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SIMULATION OF GAS LEAKAGE IN A GAS UTILIZATION SYSTEM IN HOUSEHOLD SECTOR

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ABSTRACT
The Indonesian Government is setting up a program of city gas utilization for household sector. People are not convinced of the safety of city gas utilization. One of the accidents people worry about is gas leaks in utilization systems, such as kitchen. Leaking gas is not dangerous when ones can prevent fire ignition. Therefore, information on potential fires caused by leaking gas and methods to prevent their occurrence is needed. This research was intended to obtain the information on fire prevention caused by leaking gas in a kitchen through simulation. The system simulated in the research is a rectangular room of 3 m × 2 m × 3 m. The models consider mass and momentum transfers. The simulation results show that when leaking gas is detected, the leak source must be closed. With the leak source being open, the safe limit is not reached, even if an exhaust fan is provided.

Keywords: Gas leak; Fire prevention; Simulation

1. INTRODUCTION
In order to reduce fossil fuel consumption, the Indonesian Government has implemented a conversion program from kerosene to subsidized liquefied petroleum gas (LPG). Furthermore, the government has also implemented the utilization of city gas as a substitute for LPG. Yet the program of city gas utilization still raises pros and cons. Community resistance to the program is due to their lack of confidence in the safety of city gas utilization, even though city gas has a higher calorific value per mass than LPG. Moreover, the city gas distribution using pipelines saves the fuel use compared to LPG distribution using trucks. Therefore, the government needs to ensure the safety of city gas utilization. It is necessary to build a safe system of city gas avoiding fire ignition in the event of gas leakage. This study aims to determine safety aspects of city gas utilization systems. The method is simulation of a gas utilization system to predict the distribution of city gas concentration in the event of gas leakage.
Research on simulation of indoor and outdoor gas leaks have been carried out. Wu et al. (2007) conducted a simulation of the indoor gas leak by using computational fluid dynamics applications. The regions of concentrations within the explosive limits in the room were calculated. The influence by the release rate of gas leaks and the velocity of the outdoor water flows was studied. Siddiqui et al. (2012) proposed a computational fluid dynamics (CFD) based model for indoor risk assessment considering accidental release of a sustained, small, undetected leak of a dense toxic gas in an industrial indoor environment. Liu et al. (2013) used a 3D computational model based on the building location from Google Earth to predict extent of gas leakage.

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Nourollahi (2009) has modeled of gas pipeline leakage using a one-dimensional characteristic method. The model can be used to predict the gas leaks from short pipelines under different boundary conditions. Sun (2012) has modeled the flow in a pipeline with a leak proposing an approach based on the analogy between pipeline and electric circuit. Zhu and Jing (2011) studied the leaking gas diffusion under different wind conditions by numerical simulation methods based on computational fluid dynamics theory. Kim et al. (2013) have worked on 3D simulation of hydrogen leak at a hydrogen fueling station, given conditions of a set of pressures and a set of hydrogen ejecting hole sizes using a commercial computational fluid dynamics (CFD) tool.

In the present study, gas leaks in a city gas utilization system (room) were simulated using COMSOL Multyphysics. The distribution of the diffusing gases in the room was calculated, and the times required to achieve the flammability limit were predicted. Furthermore, the simulation on the times required to evacuate leaking gas until it reaches a safe condition was also performed with various exhaust fan velocities.

