WHO Household Multiple Emission Sources (HOMES) and Performance Target (PT) Model: Input Parameter Protocol – Air Change Rate

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Version 2.3

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Model Parameter: Air Change Rate

Objective

Measure the air change rate in the room where the emissions source(s) is/are present, generally the kitchen.

Background and context

Room air change rate is an input parameter for the WHO HOMES and PT models and is the primary driver in the removal of pollutants generated in any given room. Air change rate is typically measured by analyzing how quickly tracer gas concentrations decrease in a room after the source of those gas emissions has been stopped or removed. The faster the decay rate of the gas concentration, the higher the air change rate, and vice versa. This protocol describes the process to measure decay rates and calculate the estimated air change rates from those data. It is meant to be applied to a room (or kitchen) with four walls and a ceiling, as defined in the kitchen volume protocol. A description of how to perform post-hoc analysis to derive air change rates from previously collected air quality data is provided in Annex A.

The tracer gas method used in this work relies on the rapid cessation of emissions from the given source, so that the decay of tracer gas concentrations in the room of interest may be measured without contamination from any additional tracer gas introduced during the decay period. The best source of a tracer gas is thus one that can be removed quickly from the room in which the air change rate is being assessed. There are many viable tracer gas source candidates, including CO and CO_2. Ideally, any tracer gas should be easy for a single person to move and operate safely, and large enough to substantially increase the tracer gas concentration levels in the room of interest on the time scale of minutes (e.g., a candle will likely not produce sufficient CO or CO_2 to be used in most rooms). Note that special care should be taken if using CO to minimize exposure, as CO can have acute health impacts at high concentrations. Specifically, the concentrations should be monitored and steps taken to ensure the minimum durations and magnitude of exposures occur. A stove or gas canister can serve as the source of the tracer gas. If a stove is being used as the source of the tracer gas, a stove that can be quickly and safely moved to a downwind location outside the room, such as a charcoal stove, is better suited than a stove like a three-stone fire or chimney stove which cannot be removed easily.

A single tracer gas emission may last only 1-10 minutes and the corresponding concentration decay should be measured for at least 20 minutes. The complete air change rate measurement protocol may take 1-3 hours to complete in a household, due to equipment set up, number of tracer gas concentration decay events measured, and interaction with the household. During the measurement, only a single tracer gas source (e.g., a single stove or a single gas canister) will be used. Thus, the household should be notified that before beginning the test, no other combustion sources can be used during the duration of the test, which could include other stoves, heaters, incense, lamps, candles, mosquito coils, or burning of trash. If CO_2 is being used, humans should leave the room for a period of time before the test to prevent “contamination” from human-generated CO_2.

The air change rate calculated from the measured data will be representative of the ambient wind speed and temperature conditions at the time of measurement, so performing the measurements in a variety of conditions is advisable.

Equipment required

- Real-time portable tracer gas monitor/sensor (CO or CO_2) with at least<= 10 second logging resolution.
    - Calibration requirements vary by instrument, and manufacturer recommendations should be followed.
    - Instrument should have battery life of at least one hour and data storage capacity of at least 360 samples.
- Tracer gas emission source – options include:
    - Portable stove that can be easily removed/extinguished (e.g., charcoal stoves often work well for producing CO)
    - Cylinder of CO_2 such as those used for carbonating drinks
    - Dry ice (frozen CO_2)
- Mixing fan (optional)
- Anemometer (wind speed meter) (optional)
- Temperature and humidity monitor

Procedure

1) Check gas monitor's time response to ensure that it has a fast enough response time to determine high air change rates (to be done for all gas monitors before starting study). When the air change rate is high, the gas concentration will decay rapidly, and thus requires measurements with high temporal resolution. This can be done using a small mixing chamber, or calibration manifold, in a well-ventilated area.
    a. Expose sensors to a gas concentration at 50-90% of their maximum detection range and wait approximately 5 minutes.
    b. Remove sensors immediately from the source so that they are no longer exposed to any of the gas.
    c. Use the resulting decay curve to calculate what the maximum detectable air exchange rate would be (see section 3 below).
    d. If the calculated exchange rate based on the sensor's response is less than 75 air changes per hour, then this sensor should not be used. This is because the sensor's response time is too slow to provide accurate measurements for the entire range of feasible air change rates.
2) In-home procedure:
    a. Check that sources of tracer gas only come from the introduced gas. Other sources of tracer gases that should not be used during the measurement may include stoves other than the one used as the tracer gas source, heaters, incense burning, lamps, candles, mosquito coils, and burning of trash. Humans and animals also respire CO_2 and thus should have a minimum presence in the room prior to and during the test. Additionally, check that smoke from neighbors or other nearby outdoor sources are unlikely to affect tracer gas levels inside the home. Do a visual inspection and ask the participant about these potential sources.

