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CFD MODELING OF 3D INDOOR GAS CONTAMINANT PLUMES FOR TESTING SEARCH ALGORITHMS OF MOBILE ROBOT

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ABSTRACT

Accidental chemical gas release in indoor environments such as industrial sites and office buildings could become hazardous. This has highlighted the need to localize the source of contaminant in least time possible using plume-tracing mobile robots. Due to the inconsistency of contaminant fluid flows in experiments, computational fluid dynamics (CFD) techniques are used to predict indoor flows and contaminant plumes for testing three dimensional (3D) plume search algorithms. In this study, 3D airflows and plumes of contaminant gas, H_2S, in a building were predicted by CFD techniques. The predicted velocity fields and concentration fields were used to test the capability of a previously developed two dimensional (2D) search algorithm and then a newly developed 3D search algorithm. The flows and plumes are found to be strongly three dimensional, which is typical for indoor airflows. The 2D search algorithm failed to localize the source while the 3D search algorithm was capable of locating the source in the complex environment setup. This paper presents CFD's capability to create a realistic environment for testing the developed search algorithm for plume tracing robots at low cost.

Keywords: CFD; plume; algorithm; robot

NOMECLATURE

κ	turbulent kinetic energy
ε	turbulent energy dissipation rate

INTRODUCTION

Gas emissions and plumes from early stage fires, toxic gas release and explosives in an indoor environment are of major importance for work health and safety. Such applications represent themselves in industries of minerals processing, chemical/biological and radioactive sites, labs and office buildings. Most time these emissions and plumes are harmful and dangerous for humans and animals to search, trace and localize the contaminant emitter. Plume-tracing mobile robots have been used recently to trace the plumes and localize the emission source (Edwards et al., 2005; Hayes et al., 2001; Ishida, 2009; Mcgill and Taylor, 2011).

A consistent environment with controlled variables (i.e. wind fields and plume propagation) is essential for developing, training and testing search algorithms for plume-tracing mobile robots. Therefore, it is very difficult if not impossible to control those variables or keep the consistency in an indoor setup site when initial experiments are applied (Agassounon et al., 2009; Lu, 2011).

With increasing computing power and widespread availability to commercial and open source codes, CFD techniques have been used to predict the airflows and chemical plumes in indoor environments for search algorithm development and testing. Compared to the experimental approach, CFD ensures the consistency in plume propagation and fluid fields at different testing runs. Moreover, CFD provides a safe environment when dealing with dangerous gasses. Finally, CFD does not require building a prototype and can significantly reduce cost.

Liu and Lu (2008a) were the first group to use CFD in modeling the indoor plume propagation for search algorithms testing purpose. In that work, the commercial CFD code, FLUENT, was employed to predict a 2D plane flow field in a building. Nevertheless, 3D flow patterns are dominant in indoor flows. When the density of gas contaminant is different from the air density, the gas plume is normally three dimensional. The previous CFD model used by Liu and Lu (2008a) that simulated the flow in a 2D plane of a building is not able to provide an appropriate environment for the 3D search algorithm testing. There is a need to generate a 3D indoor flow by CFD to simulate a real life search in indoor environments.

In this study, 3D indoor flows in a building with a chemical source placed in a random room were predicted based on the CFD code, ANSYS/FLUENT 14.0 (ANSYS, Inc). Plumes of the contaminant gas, H_2S, positioned at different locations in the building were predicted as well. Velocity components and species concentration from the CFD results were then exported to MATLAB (Mathworks, Inc.) and used as input to test the 2D search algorithm reported in Liu and Lu (2008a). The same data is tested on the developed 3D search algorithm presented in this paper.