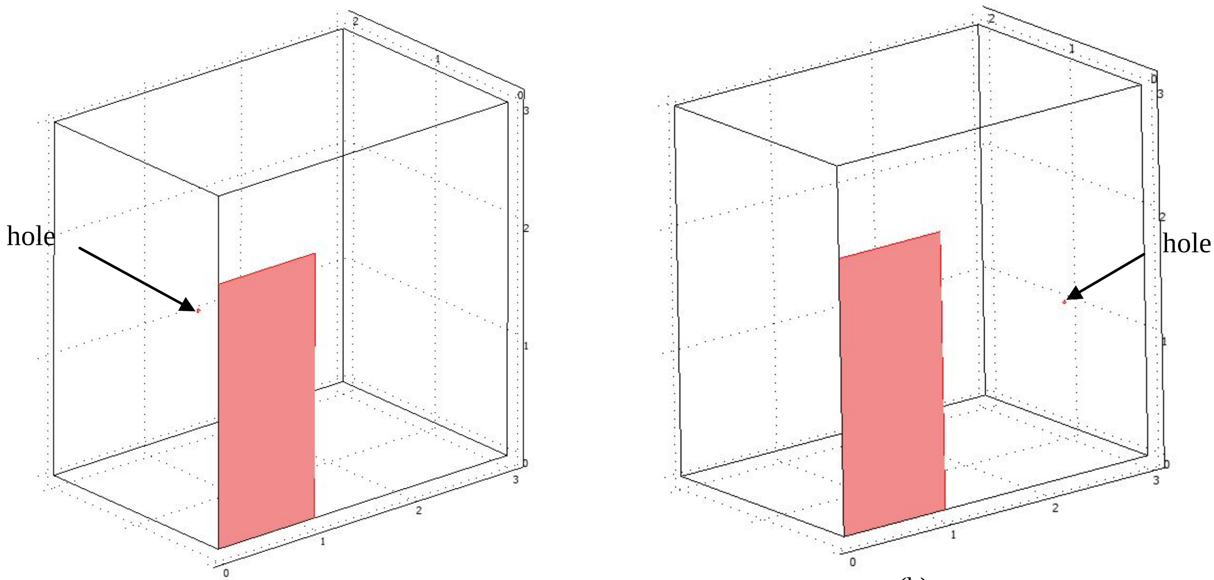
2. METHODOLOGY

The gas utilization system in this study was a rectangular kitchen of 3 m × 2 m × 3 m. City gas was represented by pure methane. The models consider mass and momentum transfers. The simulation results in the profiles of species concentration and velocity with respect to position and time. System leak safety was evaluated by considering methane concentration in air. When methane concentration is beyond its flammability limits, gas leak poses no flame, even though ignition triggers exist. Low flammability limit (LFL) and upper flammability limit (UFL) of methane are 5 mol% and 15 mol%, respectively, or 2.08 mol/m^3 and 6.25 mol/m^3.

Two models were considered. The first model was for a system without an exhaust fan, and the second one for that with an exhaust fan. In the first model, the simulation was performed to determine the time required to reach a mixture of the flammability limits from the beginning of leakage. Simulation took into account two different positions of leak source (hole). The second model was carried by varying the exhaust fan velocity to obtain the time required to achieve the safe condition after the occurrence of a leak.

2.1. The First Model

The first model simulated two different leak source (hole) positions; the hole at the *xz* plane and the hole at the *yz* plane, as shown in Figure 1.



(a) (b)

Figure 1 The first model geometry: (a) the hole at the *xz* plane; (b) the hole at the *yz* plane

Mass is the only transportation to be considered. Momentum transfer does not exist in the kitchen because there is no air movement (wind), so there is no velocity gradient. Molecular (diffusive) mass transfer occurs. The first model equation is as follows:

$$\frac{\partial c_i}{\partial t} + \nabla(-D\nabla c_i) = 0 \quad (1)$$

where c_i is methane, oxygen and nitrogen concentrations, D_i is methane, oxygen and nitrogen diffusion coefficients.

The boundary conditions of the model are as follows:

- At the wall and the closed door of the kitchen, there is no mass flux. The equation is

$$-D_i\nabla c_i = 0 \quad (2)$$

- In the leakage source (hole)

$$c_i = c_{i\text{inlet}} \quad (3)$$

where $c_{i\text{inlet}}$ is inlet concentration. Methane concentration in the leakage source (hole) was assumed to be 100% or 41.67 mol/m^3.

- The initial condition is

$$c_i = c_{i0} \quad (4)$$

where c_{i0} is initial concentration. Before the occurrence of the leak, the methane concentration in the system is zero; oxygen and nitrogen exist in the air concentration.

2.2. The Second Model

The second model is a kitchen with an exhaust fan as shown in Figure 2.

