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Numerical Study of Dispersion and Ventilation of LPG Gas in Urban Household Kitchen

Dayanand Rauniyar[a], Sudip Bhattrai [b]

[a] *Department of Automobile and Mechanical Engineering, Thapathali Campus, IOE, Tribhuvan University, Nepal*
[b] *Department of Mechanical and Aerospace Engineering, Pulchowk Campus, IOE, Tribhuvan University, Nepal*
[a] rauniyar.daya@gmail.com, [b] sudip@ioe.edu.np

Abstract

The use of LPG is increasing in South Asian Countries in different sectors like automobiles, industries and households with the increase in consumption the accident due to the LPG has been also increased. An explosion of Liquefied Petroleum Gas (LPG) in a Kitchen in Sindhupalchowk district of Nepal was reported in April 2022 in which three people were killed and there was also damage to the property. This is due to the lack of proper ventilation in the kitchen room.The present study is focused on the leakage of LPG in the kitchen room and the effect of the position of the ventilation for the evacuation of the LPG gas. The effect of the bench top on the accumulation of gas was also performed. For this CFD simulation was done in the SIMSCALE software, it was observed that the gas gets accumulated at the bottom than rising in an upward direction. The ventilation provided at the lower height shows a higher mass flow rate than the ventilation provided at the higher height. The gas gets confined in a certain region if there is any disturbance like a benchtop. There was the creation of the stratification region in the lower region of room.

Keywords

LPG, Ventilation, Kitchen, SIMSCALE

1. Introduction

LPG is one of the main source of cooking fuel in South Asian Countries. LPG is also widely used in Nepal as cooking fuel due to its high calorific value. The use of LPG has sharply increased in Nepal in the past decade. In the fiscal year 2020-2021, Nepal has imported 4, 77,422 tonnes of LPG [1] .According to report of Ministry of Forest and Environment-2021, about 54% of the total LPG imports are consumed by the residential sector, and LPG imports are expanding at a pace of about 15% per year[2]. LPG produces fewer particulate pollutants than Solid biofuel and wood and has a high calorific value. The rapid increase in the consumption of LPG has also posed the threat due to its leakage. It is becoming vulnerable and life-threatening due to improper handling and unaware hazards of it. Gas is widely used for multipurpose in the industry, hospital, home, and automobile. If we considered its vulnerability in household kitchen is higher than in other sectors.Three children lost there life in Sindhupalchowk in April 2022 [3] and 12 years old girl was killed in Tanahu district of Nepal[4] due to accident of LPG. Every year many people lose there life and get a severe burns. The data would be more than this as many cases don't come in the media and no government department keep a record of the scenario. The accident occurs mainly in the kitchen room due to improper ventilation or no ventilation. This study aims to find out the behavior of LPG gas in a kitchen room and point out the optimal position of the ventilation for efficient evacuation of the gas in the case of leakage to minimize the hazard occurring due to it.

1.1 Properties of LPG

LPG (Liquefied Petroleum Gas) is a mixture of Propane and Butane. LPG contain 60% Propane and 40% Butane.. It is heavier than the air. It shows an explosive range between volumes approximately of 2% to 10%. Properties of the LPG is presented in the table **Table: 1**.

Table 1: Properties of LPG [5]

Property	Propane	Butane
Chemical Formula	C_3H_8	C_3H_6
Boiling Point at 101.3 KPa (°C)	-42.1	-0.5
Liquid density at 15°C (Kg/m^3)	506	583
Flash Point (°C)	-104	-60
Upper Flammability Limit (% Vol. in air)	9.5	8.5
Lower Flammability Limit (% Vol. in air)	2.3	1.9
Minimum ignition temperature (°C)	470-575	380-550
Maximum Flame Temperature (°C)	1980	1990
Specific Energy(Gross) KJ/Kg	49.83	49.4

2. Literature Review

In November 1984, an enormous disaster involving leakage of LPG during installation led to the killing of more than 500 people in Mexico city, it was observed that the leakage of the gas resulted in the explosion and the presence of the gas vessel close to each other lead to the amplification of the fire [6]. It was observed that when in an enclosed park area of 30m×30m 70L fuel was allowed to leak, it form the vapour cloud of 200 m^3 and it was calculated that for the effective dilution of the gas the high flow rates of 0.060 m^3/s was required [7]. The early detection of the gas help to eliminate the accident, so the placement of the sensor should be done near to the ground not at the higher height. It is seen that the jet fan ventilation system is effective than the duct ventilation system [8]. The dispersion of gas has also dependency on the direction of the flow of the wind and it can travel larger distance in the downstream of the flow [9].Inhalation of LPG for long time can affect the Central Nervous System and may lead to the death. The blood concentration of LPG of 0.12 to 6.9mg/100g can create asphyxia[10].