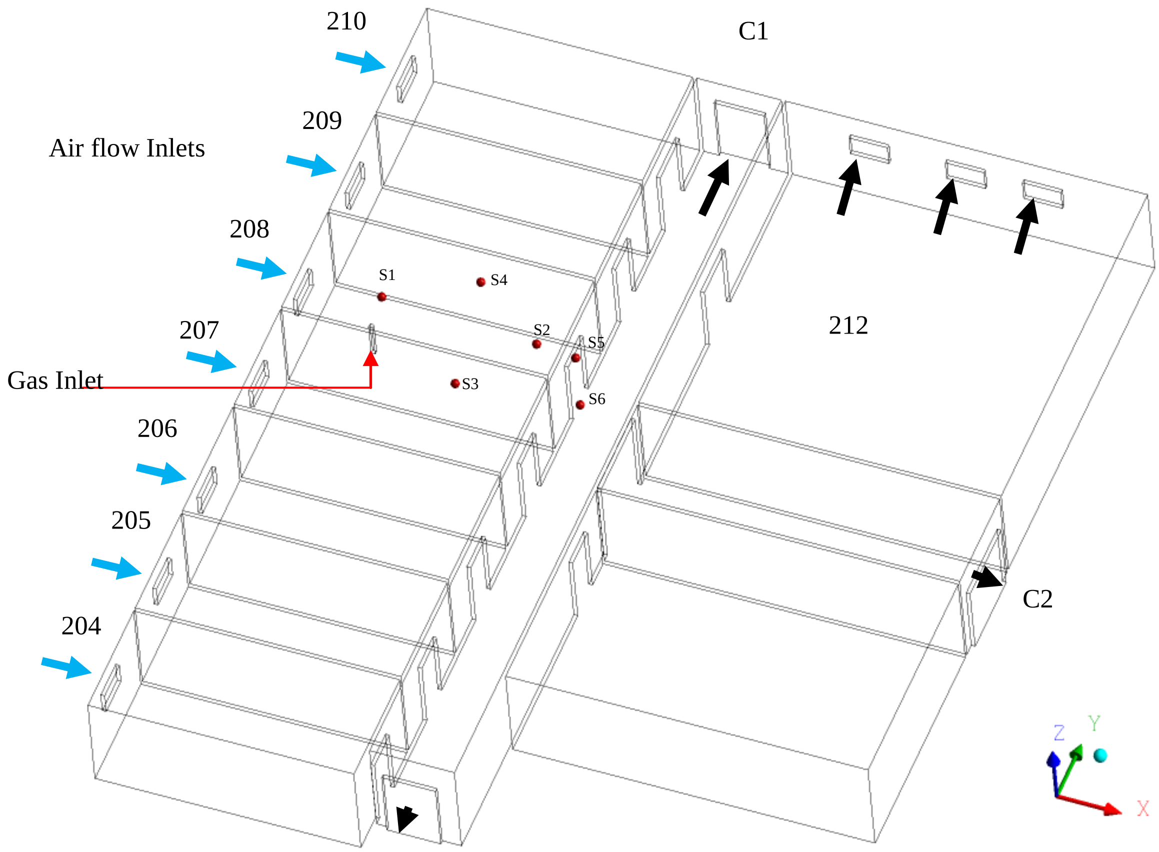

Figure 1: Simulation environment with arrows pointing towards the inlets of airflow, outlet mixture and location of the gas leak.

SIMULATION SETUP

CFD model details

The computational geometry modeled in this study is shown in Figure 1. The geometry was based on the level 2 of Engineering South Building in North Terrace Campus, School of Mechanical Engineering, The University of Adelaide.

ANSYS/DESIGNMODELER 14.0 is used to generate the model geometry. The dimensions of the building section are L_x =21.32 m, L_y =18 m and L_z = 2.7 m in the x, y and z directions, respectively. A structured mesh was generated for the domain using the meshing software ANSYS/ICEM 14.0. A grid sensitivity test was conducted as discussed in the Results and Discussions section.

