TECHNICAL NOTES

Carbon Monoxide Diffusion through Porous Walls: A Critical Review of Literature and Incidents

Izabella Vermesi
Francesco Restuccia
Carlos Walker-Ravena
Guillermo Rein
Imperial College London

Fire Protection Research Foundation

The Fire Protection Research Foundation
One Batterymarch Park
Quincy, Massachusetts, U.S.A. 02169-7471
E-Mail: foundation@nfpa.org
Web: www.nfpa.org/foundation

Acknowledgements

The Fire Protection Research Foundation expresses gratitude to those that assisted with the development and review of the information contained in this report. The Research Foundation appreciates the guidance provided by the Project Technical Panel:

- Tom Cleary, NIST
- Dan Finnegan, Siemens
- Dan Gottuk, Jensen Hughes
- Wayne Moore, Jensen Hughes
- Dave Newhouse, Gentex
- Tom Norton, Norel Service Company
- Stephen Olenick, Combustion Science & Engineering
- Richard Roberts, Honeywell
- Bob Schifiliti, RP Schifiliti Associates
- Lee Richardson, NFPA Staff Liaison

Special thanks are expressed to NFPA for funding this project through the annual Code Fund.

About the Fire Protection Research Foundation

The Fire Protection Research Foundation plans, manages, and communicates research on a broad range of fire safety issues in collaboration with scientists and laboratories around the world. The Foundation is an affiliate of NFPA.

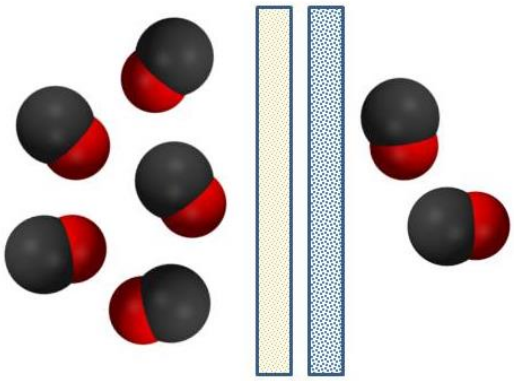
About the National Fire Protection Association (NFPA)

NFPA is a worldwide leader in fire, electrical, building, and life safety. The mission of the international nonprofit organization founded in 1896 is to reduce the worldwide burden of fire and other hazards on the quality of life by providing and advocating consensus codes and standards, research, training, and education. NFPA develops more than 300 codes and standards to minimize the possibility and effects of fire and other hazards. All NFPA codes and standards can be viewed at no cost at www.nfpa.org/freeaccess.

Keywords: carbon monoxide, CO, gas diffusion, porous walls

Imperial College London

Carbon Monoxide Diffusion through Porous Walls: A Critical Review of Literature and Incidents



Research Report to Sponsor: Fire Protection Research Foundation, Quincy, MA, USA

Authors: Izabella Vermesi, Francesco Restuccia, Carlos Walker-Ravena and Guillermo Rein
Department of Mechanical Engineering
Imperial College London
Exhibition Road
London, SW7 2AZ, UK

g.rein@imperial.ac.uk

Executive Summary

It has been reported recently that in laboratory conditions carbon monoxide (CO) diffuses through gypsum board at a surprisingly high rate (Hampson, et al., 2013). Because CO is poisonous and a by-product of systems typically present in residential housing like boilers, generators, furnaces and automobile engines, this finding could have a significant impact on the life safety standards published by National Fire Protection Association (NFPA) and International Code Council (ICC), such as the 101, NFPA 5000, International Residential Code and International Building Code. In the US, state legislation (NCSL, 2014) mandates the requirements for CO detection and warning equipment to be installed, but currently only enforces CO detection if there are communicating openings between the garage and occupied areas of a building.

With the sponsorship of the Fire Protection Research Foundation, we have conducted a literature review on CO diffusion through walls. We have analyzed in detail the data from the recent experiments with a mass transfer model and confirm the validity of the findings for gypsum board. We have also found a number of actual incidents and laboratory experiments which confirmed the transport of CO through other types of porous walls. We also found studies on the transport of other hydrocarbon gases with larger molecules than CO that can also diffuse through porous walls.

Our analysis and review independently confirms that CO can diffuse through porous walls at a fast rate and that the phenomena may merit consideration in life safety standards.

Acknowledgements

This research has been funded by the Fire Protection Research Foundation (FPRF). The authors thank the help of the advisory panel set up and chaired by Amanda Kimball at FPRF. The input and guidance of the technical panel was invaluable:

- Amanda Kimball, NFPA (chair)
- Tom Cleary, NIST
- Dan Finnegan, Siemens Inc.
- Dan Gottuk, Hughes Associates Inc.
- Wayne Moore, Hughes Associates Inc.
- Dave Newhouse, Gentex Corp.
- Tom Norton, Norel Service Co. Inc.
- Stephen Olenick, CSE Inc.
- Lee Richardson, NFPA
- Richard Roberts, Honeywell Inc.
- Bob Schifiliti, R.P. Schifiliti Associates Inc.

Keywords: carbon monoxide, diffusion, gypsum wallboard

Carbon Monoxide Diffusion through Porous Walls: A Critical Review of Literature and Incidents

1. Introduction

Carbon monoxide (CO) is a colorless, tasteless and odorless gas formed by the incomplete combustion of hydrocarbons such as wood, propane, gasoline, charcoal, natural gas and oil. It poses a threat to people, as it is poisonous in high concentrations due to its interference with oxygen transportation in the respiratory system (Nelson, 1998).

