Smoke separation with Air curtains analysed using CFD-simulations

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SUMMARY

Cfd-calculations were performed to test whether it is possible to separate a non-smoking zone from a smoking zone using an air curtain. The cfd-calculations resulted in the following conclusions: 1. A larger exhaust flow is best. 2. An air curtain with a low air curtain velocity and an air intake from the smoke zone (as opposed to an air intake from the non-smoking zone) has the lowest smoke concentration in the non-smoking zone. 3. For a maximum of 40 smokers and a ventilation flow compatible with the Dutch building law (1500 m^3/h for this smoke area) an air curtain velocity of 0.75 m/s is the best solution for the smoke zone in the hall of the faculty of Architecture in Delft. 4. With higher air curtain velocities, the air curtain will become a smoke curtain if the exhaust flow is not large enough.

INTRODUCTION

Based on the Tobacco law of 2002, smoking in many buildings is only allowed in separate smoking rooms. However, by physically separating the smokers and the non-smokers, the visual, social and function unity is lost. This problem can be solved by making smoke areas in common rooms where the smoke-free zone is separated by air curtains in stead of walls. In this article computational fluid dynamics (CFD) simulations are presented which show the effectiveness of an air curtain for various air-curtain configurations and various ventilation flows.

All simulations were performed for the hall of the faculty of Architecture of the Delft University of Technology (The Netherlands), see figure 1. The smoke area is situated on the west side of the common hall and has a floor area of 80 m2 with about 40 seats for the smokers. Three sides of the smoke area are outfitted with air curtains, the fourth side of the smoke area consists of a glass facade. A mechanical exhaust is situated on the façade side. A lowered ceiling is applied at a height of 3 meters, compatible with the average room height in the Netherlands.

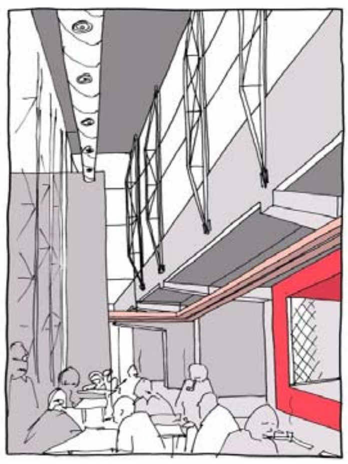


Figure 1. The smoke room in the hall of the Architecture faculty of the Delft University of Technology

THEORY

The air curtain is not only a separation between the smoking and the non-smoking zone. The air, which is blown downward by the air curtain, mixes with air from both the non-smoking zone and air from the smoking zone, see figure 10. This is not a negligible amount but can amount to 90 % of the air volume flow from a single air curtain [3]. This has the unwanted side-effect that the higher the air curtain velocity, the larger the amount of air that mixes with the air curtain air.

From the schematic drawing in figure 10 it is possible to understand why an air curtain which circulates smoking air (top drawing) has a better performance than an air curtain which circulates non-smoking air (middle drawing). The total amount of air which flows from the bottom of the air curtain to the non-smoking zone due to the air curtain is larger with a recirculating air curtain which draws its air from the non-smoking zone. This airflow from the bottom of the air curtain to the non-smoking zone does have a fair amount of unwanted smoke due to the entrainment (mixing) of air on either side of the air curtain.