Many cases of H_2S release from different locations in the building with same flow conditions have been simulated. Only one case is reported in this paper due to the page limitation. In this case, H_2S is injected into the domain through an orifice with a surface area of 0.01 m^2 in room 208 (indicated by a red arrow in Figure 1) at a rate of 43.8 g/s. Wind enters normal to the windows located in rooms 204 to 210 at a constant speed of 1 m/s. The area of each window in the domain is 0.5 m^2. These conditions are chosen arbitrarily and are designed to create a complex environment. Mixture of air and H_2S exits the CFD domain through the outlets of C1, C2 (2 m^2 each) and the windows in room 212. A pressure boundary condition is used for the outlets with an averaged gauge pressure of 0 Pa.

The commercial CFD software, ANSYS/FLUENT 14.0 was used to solve the flow of the mixture of H_2S and air in the domain. The flow is isothermal and in steady state without any reaction. The transport equations are discretised using the finite-volume method. The QUICK scheme is used to approximate the convective terms at the faces of the control volumes. Turbulence is modeled using the standard $\kappa - \varepsilon$ model (Launder and Spalding, 1972). It is able to provide reasonable results in many cases. The convergence criteria for the gas phase properties were 10^{-6}.

Plume tracing strategies

Several plume algorithms were developed to search and localize the source. Most of these algorithms are based upon mimicking the movement of flying and walking insects in search for their food in controlled environments (Kennedy and Marsh, 1974; Kowadlo and Russell, 2008). Other researches developed different search strategies to localize the source of the contaminant leak. Russell et al. (1995) used a reactive control algorithm to locate the source of the plume while having the capability of avoiding obstacles. The search was carried out in a steady air flow and assumed the leak was either coming from just above or below the robot's path and the wind blowing from one direction which is not realistic in real-life situations. Ishida et al. (1996) applied similar search by combining the gradient trace with the upwind search strategy. However, this was only carried out in an obstacle-free room. Kowadlo et al. (2006) applied a bi-modal search strategy using image recognition and plume searching to localize the source. An airflow map is predefined for the robot to define separate cells of the domain, at each cell a target would be defined as the point of the highest concentration. The robot then moves to those selected targets and rotates 360^o using visual scanning to locate the source. This method is effective in locating the source in minimum time. However, an airflow map has to be pre-defined to predict the boundaries of the domain to identify the highest concentration points. Therefore, to be able to achieve realistic plume tracing strategies, an understanding of how the plume meanders is required to test the current developed algorithm.

The plume-tracing algorithm used in this study is developed using a MATLAB simulation. The MATLAB code requires two key inputs. These inputs include air velocity vectors and gas concentration at each domain node that is exported from FLUENT results. Initially, the robot is positioned at a location at either of the nominated exits (C1, C2) in the domain developed. The reason for positioning the robots at the door exits is due to the ability of humans to orient the robot and to start its trace in the downwind position (Lu, 2011). The simulated robot is modeled on the real robot developed by Harvey et al., (2003). The robot shown in Figure 2 contains three wind sensors (F6201-1, Shibaura Electronics Co., Japan) to detect wind speed and determine direction. It also contains an ion sensor that acts as a chemical sensor in detecting the concentration and following the gradient. However, the difference between the modeled robot and the one developed is the simulated robot has the capability to measure and compare concentration readings along the vertical pole mounted where the ion sensor is located, the pole containing 4 sensors. The sensors are mounted at heights of 0.5 m, 1 m, 1.5 m and 2 m. The concentration measurements are taken at each (X,Y) location along the robots trajectory; thus, increasing the capability of the robot to scan in 3D. The pole height where the sensors are mounted is limited to the height of the current search domain ceiling.

The base of the robot contains four ultrasonic sensors capable of scanning with an angle of 180^o for any obstacles along the robots search path.