3. Methodology

For the computational domain, a simplified model of Kitchen room of 3m×2.4m×3m [11] was designed using the SOLIDWORKS software. Six model of kitchen was made by changing the position of the ventilation with and without benchtop **Table 2**

1. Kitchen room with ventilation at the top
2. Kitchen room with ventilation at the middle
3. Kitchen room with ventilation at the bottom

Table 2: Position of vent

Ventilation	Position of vent
Bottom	0.55m
Middle	1.74m
Top	2.65m

3.1 Kitchen room with ventilation at the bottom

Ventilation diameter is made up 0.3m and is kept at the distance of 0.55m above the ground as shown in **Fig 1a**

3.1.1 With benchtop

The benchtop is provided at height of 1m from the floor as shown in **Fig: 2a**

3.1.2 Without benchtop

The benchtop is removed in this model but the position of the vent is not altered **Fig 2b** .

3.2 Kitchen room with ventilation at the middle

In this model the vent is placed at the height of 1.74m and all other parameters are same**Fig 1c** .

3.2.1 With benchtop

Fig: 2c show the 3-D model of middle ventilation with benchtop

3.2.2 Without benchtop

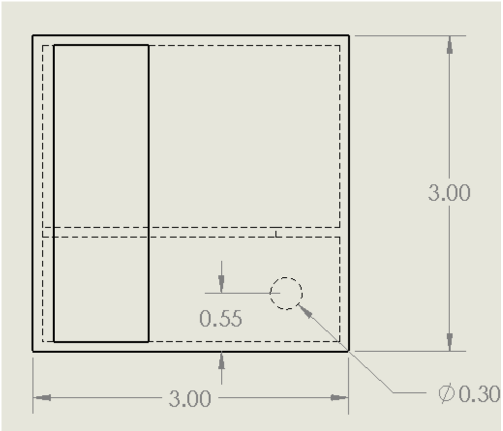
Fig: 2d show the 3-D model of middle ventilation without benchtop.

3.3 Kitchen room with ventilation at the top

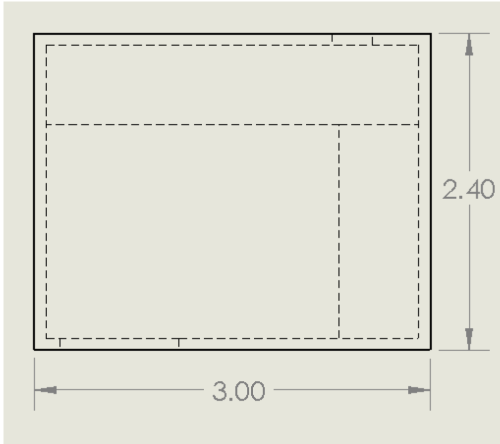
The ventilation is at the height of 2.65m from the bottom **Fig: 1e** .

3.3.1 With benchtop

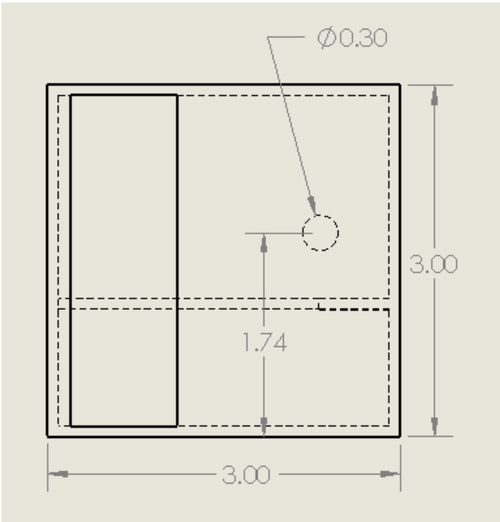
Fig: 2e show the 3-D model of top ventilation with benchtop.



