirical correlations [3,13] based on crude methods [8]. There are reservations in tall spaces with irregular shapes that the smoke exhaust system might not perform as expected. It is noted that even such design guides [e.g. 13] will be reviewed and then revised accordingly. Therefore, hot smoke tests [1] might be required by the Authority to demonstrate that the smoke exhaust systems will perform properly. Projects with smoke exhaust systems designed from only correlation formula are likely to be tested more vigorously. Even with CFD studies, hot smoke tests have to be done in many areas, such as Taiwan [14]. There are worries of inducing internal fire whirls in big halls under some conditions, and is now investigated by the author [15].

## ACKNOWLEDGEMENT

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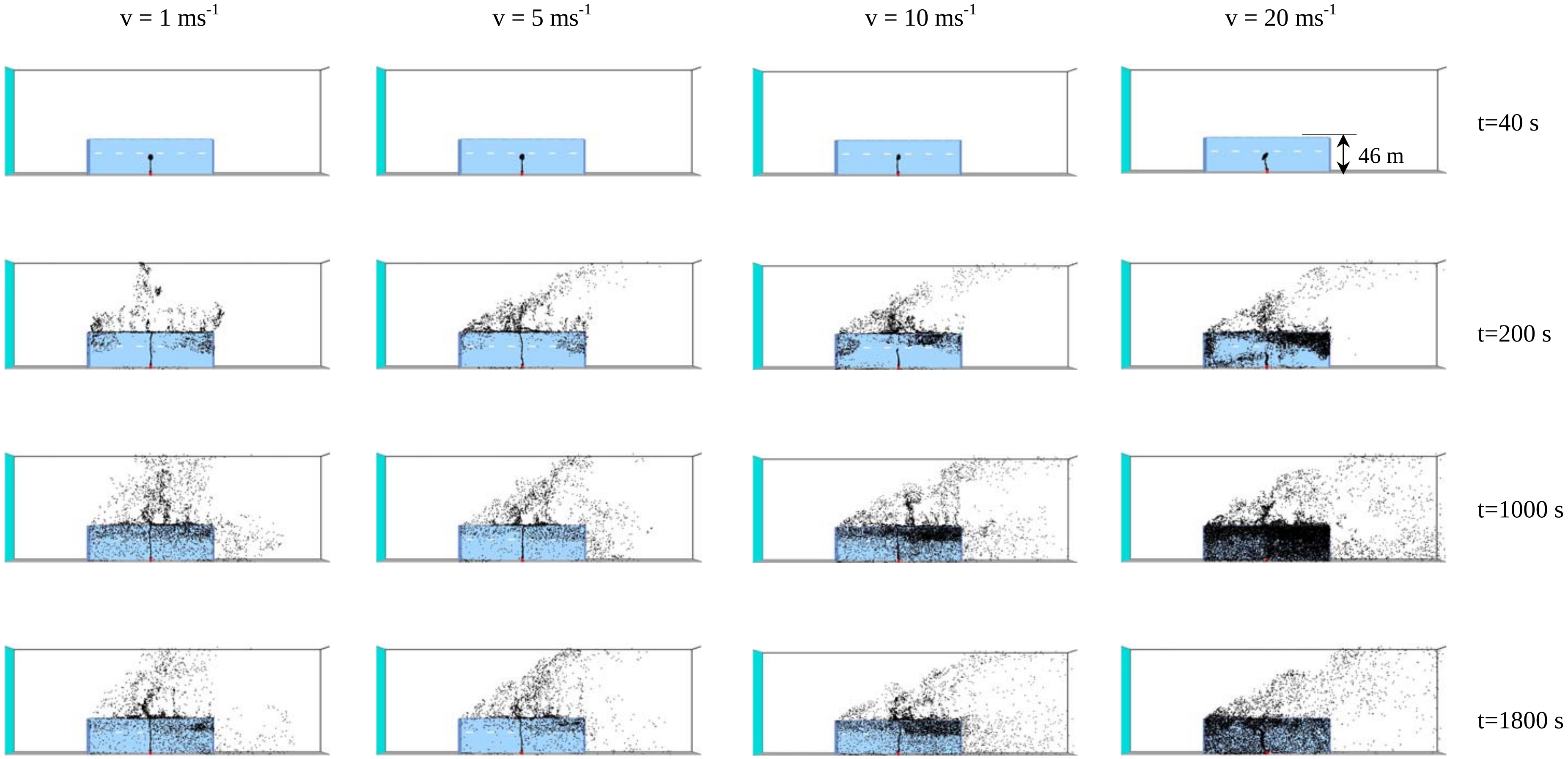