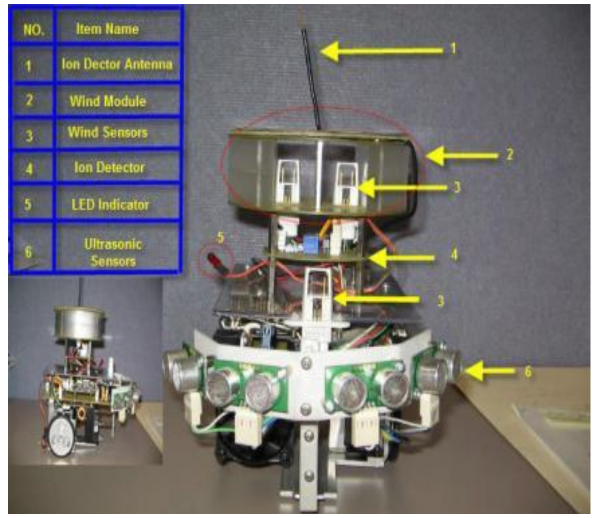

Figure 2: The physical robot used as a base for this study (Harvey et al., 2003)

The diameter of the robot is 0.2 m and turning circle is the same as its diameter.

The robot starts its search stage by comparing the concentration values recorded by the sensors mounted on the robot's vertical pole until it encounters the plume's boundary, at this stage the robot would have passed the lower concentration threshold. If the robot encounters an obstacle (wall, door frame) along its path, the robot is programmed to switch from plume searching to wall following algorithm, where it would compare the measured distance with the preset distance. If all 4 sensors detect enough distance, the robot would prefer to move in the forward direction for a set distance (10 units equal to 40 cm surge) than turning right for 45^o followed by a 90^o turn before turning left for 45^o followed by a 90^o turn. However, the strategy may change depending on the concentration gradient and current robot location. After successfully avoiding the obstacle the robot checks if it is still above the lower set threshold, if the answer is yes it would continue its trace. However, if the answer is no it will acquire the plume by retreating to the last two locations of concentration readings saved in the memory. This is built as a safety factor when the robot loses contact with the plume or there is no change in concentration in the area of search. The robot will then turn and faces wind to recommence the search. After acquiring the plume again the robot traces the gradient until the higher threshold value is triggered. This means the robot is very close to the source. When locating the source of the plume, the robot ceases operation and reports the trajectory followed. Although, if the robot encounters an obstacle and the second threshold is triggered. The robot would still avoid it and continue the trace. Thus, when the concentration drops after passing the obstacle the robot ceases operation and reports its trajectory. The flow chart of this process is shown in Figure 3.

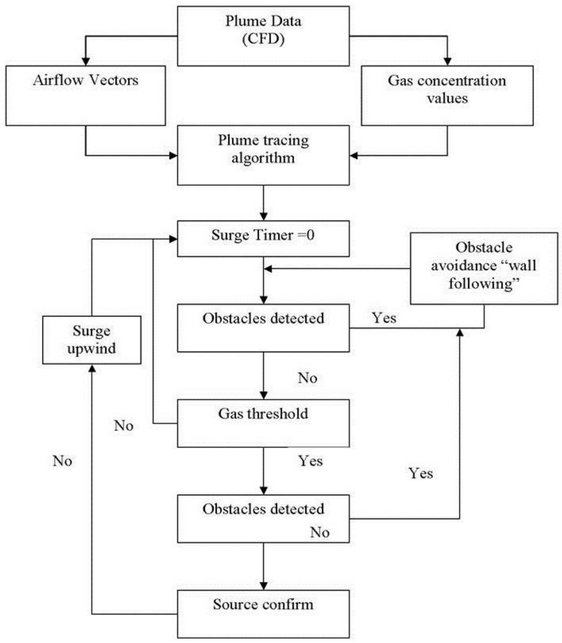

Figure 3: Plume tracing and source localization flow chart.

RESULTS AND DISCUSSIONS

Grid Independence Test

Four sets of mesh, with 877k mesh nodes, 1.2 millions mesh nodes, 1.6 millions mesh nodes and 2.1 millions mesh nodes, respectively, were generated. The predicted H_2S concentrations at six positions based on these four meshes are compared. Table 1 gives the six positions in the 3D geometry as illustrated in Figure 1. Table 2 shows the different mesh sizes used for the sensitivity test and the H_2S concentration levels (mass fraction) at each position in the room where the source is located and in the adjacent corridor. For Grid B-D, the predicted concentrations of H_2S are similar at all six positions. Mesh C with 1.6 millions mesh nodes was then used for all the simulations to embrace computational efficiency towards achieving the final results.

