REMOVING THE DISRUPTING WIND EFFECT IN SINGLE-VENTED ENCLOSURE EXPOSED TO EXTERNAL WIND

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ABSTRACT

We are addressing hydrogen release into a single-vented facility with wind blowing onto the opposite side of the vent wall. Earlier work based on tests performed by HSL with wind (within the HyIndoor project) and comparative CFD simulations with and without wind ([1],within the H2FC project), has shown that the hydrogen concentrations inside the enclosure are increased compared to the case with no wind. This was attributed to the fact that wind is disrupting the passive ventilation. The present work is based on the GAMELAN tests (within the HyIndoor project) performed with one vent and no wind. For this enclosure simulations were performed with and without wind and reproduced the disrupting wind effect. In order to remove this effect and enhance the ventilation additional simulations were performed by considering different geometrical modifications near the vent. A simple geometrical layout around the vent is here proposed that leads to elimination of the disrupting wind effect. The analysis has been performed using the ADREA-HF code, earlier validated both for the HSL and the GAMELAN tests. The current work was performed partly within HyIndoor project.

1.0 INTRODUCTION

Hydrogen is an attractive alternative fuel due to its high energy content in conjunction with its clean emissions. However, it is flammable with a wide range of flammability limits (4-75% v/v), and therefore, its use brings up safety issues. Accidental hydrogen release could lead to flammable cloud. In confined spaces efficient ventilation is necessary, in order to reduce the concentration levels inside the enclosure, and to prevent a potential fire or explosion. The buoyant behavior of hydrogen assists the passive ventilation through openings located on the top of the enclosure (chimneys) or openings in the upper side of the walls.

In general, wind can enhance or oppose the buoyancy driven ventilation dependent on the vent configuration and the wind direction relative to the vent(s). Several studies, mainly coming from the field of research on efficient ventilation in buildings, have investigated the effect of wind on natural ventilation in an enclosure with vent(s). For instance, in [2] the effect of opposing wind on natural ventilation in an enclosure with two vents (one lower and one upper in opposite sides) is presented. They concluded that buoyancy driven flows opposed by wind are characterized by the relative strengths of the wind-induced and buoyancy-induced velocities within the enclosure. At weak winds buoyancy dominates and stable two-layer stratification is established, while at high wind speeds the wind-induced flow dominates and mixing ventilation occurs without forming any stratification layer. In [3] and [4] the single-sided wind driven natural ventilation in buildings is investigated. In both studies among other remarks it is also concluded that the incident angle (wind direction) affect the ventilation rate through the vent, and they develop empirical models to predict the single-sided wind driven ventilation rate. In [3] it was reported that the absolute error of the calculated ventilation rate as estimated from the results of all measurements had an average deviation 23%, while in [4] the difference between the empirical model predictions and the experimental data were less than 25%.

In [5] the natural and wind driven mixing and dispersion of hydrogen in a partially enclosed compartment with two vents in opposite sides was investigated using both analytical models and CFD simulations. The study indicates that an effective strategy for reducing the flammable volume in the compartment is blowing outdoor air into the lower vent.

Few studies are documented that examine the case with single-sided single-vented and wind blowing onto the opposite side of the enclosure. A series of experiments and simple model calculations have been performed by HSL [6] within the Hyindoor project [7], in order to investigate the accumulation/dispersion of gaseous hydrogen released into an enclosure fitted with passive vents. The release rate and the passive vent configurations were varied: single vent, multiple vents on walls and on ceiling. The wind direction relative to the vent(s) was also varied. The case with one vent and wind blowing onto the opposite side of the vent was included in the series of experiments. In general, they concluded that multiple vent configurations provide more efficient ventilation rates than single vent configurations. As far as the single vent configurations they conclude that the wall vent provide more efficient ventilation than the chimney vent of equal area.

In the framework of the H2FC project [8] Giannissi et al. [1] simulated the test 25 of the HSL experiments. This test involves sonic hydrogen release in a single-sided single-vented enclosure with wind blowing onto the opposite side of the vent wall. Although the main objective of the study was to perform a CFD benchmark, an interesting remark regarding the effect of wind on the ventilation was made. Comparison of predictions with wind and without wind showed that wind blowing onto the opposite side of the vent side in single-sided single-vented facility reduces the ventilation rate. This negative effect is attributed to the turbulent eddies that are formed in the vent region and inhibit the buoyancy driven ventilation. As a result, the predicted concentration levels inside the enclosure in the case with no wind were lower than the case with external wind.