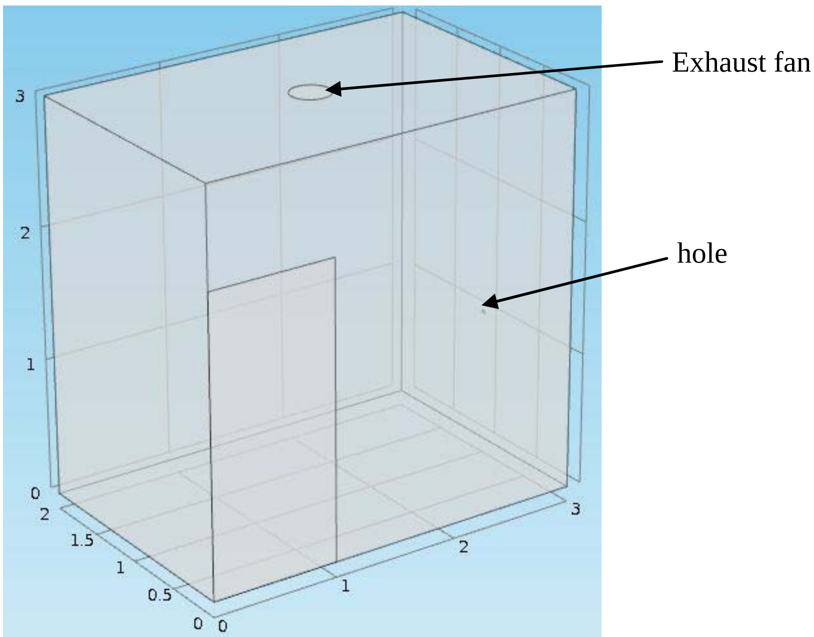


Figure 2 The second model geometry

The model considers mass and momentum transfers. Momentum transfer occurs because there are velocity gradients in the room and between the room and the exhaust fan. Momentum balance considers the effect of inertia, compressive and viscous forces. Gravitational and other forces are ignored, so the momentum balance equation is as follows:

$$\rho\frac{\partial u}{\partial t}+\rho(u\nabla)u=\nabla(-pI+\mu\nabla u) \tag{5}$$

where ρ is density, p is pressure and μ is viscosity.

Mass transfer in the second model is:

$$\frac{\partial c_i}{\partial t}+\nabla(-D\nabla c_i)+u\nabla c_i=0 \tag{6}$$

The boundary conditions are as follows:

- At the wall and the closed door of the kitchen, mass flux and velocity equal zero. The equations are

$$-D_i\nabla c_i+uc_i=0 \tag{7}$$

$$u=0 \tag{8}$$

- In the leak source (hole), the boundary condition for mass transfer is the same as that in the first model (Equation 3), and the boundary condition for momentum transfer is

$$u=u_{\text{inlet}} \tag{9}$$

  where u_{inlet} is 0.058976 m/s.

- At exhaust fan, mass convective flux dominates mass diffusive flux,

$$N=uc_i \tag{10}$$

  where N is mass flux; and pressure is a function of environment pressure, static pressure and fan velocity.

$$p=p_{\text{exit}}-f\left(p_{nf},v_f\right) \tag{11}$$

  where p_{exit} is environment pressure, p_{nf} is static pressure and v_{f} is fan velocity.