2D Search Testing

Figure 4 shows a cross section of the mass fraction contour of the propagated H_2S gas through the specified inlet at Y= 14.57, in room 208. The density of air is 1.18 kg/m^3, which is lower than the density of H_2S that is 1.46 kg/m^3. High concentration of H_2S is found above the emitter showing the plume is 3D. To test the capability of the 2D search algorithm developed by Liu and Lu (2008b) for tracing this 3D plume, the 2D search algorithm is used to trace the plume at four different horizontal planes at different heights. Figure 5 and 6 represent the search at heights of 0.5 m and 1m (in Z direction) respectively. The search algorithm is also tested at other heights. However, it shared the same result illustrated in Figure 6, with the robot failing to enter the room. Figure 5 shows the H_2S concentration contour and the trajectory of the plume tracing mobile robot (demonstrated by the black hollow circles) at the 0.5 m plane.

Sensor No.	X	Y	Z
1	3.98m	14.57m	2.23m
2	4.23m	14.57m	1.95m
3	2.3m	16m	1.89m
4	8.95m	16m	0.34m
5	7m	14.57m	1.8m
6	7m	14.57m	0

Table1: Sensor positions as presented in Figure 1.

Grid	Nodes	S1 (%)	S2 (%)	S3 (%)	S4 (%)	S5 (%)	S6 (%)
A	877k	7.8	9.4	9.1	9.2	9.5	7.9
B	1.2m	4.23	6.86	6.8	5.96	6.65	6.22
C	1.6m	5.13	6.83	6.55	5.73	6.74	6.26
D	2.1m	4.51	6.28	6.01	6.1	6.05	6.09

Table 2: Results of Mesh sensitivity test (H_2S mass fraction).

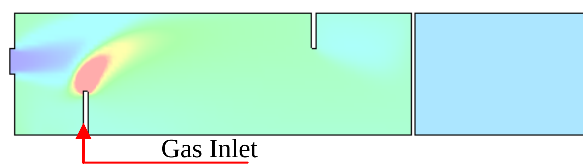

Figure 4: Side view (XZ) at Y= 14.57 m in room 208 showing the plume distribution.

The robot was able to find its way inside room 208 where H_2S is released by following the chemical gradient after achieving the set threshold of 0.04. However, due to the limited information of concentration data on the designated slice, the robot was not capable of localizing the source. Although the robot was able to roughly stop close to the source, the behavior was not consistent when the source location was shifted to a different height, different initial search position and angle heading.

In Figure 6 the robot detected the first threshold, however, during its forward surge the concentration suddenly dropped. The robot reverses two steps to compare the current concentration reading with the previous two saved in its memory. This allows the robot to use the previous saved concentration location as a reference point. From those points, the robot turns with an angle of 45^o increments to face the wind before switching to plume tracing method again as shown in the circled areas in Figure 6 and 8. Figure 7 shows the concentration contour of the area where the concentration has dropped. The reason for only storing the last two sets of data is to resemble the insect's limited brain power. Although, the robot then starts surging forward to require the plume, the concentration measured was below the set threshold. Therefore, all previous 2D searches were carried out under the assumption that the robot's sensors are positioned at the same level as the source emitter. Thus, assuming the 2D domain contains all the plumes characteristics from airflow vectors to concentration data which is not true due to the nature of the gas as it propagates in 3D not just 2D.

Therefore, in real life situation, the height of the source and its location is unknown and due the complexity of the geometry designed, it becomes harder for the robot to localize the source.