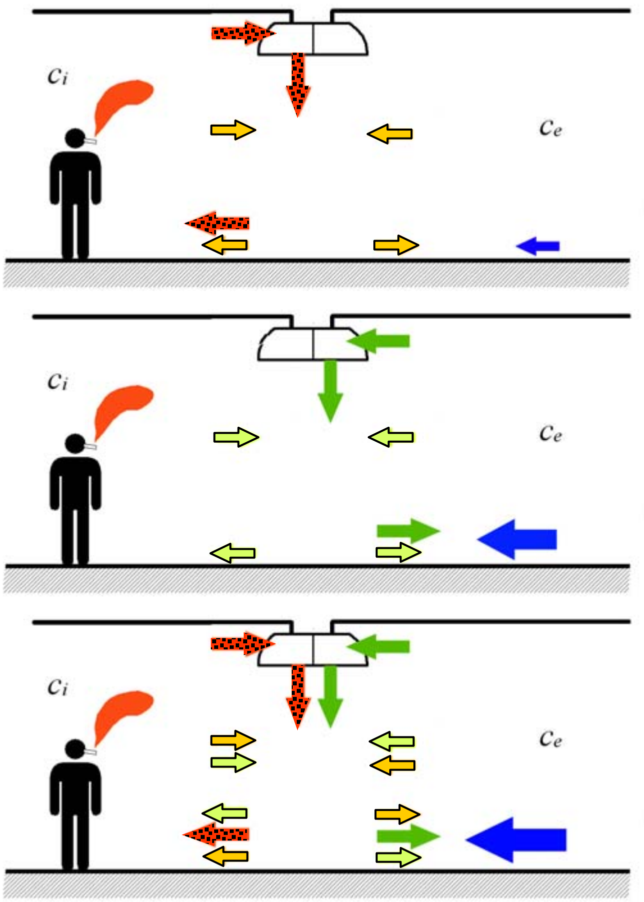


Figure 2. Schematic drawing of the working of the different air curtain configurations. From top to bottom: the smoking side air curtain, the non-smoking side air curtain and the double air curtain. The framed arrows represent the induced air. The dark arrows represent the necessary amount of exhaust air which is necessary to countermand the induction effect.

Having a larger or equal amount of ventilation air flowing in the opposite direction should be present to prevent the smoke-mixed air from reaching the non-smoking zone. A lower exhaust ventilation amount can therefore be enough to prevent the smoke-mixed air from a smoking-side air curtain to reach the non-smoking zone but not enough to prevent the smoke-mixed air from a non-smoking side air curtain to reach the non-smoking zone. Similarly, a higher air curtain velocity requires a larger exhaust ventilation flow to counterbalance the effect of a higher air curtain velocity.

As a criterion for obtaining a low smoke concentration in the non-smoking zone, the parameter G can be defined. This parameter depends on the kind of air curtain, the air curtain velocity and the amount of air curtain ventilation: $G = \frac{FQ_0}{Q_v}$. Q_0 is the air curtain flow. F Q_0 is the amount of air flow from the bottom of the air curtain to the non-smoking zone, Q_v is the amount of exhaust ventilation. The criterion is then $G < 1$ which indicates that the amount of air flow from the bottom of the air curtain to the non smoking zone is less than the amount of exhaust ventilation. F is the entrainment factor of the air curtain. This factor can be approximated by 0.9 for a smoking side air curtain, by 1.8 for the non-smoking side air curtain and by 2.7/2 for the double air curtain.

METHODS

Simulating cigarette smoke and a smoker

The smoker is simulated by block of 0.2 by 0.2 by 1.7 m^3 with a heat production of 80 W. The smoker is situated at a distance of 1.5 m from the west façade, see figure 3. The smoker exhales 1 m^3/h at a height of 1 m over a surface of 4.0 cm2 in horizontal direction facing the air curtain. The exhaled air has a temperature of 35 °C and a velocity of 0.7 m/s. The exhaled air has a concentration of 1.152 mg nicotine per kg air [2]. Nicotine is assumed to have the same density as the air (1.19 kg/m^3).

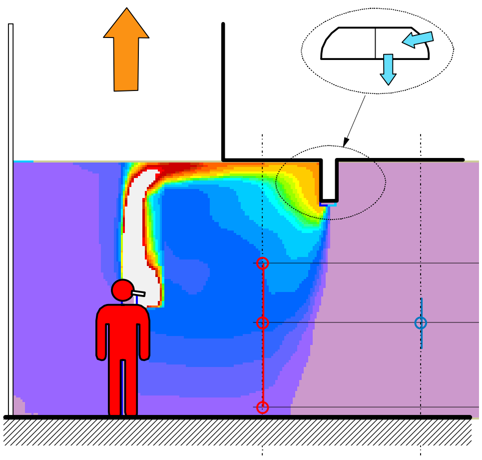


Figure 3. Schematic drawing of the smoker as a source in the cfd-simulations

Modelling the hall

Only a vertical cross section of the hall (from glass plane to glass plane, see figure 4) is modelled. In the middle of the model a smoker is situated. Perpendicular to the cross section two adiabatic boundaries are defined. The outside air is assumed to have a temperature of 20 °C. The simulated model has a length of 13.2 m a width of 10 m and a height of 3.5 m, thus a volume of 462 m^3.