**FIGURE 2.** Smoke particles for low-level fire

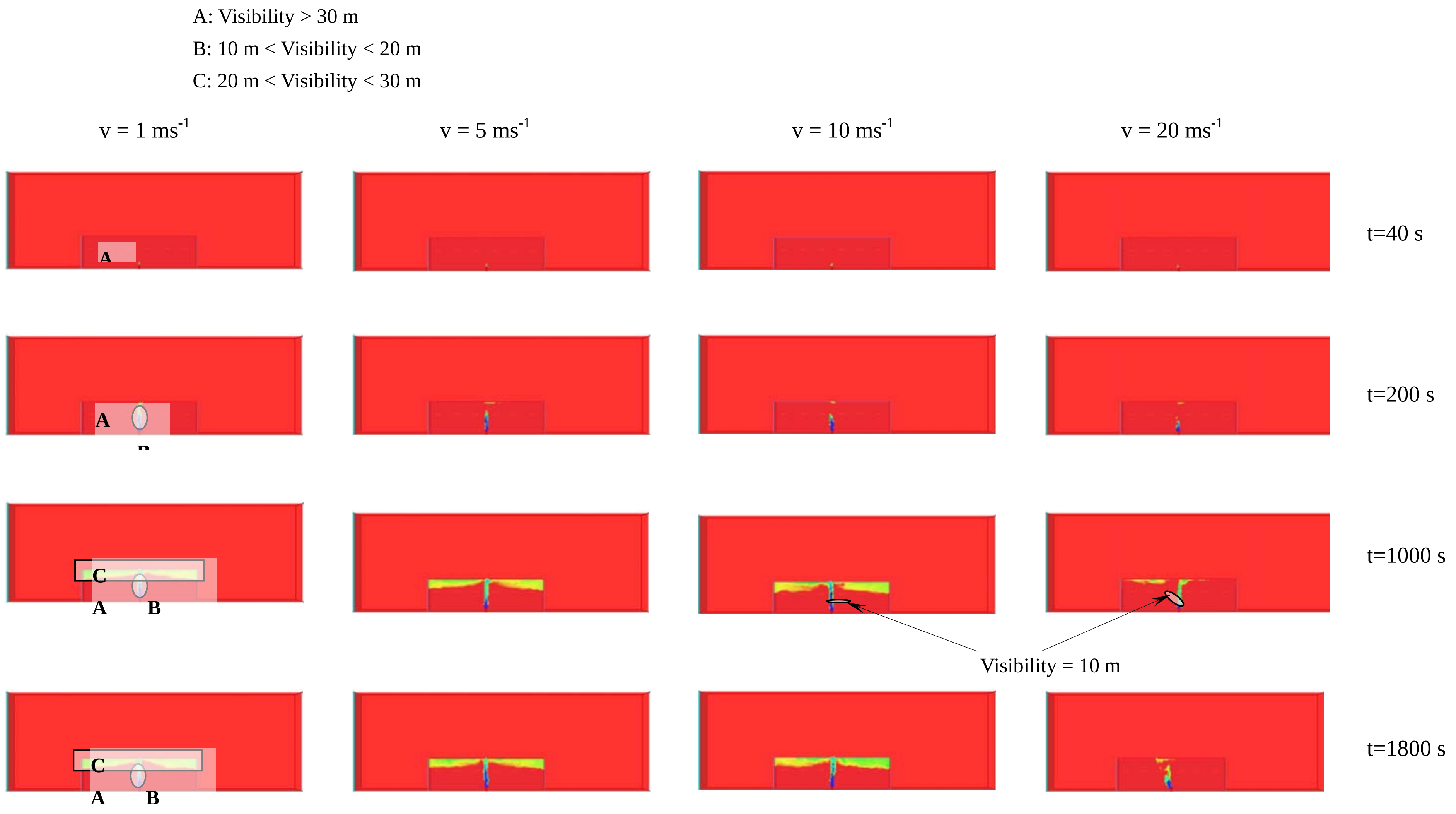


