Measurement and 3-dimensional Simulations of Carbon Monoxide (CO) Distribution in Mongolian Ger

Byambakhorol Battsetseg[1], Gantuya Ganbat[1], Battulga Nasanjargal[1,*]

German-Mongolian Institute for Resources and Technology, Nalaikh, Mongolia
*Corresponding author: battulga@gmit.edu.mn

Abstract. Ulaanbaatar is one of the most polluted cities in the world, especially in wintertime. During the past two decades, several national and internationally funded projects have been put in place to reduce air pollution. One of the implemented projects is the Government of Mongolia has decided to substitute household raw coal consumption with upgraded briquette fuels in Ulaanbaatar since 2019 in order to combat air pollution. Concentrations of particulate matter (PM2.5 and PM10) in wintertime from November 2019 to February 2020 were reduced by around 40% compared previous five years, respectively. Unfortunately, there are some negative impacts, for example, an increased number of incidences of carbon monoxide (CO) poisoning along with the coal substitution. Indoor CO poisoning causes risks to people living in Mongolian gers and houses.

In this study, we performed a numerical simulation of CO distribution by using the COMSOL Multiphysics. The study enables us to understand the CO distribution in Mongolian *ger*. The numerical simulations show, that when *ger* is assumed empty, the CO concentration is the largest around the stove, then becomes less from stove to crown, and is minimum near the lattice wall. In addition, CO concentration in *gers* and houses were recorded during the heating period. The results of this study offer important information that can be used to develop recommendations for enhancing indoor air quality in gers. By understanding the dynamics of CO distribution within traditional dwellings, strategies can be advised to improve ventilation, stove, and CO detector placements, reduce the risk of CO poisoning, and promote healthier living conditions for residents.

Keywords: Carbon monoxide, Distribution in indoor, 3-d modeling, Mongolian ger

1 Introduction

Ulaanbaatar city is located in a valley surrounded by mountains at an altitude of ~1300 meters above sea level [1], it is the coldest capital city in the world, the temperature

A. Lkhamsuren et al. (eds.), *Proceedings of the Second International Conference on Resources and Technology (RESAT 2023)*, Advances in Engineering Research 226,
https://doi.org/10.2991/978-94-6463-318-4_10

drops to –39°C, and the air is very stable during the temperature inversion in winter. 46% of Mongolia's population lives in Ulaanbaatar, and 51% of them live in *ger* quarters (National Statistics Office of Mongolia). The *ger* (yurt) is a traditional dwelling of Mongolian nomads [2] and a unique mobile home that can be utilized for extended periods by nomadic people. The *ger* area is a major source of air pollution in Ulaanbaatar in wintertime. Due to these overlaying air-polluting sources, the authorities decided to replace the burning of traditional raw coal with upgraded briquettes in *ger* areas. This solution has brought some positive aspects, such as a significant reduction in PM2.5 and PM10 particulate matter concentrations, or 37-40 percent compared to the average of the previous five years [1]. Although the reduction in fine particulate matter in the air has been beneficial, some negative effects have begun to emerge. For example, there has been an increase in carbon monoxide (CO) poisoning associated with the new use of briquette fuel. Vapor (steam) gas or CO gas is a tasteless, odorless, colorless but poisonous gas. Because it is not detected by the sense of taste and smell, it is dangerous to be deeply poisoned by this gas, and breathing it for a long time can be fatal. Exposure to CO gas is the basis of many diseases such as asthma, respiratory infections, and bronchitis, and is a dangerous gas that can lead to death. Between 2019 and 2020, a total of 2,568 people were poisoned by CO, 1,133 of them were children, and eight children died. This figure is one of the main reasons why we need to do this research. As of today, despite the installation of CO detectors in most households, cases of acute poisoning are still being reported [3]. Therefore, in this study, we aim to determine the best possible location for CO sensors, as well as to model and illustrate the distribution of CO in three dimensions.

1.1 Carbon monoxide

Carbon monoxide poisoning is frequently labeled as "the silent killer." CO is a gaseous by-product that arises primarily from the incomplete combustion of various fuels, including oil, natural gas, coal, kerosene, wood, and even tobacco products [4]. In some cases, it can be produced by photochemical reactions in the atmosphere [5], which can be toxic to humans and animals. CO is an extensively found air pollutant that is commonly encountered [6]. Due to its difficulty in detection without specialized equipment, CO is highly dangerous and can cause severe harm or even death when inhaled. During the winter season, CO becomes a prevalent indoor air pollutant, especially when fuel-burning appliances like stoves and heaters are extensively used. It is also a significant outdoor air pollutant in urban areas with high levels of traffic and industrial activities. A publication from 2011 indicated that children living in Ulaanbaatar city were exposed to three times more CO than children living in provincial centers [7].

Its harmful effects stem from its ability to bind to hemoglobin in red blood cells, preventing the transportation of oxygen to the body's tissues. Moreover, it can lead to tissue damage, brain damage, and even fatality. This type of poisoning is known to be one of the leading causes of fatal poisonings in many countries [8]. CO is an extensively found air pollutant that is commonly encountered [6]. One notable example is the situation that unfolded in Korea during the 1960s when coal briquettes started being utilized as a household fuel source.