The exhaust is modelled as an exhaust area of 0.3 m. over the entire width of the glass, see the upward arrow in figure 4. The inflow is modelled as an opening of 4.2 by 10 m^2 (again over the entire width of the glass), see the downward arrow in figure 4. For a maximum number of people of 40, the exhaust is simulated with a capacity of 1500, 3000 en 4500 m^3/h. This correspond to approximately to one to three times the Dutch Building Regulations. However, the amount of 4500 m^3/h is height and should preferably not be applied due to corresponding large energy costs and a risk at high air velocities (draught).

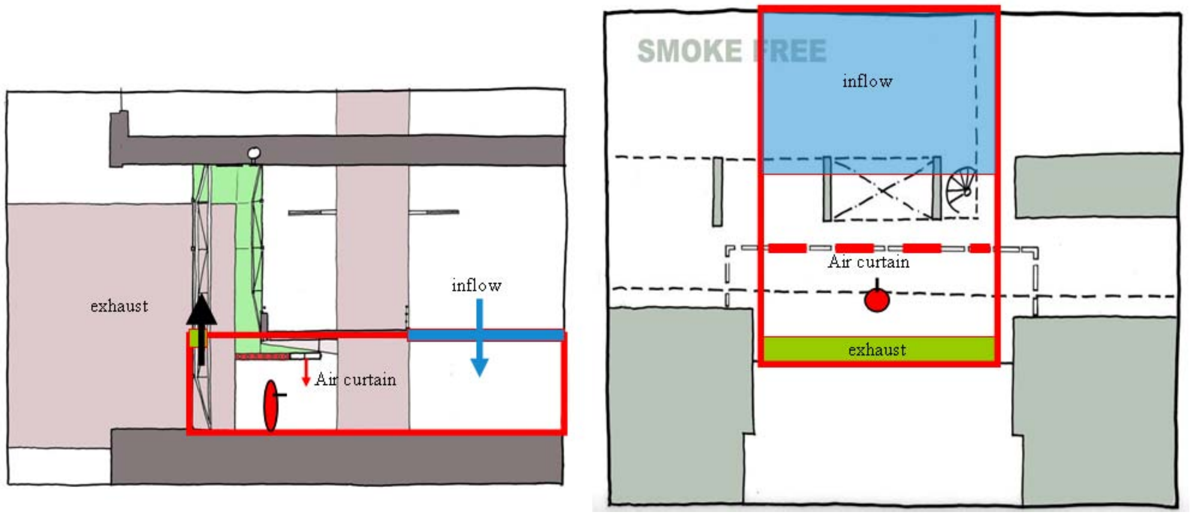


Figure 4. Cross section and floor plan of the hall of the Architecture faculty of the Delft University of Technology.

Modelling the air curtain

Cfd-simulations have been performed for 21 combinations of air curtain configurations (7) and exhaust volume flows (3) in order to calculate the lowest smoke concentration in both the non-smoking zone, and the smoking zone. The simulated air curtain configurations are given in table 1.

Table 1. The simulated variants and their names, totalling 7 air curtain combinations.

Name	**Air curtain**	**Air curtain velocity (m/s)**	**Air curtain volume (m^3/h)**
Er_0.75	Non-smoking side	0.75	2700
D_0.75	Double	0.75	2700
Er_0.5	Non-smoking side	0.5	1800
D_0.5	Double	0.5	1800
El_0.75	Smoking side	0.75	2700
El_0.5	Smoking side	0.5	1800
no	No air curtain	0.0	0

The air curtains are simulated as simple air curtains without any heating or cooling capacity. The simulated downward velocities from the air curtain(s) are: 0.0, 0.5 en 0.75 m/s with corresponding air curtain volume flows of 0 m^3/h, 1800 m^3/h and 2700 m^3/h. The total installed air curtain configuration consists of two air curtains. One inside ring with an inflow from the smoking area, and one outside ring with an inflow from the non-smoking area, see figure 2. The air curtain size is 0.2 by 0.6 m^2 over the entire width of the glass plane at a distance of 4.2 meters from the glass plane. Both the outside and the inside ring are simulated as recirculation elements in the cfd-simulation.

Points

To quantify the results, the smoke concentrations have been calculated at three positions in the smoking area and 1 position in the non-smoking area, see figure 5. The points are taken in the smoking zone at a height of 0.1 m., 1.1 m. (sitting position) and 1.8 meter (standing position). The point in the non-smoking room [ce] is taken at a height of 1.1. m.