This wind disrupting effect is studied in the present work. The first phase of this study was to reproduce the wind “disrupting” effect in another facility and under different release conditions. The second and basic phase of this study was to test simple geometrical configurations, in order to find out a configuration that could eliminate the wind disrupting effect. This analysis was based on the GAMELAN experiments [9], which have been performed within the Hyindoor project.

For the analysis the GAMELAN test with one vent (930x180mm) and release rate 60NL/min was simulated. Although the experiment was performed indoors and it was not exposed to wind, simulations with hypothetical external wind have been carried out to conduct the present study. There are no experimental results available for comparison, however, it can be considered safe to extract conclusions only by the predictions, because previous simulations of the GAMELAN test showed good agreement with the measurements [10].

During the first phase simulations with weak and strong wind with direction onto the opposite side of the vent wall, similar to test 25 of the HSL experiments, were performed. The wind disrupting effect was reproduced regardless the wind strength. In the second phase additional simulations were performed by considering different geometrical modifications near the vent, in order to remove the wind disrupting effect and to enhance the ventilation. A simple geometrical layout with one horizontal plate placed in the middle of the vent is proposed for elimination of the wind disrupting effect.

All simulations have been performed using the ADREA-HF CFD code, earlier validated both for the HSL and the GAMELAN tests [1,10]. The predictions exhibited good agreement with the measurements in both experimental series.

2.0 FACILITY, RELEASE AND WIND CONDITIONS

The facility used for the analysis in the present work is based on the GAMELAN facility [9]. It is a parallelepiped of 1 m^3 volume with a square base of 0.93 m width and 1.26 m height. There is one vent (0.162 m^2) in the middle of the wall and at a distance 20 mm from the ceiling. Gaseous helium (as hydrogen surrogate) is released upwards through a nozzle of 20 mm diameter. The injection point is located in the middle of the floor and 21 cm from it (see Figure 1). The release rate is 60NL/min. The temperature of both the released helium and of the ambient air is approximately 26^{o}C.

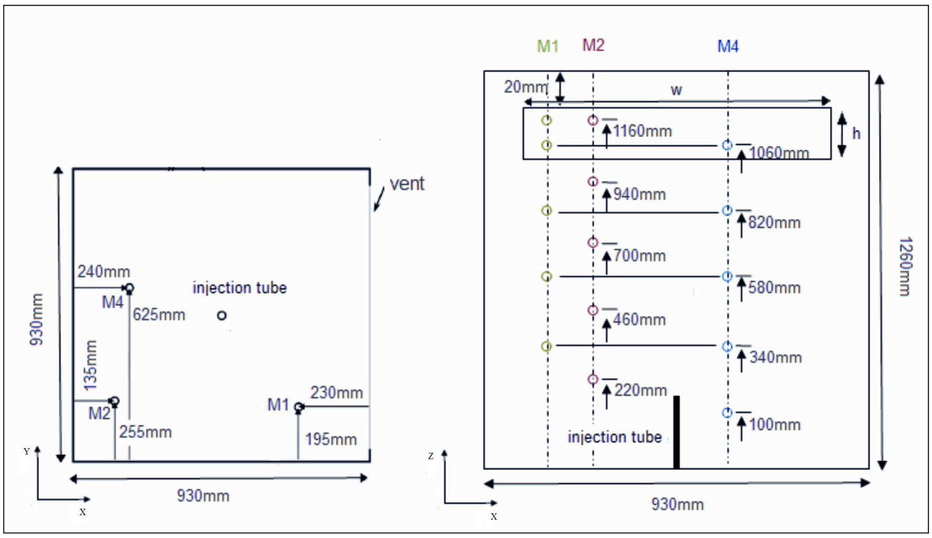


Figure 1. The top (left) and the side view (right) of the facility. The sensors' position is also indicated.

In the simulations the wind that was tested was blowing towards the opposite side of the vent wall (see Figure 2). Two different wind speeds were tested, in order to investigate whether the wind disrupting effect occurs regardless the wind strength. A weak wind speed of 1.8 m/s and a stronger wind speed of 3.6 m/s at 3 m height were tested.

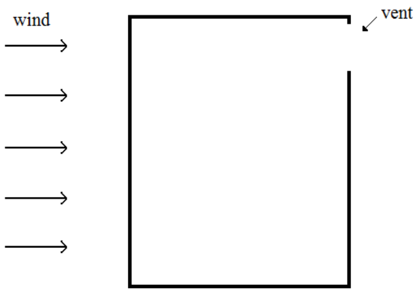


Figure 2. Schematic representation of the wind blowing towards the facility.