1.2 Exposure of carbon monoxide in Ulaanbaatar

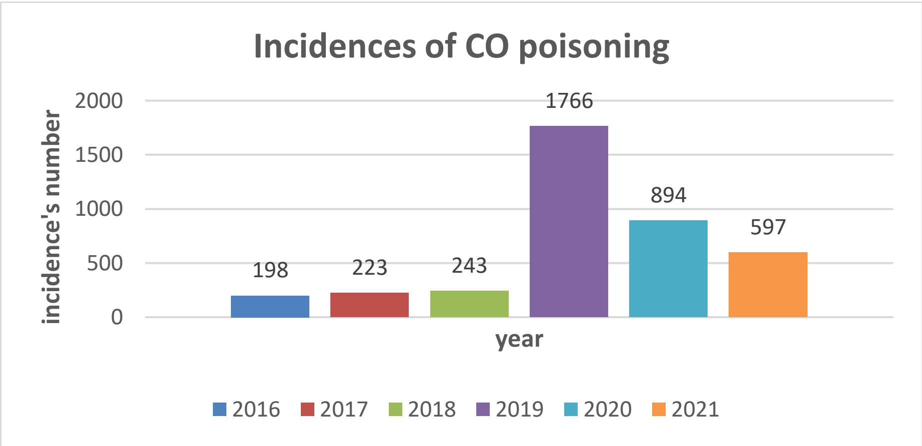
Fuel transition resulted in a significant increase in incidences of carbon monoxide poisoning (COP), posing a grave concern to public health and society at large [9]. Thus, the sudden increase in the incidences of COP has become a pressing concern in actions to combat the air pollution in Ulaanbaatar [9]. In 2019, the case of unintentional COP has become a public health issue in Ulaanbaatar city [3].

Figure 1 presents the number of deaths due to COP along with the corresponding incidences of COP over a six-year period, from 2016 to 2021. During 2016-2018, there were 10-13 reported deaths related to COP, while the total number of COP incidences was 198-243. A notable increase occurred in 2019, with 17 reported deaths and a significantly higher number of COP incidences, totaling 1766. It is important to consider that in the same year, the ban on the consumption of raw coal was implemented in central districts of Ulaanbaatar, which could have contributed to the increase in reported cases due to improved awareness and detection.

In 2020, the number of deaths due to COP increased to 20, while the overall incidences decreased to 894. This suggests a higher fatality rate among the reported cases compared to the previous years. In 2021, the number of deaths decreased to 9, and the incidences of COP also declined to 597.

This data highlights the potential dangers and risks associated with COP. While the number of reported incidences fluctuated over the years, indicating variations in awareness and prevention efforts, the number of deaths serves as a critical indicator of the severity and potential consequences of COP incidents.

Before 2019, the issue of COP was not a prominent topic, so decision-makers and the public did not pay much attention to it. It is possible that the majority of people were not fully aware of the toxicity and lethality of CO. However, during the winter season, incomplete combustion by-products were released into the indoor environment, leading to increased CO concentration in the indoor air. The sudden increase in the number of COP cases has become a pressing concern in the fight against air pollution [9].



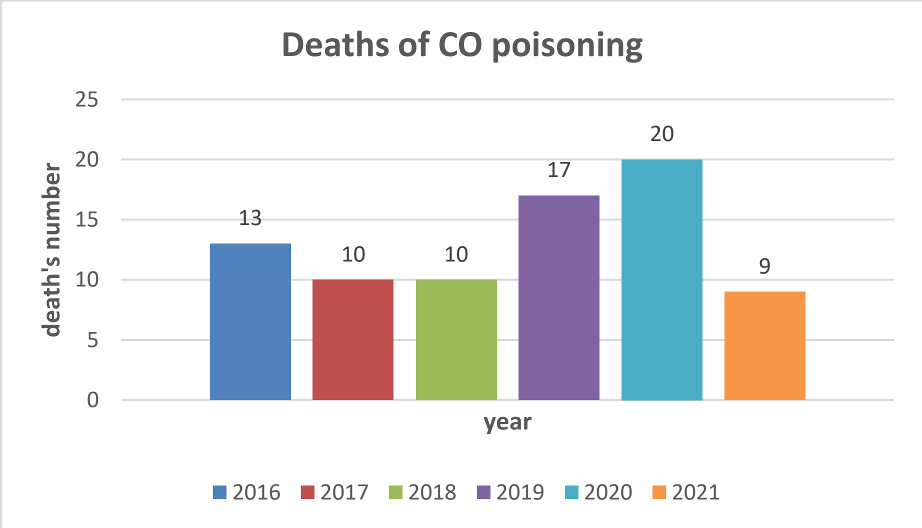


Fig. 1*. Incidences and deaths of carbon monoxide poisoning from 2016 to 2021. Source: National Emergency Center for Poisoning Mongolia.*

2 Materials and method

This study has two components: data collection and numerical simulation. Indoor measurements of CO, indoor temperature, and stove temperature were collected for continuous 2 hours. Two periods (December 2022 and early March 2023), when burning is effective were selected. Indoor CO, CO_2, indoor air temperature, and stove temperature were measured and the data were collected for continuous 2 hours. These measurements will determine how CO, CO_2, and other parameters in the indoor environment will change when the improved briquettes are used. The main goal was to model the diffusion of CO, and therefore to test possible scenarios for high CO concentration and obtain instrumental measurements in the measurement part. For example, the change in CO content was measured when the stove door was left open and the top lid of the stove was open. Quantitative values collected by this direct measurement method will be used to run a numerical model of CO distribution in the indoor environment. In this study, experimental measurements were performed with the Testo-317-3 carbon dioxide gas meter, Extech-100 for carbon dioxide, air humidity, and temperature monitoring, and Drager x-am-2500 multi-gas meter. A CO measurement was performed in one household which consume the briquette fuel.