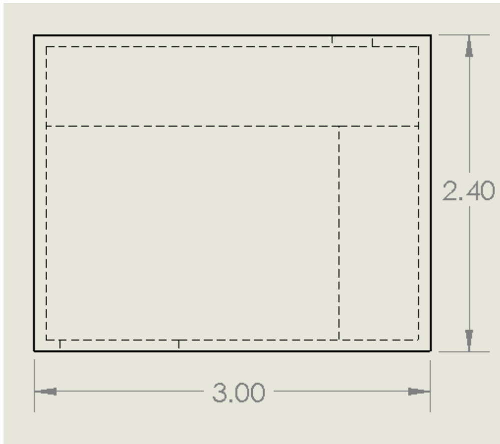
(a) front view bottom ventilation



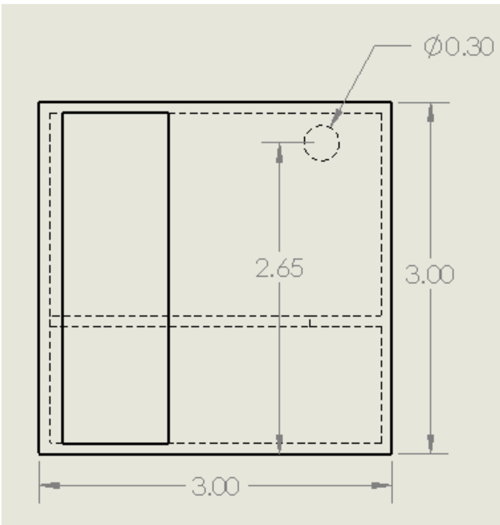
(b) top view bottom ventilation



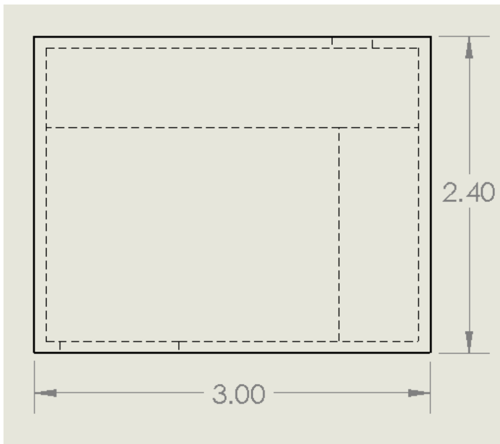
(c) front view of middle ventilation



(d) top view of top ventilation

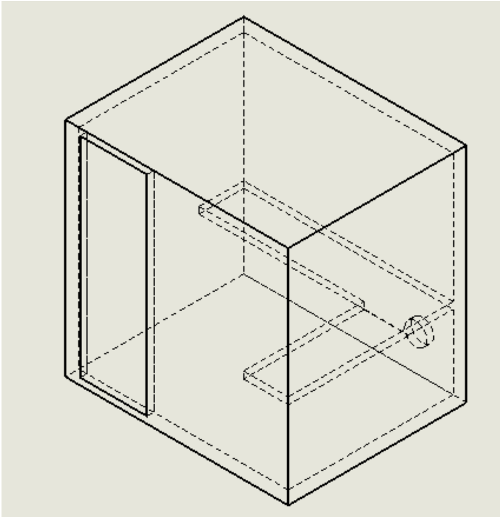


(e) front view of top ventilation

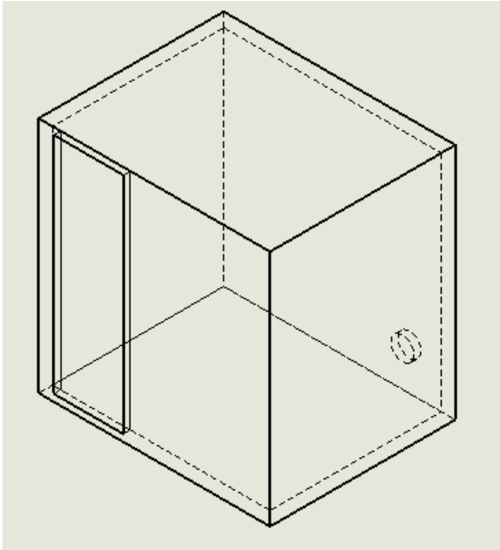


(f) top view of top ventilation

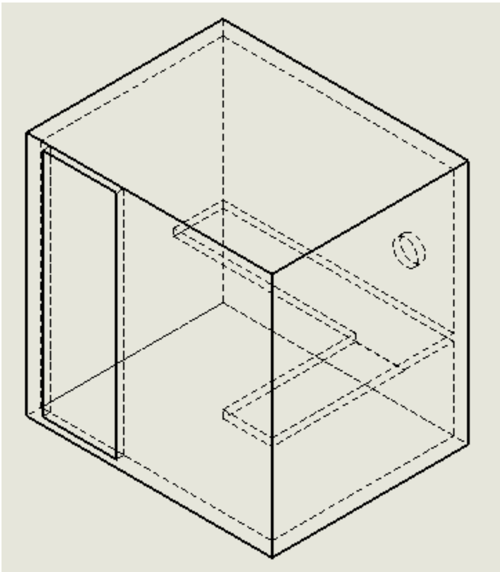
Figure 1: 2-D model showing different position of ventilation