b. Check with participant that the windows and doors are open or closed as they typically would be for that time of year during stove use events.

c. Record the following contextual information (an example log sheet is provided in Annex B):
    i. Time of day (both specific time and morning, afternoon, evening, night)
    ii. Wall construction materials
    iii. Roof construction materials
    iv. Number of open doors
    v. Number of open windows
    vi. Number of eaves (number of walls of the room that have a space between the wall and roof, allowing for ventilation)
    vii. Room volume (see room volume measurement protocol)
    viii. Indoor temperature and humidity, taken standing in the center of the room
    ix. Outdoor temperature and humidity, taken more than 5 meters from the house
    x. Outdoor wind speed (measure facing into the prevailing wind direction)
d. Turn on CO or CO_2 monitors, start logging, and check that the background concentrations inside the room are below 3ppm for CO and below 500ppm for CO_2.
e. Install the gas monitor at a height of 1.5 meters above the ground in the center of the room, and out of the plume of emissions source. The monitor can be hung from the ceiling or placed on a tripod.
f. Check that the sensor is logging (at intervals of 10 seconds or less).
g. Set up and turn on the mixing fan if available/possible so that the air in the room is well mixed. The fan is meant to mix the air in the room, not to change ventilation conditions, so windows or door should not be adjusted to accommodate it. Rather, place it so that the tracer gas emissions are evenly distributed throughout the room (oscillating fans can be used for this). The mixing fan will not affect the decay rate, as the fan is turned off when the emission source is removed/extinguished. Alternatively, a flat piece of cardboard or other mechanism may be used as a fan to manually mix the air in the room.
h. Introduce the source gas into the room until the concentrations in the room exceed 3000 ppm for CO_2 or 100 ppm for CO. Note that the participants should not be present in the kitchen and the technicians should minimize exposure by not being present in the room for any more time than required.
i. Remove or turn off the source of tracer gas in the room. If a cookstove or another combustion source is being used to introduce the tracer gas, ensure that it is completely extinguished or placed far and downwind from the room so that its emissions cannot infiltrate the room while the decay is being measured.
j. Turn off the mixing fan (if used) or stop fanning room at the same time the source has been stopped or removed so that the fan does not impact the air change rate.
k. Wait for the gas concentrations to return to ambient levels.
l. Repeat procedure three to five times (if possible).

3) Calculate the air exchange rate from the real-time data (this is done in laboratory or office):
    a. In the downloaded data file, convert the timestamp to units of hours.
    b. Take the natural log of each concentration data point.
    c. Plot a real-time trace of the data with the time in hours on the x-axis and the concentration on the y-axis, including the natural log of the concentration.

d. Select a section of the decay curve after the source has been removed which shows a smooth exponential decay. High air change rates will decay quickly and sections may be as short as two minutes while low air change rates may require selecting time intervals of up to 30 minutes showing a selected period of around 4 minutes. An illustrative example has been provided below.