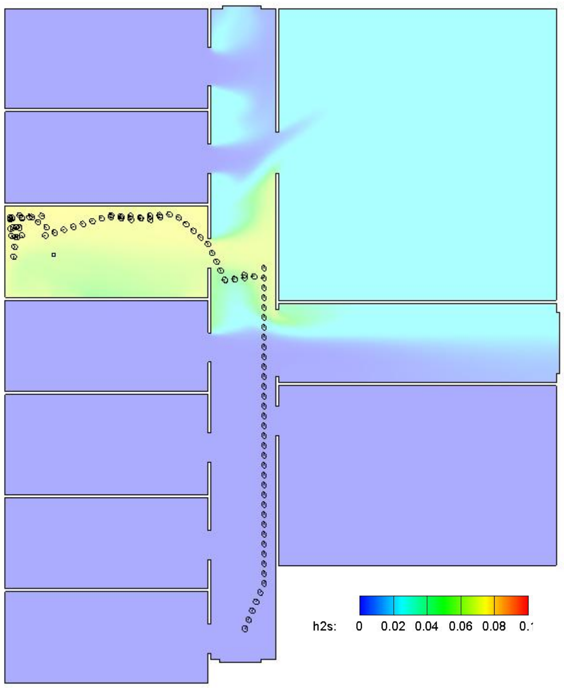

Figure 5: 2D slice search at height 0.5 m.

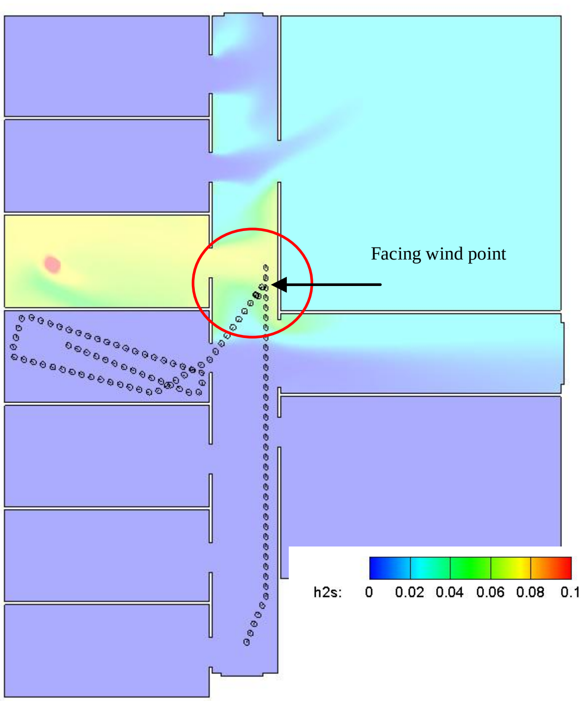

Figure 6: 2D slice search at height 1 m.

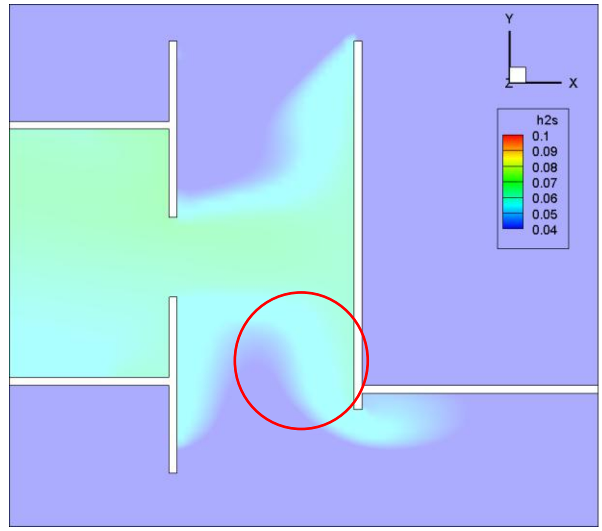

Figure 7: Concentration of H_2S (% mass fraction) at the entrance of the suspected room at height 1 m.