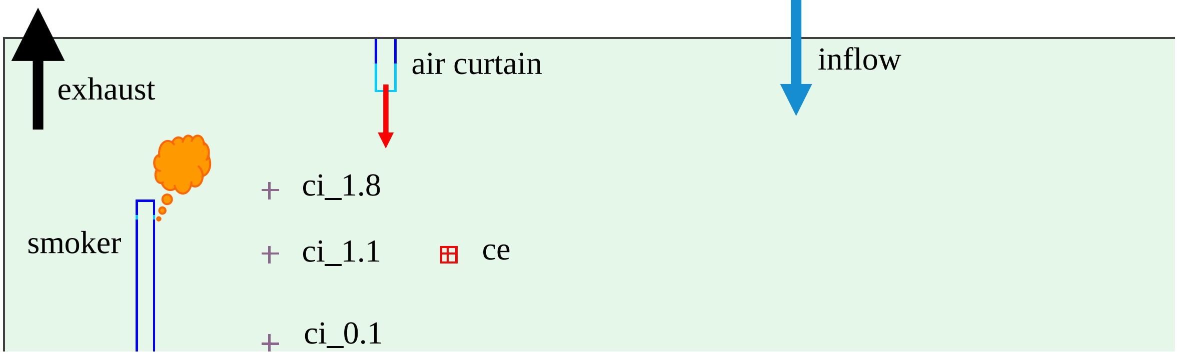


Figure 5. Position of all measured points. At 3 meters from the left glass wall in the smoking zone the point ci_0.1, ci_1.1, ci_1.8 at a height of 0.1, 1.1 en 1.8 meters; at 5 meters form the left glass wall in the non-smoking zone, the point ce at a height of 1.1 meters.

CFD-simulations

The simulations were performed with the commercial computerprogramm Flovent [2], version 5.1. Flovent uses a rectangular grid. A single simulation is performed with around 140.000 grid cells, the k-ε model, and a calculation time of around 2 hours until convergence on a Pentium computer.

RESULTS

In figure 6 the cfd-simulations are shown. In figure 6 both the smoke concentration and the route of certain selected air particles from the inflow of clean air (see the square in figure 7) to the exhaust point is shown for various configurations. The legend of figure 6 ranges from light (purple, 0.0 kg smoke/kg air) to dark (red, 8.4 10^{-6} kg smoke/kg air). A smoke concentration of 8.4 10^{-6} kg/kg air corresponds to a percentage of 8.4 10^{-6} kg / 1.512 mg = 0.5 % of the smoke concentration which is exhaled by the smoker. Areas with a smoke concentration higher than 0.5 % are white.

The lighter (purple) area is larger for a larger exhaust flow; a larger exhaust flow therefore leads to a lower smoke concentration over a larger area. When the flow pattern of the clean air is compared with the smoke concentrations in the non-smoking room, it can be seen that the lowest concentrations are obtained when the clean air passes the air curtain with the smallest distance from the floor. This is exceptionally clear for a smoking side air curtain with a velocity of 0.5 m/s and an exhaust flow of 4500 m^3/h and for the no air curtain configuration with an exhaust flow of 4500 m^3/h.

In figure 7 the smoke concentration in a number of points is shown as a function of the air curtain configuration. As expected from figure 6, the smoke concentrations decrease with increasing exhaust volume flow. Also concluded from figure 6 is the fact that the smoking side air curtain (El) is to be preferred over a non-smoking side air curtain or a double air curtain. A non-smoking side air curtain is simulated to have a higher smoke concentration than a double air curtain for most velocities and exhaust flows.