To compare the predicted helium concentrations inside the enclosure the sensors that were employed in the GAMELAN experiment were also used in this study. In the experiment the sensors were distributed along three vertical lines (M1, M2, M4) as shown on Figure 1 (top view). The sensors were distributed on different heights, as Figure 1 indicates (side view).

3.0 INVESTIGATED GEOMETRICAL CONFIGURATIONS AROUND THE VENT

In general, in buoyancy driven passive ventilation with one vent the gas flows through the upper part of the vent and fresh air flows in through the lower part of the vent due to pressure difference. This is called bidirectional flow. The height at which internal pressure is equal to external pressure and no inflow or outflow occurs is designated as the neutral plane. In the presence of wind, wind can enhance or oppose the buoyancy driven ventilation dependent on the wind direction in respect with the vent(s), the vent configuration and the wind strength.

In single-sided single-vented configuration the wind blowing upwind the vent wall hinders the buoyancy driven ventilation [1]. This wind disrupting effect can be attributed to the turbulent eddies that are formed in the vent region and block the bidirectional flow through the vent. Less helium flows out and less air flows in through the vent leading to less efficient ventilation. Consequently, the helium accumulates inside the enclosure and forms a flammable mass of high risk.

In order to reduce or eliminate this wind disrupting effect several simple geometrical configurations near the vent were examined here. The main idea for the configurations' design was that they should destroy the eddies and "break" the recirculation area that is formed downstream the facility, in order to assist the bidirectional flow. Five different geometrical layouts have been tested:

A) Up plate: A horizontal plate with dimensions 0.93 m (box's width) x 0.23 m is placed on the upper side of the vent.

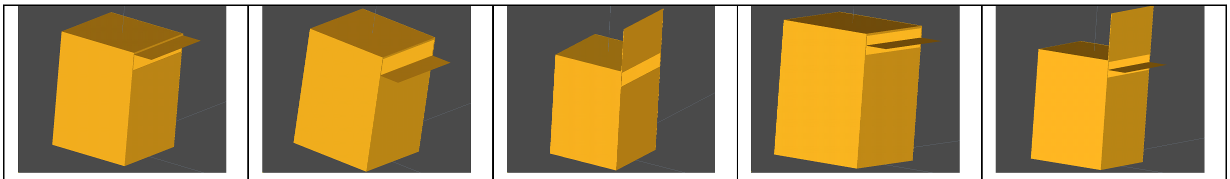
B) Down plate: A horizontal plate with the same dimension as above is placed on the lower side of the vent.

C) Vertical plate: A vertical plate is placed on the box's roof at the edge of the vent wall. The dimensions of the plate are 0.93 m length and 0.54 m height.

D) Middle plate: A horizontal plate with dimensions 0.93 m x 0.23 m is placed in the middle of the vent.

E) Complex: This configuration is a combination of (C) and (D) layout: a vertical plate on the box's roof at the edge of the vent wall and a horizontal plate in the middle of the vent.

Figure 3 shows the geometrical configurations accompanied by an abbreviation for their name.



A. up plate **B. down plate** **C. vertical plate** **D. middle plate** **E. complex**

Figure 3. The various geometrical configurations that were tested.

The results with wind for each configuration are compared with the results predicted using the facility without any configuration around the vent exposed to external wind, in order to find the configuration with which wind does not disrupt the exchange flow rate through the vent. For the best configuration the simulation was repeated without wind, in order to examine the effect of the geometrical modification on the passive ventilation in the case with no wind too.

4.0 SIMULATION SET-UP

For the simulations the ADREA-HF CFD code is used, which has been validated against both the HSL experiments and the GAMELAN experiments [1,10]. The time dependent conservation equations for the mixture (mass, momentum) are solved along with the conservation equation for the helium mass fraction [11]. The conditions are isothermal. For the turbulence the k-ε turbulence model with extra buoyancy terms [12] is used. In all simulations symmetry along the y- axis was assumed.

In the cases with no wind the computational domain was extended in the x-direction downwind the facility, in the y-direction and in the z-direction. The grid of all cases consists of 396000 cells. 4 cells were placed along the source diameter. Grid refinement is imposed near the helium inlet, the ceiling and the vent region.

In the cases with wind four steps were followed:

1. 1D steady state problem was solved, in order to obtain the vertical wind profile. For this problem at the top boundary a fixed value (Dirichlet condition) was imposed, such as that the desired velocity at 3 m height is predicted.

2. An extended 3D steady state problem was solved using as initial and inflow boundary conditions the 1D wind profile, in order to predict the flow field around and inside the facility. The domain in the 3D steady state problem was extended, so as the imposed inflow boundary and the outlets to be unaffected by the presence of the facility. It was extended approximately 10 facility's height in the lateral directions and about 7 facility's height in the vertical direction.