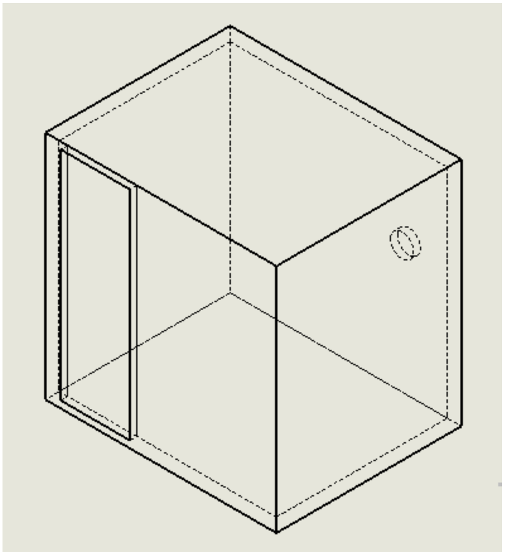
(a) 3-D model of bottom ventilation with benchtop



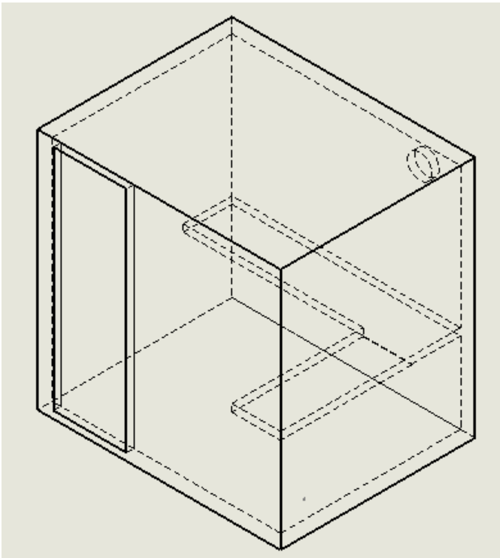
(b) 3-D model of bottom ventilation without bench top



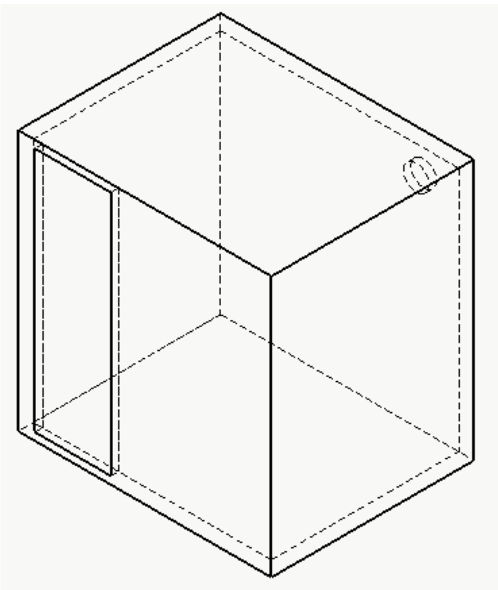
(c) 3-D model of middle ventilation with benchtop



(d) 3-D model of middle ventilation without benchtop



(e) 3-D model of top ventilation with benchtop



(f) 3-D model of top ventilation without benchtop

Figure 2: 3-D model showing different position of ventilation

3.3.2 Without benchtop

Fig: 2f show the 3-D model of top ventilation without benchtop.

3.4 Numerical Methods

The CFD (Computational Fluid Dynamics) software Simscale was applied for the analysis. Air and Propane gas was taken in consideration for the purpose of study. The model which was adopted to solve the continuity, momentum and turbulent flow equation are passive scalar, energy and viscous respectively. Mixture of air and propane was assumed as incompressible gas. The diffusion coefficient of (1×e-5 m^2/s) propane in air was used to relate the density variation and passive scalar transportation calculation in the study. The gas was diffused in the air according to Fick's law of diffusion. The following assumption were made for the calculation are given below:

1. The propane leak at the constant rate
2. . The chemical reaction and phase change were not taken into account.
3. The wall was adiabatic and isothermal
4. There was no heat transfer from the propane to the air.