**FIGURE 3.** Visibility levels for low-level fire

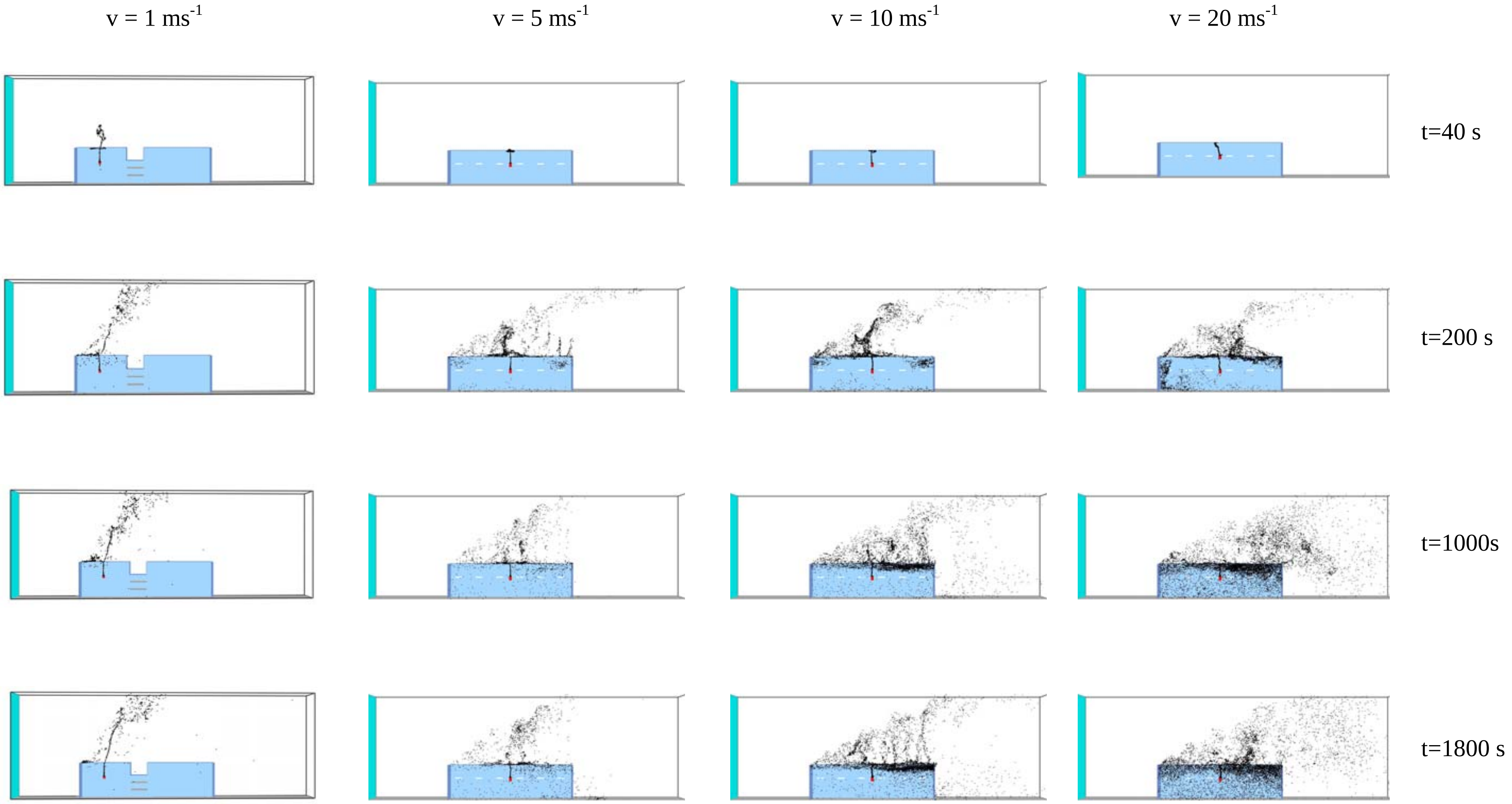


**FIGURE 4.** Smoke particles for high-level fire