Previously, it was thought that the threat of CO poisoning was confined to direct sources, such as gas cookers and coal-burning fires, and that if none of these sources were present inside a dwelling then neither was the threat of CO intoxication. However, this notion has now come under scrutiny due to investigation and reporting of several incidents in which CO might have been introduced into homes through non-communicating walls and floors (Keshishian, et al., 2012).

The main driver of this investigation is in (Hampson, et al., 2013), in which CO is observed to transport from one chamber to an adjacent chamber by crossing a sample of gypsum wallboard. The aim was to study how fast a noxious concentration (100ppm) is reached on the side that has no source of CO being infused. The gypsum boards used for this investigation were single layer 0.25" and 0.5" gypsum wallboards, as well as double layer 0.5" wallboard and double layer 0.5" wallboard that was painted on one side. For these wall configurations, the toxic concentration was reached in a much shorter time than was expected, i.e. from 17 to 96 min, depending on the test.

The consequence of these findings is the acknowledgement of the increased susceptibility to CO intoxication and the possible changes in life safety legislation to accommodate for this previously dismissed pathway. Currently, life safety codes such as NFPA 720 (NFPA, 2012) and the NFPA (National Fire Protection Association) and ICC (International Code Council) model codes only require the installation of CO detection in buildings that have openings between the garages and the occupied areas. However, the realization that this assumption is not valid and openings are not the only means of CO transmission may bring about stricter regulations regarding CO detection.

Such repercussions require the study (Hampson, et al., 2013) and phenomenon to be independently confirmed. A literature review is done in order to assess any previous studies that are relevant to the transport of CO through porous walls. Works focusing on the diffusion of gaseous species through membranes are reviewed. Afterwards, a

mass transfer study of the experimental paper by (Hampson, et al., 2013) is performed using a simple mathematical model.

2. Previous Studies on CO Transport

Diffusion in Porous Media

Diffusion is the transport of mass from a region of high concentration to a region of lower concentration (Incropera, et al., 2013). There are several mechanisms of diffusion depending on the ratio between the mean free path of gas molecules and the mean pore diameter (Gilliland, et al., 1974). Affinity towards transition (Knudsen) diffusion is shown when the mean free path of the molecules is larger than the mean pore radius of the porous medium, while a tendency for laminar/molecular flow is shown when the mean free path of the molecules is smaller than the mean pore radius of the porous medium. Essentially, this allows us to characterize these two diffusion mechanisms by their collisions: Knudsen diffusion constitutes molecule-wall collisions and is typical of smaller pores whilst molecular diffusion is represented by molecule-molecule collisions and occurs in large pores (Kontogeorgos & Founti, 2013). A third diffusion mechanism has been observed in which the gas moves along the surface of the separating media, this form of diffusion is known as surface diffusion. The surface diffusion is typically of the order of 10^{-7}–10^{-9} m^2/s (Treybal, 1981) which is several orders of magnitude smaller than both molecular and Knudsen diffusion.

The needle-like structure of the gypsum wallboard allows diffusion transport to occur due to a very complex process that involves molecular, Knudsen and surface diffusion within the porous interstices (Kontogeorgos & Founti, 2013). Various indoor climate experimental tests, (Blondeau, et al., 2003) (Meininghaus & Uhde, 2002) (Meininghaus, et al., 2000), have studied the diffusion through porous walls of volatile organic compounds (VOC). The results presented in these works clearly show the transport of gases through the pores of the material. Therefore, the claim that CO diffuses through porous walls is supported.

Experimental Studies Involving Drywall

The effects of heating and air conditioning, interior doors, windows and exhaust fans on gas movement were evaluated using CO as the tracer gas in (Chang & Guo, 1992). The tests were carried out in a test house designed to replicate the interior of a residential dwelling. One of the test cases had the CO source in the bathroom, with the bathroom doors closed, the heating, ventilation and air-conditioning system of the house turned off and the bathroom fan turned off. While the bathroom door was not purposely sealed off with impermeable materials, so some leakage might have existed,

the main increase of CO concentration in the rest of the house was attributed to diffusion. The CO started to diffuse from the source room after the 10h, with the rate of diffusion increasing as the time passed.

The main transport process investigated in (Singer, et al., 2004) was sorption. As diffusion is a process that contributes to sorption it is of interest to relate the findings of this investigation. In this experiment a $50m^3$ chamber with walls made from gypsum wallboard with a layer of low VOC flat latex paint was sealed. Twenty VOC gases were infused in the chamber, which was placed inside a test house. The gases were observed to diffuse through the gypsum walls of the chamber. The time frame for these experiments ranged from 2h to 12 h. It was acknowledged that the chamber infiltration rates might reflect pore diffusion rates rather than air exchange.

Through the experimental study of indoor air quality, these two investigations confirm the possibility of CO transport through porous walls at a rate that presents a danger to people, despite the fact that the first case did not contain an airtight chamber, and the second investigated VOC. The first one represents a scenario that can be found in everyday conditions, therefore it is important to acknowledge the influence of diffusion.

Diffusion of Hydrocarbons Through Porous Walls

Amongst the literature reviewed there were examples of other, larger hydrocarbon gases transported through porous interfaces. In particular, cases were found where gypsum wallboard was used.