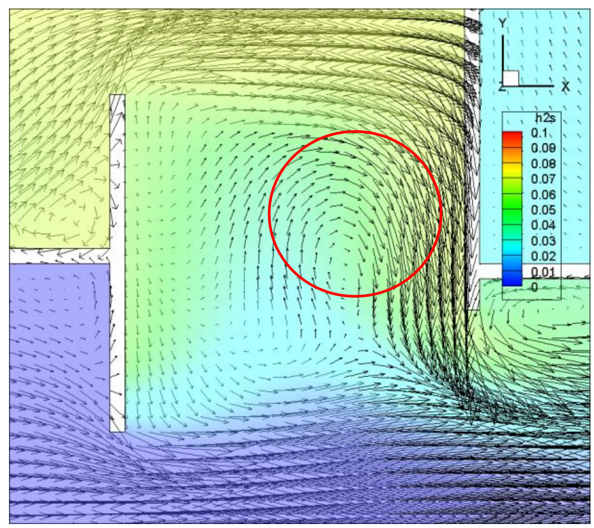

Figure 8: Effects of airflow vectors on robots heading when concentration drops below set threshold at height 1 m.

3D Search Testing

A full 3D search algorithm is developed and numerically tested with successful results. The simulations carried were aimed to investigate the advantages of 3D search over 2D search.

The 3D search algorithm was tested based on the 3D flow domain predicted by the CFD model. Figure 9 and 10 illustrates the robots initial start position point along with the trajectory followed till the robot localizes the source position. The robot is able to locate the source successfully using the developed algorithm. The search time taken was 82 Seconds, based on each position plotted on the superimposed image. Figure 11 illustrates the trajectory formed by the robot; from the initial search location to the highest concentration located at height 1m. The maximum concentration recorded at each (x,y) position is plotted as presented in Figure 10.

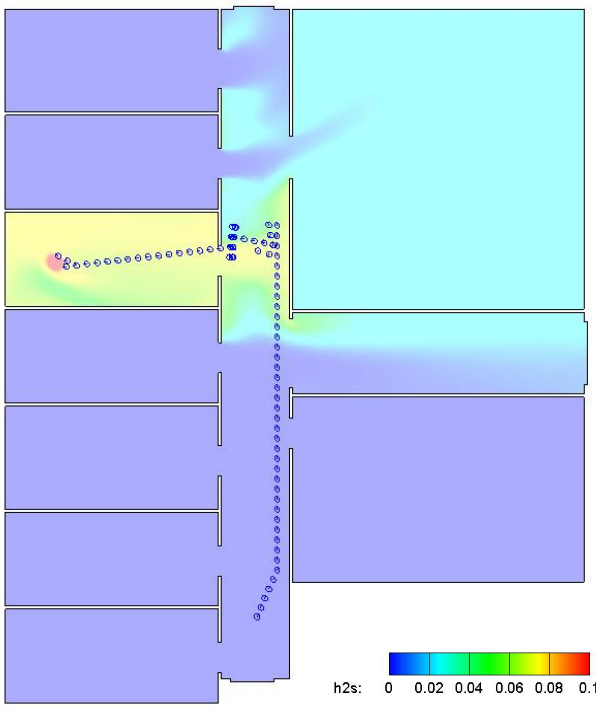

Figure 9: Top view of robots trajectory superimposed in a 3D search. The concentration contour is at the horizontal plane at height 1 m.

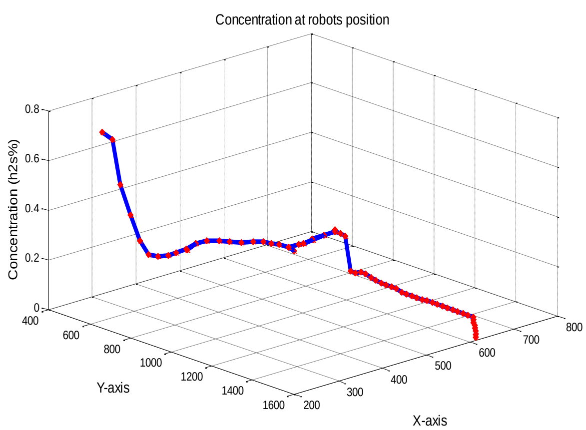

Figure 10: MATLAB simulation showing the concentration gradient trajectory set by the robot from the initial search till the highest point at the source.