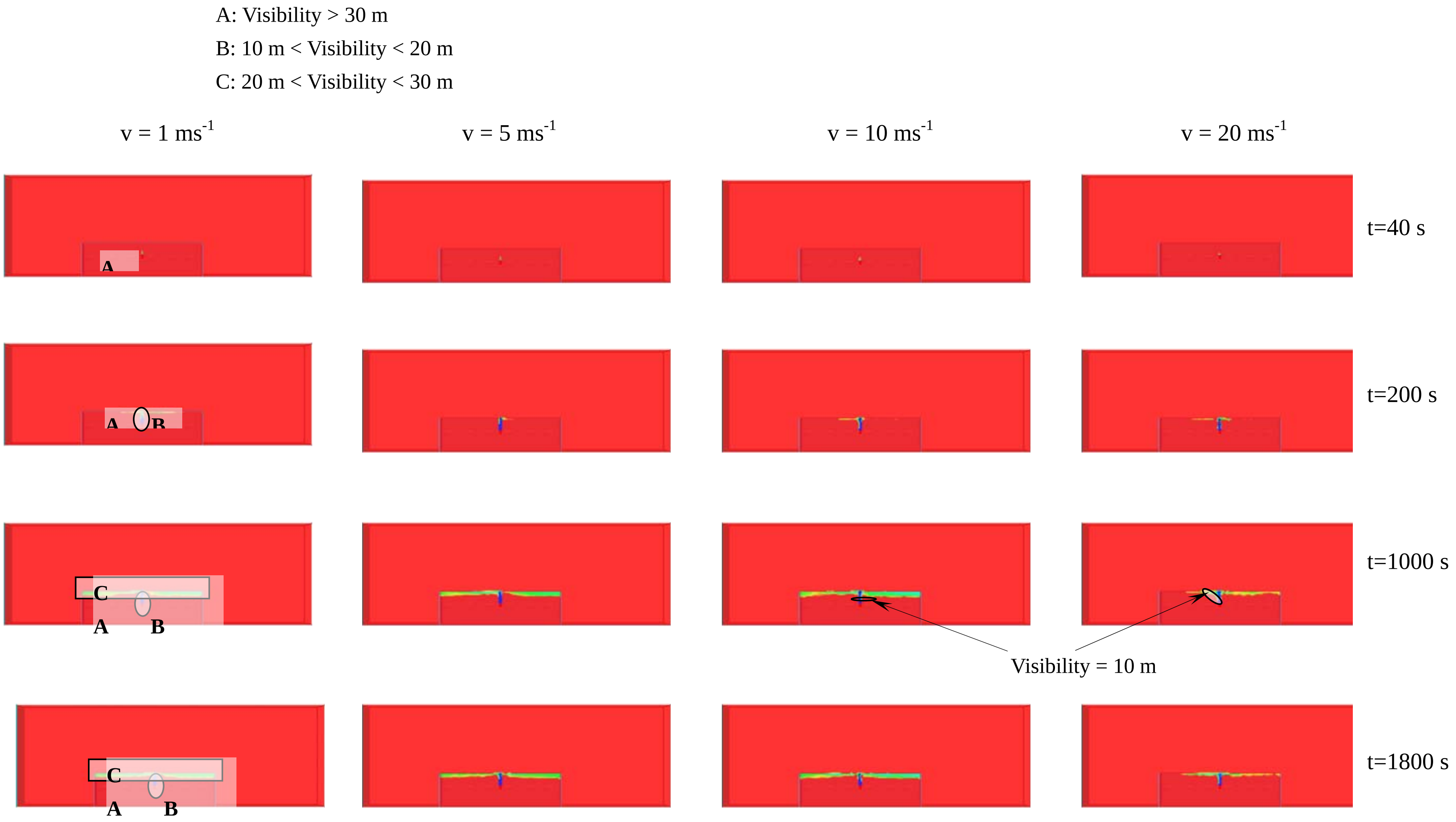
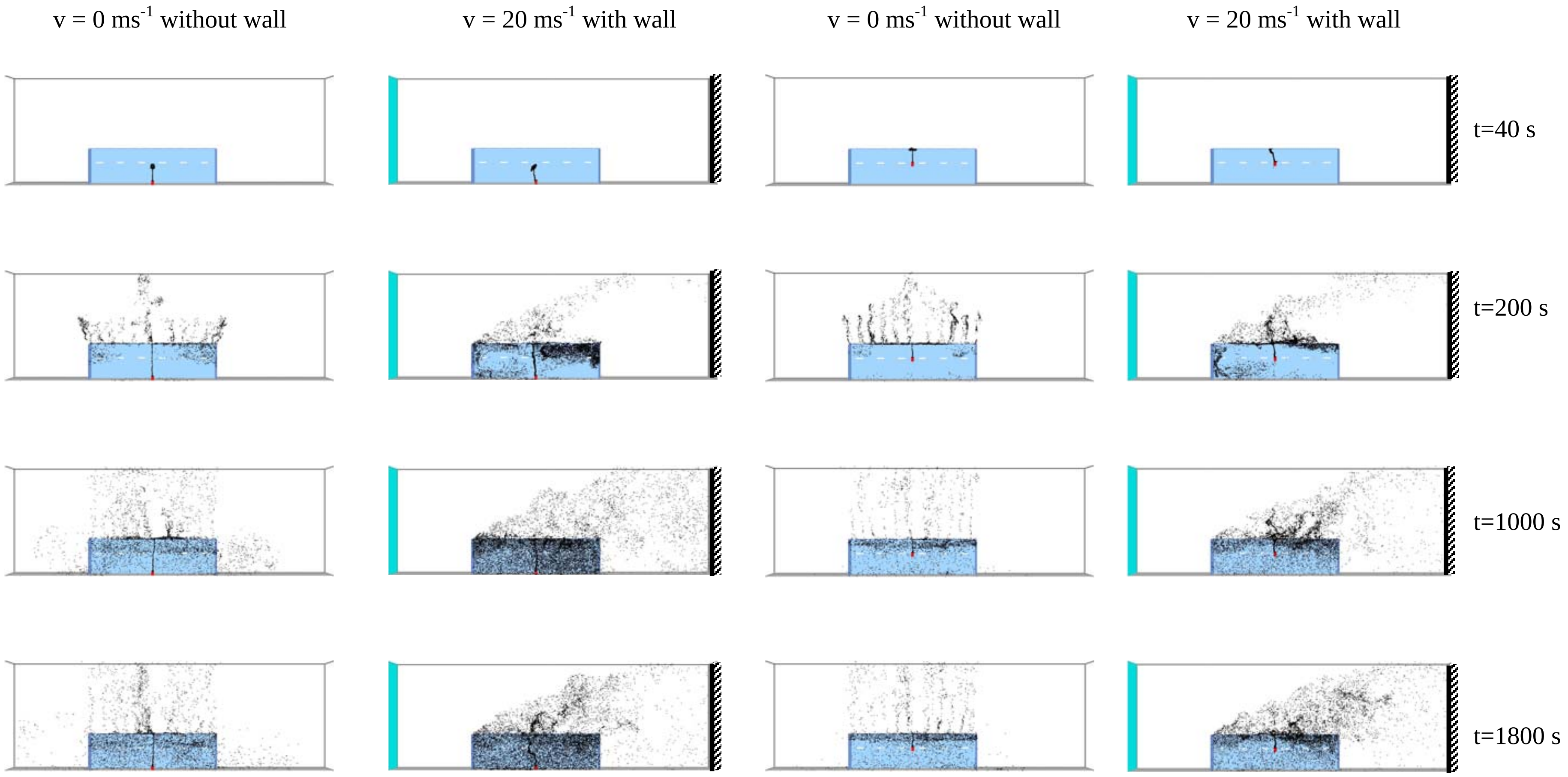