Mass and momentum transfer models was used in the study of the LPG gas behaviour. Mass is only transferred in the room with the natural ventilation process, whereas there will be the transfer of the mass and momentum transfer in the room with the exhaust as there will be the creation of the velocity gradient. The ventilation position will be changed to study the flow of the mass.

Reynolds Naiver-Stokes conservation equation were applied to solve momentum, mass, energy and passive scalar.

Mass conservation equation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho v = S_{source} \tag{1}$$

Momentum conservation equation

$$\rho \cdot \left(\frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \nabla)\vec{v} \right) = \rho \vec{g} - \nabla p + \mu \cdot \nabla^2 \vec{v} \tag{2}$$

Where ρ is the density of the gas v is the velocity, p is the pressure, g is the acceleration due to gravity and S is the source for leakage of the gas.

The mesh quality has a great importance on the results of numerical computation. The mesh quality was taken is 0.2036 which is in the acceptable range of 0.035 to 1. The total no cell is more than 6, 70,000 in all the meshing condition. Hex element core and physics based meshing was used. Inlet boundary was taken as velocity inlet of -5×e-5 m/s normal to the surface. The ventilation outlet was taken as the zero gauge pressure and fluid wall was taken as no slip for the simulation. K-omega SST model was selected for the study with steady flow mode. SIMPLE (Semi-Implicit Method Pressure Linked Equation) algorithm was used in all the model for the simulation.

3.5 Position of source

The position of the source is kept same in all the cases and only the position of the ventilation is varied. The position of the leakage is X= 2.4m Y= 0.5m Z= -1m.

S.No	Vent Size	Height	Leakage rate
a	0.07069 m^2	0.55m	32 mg/s
b	0.07069 m^2	1.74m	32 mg/s
c	0.07069 m^2	2.65m	32 mg/s

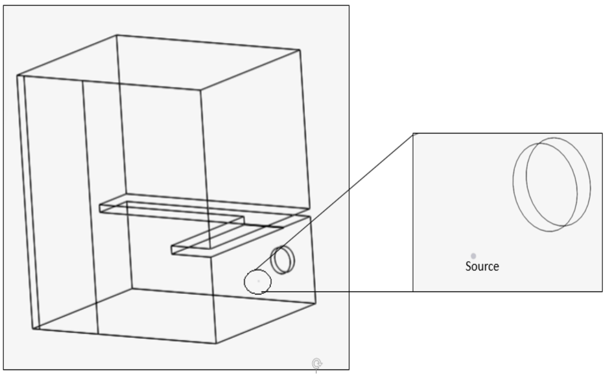


Figure 3: Location of source

4. Result

4.1 Study of dispersion behaviour of LPG

It is observed from the **Fig: 4** and **Fig: 5** that the gas is more concentrated at the bottom area within the range of 0-1.5m. This shows that the gas is heavy and tries to settle at the bottom.

There is the creation of the stratification region in the lower area of the kitchen. It is seen that the gas