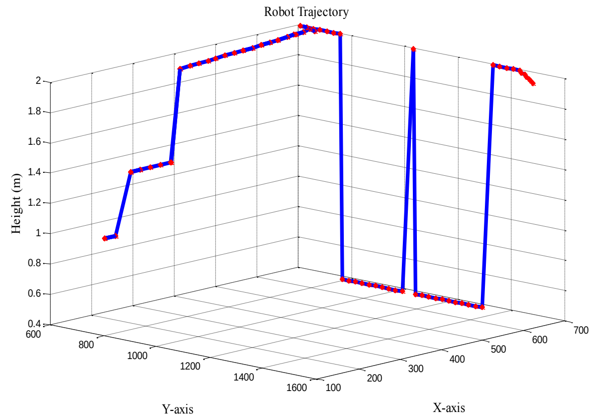

Figure 11: MATLAB simulation of the 3D plume search trajectory.

Discussion on Steady State Simulation and Turbulence Models

In this study, flows and flumes are simulated in steady state using the standard $\kappa - \varepsilon$ model. The steady state simulation is conducted in order to save the computational time and reduce the data required for algorithm testing. The standard $\kappa - \varepsilon$ model is used since it is the widely used turbulence model in industries. It is simple, robust and less computationally intensive compared to some other turbulence models such as Reynolds stress models.

However, indoor flows are mainly low-Reynolds number (LRN) turbulent flows and the improper modeling of LRN flows and turbulence can contribute to the in accurate calculation of indoor airflows (Tian et al., 2007). Tian et al. (2006) compared Large eddy simulation (LES), standard $\kappa - \varepsilon$ model and Renormalization group (RNG) $\kappa - \varepsilon$ model in an indoor air flow and found LES yields better agreement with the experimental data than the other models. Furthermore, LES that is an unsteady simulation approach can account for the history and transport effects of turbulence on flows and species concentration while steady state $\kappa - \varepsilon$ models are incapable of. Studies using LES are undergoing to take into consideration of fluctuations of gas concentrations.

CONCLUSION

CFD techniques were used to model H_2S plumes in 3D flow fields in a building. The predicted flow fields and H_2S plumes were then imported to MATLAB to test research algorithms for plume-tracing mobile robots. The 2D algorithm that was previously developed in our group is initially tested at selected heights 0.5 m, 1 m, 1.5 m and 2 m from the 3D CFD results. It is found the robot with 2D search algorithm was capable of entering the suspected room but failed to find the source at 0.5 m plane. When tests were carried out at different heights the robot failed to even enter the suspected room. CFD results show the flows and plumes are strongly three dimensional and the previous 2D search algorithm is not appropriate for this kind of indoor flows and plume.

By applying a full 3D search algorithm, the robot is capable of finding the source easily. This was achieved by measuring the concentration at each (x,y) location at different heights and comparing the concentration levels. The robot would continue the search at the level with the highest concentration until a higher concentration measurement is detected at a different height, where the robot would move to the selected height and continue its search.

Generally, CFD shows the capability to create a realistic environment for testing the developed search algorithm for plume tracing robots at low cost. This well controlled environment enables the researchers to conduct sensitivity studies quickly and precisely. Furthermore, 3D CFD flow field and plumes are more realistic than the 2D flows developed in a previous study, due to the fact that the indoor flows and plumes are strongly 3D in indoor environment. Towards the end of series of investigations, it becomes clear that applying a sensor array and testing the search method in a more complicated geometry where obstacles would be introduced in the pathway of the robot could further improve the search algorithm.

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