Formaldehyde (CH_2O) was used as the test gas in (Deng, et al., 2009). Four building materials were tested, namely particleboard, vinyl floor, medium-density board and high-density board. Formaldehyde was observed to travel across them. Each of the four building materials' diffusion coefficient was evaluated at different temperatures: particleboard had the highest diffusivity ($3.18 \cdot 10^{-12}$ m^2/s at 18°C) followed by high-density board ($6.87 \cdot 10^{-13}$ m^2/s at 18°C), medium-density board ($7.68 \cdot 10^{-13}$ m^2/s at 18°C) and finally vinyl flooring with the lowest ($9.17 \cdot 10^{-14}$ m^2/s at 18°C). These results not only show diffusion of a gaseous species through a porous media but support the case for CO diffusion as CO has a smaller molecule size than formaldehyde and therefore it can diffuse more easily.

Diffusion through a gypsum board was found in (Blondeau, et al., 2003). It aimed to determine the diffusion of ethyl acetate (CH_3-COO-CH_2-CH_3) and n-octane (C_8H_{18}) in building materials by analysing the material porosity first and afterwards applying Carniglia's mathematical model. The computed effective diffusivities for various building materials were subsequently compared to data from previous experiments, showing good agreement. The calculated effective diffusivity of ethyl acetate and n-

octane through gypsum board are around$1.2 \cdot 10^{-6}$ m^2/s for the former and $0.9 \cdot 10^{-6}$ m^2/s for the latter. It should be noted that in this experiment these gases both have larger molecules than CO and hence, under the same conditions, one would assume that CO would diffuse to a greater extent if not to a similar extent.

Further examples of diffusion of ethyl acetate and n-octane through gypsum wallboard were shown in (Meininghaus, et al., 2000). The purpose was to present quantitative experimental results on diffusion and sorption of volatile organic compounds (VOC) in indoor materials and was done using a Climpaq style chamber (Gunnarsen, et al., 1994), the edges of which were sealed to inhibit air leakage. It was found that mass transport of these gases can occur very quickly, with some effective diffusion coefficients being one order of magnitude below those found in air – similar to the findings in (Blondeau, et al., 2003). Also, it was found that gypsum board showed the highest diffusion coefficient of all studied materials, followed by aerated concrete, carpet, brick wall, solid concrete, wallpaper with paste, and acrylic paint on wallpaper. Hence, we can conclude that the fast diffusion of carbon monoxide through gypsum wallboard is plausible.

Further diffusion through building materials was found reported in (Meininghaus & Uhde, 2002). In this paper the mass flow rate of VOC mixtures across a gypsum board was studied using two setups, both of which include a FLEC (Field and Laboratory Emission Cell) and were sealed with either Teflon or aluminium tape to ensure no air leakage. The results of this paper showed that the transport of certain VOC across a gypsum board could be fast especially in the case of less polar compounds. Furthermore, it was found that the mass transport was dependent on molecular properties such as the boiling point and the molecular area and that similar compounds show similar mass transport processes. Thus this validates the possibility of using other gas tests to approximate the diffusion of CO.

Hence, from these cases we can see that the support for carbon monoxide diffusing through gypsum is well documented. The experimental observation of gases with increased molecular mass diffusing through gypsum wallboard alludes to the possibility of carbon monoxide diffusing through gypsum wallboard, as the ability of a molecule to undergo diffusion increases with decreasing molecular mass.

Reported Incidents

It was found that most reported cases of CO intoxication in the literature were attributed to vehicles and appliances in the same room as the victim of the intoxication with little details being given about the cases involving a potential CO source located in a non-communicating area. This is due to the lack of understanding of whether CO can transport through non-communicating rooms. However, there are

a few available reported incidents that deal with potential instances where CO transport took place through walls.

Three incidents are highlighted (Keshishian, et al., 2012) where CO, produced in neighboring restaurants, travelled through the walls and floor and resulted in toxic levels within the adjacent residencies. All three restaurants used charcoal-burning tandoor ovens or grills which, although ventilated during the day, were left smoldering overnight with the ventilation turned off, resulting in a build-up of CO. These periodic accumulations of CO were seen reflected in the residencies indicating that the levels in the two properties were not independent of one another and that transport of the gas was taking place. Because there were no communicating openings between the restaurants and the homes, it is most probable that CO travelled through diffusion.

A similar situation was reported in (West, et al., 2008) in which a neighboring restaurant was influencing CO levels within a residency. The report focuses on identifying the symptoms of CO poisoning and on giving recommendations on the optimal ventilation to avoid build-up of CO. While the restaurant was placed below the apartment, there are no further descriptions of the configuration. However, it is most probable that the transport of CO was through the floor.

An incident was reported by (OSHA, 2012) in which the exhaust of a swimming pool natural-gas heater was channeled through a detached pipe through four of the five floors of a hotel building, contained within a large shaft. However, the ventilation system was not functioning correctly and a build-up of CO was produced within the shaft. As a consequence two employees, in a room adjacent but not communicating to the shaft, were affected by CO poisoning. Despite the report being very short, it is conclusive to say that CO travelled through the walls.

It was reported in (Hampson, 2009) that levels of CO in a first floor bedroom were being affected by emission from a water heater in the ground floor utility room. However, this report is just a reply to an article, therefore the incident is not detailed extensively and so one can only assume that diffusion or air leakage was the main transport mechanism.

