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Mitigation of buoyant gas releases in single-vented enclosure exposed to wind: Removing the disrupting wind effect

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ABSTRACT

Hydrogen is a promising alternative fuel, however, its flammable nature raises safety concerns. In case of accidental hydrogen release inside an enclosure a common mitigation measure is natural ventilation. The enclosure is likely to be exposed to wind and thus the wind effect on the ventilation should be thoroughly investigated. In the present study, we address the hydrogen release into a single-vented facility with wind blowing onto the opposite side of the vent wall. Wind can either assist or oppose the ventilation dependent on the vent configuration and the wind direction. Previous study has shown that wind blowing onto the opposite side of the vent wall in single-vented enclosure inhibits the exchange flow rate through the vent. Therefore, this study aims in removing this disrupting wind effect by considering different flow deflectors around the vent. A flow deflector is proposed which drastically enhances the ventilation and eliminates the negative effect of wind. For this deflector a parametric analysis of its length is also carried out. The analysis shows that a size equal to the vent height is considered a good compromise between efficient ventilation and practical considerations. For the analysis, CFD simulations were performed using the CFD code ADREA-HF earlier validated against several similar cases.

Introduction

Hydrogen is an attractive alternative fuel due to its high energy content in conjunction with its clean emissions. However, it is flammable with wide flammable ranges (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.

The enclosure is likely to be located outdoors and thus to be exposed to naturally varying wind conditions. Wind can enhance or oppose the buoyancy driven ventilation dependent on the vent configuration and the wind direction relative

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Nomenclature

x_i	Cartesian i coordinate, m
u_i	i component of velocity, m/s
p	pressure, Pa
g_i	gravity acceleration in the i-direction, m/s^2
q_{He}	mass fraction of helium, dimensionless
t	time, s
Sc_t	turbulent Schmidt number, dimensionless
d	molecular diffusivity of helium to air, m^2/s
Greek	
μ	laminar viscosity, kg/m/s
μ_t	turbulent viscosity, kg/m/s
ρ	mixture density, kg/m^3

to the vent(s). Several studies have investigated the effect of wind on natural ventilation in an enclosure with vent(s). For instance, in Ref. [1] 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. In Ref. [2] 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. In Refs. [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) affects the ventilation rate through the vent, and they develop empirical models to predict the single-sided wind driven ventilation rate.

Few studies are documented that examine the case with single-vented facility and wind blowing onto the opposite side of the vent wall. A series of experiments and simple model calculations have been performed by HSL [5] within the Hyindoor project [6], in order to investigate the accumulation/dispersion of gaseous hydrogen released into a real scale room fitted with passive vents. In general, they concluded that multiple vent configurations provide more efficient ventilation rates than single vent configurations. The case with one vent and wind blowing onto the opposite side of the vent (test 25) was included in this series of experiments and it was simulated by Giannissi et al. [7] in the framework of the H2FC project [8]. Comparison of predictions with wind and without wind showed that wind blowing onto the opposite side of the vent wall in 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 wind were higher than the case with no wind.

This disrupting wind effect is studied here. The first phase of this study is to reproduce the disrupting wind effect in another facility and under different release conditions. The second phase is to test simple flow deflectors around the vent, in order to find out a geometrical layout that could eliminate the disrupting wind effect. This analysis is based on the GAMELAN experiments [9], which have been performed by CEA. Although the experiments were not exposed to wind, simulations with hypothetical wind are carried out to the present study. During the first phase simulations with weak and strong wind with direction onto the opposite side of the vent wall are performed. The disrupting wind effect is reproduced regardless the wind strength. In the second phase additional simulations with weak wind are performed by considering different flow deflectors around the vent, in order to remove the disrupting wind effect and enhance ventilation. A simple geometrical layout with one horizontal plate placed in the middle of the vent is proposed for elimination of the disrupting wind effect. For this best layout further sensitivity study is performed regarding the plate's length. Several sizes are tested with both the weak and the strong wind to assess their effect on the ventilation rate.

All simulations are performed using the ADREA-HF CFD code, earlier validated against both the HSL and the GAMELAN tests [7,10]. The predictions exhibited good agreement with the measurements in both experimental series. The statistical performance measures indicated an overall slightly over-prediction of the concentrations at steady state (geometric mean bias, MG = 0.97 and geometric variance, VG = 1.04) in the GAMELAN simulation (for the test investigated also here). In the HSL prediction the relative error of the maximum concentration was ranged between 10 and 20% at most sensors. Therefore, ADREA-HF code can be considered as a reliable tool to perform the present analysis.

Facility, release and wind conditions

The facility used for the analysis in the present work is 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. This facility is selected for the current study instead of larger facility, in order to reduce the computational cost of the simulations. There is one vent (900 × 180 mm) in the middle of the wall and at a distance 20 mm from the ceiling. Gaseous helium (as hydrogen surrogate for safety reason) 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 (Fig. 1). The injection rate is 60 NL/min (helium injection velocity is 3.5 m/s). The temperature of both the released helium and of the ambient air is about 26 °C.

The volumetric Richardson number (Ri_v) is approximately 5. For $Ri_v > 1$ and single vented enclosures the helium distribution inside the enclosure exhibits some common characteristics regardless the vent size [9]. There is an upper homogeneous layer followed by a steep gradient and a lower homogenous layer. Depending on the vent size, these regimes are characterized by different thickness, concentration and gradient. Large vent surface and vertical extension form a weakly apparent top homogeneous layer. Decreasing the vent surface, but keeping the vertical extension large, the top homogeneous layer is more apparent. In the facility of the current work, the size of the vent is such that a more or less