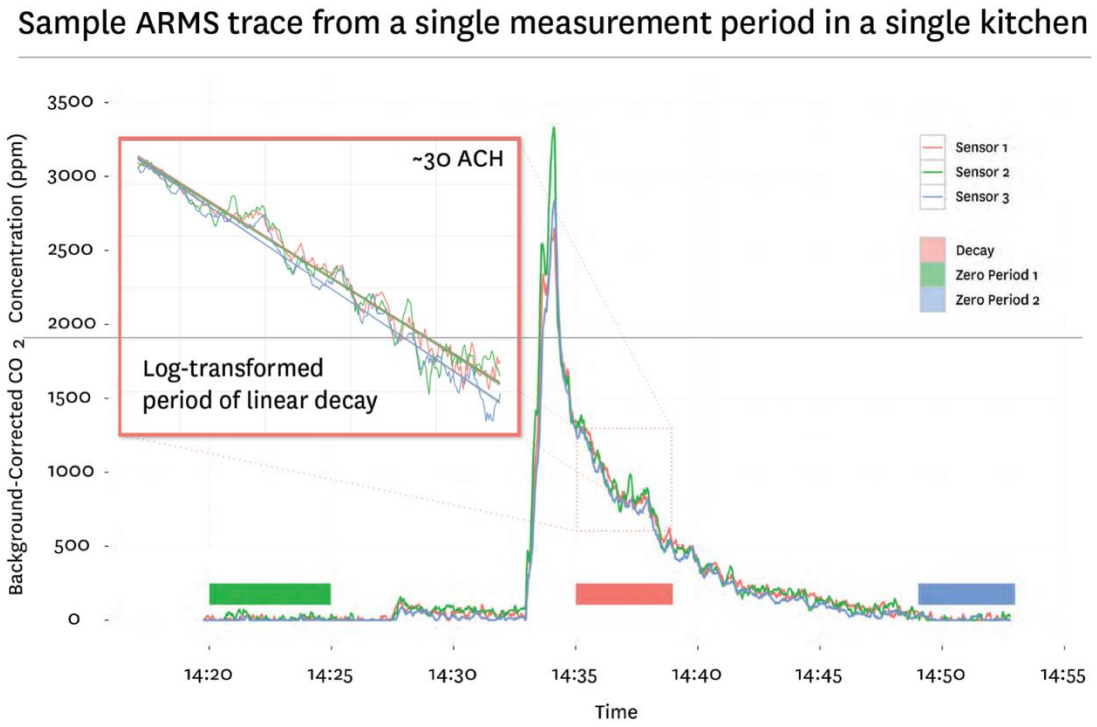

Figure 1: Graph of sample decay curve of CO_2 concentrations, adapted from Pillarisetti et al. 2015

e. The slope's magnitude of the natural log of the decay curve is the estimated air change rate in air changes per hour. An example has been provided below:
   i. The slope of the decay curve is calculated using least squares regression analysis, with the natural log of the tracer gas as the dependent variable, and time (in hours) as the independent variable.
   ii. Since the units of time are hours, the air change rate for the data presented in Figure 2 is 24.1 air changes per hour, as can be seen in the slope of the equation ($y = -24.1x + 6.63$, where y is the natural log of CO, and x is the time in hours, generally measured from the start of the emissions test).
   iii. Convert the air change units as necessary. For example, the WHO air quality model requires air changes per minute, and thus the above estimate would need to be divided by 60 min/hour to get air changes per minute.
   iv. An R^2 value of 0.98 in this example shows that the model fits the data well. Note the quality of the fit and consider redoing the experiment, or selecting a different section of data for analysis, if the R^2 is lower than 0.95, or if the regression analysis assumptions are not met (Chatterjee and Hadi, 2015). A poor fit may indicate that variability from other tracer gas sources or from a rapidly varying air change rate has been introduced.

f. If multiple measurements of the same home were conducted, take the mean of those air change estimates to represent the average air change rate of the room.