3. In order to obtain the velocity field with the resolution of the dispersion problem, a small 3D wind problem with the same grid and domain size as in the dispersion problem (step 4) was solved. This grid is finer than the grid designed for the problem in step 2, especially inside the facility. Furthermore, the domain was reduced in extends where no recirculation zones were predicted in the simulation of step 2, in order to decrease the computational time. In details, the domain was extended in the x-direction upwind the facility and in the y-direction almost 3.5 m, while in the x-direction and downwind the facility 5.5 m. Along the z-direction the domain was extended about 2.75 m. A more extended domain (11.5 m) downwind the facility in the x-direction was also examined showing no effect on the results. In this small 3D wind problem, the solution of step 2 was used as initial and inflow boundary conditions.

4. The 3D transient dispersion problem was solved using the domain and the grid of the previous step. The small 3-D wind problem was set as initial and inflow boundary condition in the dispersion problem. The grid consists of 675000 cells. As in the case with no wind 4 cells were placed along the source diameter. Refinement is imposed near the helium inlet, the ceiling and the vent region. In general, inside the enclosure the grid that was used was the same in all cases (with and without wind). The grid on the symmetry plane in the region near the injection point and the vent is illustrated in Figure 4.

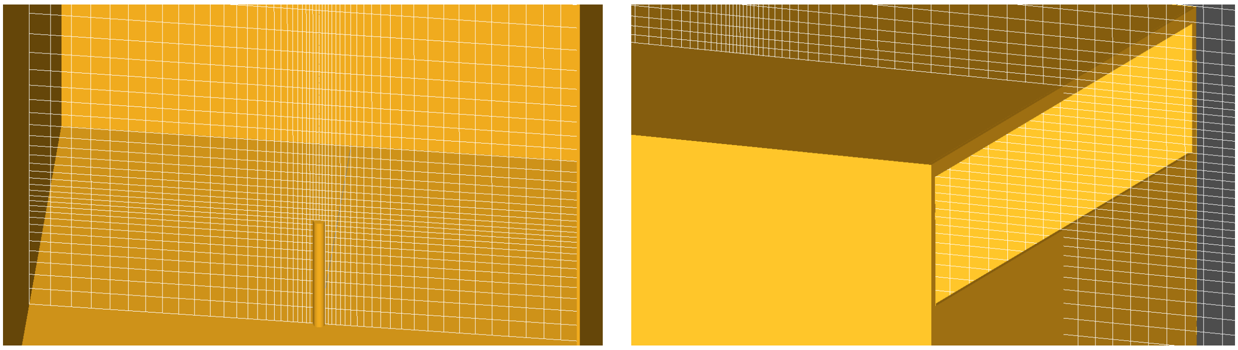


Figure 4. The grid on the symmetry plane (y=0) in the region around the injection point (left) and the vent (right) for all cases.

As far as the numerical procedure is concerned the 1st order fully implicit scheme was used for the time integration, the MUSCL scheme (2nd order) and the central differences scheme was applied for the convective terms and for the diffusive terms respectively. For the control of the time step increase a CFL restriction equal to 10 was imposed.

5.0 RESULTS AND DISCUSSION

In Figure 5 the helium concentration (%v/v) inside the enclosure versus time and at several positions for the case with no wind, with weak wind and with strong wind is displayed. The facility was the experimental one without any additional geometrical configuration around the vent. In the presence of wind the helium concentration is increased inside the enclosure at all sensors. The stronger the wind the higher the concentrations are.