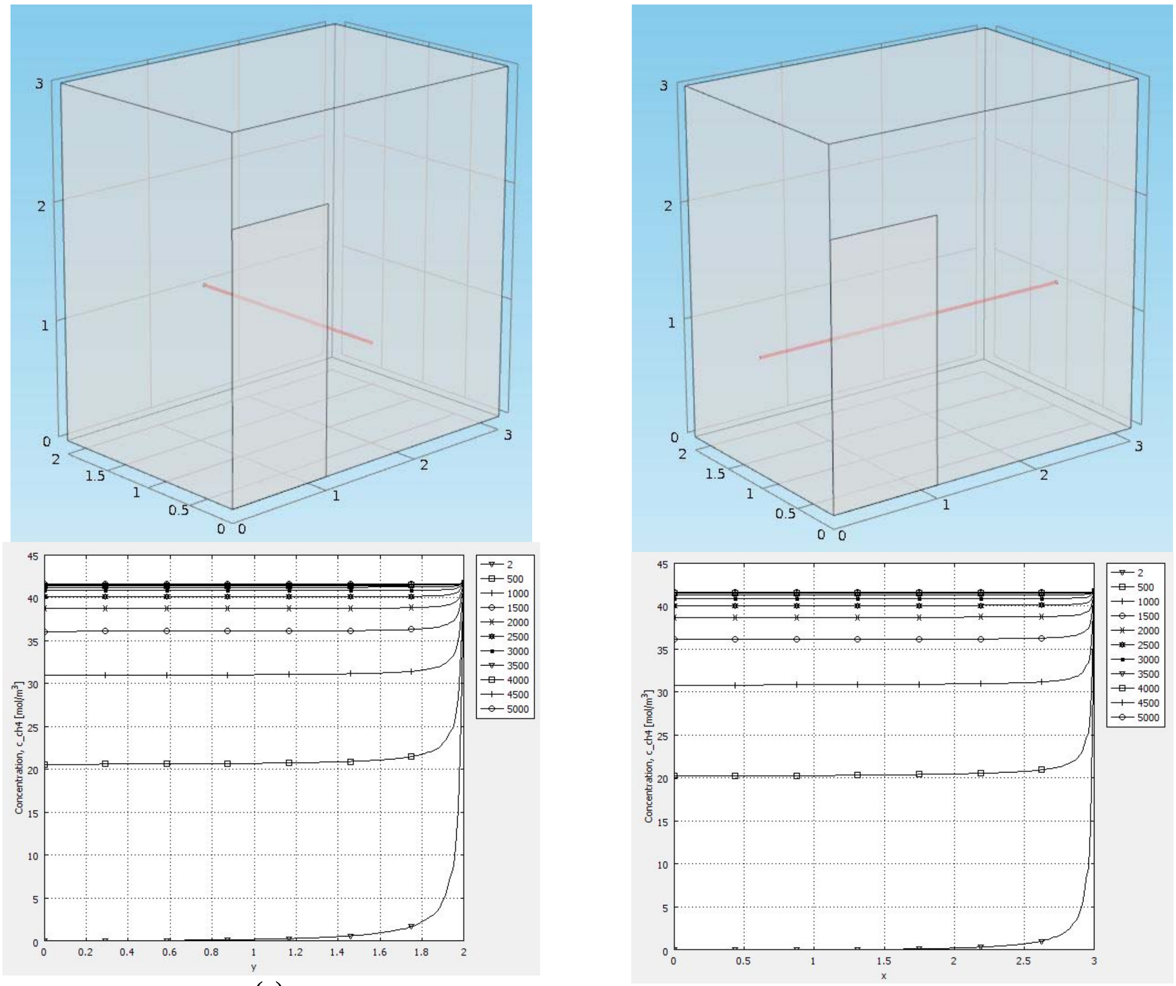
- Initial condition for mass transfer is in accordance with Equation 4, and for momentum transfer, velocity equals zero.

3. RESULTS AND DISCUSSION

3.1. The First Model

When leakage occurs, methane diffuses from the leakage source to the kitchen room. The change in the distribution of the methane concentration in the room occurs. The methane concentration increases with time until it reaches equilibrium.

The curves of the methane concentration with time along lines in the room was made, i.e. the horizontal lines inside the room as shown in Figure 3, which are perpendicular to each leakage source.