2.1 Numerical simulation

Simulations of the dispersion of pollutants, specifically CO, in both two-dimensional and three-dimensional modeling were conducted. To achieve this, fluid motion, velocity gradient, and the conservation of fundamental laws were all taken into consideration [11], all of which are based on Newton's second law. In order to integrate these equations into COMSOL, the CO dispersion process was governed by several equations, including the momentum equation, the continuity equation, heat transfer equation, and mass conservation. As a result of these computations, a number of results on CO dispersion were obtained, both in two-dimensional and three-dimensional settings. Ultimately, the study provides valuable insights into the dispersion of pollutants, promoting better understanding of the emission and behavior of harmful gases.

$$\rho\frac{\partial u}{\partial t} + \rho(u\nabla)u = \nabla[-\rho I + K] + F + \rho g \qquad \text{Equation 1}$$

With $K=\mu(\nabla u+(\nabla u)^T)$ $\quad \rho\nabla u=0$

where and ρ is the fluid density, u is gas velocity, F stands for body forces.

This is the Navier-Stokes equation, which describes the motion of a fluid under the influence of external forces. the left-hand side of Equation 1 represents the rate of change of momentum of the fluid, while the first term on the right-hand side represents the pressure gradient force. The second term on the right-hand side represents viscous forces due to the fluid's resistance to deformation, where μ is the viscosity of the fluid and ∇u is the rate of strain tensor. The third term on the right-hand side represents any external body forces acting on the fluid, such as gravitational forces or electromagnetic forces. The term ρg represents the buoyancy force due to gravity. The equation also incorporates the continuity equation, which states that the rate of change of mass in a fluid is equal to the divergence of the fluid velocity multiplied by the fluid density ($\rho\nabla u=0$).

$$\rho C_p\frac{\partial T}{\partial t}+\rho C_p u\nabla T+\nabla q=Q+Q_\rho+Q_{Vd} \text{ with } q=-k\nabla T \qquad \text{Equation 2}$$

where and k is fluid thermal conductivity, C_p denotes heat capacity at constant pressure, T is absolute temperature, q is heat flux vector, Q stands for heat source, Q_ρ is heat transfer at constant pressure, Q_{Vd} heat source via viscous dissipation including viscous stress tensor. This equation is known as the heat equation and it describes the flow of heat in a fluid. The first term on the left-hand side represents the rate of change of heat energy per unit volume with respect to time. The second term represents the heat transfer due to advection. The third term represents the heat transfer due to conduction. The right-hand side of the equation represents the heat sources, including heat generation due to internal friction and heat transfer due to external sources. Equation 2 is a fundamental equation that governs the transport of heat in fluids. It is an important tool for modeling and analyzing various thermal processes.

$$\frac{\partial c_i}{\partial t}+\nabla J_i+u\nabla c_i=R_i \qquad \text{Equation 3}$$

with $J_i=-D_i\nabla c_i$

where and c_i is the concentration of the gas, D_i presents diffusion coefficient of the gas, R_i denotes the reaction rate.

In here u is the velocity of a fluid. Equation 3 describes the conservation of mass for a gas species i in a fluid, taking into account diffusion, advection, and reaction. The first term on the left-hand side represents the temporal change in gas concentration, while the second term represents the spatial change due to diffusion. The third term represents the spatial change due to advection, and the right-hand side represents the source or sink term due to chemical reactions. The negative sign in the definition of J_i implies that gas flows from higher to lower concentrations.

2.2 Construction of application

The next significant phase of our study involves building a ger model in COMSOL Multiphysics, as illustrated in Figure 1. The model of the Mongolian ger we considered was unfurnished/empty, and semi-furnished. As depicted in Figure 1a, the stove is a source of CO emissions, and the surfaces are heat-insulated with "*deewer*" and "*tuurga*" materials. Additionally, the model does not include any air exchanges, and the stove and chimney are treated as a single entity, with the chimney being well-sealed and free of any holes. We estimated that the furnace has lost around 50% of its seal. For detailed geometric dimensions of Mongolian houses, please refer to Figure 1b. The locations of CO measuring devices are indicated by two oval circles highlighted in red in Figure 1b. These devices were placed in this location because COP cases tend to occur during the night when individuals are in a deep sleep. To simulate this scenario, the average height of a bed in a typical household was considered, and the CO measuring device was placed at a height of 80 meters from the *ger* floor.