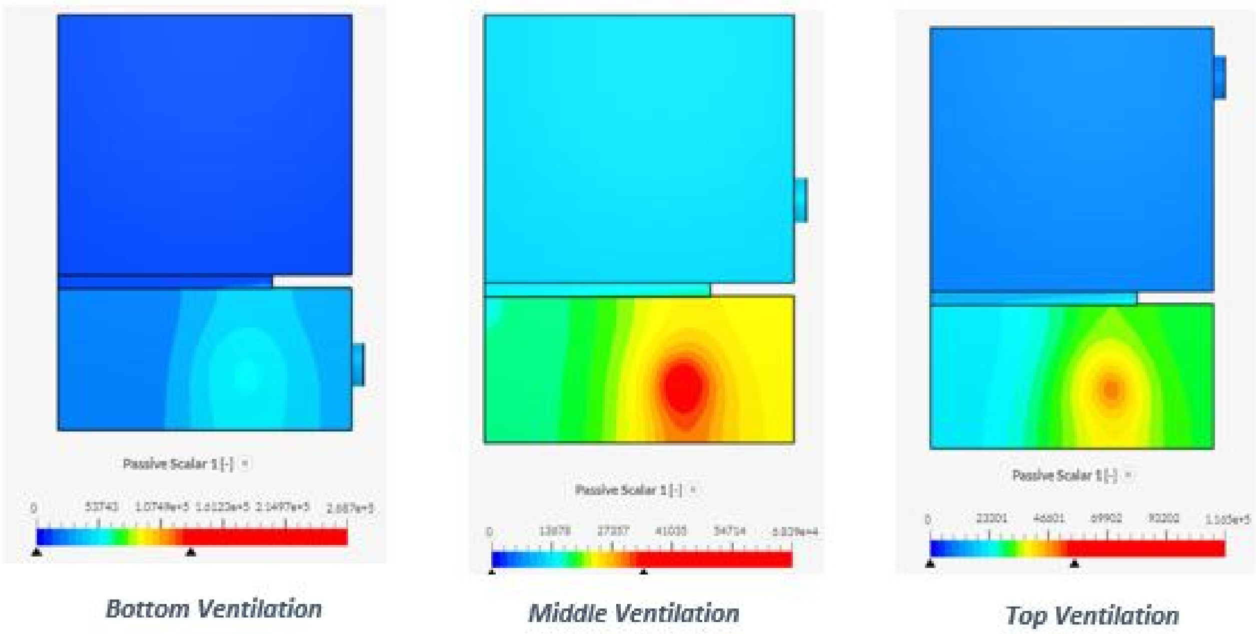


Figure 4: Concentration of LPG for different position of ventilation with benchtop

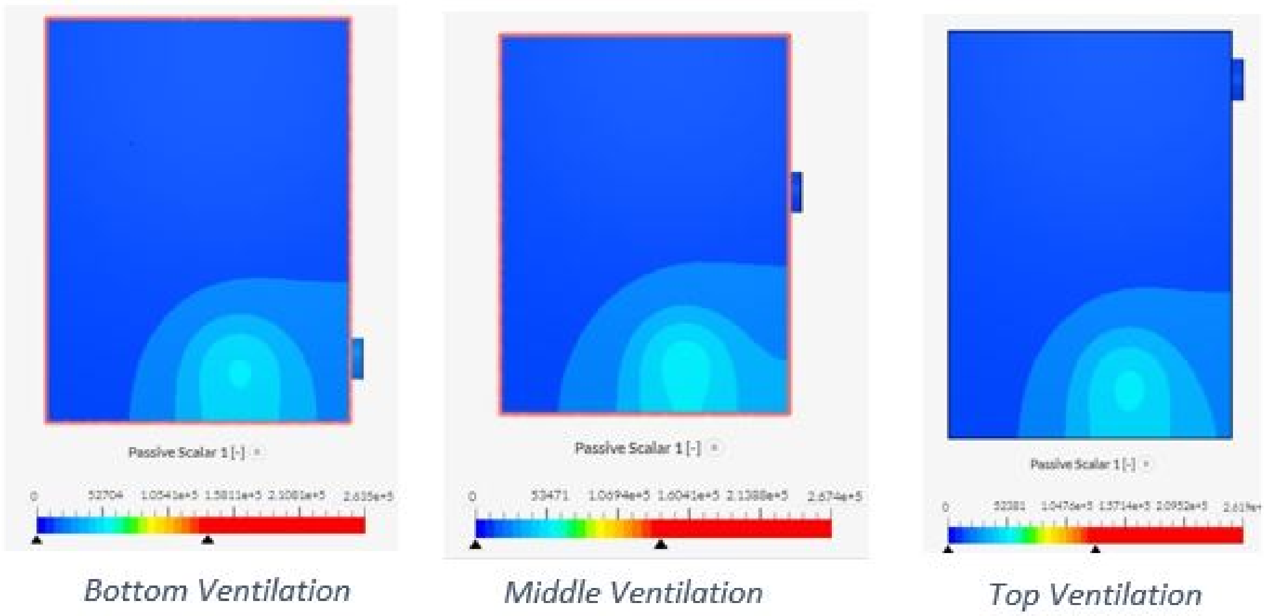


Figure 5: Concentration of LPG for different position of ventilation without benchtop

concentration at the bottom vented kitchen room is quite low in comparison to the other two middle and the top vent. The gas in the second and third cases is seen to be in the Upper Flammability Limit (UFL) and Lower Flammability Limit (LFL) limits. This shows that there is high probability of catching the fire in the case of spark or contact with the source of the ignition.

4.2 Effect of mass flow rate for different position of ventilation

4.2.1 With benchtop

Initially, till the 150s the mass flow rate is seen to be constant after that there is an increase in the mass flow rate and after the 500s mass flow rate for the top, middle and bottom vent reaches 0.98 mg/s, 1.02 mg/s, and 2.92 mg/s. It is seen from **Fig: 6** that the mass flow rate for the bottom ventilation is approximately 3 times that of the middle and the top vent. It depicts that the bottom vent can evacuate the gas more efficiently than the other two.