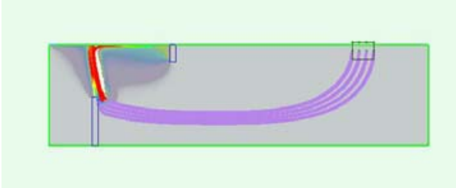
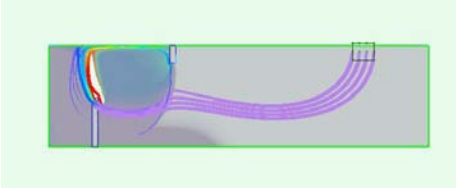
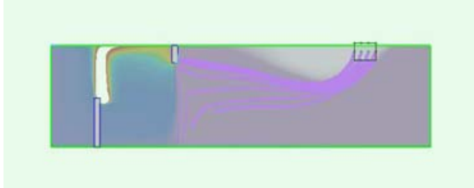
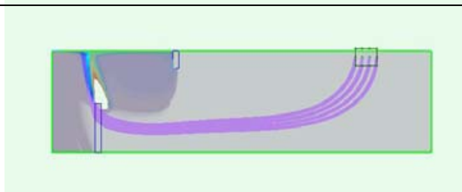
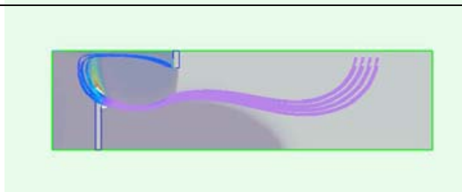
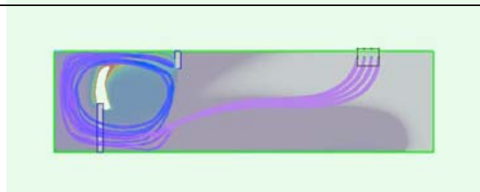
	Exhaust flow: 4500 m^3/h	Exhaust flow: 1500 m^3/h
no		
Er_0.5		
El_0.5		
El_0.75		

Figure 6. Simulated smoke concentrations and simulated airflow patterns for certain inflow air particles for a number of air curtain configurations and two exhaust flows(1500 m^3/h and 4500 m^3/h).

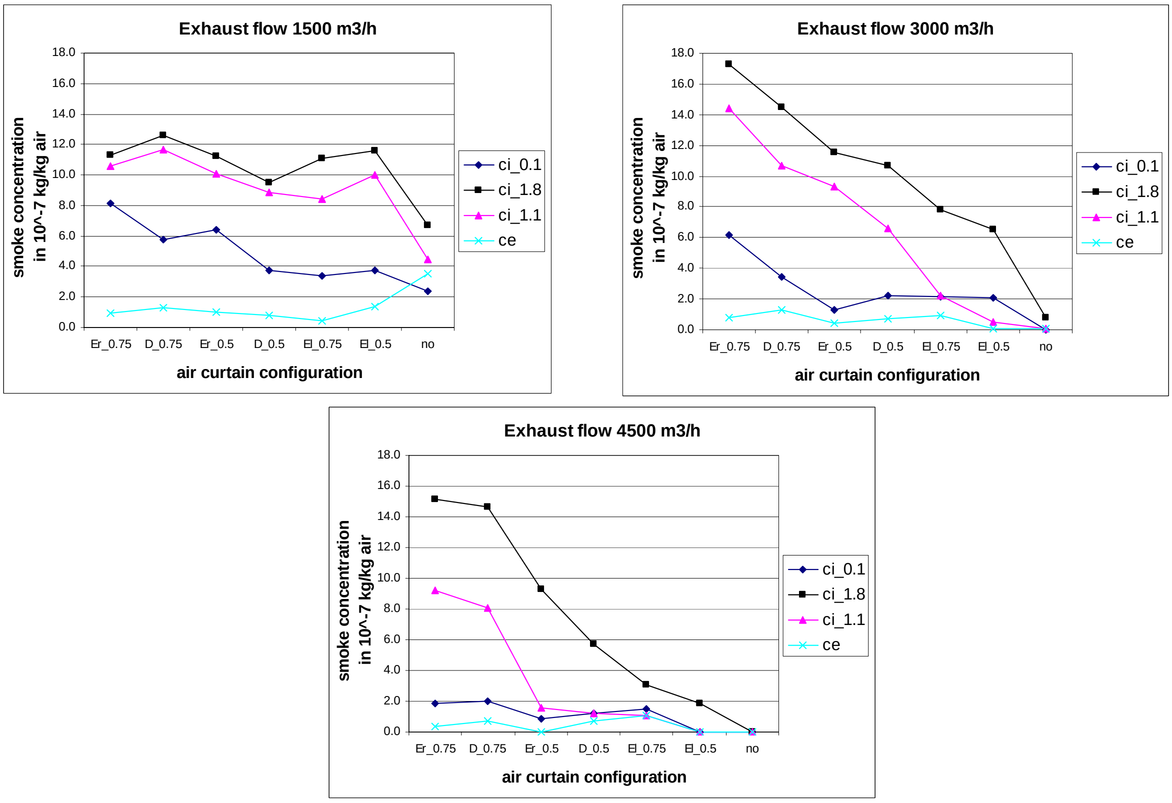


Figure 7. Simulated smoke concentrations ce, ci_0.1, ci_1.1 en ci_1.8 as a function of the air curtain configuration for three exhaust flows (4500, 3000 and 1500 m^3/h).