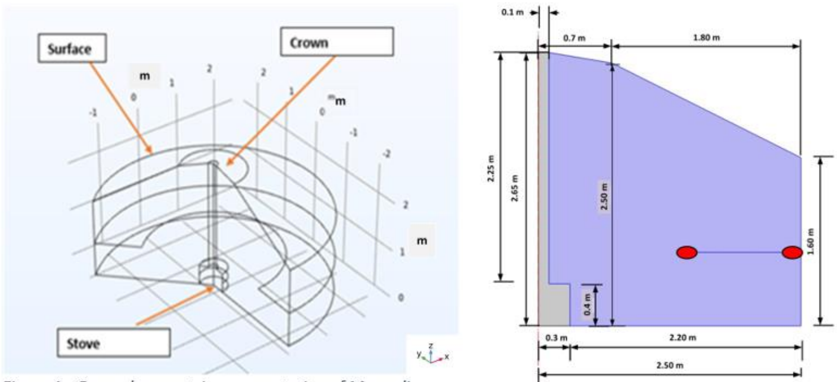


Figure 1a.General geometric representation of Mongolian ger in 3D in COMSOL model.

Figure 1b. Representation detailed geometric of Mongolian ger.

Figure 1. General geometric representation of Mongolian ger in 3D model.

3 Results and discussions

3.1 Measurements

Figure 2 presents the time series of measured CO concentration and temperature in indoor *ger*, with important changes marked by green arrows. The graph clearly depicts the impact of specific events on the CO concentration and temperature in the indoor environment. The first significant change occurs when the furnace is deliberately opened, causing a rapid increase in the CO concentration over time. However, as the measurement continues, the CO concentration gradually decreases. Furthermore, the addition of dry pine wood to the stove results in another abrupt temperature change. Interestingly, despite the sudden shift in temperature during this period, there is a gradual decrease in the amount of CO gas. In order to further evaluate the CO emission, the lid of the stove is removed and the burning coal on the stove is repositioned. This action leads to a sharp increase in CO levels, subsequently triggering the continuous ringing of the CO detector alarm. However, once the stove lid is closed again, the CO gradually decreases over time.

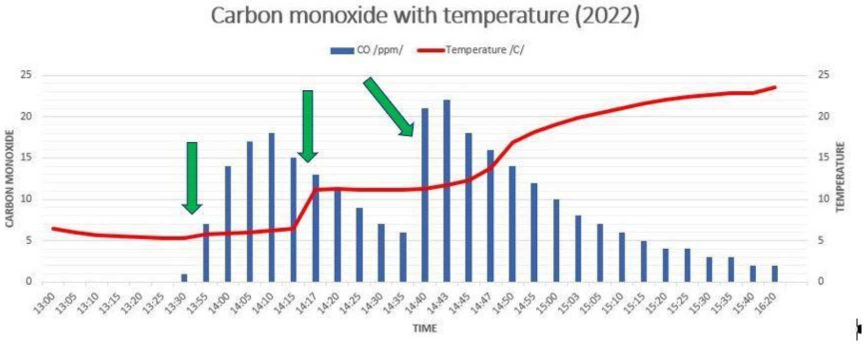


Figure 2. Time series of measured temperature and carbon monoxide. Measurements were conducted in December 2022.

Figure 3 presents the time series of measured CO concentration and temperature in indoor *ger*. At the beginning of time, both CO and air temperature remain low and stable, indicating a safe and normal living environment. However, when the stove door is opened for 3 minutes at 20:00, CO starts to rise significantly. The lid of the stove is removed, carbon monoxide levels continue to rise, eventually reaching a dangerous level of 58 ppm at 20:26. At this level, it is important to evacuate the area and seek medical attention immediately, however, in this situation CO detector's alarm still did not work. The air temperature also rises as the stove is used, reaching a maximum of 11.3°C at 20:47. The temperature rise is expected during heating events that involve stoves. Overall, the data shows that cooking with gas stoves can potentially produce dangerous levels of CO if indoor is not properly ventilated. It is important to ensure proper ventilation and use safety measures to prevent exposure to elevated levels of carbon monoxide.

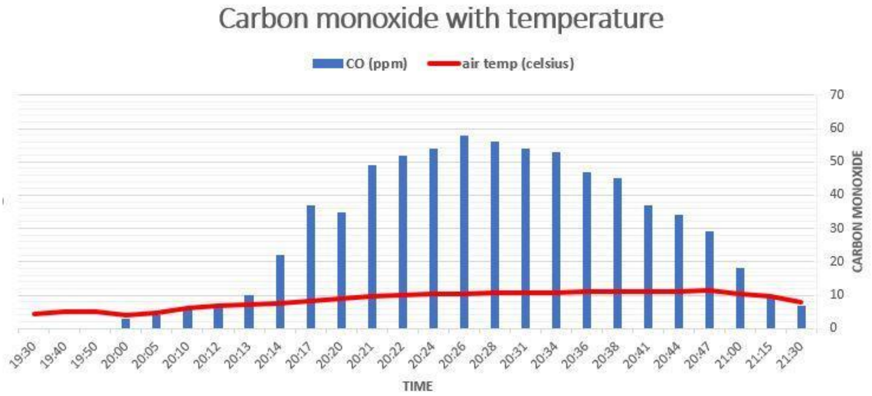


Figure 3. Time series of measured temperature and carbon monoxide. Measurements were conducted in March 2023.