Many reports of CO intoxication focus mostly on presenting the symptoms of CO poisoning and identifying the source which produces CO, as well as recommendations for avoiding intoxication. Details such as building materials, presence of vents or openings are not presented, making it difficult to pinpoint diffusion as a means of transport of CO through walls. However, the cases presented support the evidence of CO transport through walls, given that there were no clear communicating openings between the CO-producing room and the adjacent rooms where high levels of CO were measured.

3. Mass Transfer Analysis of Hampson et al., 2013

The experiments that signaled the possibility of diffusion of CO through gypsum wallboards (Hampson, et al., 2013) were carried out in a test chamber made of Plexiglass supported by a wooden frame, with the exterior dimensions of 0.6 by 0.6 by 2.44m (24 by 24 by 96 inches) and sealed with silicone caulk at all junctions, as shown in Fig 1. The chamber consisted of two sides separated by a gypsum wallboard of various thicknesses (single layer 0.25"-6.35mm- and 0.5"-12.7mm-, as well as double layer 0.5"and double layer 0.5"painted). Carbon monoxide test gas at 3000ppm was infused on one side at 15l/min until it reached a concentration of 500 to 600ppm. Measurements were taken at the control side every 1 min for 24h, in order to establish how long it takes for the concentration to reach levels that affects humans (100ppm). Fig. 2 shows a summary of these experiments, presenting on the left side the CO concentration levels in the chamber where the gas was infused for every configuration used. The right side of the figure shows the CO concentration levels in the control chamber after CO diffused through the wall. The complete raw data set can be found online (Hampson, 2014). It was found that depending on the configuration, this concentration was reached in 17 to 96 min. Also, the CO concentration in both chambers differed by only 5% after 12h.

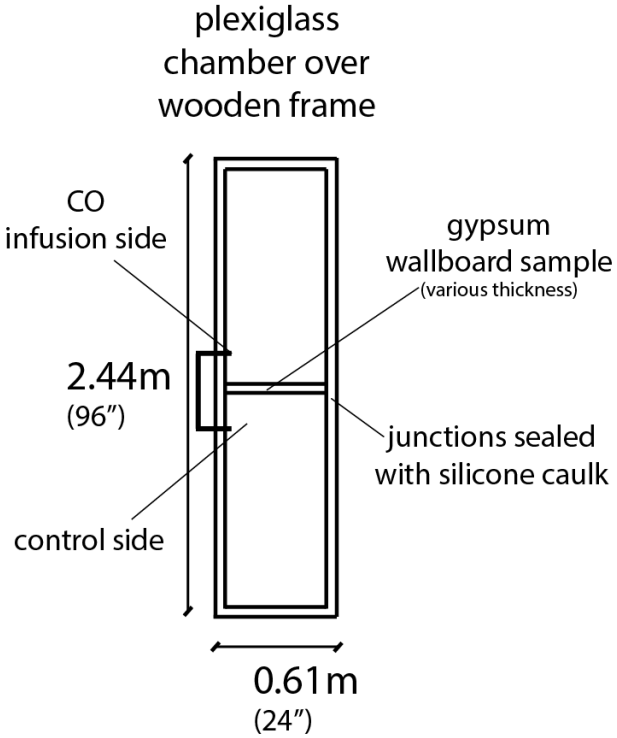


Figure 1. Sketch of experimental setup used in (Hampson et al. 2013)

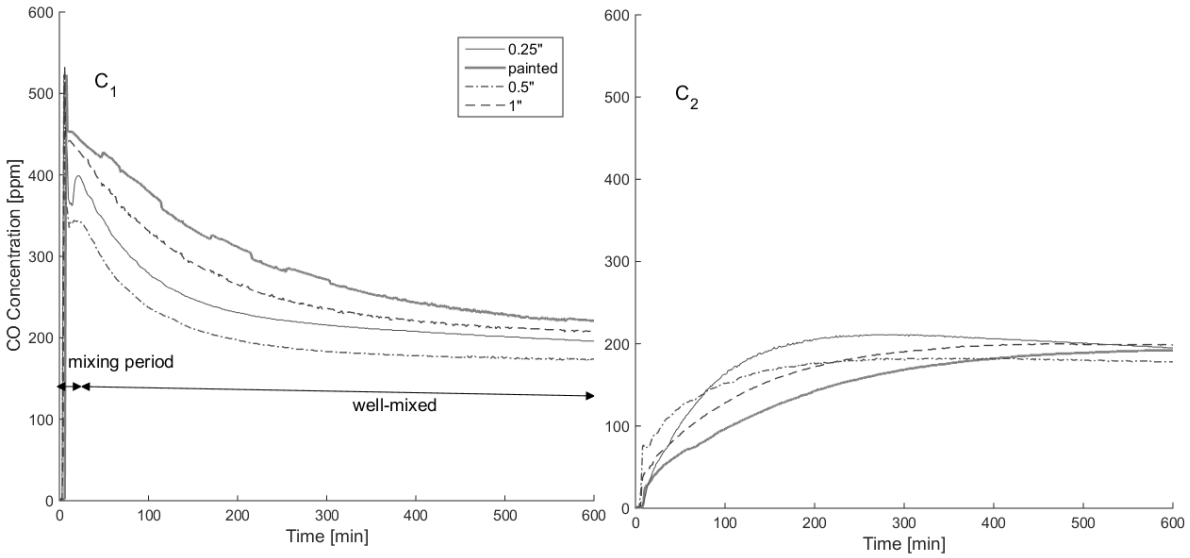


Figure 2 Summary of the experiments in (Hampson et al, 2013); left: CO concentration in the infusion chamber, right: CO concentration in the control chamber