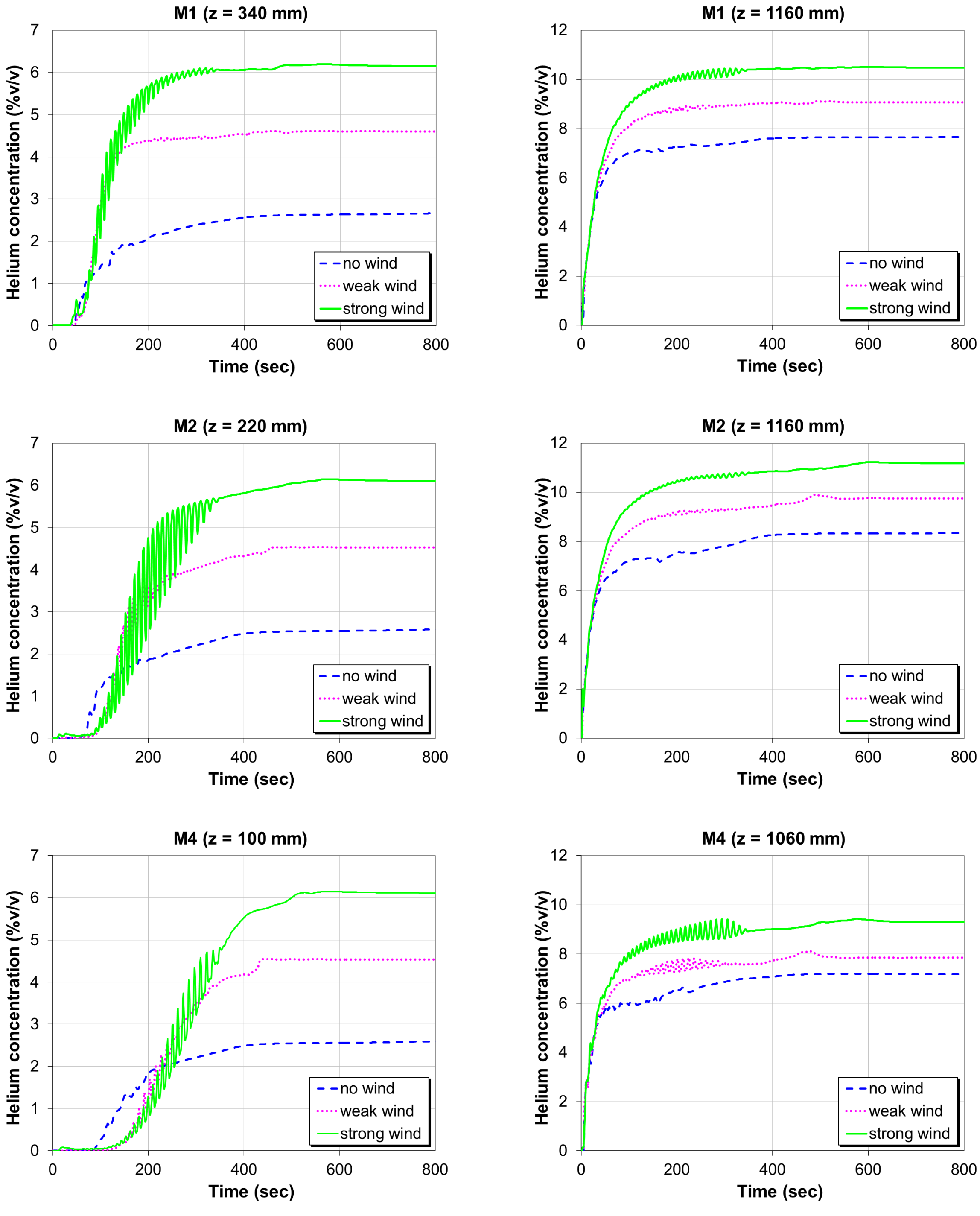


Figure 5. Time histories of helium concentration (%v/v) for the case with and without wind at several sensors. The facility is without any additional configuration around the vent.

Figure 6 shows the velocity vectors at steady state in the vent region as they were predicted by the 3-D wind problem for the case with weak wind. A recirculation area is formed near the vent, and as a result the vent seems to be blocked by the upcoming air. This remark is supported also by Figure 7 which shows the velocity vectors at steady state in the vent region colored by the helium concentration for the dispersion case without wind and for the dispersion case with weak wind. The upcoming air blocks the vent and disrupts the ventilation.

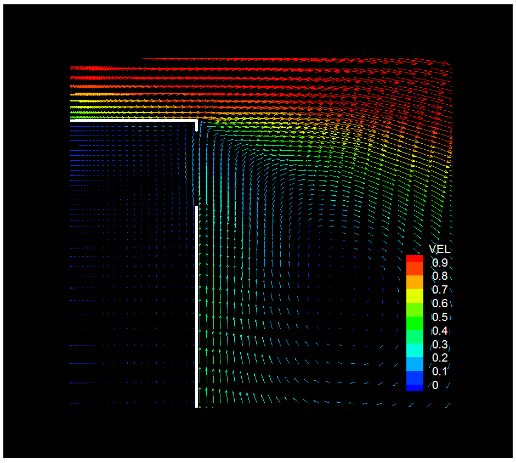


Figure 6. The predicted by the 3-D wind problem velocity vectors around the vent for the case with weak wind at steady state.