3.2 Numerical simulations

Figure 4 shows the three-dimensional distribution of flue gases inside unfurnished *ger* with time. To note, the simulations did not consider temperature. CO spreads upward from the stove and then descends along the surface of *ger*. Its dispersion shape is U-like. CO level is the lowest at the ger floor, while maximum near the *ger* center. This information can be used to better understand the factors that contribute to CO emissions and to develop strategies to mitigate their harmful effects. During the simulation, high concentrations of CO can be observed near the *ger* center within the U-like sector. However, CO emission continues, it can be seen that the concentration of CO is the lowest where the CO sensors are suggested to be placed. This location is above the beds where people sleep.

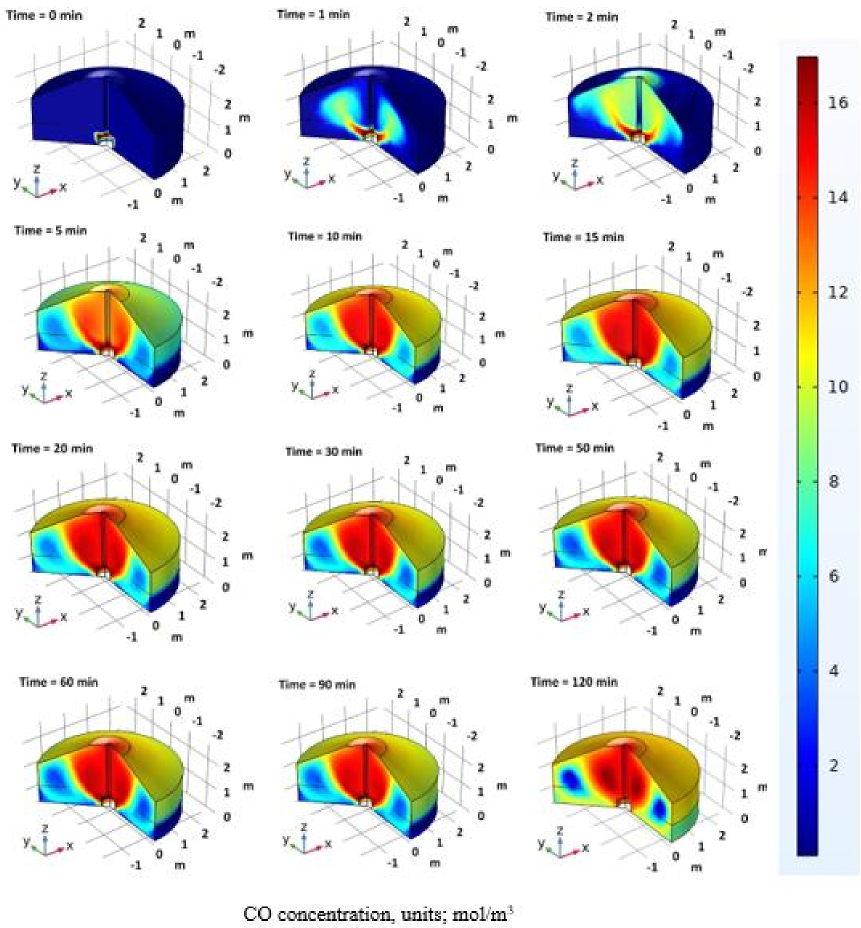


Figure 4. Temporal and spatial variations of CO distribution in unfurnished ger.

Next simulations with heat distributions provide valuable insights into the spatial and temporal variations of indoor tempearature (see Figure 5). These simulations specifically involve a furnished ger, where the temperature is estimated to vary between 0 and 37°C. Based on the simulation results, it becomes evident that the temperature spreads upwards from the heat source, progressively warming the internal environment of the ger. However, despite the overall overheating of the indoor temperature, the area beneath the bed exhibits a slightly lower temperature compared to the surrounding area.