The simple model used to replicate the experiments is a simplified 1D mass transfer model which assumes well-mixed CO in the chamber, an assumption which is investigated further on. The equations for this model, as well as the initial conditions are specified in Eq. 1-5, where c_1 and c_2 are the concentration in the infusion (first) and control (second) chamber, which are dependent on time, c_1^0 is the initial CO concentration in the infusion chamber, and K is a constant. K (s^{-1}) is a diffusion parameter that is found by equating the mass lost from a chamber per unit time to the flux by diffusion. It is represented by Eq.6, where D is the diffusivity of the gas into the gypsum board, units of $m^2 s^{-1}$, A (m^2) the area of the gypsum board, L (m) the thickness of the gypsum board, V (m^3) is the volume of the tank.

$$\frac{dc_1}{dt} = (c_2 - c_1)K \quad (1)$$

$$\frac{dc_2}{dt} = (c_1 - c_2)K \quad (2)$$

Initial conditions:

$$c_1(0) = c_1^0 \qquad c_2(0) = 0 \quad (3)$$

$$c_1(t) = \frac{c_1^0}{2}(1 + e^{-2Kt}) \quad (4)$$

$$c_2(t) = \frac{c_1^0}{2}(1 - e^{-2Kt}) \quad (5)$$

$$K = \frac{DA}{LV} \quad (6)$$

When calculating the mean diffusivity, we ignore the transient and study the values calculated from measurements in the non-transient diffusion region, so after the mixing of the gas in the infusion side of the tank is complete. The differences caused by this assumption are negligible.

Mass conservation was invoked in the analysis, but in the experimental data there were mass losses in the system. To quantify these, mass loss out of the setup during the first 10h of the experiment was also calculated. This was done by summing $c_1(t)$ + $c_2(t)$ and comparing it to c_1^0. 10h was chosen as the length of time to ensure that in all the different experiments the concentration on both sides of the setup had stabilized, so as to ensure that all relevant diffusive processes are included in this analysis. Mass loss is less than 8% for the published experiments (0.5" gypsum wallboard), but is considerably greater for those at the other thicknesses (0.25", double 0.5", double 0.5" painted). Therefore mass was not conserved in all experiments, which is another factor not considered in the model proposed here since the equations assume mass conservation. The mass loss can be explained by the CO being absorbed by the Plexiglass walls or leaking through the junctions.

The initial value of CO in the infusion was taken to be the value of CO present after the mixing was complete. Therefore we ignore the mixing time and assume perfectly mixed gases in the diffusion tank for the model. In the experimental data, the initial CO concentration reported is different because it is measured in the mixing period prior to the well-mixed state being reached. Note that the effective diffusivity D_e is calculated using the values from Eq. 7 and 8, and averaging the two as shown in Eq 9. This means that diffusivity is being calculated with concentrations from both sides of the tank.

$$D_1 = \frac{-VL}{2At} ln\left(\frac{2c_1}{c_1^0} - 1\right) \quad (7)$$

$$D_2 = \frac{-VL}{2At} ln\left(1 - \frac{2c_2}{c_1^0}\right) \quad (8)$$

$$D_e = \frac{\mathrm{D}_1 + D_2}{2} \quad (9)$$

The effective diffusivity D_e is calculated averaging the D values provided by Eqs. (7) and (8) onwards 15 min since CO infusion (to assume well-mixed conditions) until the infusion side of the tank reaches a CO concentration half its initial value, which is considered to be the theoretical steady-state point. The ranges of diffusivities found are between $1.6 \cdot 10^{-6}$ and $4.0 \cdot 10^{-6}$ $m^2\ s^{-1}$. The difference in values can be explained by differences in mass losses for each experiment and slight variation in the experimental setup when changing the thicknesses of the gypsum board, but all of the results are in the same order of magnitude. The results for the mean diffusivities are gathered in Table 1.

Table 1. The values of calculated effective diffusivities for all 12 experiments

Test	c_1^0	Mean D [m^2s^{-1}]	% Mass Loss after 10h (m_l)
0.25" - Test 1	480	1.71×10^{-6}	14.2%
0.25" - Test 2	440	1.75×10^{-6}	11.1%
0.25" - Test 3	470	1.60×10^{-6}	10.2%
0.5" - Test 1	330	4.03×10^{-6}	6.1%
0.5" - Test 2	380	4.00×10^{-6}	7.4%
0.5" - Test 3	350	4.06×10^{-6}	4.9%
1" - Test 1	490	4.80×10^{-6}	18.0%
1" - Test 2	490	5.00×10^{-6}	17.6%
1" - Test 3	485	4.46×10^{-6}	15.8%
Painted 1" - Test 1	500	2.89×10^{-6}	15.6%
Painted 1" - Test 2	485	3.08×10^{-6}	14.8%
Painted 1" - Test 3	495	3.19×10^{-6}	14.1%