(a) (b)

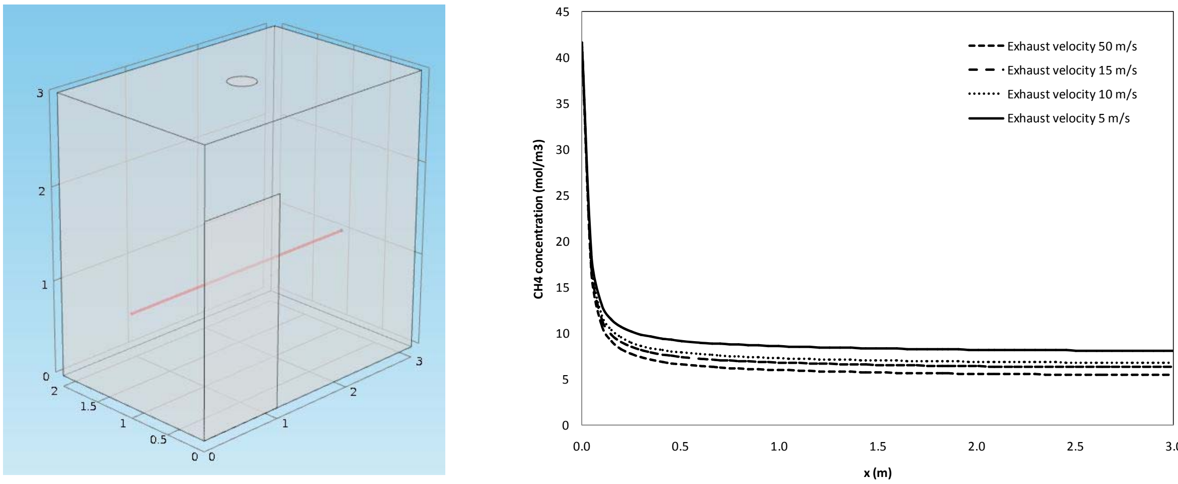
Figure 3 The profiles of the methane concentration along a perpendicular line from the leak source: (a) the hole at the *xz* plane; (b) the hole at the *yz* plane

From these curves, it can be seen that the methane concentration in the room increases with increasing time. The declining curve indicates that methane diffuses from the area of high concentration (hole) to the area of low concentration (kitchen room). When the methane concentration in the room is the same as that in the hole, the equilibrium is reached. The times required to reach the equilibrium for the two different hole positions are about 4500 seconds.

The flammability limit of methane is in the range of 5 mol%–15 mol% or 2.08 mol/m^3–6.25 mol/m^3. When the room is in the flammability limit of methane, fire occurs by triggers such as lighters, cigarette butts, and electronic ignition. From Figure 3, it can be seen that the LFL and UFL mixtures in the middle of the room are reached at 38 seconds and 117 seconds, respectively, after the leakage began. Thus, in that time range, the room should be free from the triggers.

3.2. The Second Model

The second model uses an exhaust fan on the top of the room so that there are mass and momentum transfers through the fan (Figure 4a). The door is closed and the hole is still open. The simulation begins with the room being filled by equilibrium-state methane. Figure 4b shows the effect of the exhaust velocity to the steady-state methane concentration along the horizontal line inside the room (Figure 4a) where the leakage source is in the *yz* plane (coordinates 0, 0).

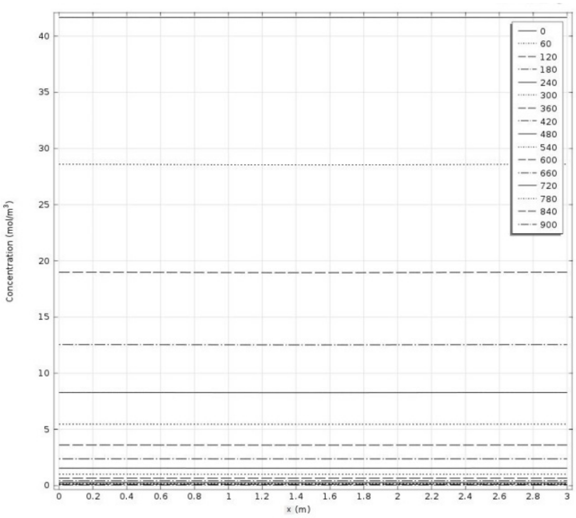


(a) (b)