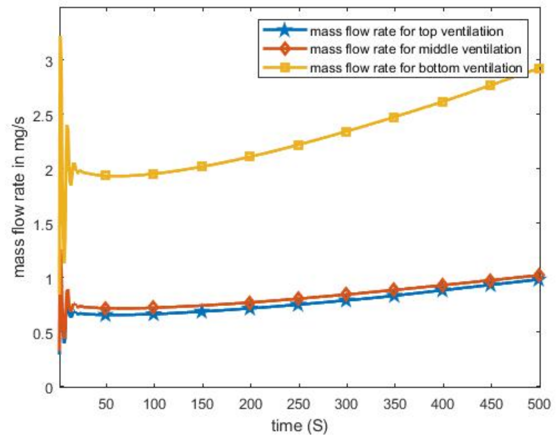


Figure 6: Mass flow rate with benchtop

4.2.2 Wihout benchtop

It is obtained that the mass flow rate after 500s for the bottom ventilation, middle, and top ventilation reaches 2.137 mg/s, 1.365mg/s, and 1.133 mg/s. In this scenario also the bottom ventilation is more effective than the top and middle vent. The mass flow rate is 1.56 times more than the middle vent and 1.88 times the top vent. In a comparison of the top and middle vent with and without a benchtop, it is observed that the vent in the case without a benchtop has high flow rate than with the benchtop. This shows that in the case without a benchtop the middle and top vent is efficient but not as much as the bottom vent. In both conditions the bottom vent mass flow rate seems to be higher, this shows to prevent the accumulation of the gas the room should be provided with a bottom ventilation system.

4.3 Effect of benchtop

In this section,the effect of the placement of the bench top is examined. It is observed that the bench top has a major effect on the accumulation of the gas. It is preventing the gas to disperse in the kitchen. Most of the gases are being accumulated below the slab provided generating the stratification region. This region is more prone to accidents due to the high concentration of gas. In the case when there is no bench top the gas is being dispersed in the kitchen room. It is observed from the plot **Fig: 8** that the concentration at the height of 1.74m is more without a

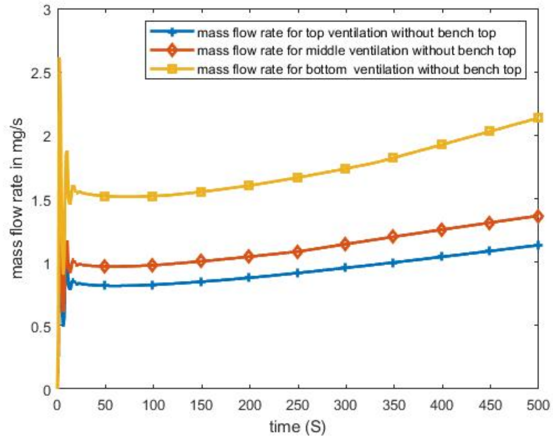


Figure 7: Mass flow rate without benchtop

benchtop than the benchtop. The concentration at the point reaches 10800 mg/m^3 without a benchtop whereas it reaches only 7850 mg/m^3 with benchtop. This shows that if we keep the gas under the slab the gas is unable to disperse and get accumulated beneath the slab.

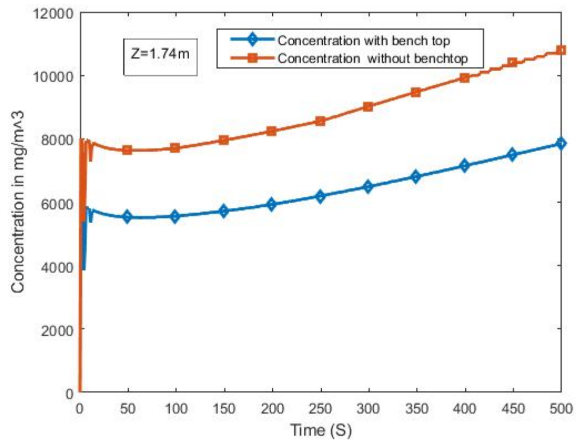


Figure 8: Concentration variation at height=1.74m

4.4 Effect of height on concentration

It is noticed that the LPG layer starts to form at a lower level after the leak of the gas. The gas concentration starts to increase with time and increase in concentration at the lower height is pre-dominant than the upper height. The concentration which is achieved by the point (Z=0.2m) after 100s is reached by the point (Z=1m) after 400s in bottom ventilation **Fig: 11**