The test case chosen to be presented fully is test 2 from the 0.5" gypsum wallboard, which was also shown in (Hampson, et al., 2013). Fig. 3 shows the mass loss over 10 hours, where the dotted line represents the initial CO concentration in the infusion chamber c_{1^0} and the solid line the sum of the concentrations on both sides of the setup $c_1(t) + c_2(t)$. Fig. 4 shows the calculated diffusivity, having an average of $4 \cdot 10^{-6}$ $m^2\ s^{-1}$. Fig. 5 directly compares the results from the experiments with the model results which use the calculated diffusivities. They are in the same order of magnitude with the results of separate tests carried out by Cleary (Cleary, 2014). The values of the effective diffusivities are summarized in Fig. 6 where they are compared to Cleary's test results as well as the effective diffusivity of several other gases through gypsum found in literature and given for reference (Blondeau, et al., 2003). It should be noted however, that these values do not represent the diffusion, which is clearly faster for thinner materials, but the diffusivity which is a material property and thus does not depend on thickness. The differences in diffusivities stem from the errors from the experimental setup as explained in the previous paragraph, but all of the results are within the same order of magnitude.

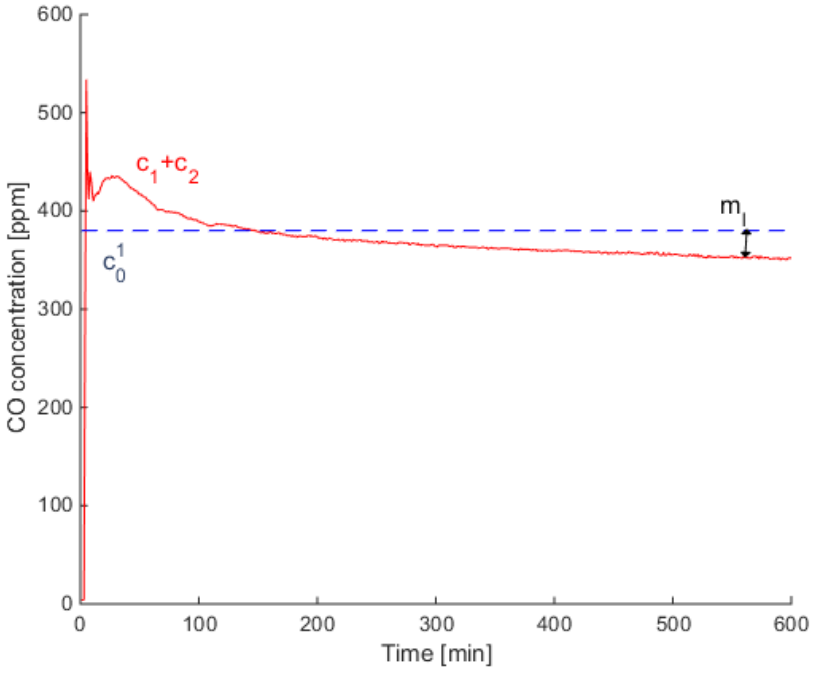


Figure 3 Mass loss rate comparison for 0.5" test 2. c_{1_0} is compared to $c_1(t) + c_2(t)$ over 10 hours

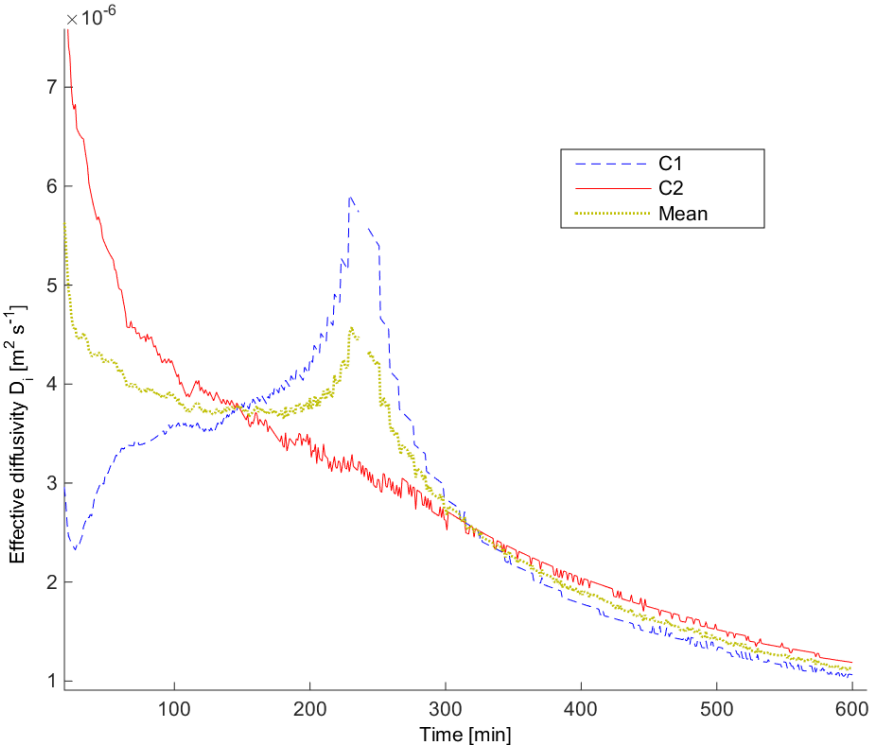


Figure 4 Effective diffusivity values for 0.5" test 2, obtained using the inverse model given in Eq. 9