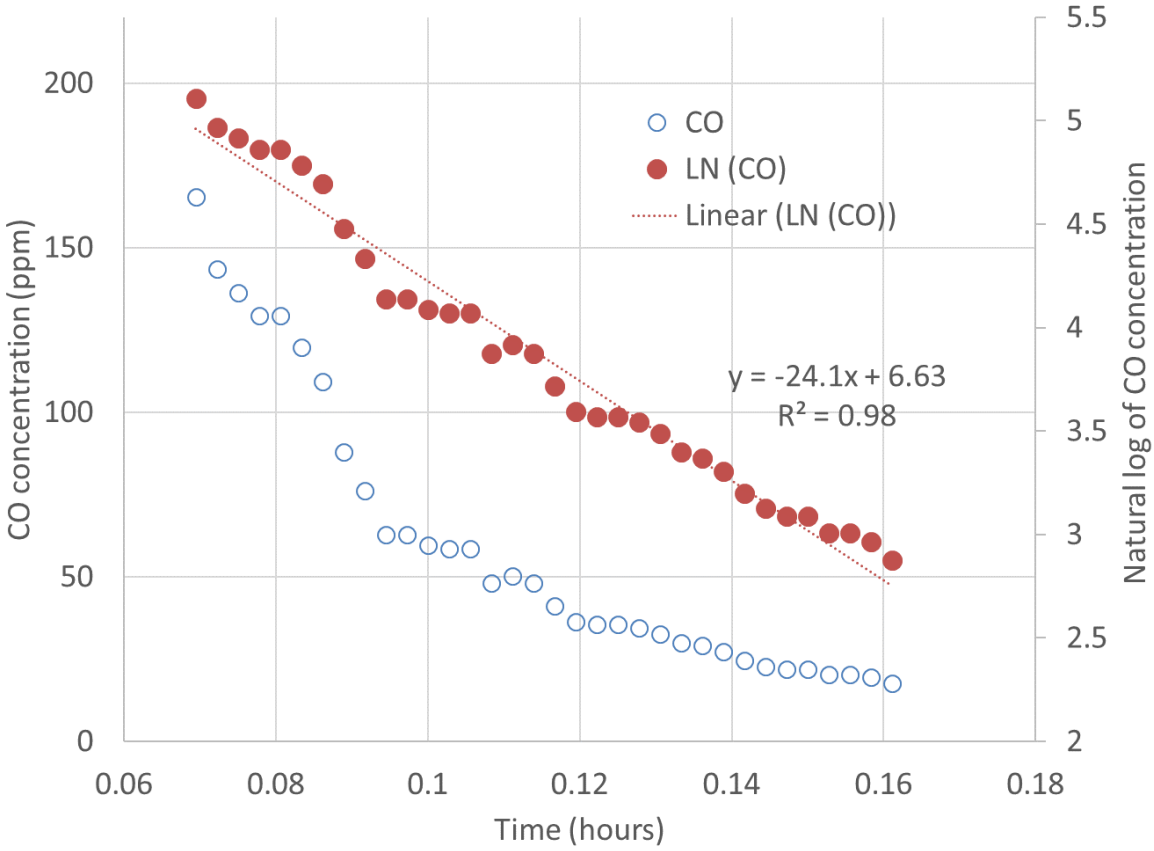

Figure 2. Graph showing example slope of natural log of decay curve

Tips

- CO_2 is an excellent tracer gas to use as it is non-toxic and non-reactive, but it is also exhaled by people, so make sure that no people are breathing in the room after the source has been removed or stopped.
- If a cylinder of gas is used, make sure to follow all relevant safety protocols for handling a pressurized cylinder.
- Air change rates can change hourly, daily, and seasonally. If possible, it is recommended to repeat the sampling in homes during the morning and afternoon and average those results, and to avoid sampling during unusually windy conditions. If there are seasonal differences in heating or how people ventilate their homes, then it is recommended to repeat the procedure during the different seasons and weight the results by the fraction of time for the different ventilation scenarios. If repeated sampling is not possible, this limitation should be recorded and stated as a caveat with the results.

Example studies

Cowlin, S.C. (2005). Tracer Decay for Determining Kitchen Ventilation Rates in San Lorenzo, Guatemala. Maxwell Student Projects, Max-04-4, EHS, School of Public Health, University of California, Berkeley. https://www.yumpu.com/en/document/view/36182577/tracer-decay-for-determining-kitchen-ventilation-rates-in-san-

Park, E., and Lee, K. (2003). Particulate exposure and size distribution from wood burning stoves in Costa Rica. *Indoor Air*, 13: 253–259.

References

ASTM Standard (2011). Standard Test Method for Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution.

Chatterjee, S., & Hadi, A. S. (2015). Regression Analysis by Example. John Wiley & Sons.

Pillarisetti, A., Lam, N., Pokrel, A., Hill, L., Allen, T., Kunwar, B., Pandey, B., Thapa, S., Sijali, T., Smith, K., et al. (2015). A Low-Cost, Carbon Dioxide Monitoring System for Estimating Household Air Exchange Rates. International Society of Exposure Science, Henderson, Nevada.