The concentration at point 4 after 500s (Z=2.6m) is about 5000 mg/m^3 and point (Z=0.2m) is about 11700 mg/m^3 which is two times more **Fig: 11**. So, if we

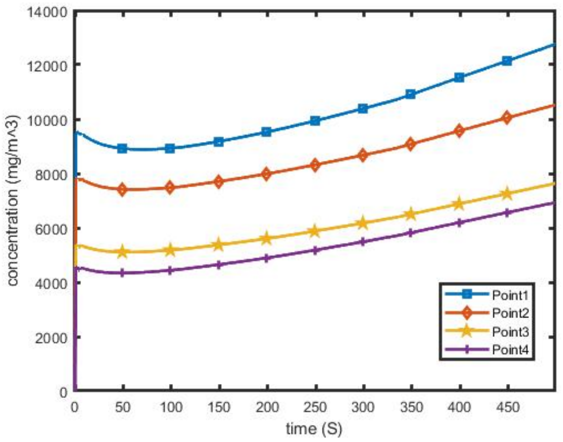


Figure 9: Variation of concentration with height for top ventilation with benchtop

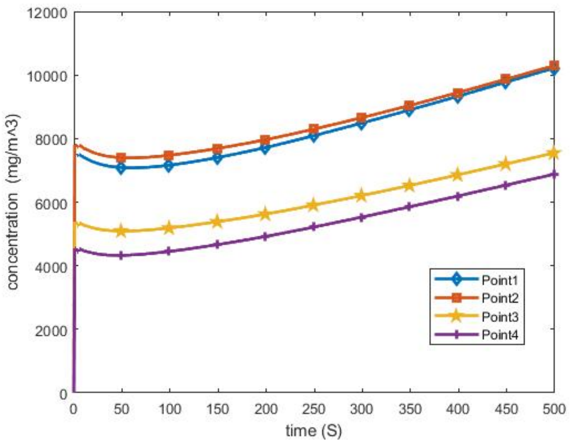


Figure 10: Variation of concentration with height for middle ventilation with benchtop

want to keep the sensor to detect the leakage of the LPG it would be recommended to keep it below 0.2m for the early detection of the gas.

It is observed that the concentration at point 1 Z=0.2m is more for the top vent than the middle and bottom.

5. Conclusion

For the leakage taking place, the gas gets accumulated near the basement up to the height of 0-1.5m and accumulation is more for the top and middle vent. There is the creation of the stratification region due to the effect of the benchtop as the gas is not able to disperse. It is advisable not to keep the gas under the benchtop if there is a leakage of the gas from a safety valve, regulator, or from the cut on the pipe the gas accumulated nearer to the vicinity of the leakage area giving rise to a huge accumulation of the gas that can

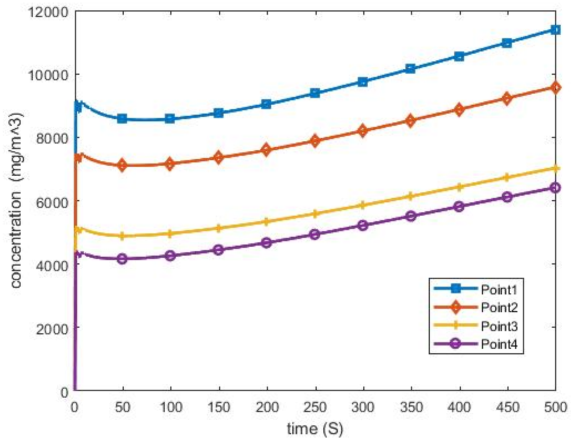


Figure 11: Variation of concentration with height for bottom ventilation with benchtop

cause the hazard. The mass flow rate of the bottom vent is more in both the situation with and without a benchtop. There is less effect of the benchtop on the mass flow rate as there is no any such significant increase in the mass flow rate of the top and middle ventilation but there is a somewhat drop in the mass flow rate for bottom ventilation without benchtop. Therefore, Bottom vent is effective to evacuate the gas than the top and middle vent. The optimal position of keeping the ventilation in lower height is advisable. The gas concentration decreases with the increase in height. The gas gets accumulated more at a lower height than at a higher altitude. It shows that the placement of the sensor or any device which detects leakage of LPG should be kept at a lower altitude within the range of 0-0.2m. The gas at the lower altitude reaches UFL and LFL limit faster than the higher altitude point.

(**Validation:** There is no any previous study carried out by changing the position of ventilation in the kitchen room and studying the effect of bench top. Simscale is one of the reliable software for simulation. Future research can be done on it for the purpose of validation.)

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