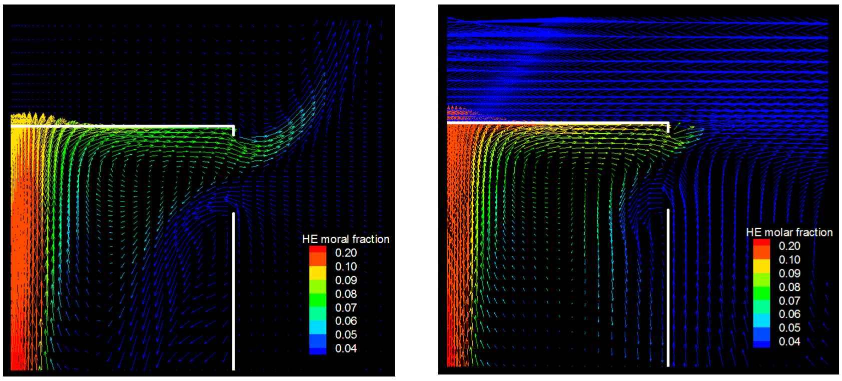


Figure 7. The velocity vectors coloured by helium concentration showing the flow in the vent region without wind (left) and with the weak wind (right) at steady state.

Figure 8 shows the outflow and inflow through the vent as predicted with and without wind. In the upper part of the vent the helium flows out the enclosure, whilst in the lower part of the vent fresh air flows in the enclosure. It is shown that helium outflow at steady state in the case with weak wind is about 15% less than the case without wind. Similarly, air inflow is almost 17% less than in the case with weak wind. Similar differences are predicted between the results with weak wind and the results with strong wind.

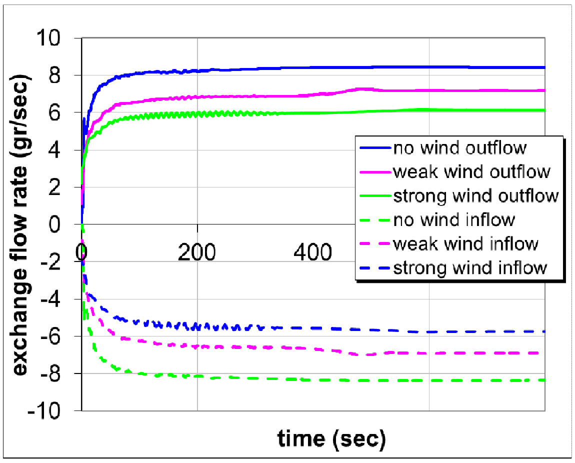


Figure 8. Comparison of the outflow and the inflow through the vent between the predictions with wind and with no wind for the case with no configuration.

At this point we should mention that for the rest of the analysis only the weak wind was applied. However, similar behavior is expected for the stronger wind, too.

In Figure 9 the total helium mass (gr) and the helium mass (gr) corresponded to 4-75% v/v concentration (the flammability range of hydrogen) inside the enclosure for each configuration with wind and with no configuration (the initial experimental facility) with and without wind at steady state are presented. It is shown that without any configuration around the vent in the presence of wind both total mass and flammable mass are increased significantly. Especially, the flammable mass inside the enclosure is more than doubled when wind is blowing.

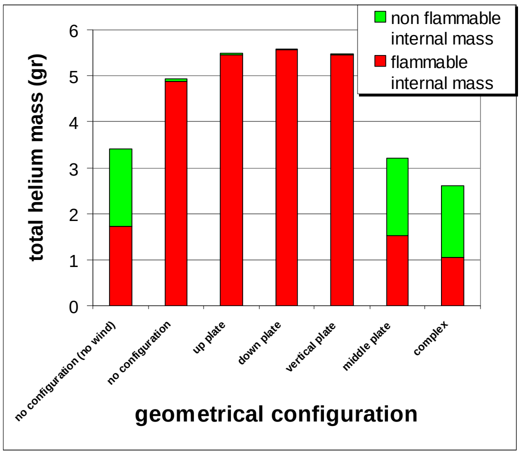


Figure 9. Total mass and flammable mass inside the enclosure for all the tested configurations with wind and for the case without any configuration with and without wind.

Among the five examined configurations the middle plate and the complex layout are the ones that provide efficient ventilation and eliminate the wind disrupting effect. The up and down plate seem not to have the desired effect, i.e. to "intercept" the turbulent eddies in the area close to the vent and to prevent the upcoming air to block the vent, respectively. This is also shown in Figure 10, which illustrates the velocity vectors around the vent colored by the velocity magnitude for each configuration at steady state. Furthermore, the configuration with the vertical plate does not solve the problem. Although the eddies have been moved compared to the case with no layout they are still present near the vent region.