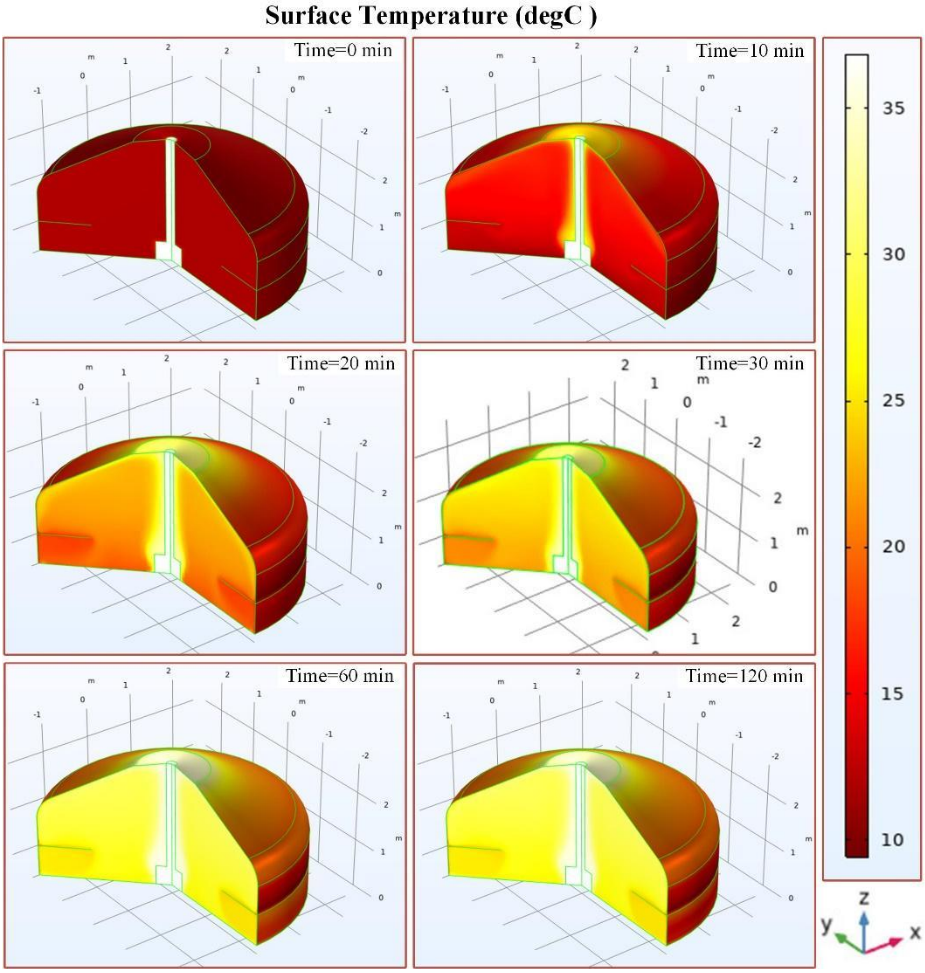


Figure 5. Temporal Variation of temperature distribution process on COMSOL in furnished ger.

Thus, another simulation is conducted to test whether CO is the lowest over the bed area in furnished ger. Figure 6 illustrates the distribution of CO. The simulation results show that CO initially spreads directly upwards from the source and then descends along the inner wall of the house. The flow in the furnished *ger* is different that in unfurnished *ger*. Upon reaching the next obstacle (bed), the direction of CO dispersion flow changes once again. Notably, the area with the lowest concentration of CO is situated in space between the stove and beds, but slightly above the beds. The highest concentration of CO is observed along the ger center above the stove. CO, a frequent indoor air pollutant, spreads indoor due to flow.

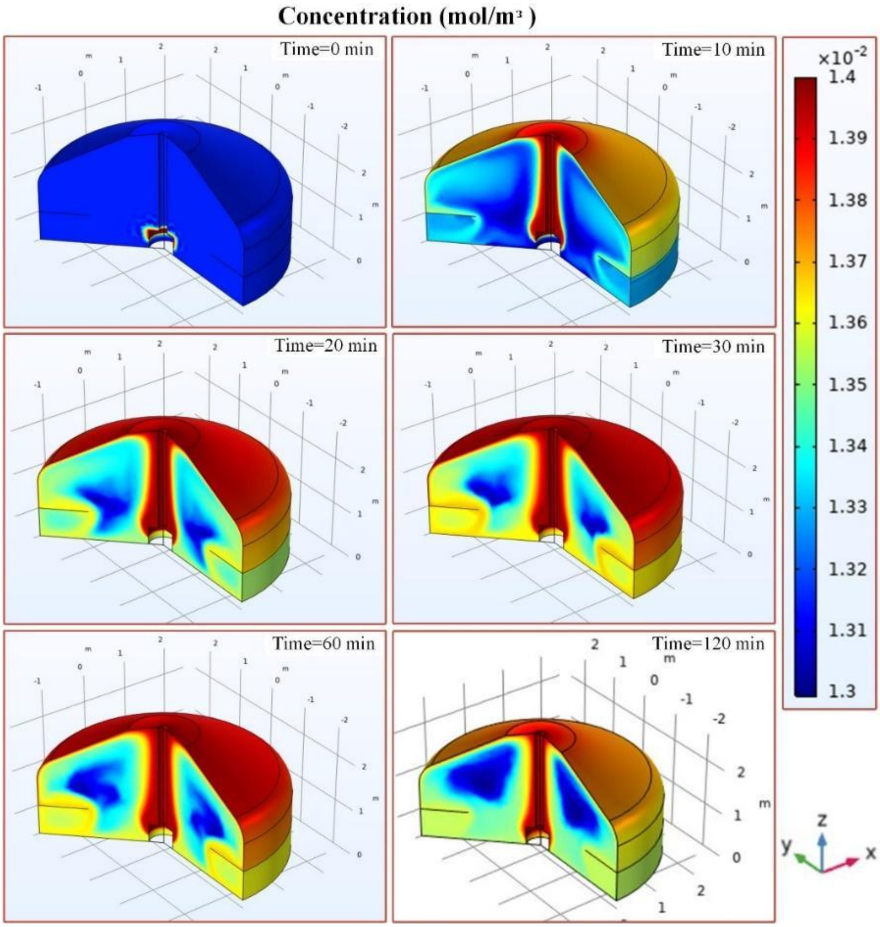


Figure 6. Temporal and spatial variations of carbon monoxide distribution in furnished ger.