Contrary to expectations by a general public, the lowest possible air curtain velocity should be applied in order to obtain the lowest smoke concentration in the non-smoking and the smoking room. For high exhaust flows, this velocity is close to 0.0 m/s, for lower exhaust flows this value increases due to the adverse effects of diffusion of smoke to the non-smoking zone.

DISCUSSION

The most important value which determines the smoke nuisance is the smoke concentration in the non-smoking zone: ce. In figure 8, this value is presented as a function of the above defined G (= FQ_0/Q_v). Figure 8 shows that the value of G indeed influences the smoke concentration in the non-smoking zone (ce). However, for one point the cfd-simulated ce concentration is far too high although G is smaller than 1. This is the situation where there is no air curtain (FQ_0 = 0 and thus G = 0) and where the exhaust flow is not high enough to counterbalance the effect of diffusion (1500 m^3/h). For G-values between 0.8 and 1.0, the cfd-simulations show an increase in smoke concentration in the non-smoking zone. In practice a criterion of G < 0.8 seems more appropriate from these cfd calculations.

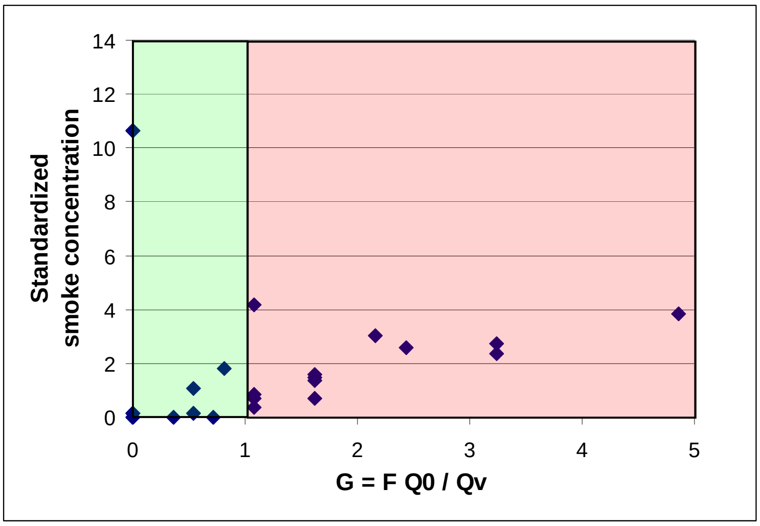


Figure 8. Standardized smoke concentrations in the non-smoking zone as a function of G. The smoke concentration in the non-smoking zone (ce)is standardized with respect to the smoke concentration in the exhaust air at an exhaust flow of 4500 m3/h.

That the G value is an appropriate criterion can also be seen when two simulations with the same G-value are compared. Compare for example the configuration of a double air curtain with an air curtain velocity of 0.5 m/s and an exhaust flow of 3000 m3/h and the double air curtain configuration with an air curtain velocity of 0.75 m/s and an exhaust flow of 4500 m3/h, see figure 8. Both simulations look remarkably alike.

	Exhaust flow: 3000 m^3/h Air curtain velocity: 0.5 m/s	Exhaust flow: 4500 m^3/h Air curtain velocity: 0.75 m/s
Double air curtain		

Figure 9. Comparing two simulations with the same G-value.

CONCLUSIONS

From the cfd-calculations the following conclusions can be deduced:

- A larger ventilation flow is best.
- An air curtain with a low outlet velocity and an air intake from the smoke zone (as opposed to an air intake from the non-smoking zone) has the lowest smoke concentration in the non-smoking zone.
- For the maximum of 40 smokers and a ventilation flow compatible with the Dutch building law (1500 m^3/h for this smoke area) an air curtain velocity of 0.75 m/s is the best solution for the smoke zone in the hall of the faculty of Architecture in Delft, according to the CFD-simulations.
- With higher air curtain velocities, the air curtain will become a smoke curtain if the exhaust flow is not large enough.

REFERENCES

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