The two configurations with the middle plate proved to provide the most efficient ventilation compared to the other examined layouts, because it assists and enhances the bidirectional flow. The upcoming air from the recirculation area meets the horizontal plate in the neutral plane, and is forced to enter the facility, whilst helium flows out along the upper side of the plate. The vent is not blocked any longer. Finally, the presence of the vertical plate (complex layout) improves little the ventilation compared to the case only with the middle plate.

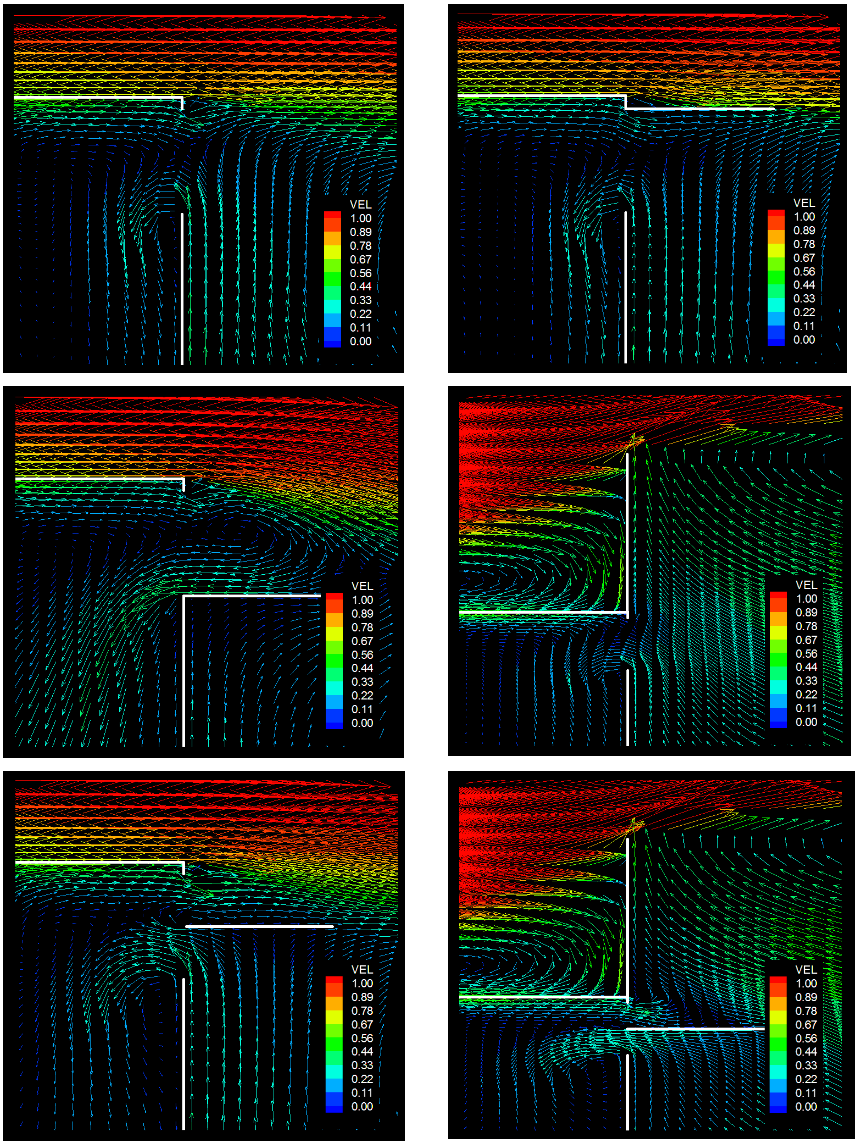


Figure 10. The velocity vectors around the vent coloured by the velocity magnitude in the case with no layout (top, left), the up plate (top, right), the down plate (middle, left), the vertical plate (middle, right), the middle plate (bottom, left) and the complex layout (bottom, right).

Although the minimum total and flammable mass inside the enclosure is produced using the complex layout, however, the simplest layout with the middle plate is considered best solution, because it is more practical than the complex layout and produce similar results with the complex layout.

Figure 11 displays the helium concentration versus time for the case with the best configuration (middle plate) and the case with no configuration both with wind and without wind at several positions. It is shown that the configuration does not affect significantly the concentration levels in the case without wind. However, large discrepancies are observed for the case with wind. With no configuration the helium concentration at steady state is doubled the concentration levels with the best configuration in the lower part of the enclosure and approximately 1.5 times in the upper part of the enclosure.