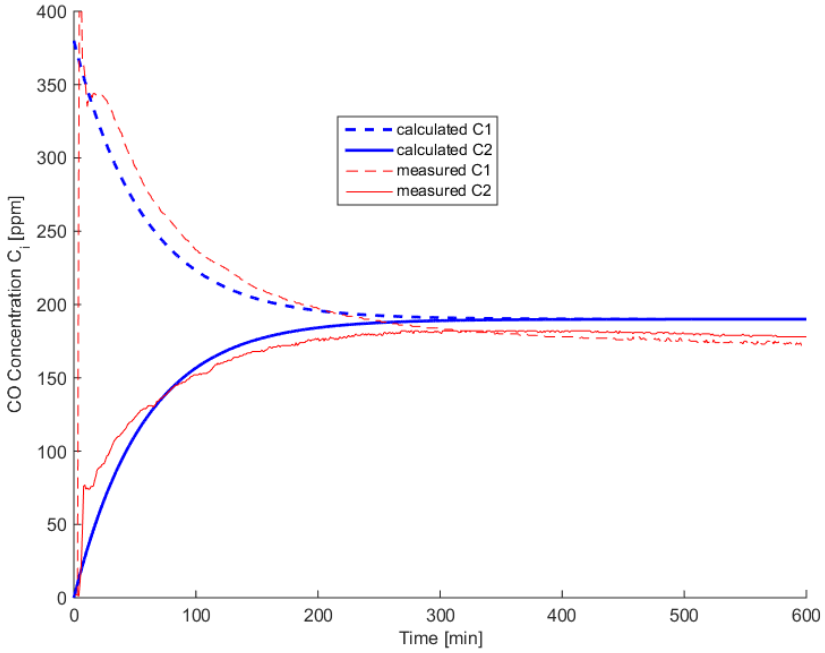


Figure 5. Comparison between the experimental results and the calculated diffusivity for experimental data using 0.5" gypsum wallboard

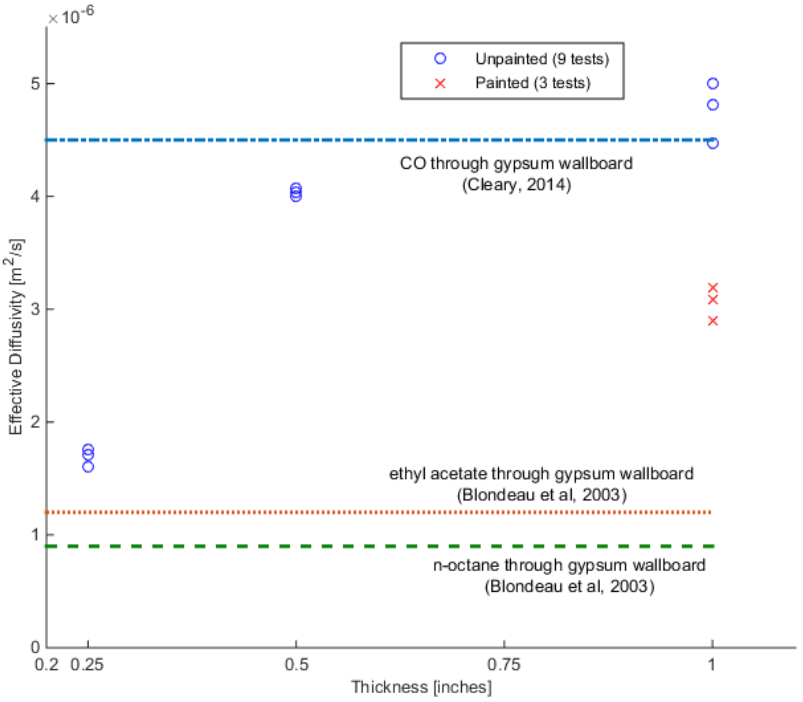


Figure 6. Comparison of mean diffusivities for the 12 experiments, along with values from literature

The simple mass transfer model confirms the fast transport of CO through porous walls, independently assessing the experimental results from (Hampson, et al., 2013). This is further demonstrated by obtaining results in the same order of magnitude as another parallel computational study by Cleary (private communication). The computational and experimental results show good agreement, highlighting the danger posed by CO in rooms adjacent to places with CO sources such as garages or kitchens.

4. Conclusion

The literature review offers support to the claim that carbon monoxide can diffuse through porous walls at a rate that presents a danger to the occupants. There are experiments in literature that use various VOC that prove gases are able to migrate through the pores in the walls. As CO is a smaller molecule than these, it can be concluded that it can diffuse at least as fast as those. In addition, experiments that replicate realistic conditions have shown the ability of CO to diffuse through walls.

There have been 5 reported incidents of carbon monoxide intoxication which can be attributed to diffusion, with one additional incident where diffusion is thought to have contributed to the high concentration of CO in two separate rooms. These reports do not give many details about the building materials and give basic information about the configuration, but from what they provide it is very likely that CO can diffuse through walls.

The mass transfer model made to verify the experimental results of (Hampson, et al., 2013) that have brought attention to this phenomenon gave conclusive results. The diffusivity of CO across gypsum board can be quantified and it is inside the range from $1.6 \cdot 10^{-6}$ to $4 \cdot 10^{-6}$ m^2/s^{-1}. This range is in the same order of magnitude as the results obtained for recently for the same materials by researchers at NIST (Cleary, 2014).