Figure 7 visualizes the distribution of velocity magnitudes and provides a quick overview of the data points. It reveals that velocity magnitudes are larger along the center of the Mongolian *ger*. Higher velocity promotes efficient CO spread along the *ger* center. The distribution pattern indicates that the maximum speed values originate from the sources (stove), rapidly propagating to distant areas with speeds ranging between 0.6 and 1.4 m/s. Notably, the direction of the speed distribution changes and disperses at an average speed of 0.8 m/s.

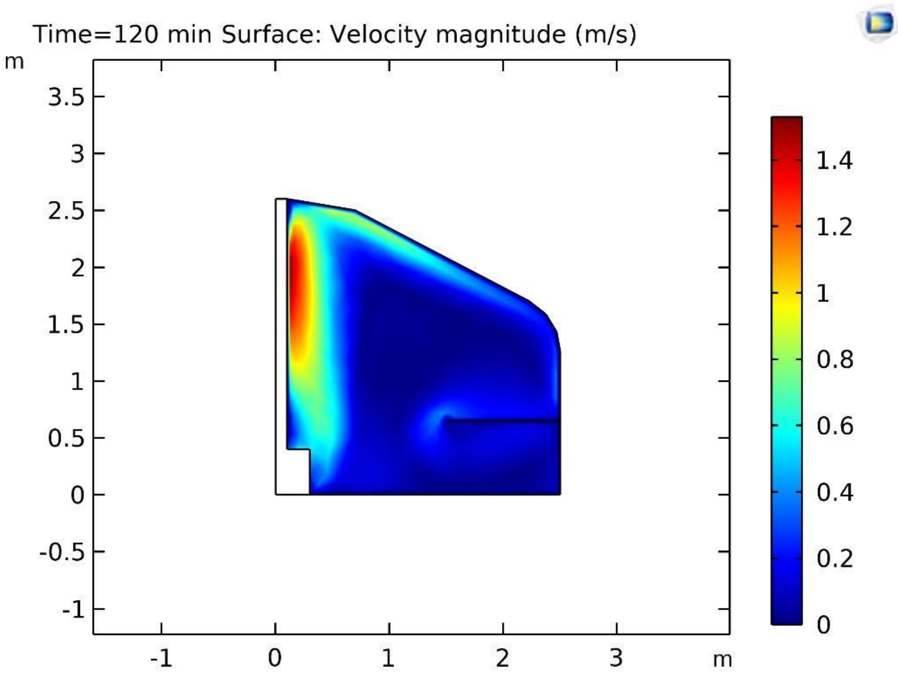


Figure 7 The color coded of Velocity magnitude of CO on COMSOL.

So far, there are no national standards on CO for indoor air in Mongolia, but there is World Health Organization (WHO) recommendation value. It was shown that the CO concentration was 27 and 50 times higher [12] than the WHO-recommended guidelines in Ulaanbaatar city. Studies [1] and [12] investigated the concentration of fine particulate matter (ppm) in air, and indicators of air quality in the external and internal environments, which are somewhat similar to our research. There are limited studies focusing on results of the numerical models for airflow or distribution of pollutants in Mongolian *ger*. A numerical study of heat distribution (dispersion) modeling in Mongolian *ger* was designed [13], but differs from our study in terms of objectives. As seen from the simulation results, it is observed that CO spreads from the source upward and descends along the inner wall cover of *ger*. In order to verify our simulations, we compared the simulation results with the data obtained from measurements. There is no significant difference between the simulation results and measured values, which indicates that our modeling was successful.

From the simulation results, maximum values of CO concentration are found around a stove and *ger* center, and the minimum value is near the lattice wall (bed). Besides, it should be noted in this numerical model that we considered the ger as unfurnished or semi-furnished to simplify the numerical simulations. WHO recommended that indoor CO is about 6 ppm, while the CO concentration obtained by our simulation and mechanical measurement is around 22 ppm which is three times greater than the WHO recommended. This means a majority of people are subject to get experience the COP

[16]. Similarly, the results of this simulation show that lack of ventilation during significant CO emissions increases the risk of COP. To confirm the results from the numerical simulations, differences were acceptably negligible compared (see Figure 8).

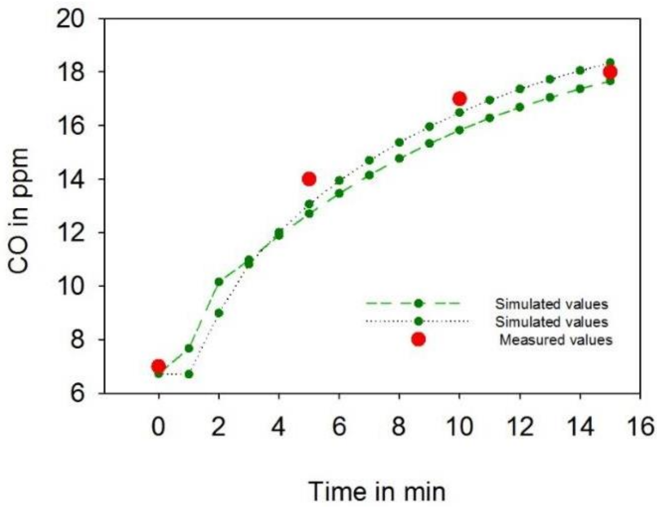


Figure 8. A graph comparing the measurement result with the simulation results.