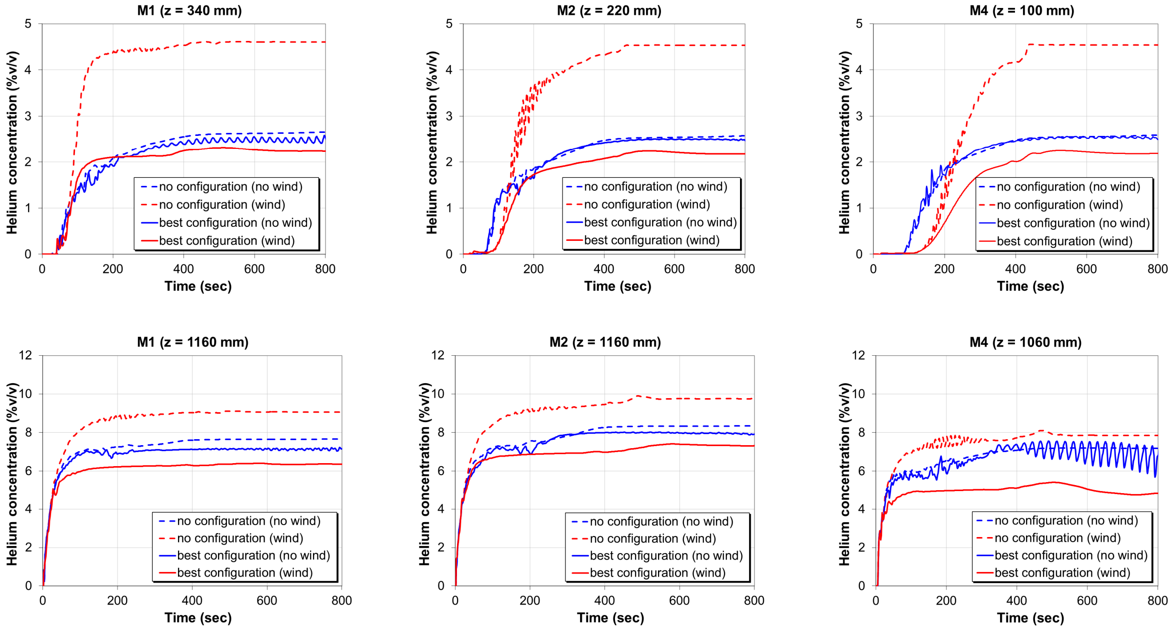


Figure 11. Time histories of helium concentration (%v/v) for the case with no configuration and the best configuration (middle plate) with and without wind.

Finally, Figure 11 shows also that the case with the best configuration and wind provides more efficient ventilation even than the case with no configuration and no wind. Consequently, if the facility is equipped with the proposed geometrical modification wind blowing windward the facility is now desired.

6.0 CONCLUDING REMARKS AND FUTURE RESEARCH

Hydrogen release into a single-vented facility with wind blowing onto the opposite side of the vent wall is investigated. Earlier work based on tests performed by HSL with wind and comparative CFD simulations with and without wind has shown that the hydrogen concentrations inside the enclosure are increased compared to the case with no wind. This was attributed to the fact that wind is disrupting the passive ventilation.

The present simulations are performed in an enclosure with parameters of the GAMELAN facility performed with one vent and no wind. For this enclosure simulations were performed with and without wind. Two different wind strengths were examined and the disrupting wind effect was reproduced by both wind strengths. The stronger the wind the higher the wind disrupting effect is.

In order to remove this effect and enhance the ventilation additional simulations were performed by considering different geometrical modifications near the vent. The lower wind speed was used for the analysis. The simulations showed that a configuration with a horizontal plate in the middle of the vent is the simplest geometrical modification that reduces the total and flammable mass inside the enclosure compared to the case with no configuration. This is attributed to the fact that the horizontal wall placed in the middle of the vent assists the bidirectional flow. The formed turbulent eddies downstream the enclosure are broken. This configuration does not affect the results without wind which are very similar with the results with no configuration.

A more complex layout with a horizontal plate in the middle of the vent and a vertical plate at the edge of the vent wall produces more efficient ventilation. However, this configuration is complex to construct. Therefore, the simpler modification with horizontal plate alone is considered more appropriate, since it achieves ventilation efficiency similar to the complex layout.

Even though the simple configuration is easy to be constructed it has a drawback under extreme weather conditions, like rain and snow. The drawback is that the rain or the snow might accumulate on the horizontal plate and hinder the outflow of hydrogen. To prevent that a shed could be placed on the roof or the horizontal plate could be placed with inclination. However, more CFD simulations with these geometrical configurations should be performed, in order to investigate their effect on the ventilation rate.

In the future, a parameterization of the plate’s dimension will be performed. Furthermore, the performance of the best layout can be tested imposing several wind strengths, release flow rates and using different vent sizes.

7.0 ACKNOWLEDGMENTS

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