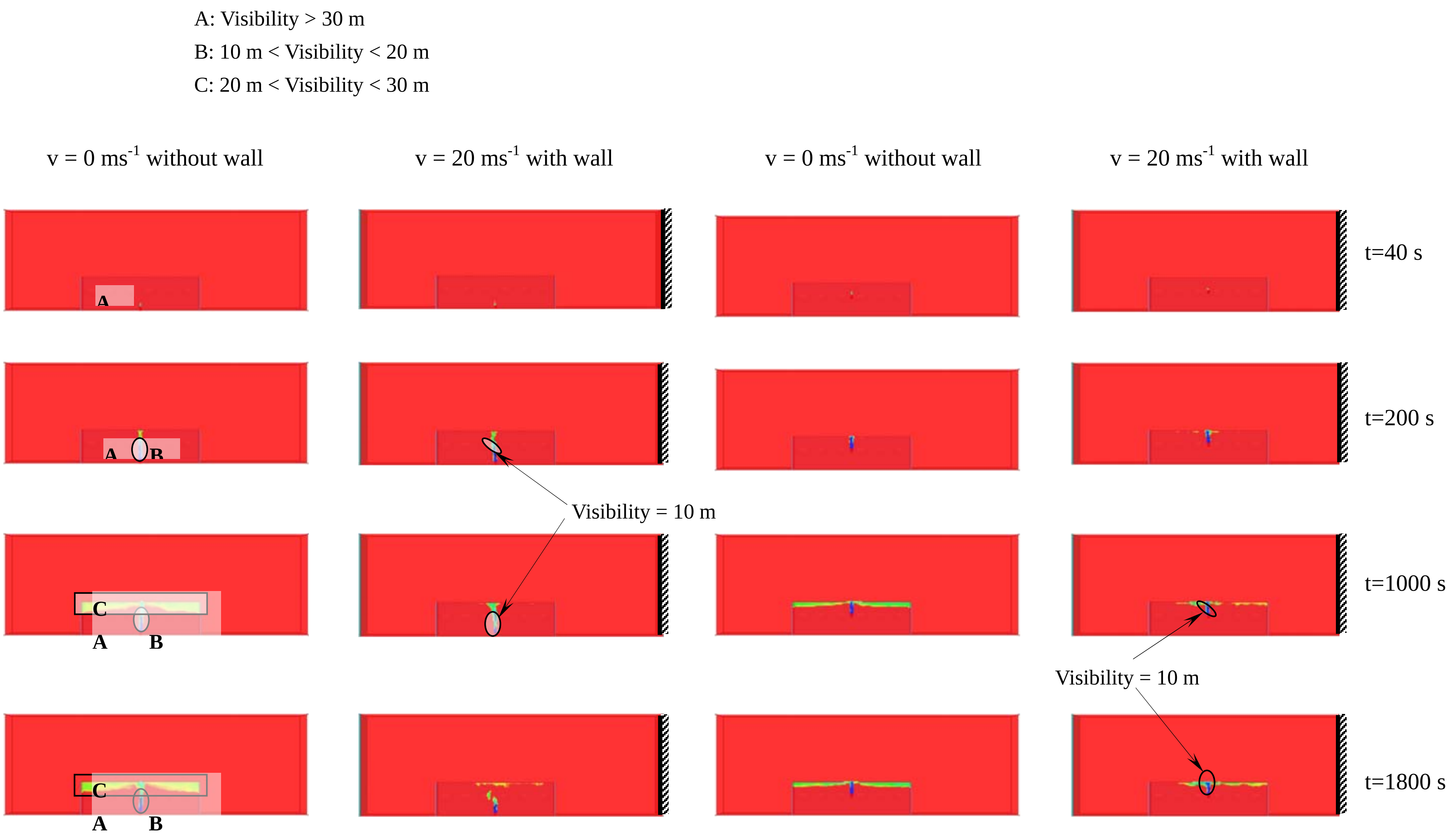
**FIGURE 5.** Visibility levels for high-level fire



(a) Scenario 1

(b) Scenario 2

**FIGURE 6.** Smoke particles for 0 ms$^{-1}$ without wall and 20 ms$^{-1}$ with wall



(a) Scenario 1

(b) Scenario 2

**FIGURE 7.** Visibility levels for 0 ms$^{-1}$ without wall and 20 ms$^{-1}$ with wall

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