4 Conclusion

The goal of this study is to simulate CO distribution in Mongolian *ger* by using a three-dimensional numerical model. To validate the simulation results, measurements of CO were conducted. Results showed that the CO concentration is different depending on locations in *ger* being the maximum above or nearby ger center and stove and the minimum near bed space. The following results can be summarized:

- CO distribution in *ger* indoor is simulated using the COMSOL Multiphysics.
- The difference between the numerical model and the actual CO concentration measured was relatively small.
- Leaving the stove door open for extended periods increases the risk of COP, even with standardized stoves.
- According to the simulations results, the pattern of CO diffusion in Mongolian *ger* is found at first going upwards from the source (stove) and then reflecting down along the inner wall of *ger*.
- Even with a good-quality stove, leaving the flue flap or the stove open for long time increases the risk of COP. Therefore, it is necessary to carry out air exchange at a certain frequency.
- While the general patterns of CO distribution in furnished and unfurnished environments exhibit different patterns.
- Based on the simulation results, the best to place CO detectors would be the area where the CO concentration reaches its maximum along the tilted wall.

In the future, it is necessary to accurately approve indoor air quality standards. The simulation settings in this study can be extended further to provide detailed explanation of indoor air quality in Mongolian *gers*. Although indoor air quality studies in Mongolia have been extensively conducted, few studies have been focused on the dispersion of air pollutants. This study is the first to model CO distribution in Mongolian *ger*.

4 ACKNOWLEDGEMENT

The research was carried out within the framework of the "COINGER" project funded by SRDF, German-Mongolian Institute for Resources and Technology – (GMIT).

References

1. Ganbat G, Soyol-Erdene TO, Batbayar J. (2020) Recent Improvement in Particulate Matter (PM) Pollution in Ulaanbaatar, Mongolia. Aerosol and Air Quality Research 20: 2280–2288
2. Mauvieux B, Reinberg A, Touitou Y. (2014) The yurt: A mobile home of nomadic populations dwelling in the Mongolian steppe is still used both as a sun clock and a calendar. Chronobiology International 31:151–6.
3. Otgonbyamba O, Altangerel E, Ganbat G, Ganbold B, Sodnomjamts A, Chuluunbaatar B, Badrakh B, S Batbaatar (2023) Unintentional Carbon Monoxide Poisoning Outbreak from 2 to 9 October 2019 in Ulaanbaatar, Mongolia. Occupational Diseases and Environmental Medicine, 11, 97-114. doi:10.4236/odem.2023.112006.
4. Pillarisetti A. et al. (2019) Advanced household heat pumps for air pollution control: A pilot field study in Ulaanbaatar, the coldest capital city in the world. Environ Res. 176. https://doi.org/10.1016/j.envres.2019.03.019
5. The RBC as A Physiological Object (2014) Pathobiology of human disease, p. 3049.
6. Ganbat G. The Fundamentals of Air Pollution. UB: 2022.
7. Tulchinsky TH, Varavikova EA, MJ Cohen (2023) The New Public Health. Academic Press.
8. Dashdendev B et al. (2011) Carbon monoxide pollution and lung function in Urban compared with rural Mongolian children. Respirology 16:653–658.
9. Omaye ST (2002) Metabolic modulation of carbon monoxide toxicity. *Toxicology* 180:107.
10. Kim OJ, Park SH (2012) A social history of carbon monoxide poisoning in Korea in 1960s: from an accident due to carelessness to a social disease. The Korean Society for the History of Medicine 21:279–344.
11. Dickson-Craig E et al. (2022) Carbon monoxide levels in households using coal-briquette fueled stove exceed WHO air quality guidelines in Ulaanbaatar, Mongolia. International Journal of Environmental Health Research 7:1–12.

12. Furlan, Jacqueline, Aparecido, Jairo and Claro, Estaner. 2019, Ain Shams Dispersion of toxic gas (CO and CO2) by 2D numerical simulation. Engineering Journal.
13. Galsuren J et al. (2022) Indoor air quality study among the households of Ulaanbaatar, Mongolia.
14. Badarch A et al. (2017) Numerical Analysis of different Heating Techniques for a Mongolian Ger by the Lattice Boltzman Method. Khurel togoot.
15. Carbon Monoxide (Second edition). 1999.
16. Flachsbart G (2006) Exposure to Carbon Monoxide. [book auth.] Wayne R. Otto, Anne C. Steinemann and Lance A. Wallace. Exposure Analysis. p. 113.
17. Wright, J. (2002) Chronic and occult carbon monoxide poisoning: we don't know what we are missing. 5, s.l.: Journal of Emergency Medicine , 2002, Vol. 19.