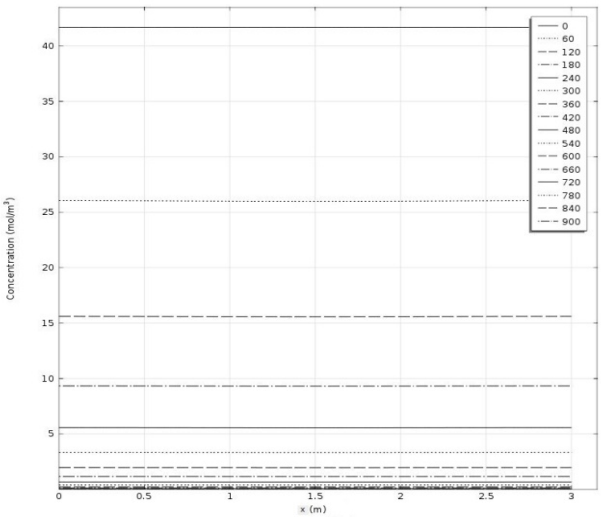
Figure 4 The effect of exhaust velocity to the methane concentration

In Figure 4b, it can be seen that the exhaust velocity affects the methane concentration. In the position of one meter from the leakage source, the methane concentration with the exhaust velocity of 5 m/s is 8.600 mol/m^3. The concentration becomes 7.307 mol/m^3 (or decrease by 15%) while the exhaust velocity increases twice to 10 m/s, and becomes 6.004 mol/m^3 (or decrease by 30%) while the exhaust velocity rises ten times to 50 m/s. This indicates that the increase in the exhaust velocity does not decrease linearly the methane concentration. The methane concentration below the LFL is not achieved despite the exhaust velocity ten times higher than the commercial exhaust velocity (50 m/s). Therefore, if a gas leakage occurs, then the gas flow must immediately be stopped and the door must be opened.

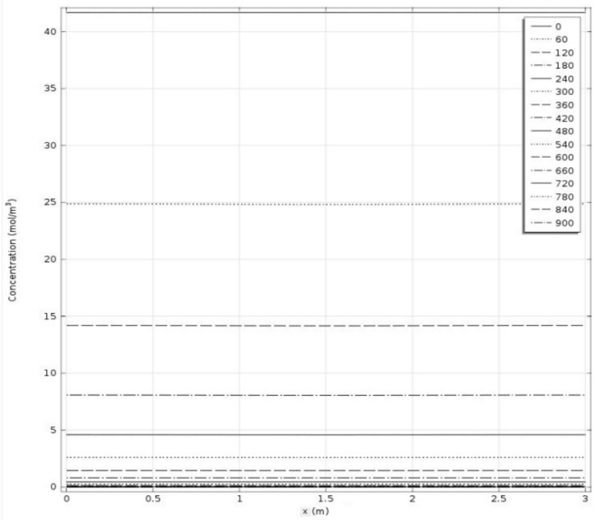
Simulations were also conducted to determine the time required to achieve a safe mixture, i.e. below the methane LFL, after an equilibrium mixture and the hole is closed. As can be seen in Figure 5, for the exhaust velocities of 5 m/s, 10 m/s, and 15 m/s, a safe condition is reached after 540 seconds, 490 seconds, and 450 seconds, respectively. This happens because when the exhaust velocity is greater, the convection flux is also higher.



(a)



(b)



(c)

Figure 5 The profile of the methane concentration in the second model when the hole is closed: (a) velocity of 5 m/s; (b) velocity of 10 m/s; (c) velocity of 15 m/s

4. CONCLUSION

- In the first model, the mixtures of methane LFL and UFL occur 38 seconds and 117 seconds, respectively after the gas leakage began.
- In the first model, the time needed to reach steady state is 4500 seconds.
- In the second model with the exhaust velocity of 5 m/s, the time required to reach the safe limit is 540 seconds.
- In the second model with the exhaust velocity of 10 m/s, the time required to reach the safe limit is 490 seconds.
- In the second model with the exhaust velocity of 15 m/s, the time required to reach the safe limit is 450 seconds.

5. ACKNOWLEDGEMENT

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