5. Research Needs

During the progress of this study we have identified three areas of CO diffusion that are in particular need of further research. These are the following.

1) Porous walls: There is a need for a robust definition of what it is meant by a porous wall in the context of CO diffusion.

2) The task of defining a porous wall is complicated further by the concept of wall systems. Possible wall systems used in modern buildings encompass a wide range

of configurations that include ceilings and floors as well. They can range from simple multilayers of plaster board, to composite systems made of steel and polymers which can include cavities and gaps. Wall systems can combine different porous materials and also present channels of some tortuosity that allow leaks. All of these would need to be considered within the context of CO diffusion through the building fabric.

3) It is desirable to be able to measure the permeability of materials to CO diffusion. This would provide knowledge on how each material of the building fabric behaves and so enabling the ranking this behavior by establishing a framework for testing and classification. One such method could be a diffusion test with a gaseous agent which would establish how fast the diffusion is. Possible gaseous agents for consideration could be CO itself (most realistic but flammable and toxic), hydrogen (which provides the quickest possible diffusion but is flammable) or Helium (or similar noble gases; which provide quick diffusion and are inert).

BIBLIOGRAPHY

Blondeau, P. et al., 2003. Assessment of Contaminant Diffusivities in Building Materials from Porosimetry Tests. *Indoor Air,* Volume 13, pp. 302-310.

Chang, J. & Guo, Z., 1992. The Effects of Building Features on Air and Pollutant Movement. *Building Research Journal,* 1(1), pp. 55-63.

Cleary, T., 2014. *Private communication.*

Deng, Q., Yang, X. & Zhang, J., 2009. Study on a New Correlation Between Diffusion Coefficient and Temperature in Porous Building Materials. *Atmospheric Environment,* Volume 43, p. 2080–2083.

Dodson, R. et al., 2008. Influence of Basements, Garages, and Common Hallways on Indoor Residential Volatile Organic Compound Concentrations. *Atmospheric Environment,* Volume 42, pp. 1569-1581.

Emmerich, S., Persily, A. & Wang, L., 2013. *Modeling and Measuring the Effects of Portable Gasoline Powered Generator Exhaust on Indoor Carbon Monoxide Level,* s.l.: National Institute of Standards and Technology.

Gilliland, E., Baddour, R., Perkinson, G. & Sladek, K., 1974. Diffusion on Surfaces. 1. Effect of Concentration on the Diffusivity of Physically. *Industrial And Engineering Chemistry Fundamentals,* 13(2), pp. 95-100.

Gunnarsen, L., Nielsen, P. & Wolkoff, P., 1994. Design and Characterization of the CLIMPAQ, Chamber for Laboratory Investigations of Materials, Pollution and Air Quality. *Indoor Air,* 4(1), pp. 56-62.

Hampson, N., 2009. Saved by the Carbon Monoxide. *American Journal of Preventive Medicine.*

Hampson, N., 2014. *CO Bibliography.* [Online]
Available at: http://neilhampson.com/carbon-monoxide-bibliography.html
[Accessed December 2014].

Hampson, N., Courtney, T. & Holm, J., 2013. Diffusion of Carbon Monoxide Through Gypsum Wallboard. *JAMA,* 310(7), pp. 745-746.

Incropera, F., Dewitt, D., Bergman, T. & Lavine, A., 2013. *Principles of Heat and Mass Transfer.* Seventh ed. s.l.:John Wiley & Sons.

Keshishian, C. et al., 2012. Carbon Monoxide from Neighbouring Restaurants: the Need for an Integrated Multi-agency Response. *Journal of Public Health,* 34(4), p. 477–482.

Kontogeorgos, D. & Founti, M., 2013. A generalized methodology for the definition of reactive porous materials physical properties: Prediction of gypsum board properties. *Construction and Building Materials,* Volume 48, p. 804–813.

Meininghaus, R., Gunnarsen, L. & Knudsen, H., 2000. Diffusion and Sorption of Volatile Organic Compounds in Building Materials-Impact on Indoor Air Quality. *Environmental Science & Technology,* 34(15).

Meininghaus, R. & Uhde, E., 2002. Diffusion Studies of VOC Mixtures in Building Materials. *Indoor Air,* Volume 12, pp. 215-222.

NCSL, 2014. *Carbon Monoxide Detector Requirements, Laws and Regulations.* [Online]
Available at: http://www.ncsl.org/research/environment-and-natural-resources/carbon-monoxide-detectors-state-statutes.aspx
[Accessed December 2014].

Nelson, G., 1998. Carbon Monoxide and Fire Toxicity: A Review and Analysis of Recent Work. *Fire Technology,* 34(1), pp. 39-58.

NFPA, 2012. *NFPA 720: Standard for the Installation of Carbon Monoxide (CO) Detection and Warning Equipment.* s.l.:s.n.

OSHA, 2012. *Accident Investigation Summary,* South Charleston: s.n.

Singer, B. et al., 2004. Sorption of Organic Gases in a Furnished Room. *Atmospheric Environment,* Volume 38, pp. 2483-2494.

Treybal, R. E., 1981. *Mass-transfer operations.* Paris: McGraw-Hill International.

West, F. et al., 2008. *Odour as a Potential Proxy for Carbon Monoxide Exposure,* s.l.: s.n.