Annex A: Post-hoc analysis of real-time concentrations

Decay rates can also be estimated from real-time concentrations measured in homes during household air pollution studies. The major assumption for this analysis is that sections of the real-time trace can be selected, for which the source emissions discontinue after a peak event. Sections with acceptable decay rates to analyze are generally assumed to happen when a cooking event ends or when a stove is moved from the kitchen to another area. Note that it may not be possible to know if this assumption is correct. The following criteria, which are adapted from Carter et al. 2016, can be applied to select events with eligible decay phases for CO and particulate data:

- $C(t_{initial}) = C_{max}$ > 20 ppm for CO or > 100 µg/m^3 for particulate matter and $C(t_{final})$ ~background outdoor concentration;
- no local maxima occurring between $t_{initial}$ and t_{final} (i.e. single or final emissions event in a series of sequential events);
- ln[$C(t)$] versus t is approximately linear;
- few or no points higher or lower than the linear trend line.

It is recommended that the analysis is conducted on real-time air quality data from kitchens where a minimum of 24 hours of data has been collected. The analysis can be conducted using a variety of statistical software.

An example of this analysis can be found in:

Carter, E., Archer-Nicholls, S., Ni, K., Lai, A.M., Niu, H., Secrest, M.H., Sauer, S.M., Schauer, J.J., Ezzati, M., Wiedinmyer, C., Yang, X., Baumgartner, J., 2016. Seasonal and Diurnal Air Pollution from Residential Cooking and Space Heating in the Eastern Tibetan Plateau. *Environ. Sci. Technol*., 50: 8353–8361. https://doi.org/10.1021/acs.est.6b00082

Annex B: Example log sheet for in-field tracer decay measurement

Gas Tracer Decay In-Field Measurement Form

A. Pre-sampling • **Go through the consent form with the participant. Explain the process that will occur and obtain consent** • **Check that the emissions source in use for the test is the only one in the household and nearby outdoors that may affect the measurements. Come back later if a source is found that may affect the measurements.**					
A1 HH_ID:	A2 Technician Initials:		A3 Date: [dd/mm/yy]		A4 Event #:
A5 Source Type:		A6 Fuel Type:		A7 Tracer Gas:	
Initial Background Concentrations • **Install the tracer gas monitor in the center of the room, at a height of 1.5m** • **Start the tracer gas monitor and begin recording data 20 minutes before the start of the test**					
A8 Initial BG START [hh:mm:ss]			A9 Initial BG END [hh:mm:ss]		
A10 Ambient Temp (C):		A11 Ambient Pressure (hPa):		A12 Ambient Humidity (%RH)	
A13 Outdoor wind speed (m/s):		A14 Outdoor wind direction:			
A15 Indoor Temp (C):		A16 Indoor Pressure (hPa):		A17 Indoor Humidity (%RH)	

B. Room/kitchen dimensions and characteristics							
B1 Wall material		B2 Floor material		B3 Roof material		B4 Number of walls	
B5 Room length (longest) (m)		B6 Room width (shortest) (m)		B7 Room height (m)		B8 Number of walls	
B9 Height of open window 1		B10 Width of open window 1		B11 Height of open window 2		B12 Width of open window 2	
B13 Height of open window 3		B14 Width of open window 3		B15 Height of open window 4		B16 Width of open window 4	
B17 Height of open door 1		B18 Width of open door 1		B19 Height of open door 2		B20 Width of open door 2	
B21 # of walls with eaves							

C. Tracer gas emissions • **Start mixing fan if available** • **Repeat 3-5 times** • **Ensure that background conditions are reached before the start of each repeat test (below 3ppm for CO and below 500ppm for CO_2)**					
	Test 1	Test 2	Test 3	Test 4	Test 5
C1 Tracer gas concentration before start of emissions:					
C2 Gas emissions start time [hh:mm:ss]:					

C3 Gas emissions end time [hh:mm:ss]:					
D. Decay measurement • **Ensure the room concentration has reached 3000 ppm if using CO2, and 100 ppm if using CO** • **Turn off mixing fan** • **Rapidly remove or turn off the emissions source at the end of the emissions release**					
	Test 1	Test 2	Test 3	Test 4	Test 5
D1 Decay measurement start time [hh:mm:ss]:					
D2 Decay measurement end time [hh:mm:ss]:					