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Verifying mixing in dilution tunnels

How to ensure cookstove emissions samples are unbiased

Authors:

Daniel L. Wilson, Vi H. Rapp, Julien J. Caubel, Sharon S. Chen, Ashok J. Gadgil

Energy Analysis and Environmental Impacts Division
Lawrence Berkeley National Laboratory
Cookstove Research Group

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1 BACKGROUND

A well-mixed diluted sample is essential for unbiased measurement of cookstove emissions. Most cookstove testing labs employ a dilution tunnel, also referred to as a "duct," to mix clean dilution air with cookstove emissions before sampling. It is important that the emissions be well-mixed and unbiased at the sampling port so that instruments can take representative samples of the emission plume. Some groups have employed mixing baffles to ensure the gaseous and aerosol emissions from cookstoves are well-mixed before reaching the sampling location [2, 4]. The goal of these baffles is to to dilute and mix the emissions stream with the room air entering the fume hood by creating a local zone of high turbulence. However, potential drawbacks of mixing baffles include increased flow resistance (larger blowers needed for the same exhaust flow), nuisance cleaning of baffles as soot collects, and, importantly, the potential for loss of $PM_{2.5}$ particles on the baffles themselves, thus biasing results.

A cookstove emission monitoring system with baffles will collect particles faster than the duct's walls alone. This is mostly driven by the available surface area for deposition by processes of Brownian diffusion (through the boundary layer) and turbophoresis (*i.e.* impaction). The greater the surface area available for diffusive and advection-driven deposition to occur, the greater the particle loss will be at the sampling port. As a layer of larger particle "fuzz" builds on the mixing baffles, even greater $PM_{2.5}$ loss could occur. The micro structure of the deposited aerosol will lead to increased rates of particle loss by interception and a tendency for smaller particles to deposit due to impaction on small features of the micro structure. If the flow stream could be well-mixed without the need for baffles, these drawbacks could be avoided and the cookstove emissions sampling system would be more robust.

2 WELL-MIXED FLOW IN A DUCT

Mixing in a cookstove emissions sampling system is controlled almost entirely by turbulent mixing. Turbulent mixing, as contrasted with diffusive mixing, is the mixing of aerosols and gases primarily by transport[1]. The Reynold's number in a duct is described by Equation 2.1 as a function of the volumetric flow rate, Q, duct area, A, duct diameter, d, and kinematic viscosity, ν.

$$Re = \frac{vd}{\nu} = \frac{Qd}{A\nu} \tag{2.1}$$

The characteristic mixing time for a passive scalar by transport is given by Equation 2.2 where D_t is an estimate of the turbulent diffusivity calculated as the product of species diffusivity and Reynold's number as shown in Equation 2.3 [3].

$$t_{mix} = \frac{d^2}{D_t} \tag{2.2}$$

$$D_t = ReD \tag{2.3}$$

Combining Equations 2.2 and 2.3, we calculate the characteristic mixing time as:

$$t_{mix} = \frac{d^2}{ReD} \tag{2.4}$$

Substituting Equations 2.1 for the Reynold's number:

$$t_{mix} = \frac{d^2}{\frac{Qd}{A\nu}D} = \frac{dA\nu}{QD} \tag{2.5}$$

In the case of cookstove emissions mixing, we can assume both the emissions plume and dillutant are air. The species diffusivity of air in air is equivalent to air's kinematic viscosity, *i.e.* $D_{air/air} = \nu_{air}$, therefore we can simply to find that, for turbulent flows:

$$t_{mix} = \frac{dA}{Q} \tag{2.6}$$

Equation 2.7 demonstrates that the characteristic mixing time of cookstove emissions in air is invariant with kinematic viscosity, a fundamental property of turbulent diffusion of similar species that emphasizes that mixing is almost entirely a function of transport. In the case of monitoring cookstove emissions, we are less concerned with mixing time as with the distance pollutants must travel down a turbulent duct before becoming well-mixed. We can convert from characteristic mixing time to characteristic mixing displacement, x, as follows:

$$x = vt_{mix} = v\frac{dA}{Q} = \frac{Q}{A}\frac{dA}{Q} = d \tag{2.7}$$

Therefore, for turbulent flow of air in air, the characteristic displacement for mixing, x, is simply the diameter of the duct, d. Because all of these calculations assume fully-developed turbulent flow, it is advisable to have several mixing displacements of duct between the mouth of the duct and the sampling port; most standards recommend 7 to 10 duct diameters between the mouth and sampling port. It is not necessary to have fully-developed turbulent flow to have well-mixed emissions; if the flow is turbulent and the sample is taken 7-10 duct diameters downstream for the duct's mouth, the sample should be well-mixed and no mixing baffles would be needed.

3 LABORATORY EXAMPLE

To illustrate the effectiveness of baffle-less mixing, we performed an experiment at LBNL's Cookstove Research Lab. This lab uses a 25 cm diameter duct with a flow rate of $340\,\mathrm{m^3\,h^{-1}}$ (Re = 3.9E+4). A schematic of this setup is shown in Figure 3.1. Figure 3.2 illustrates three regimes of turbulence as a function of volumetric flow rate and diameter of a duct:

laminar, transitional, and turbulent. LBNL's setup is well into the turbulent regime within which Equation 2.7 applies. Because this setup is turbulent, we designed the lab with roughly 8 duct diameters of mixing before the sampling port to ensure good mixing.

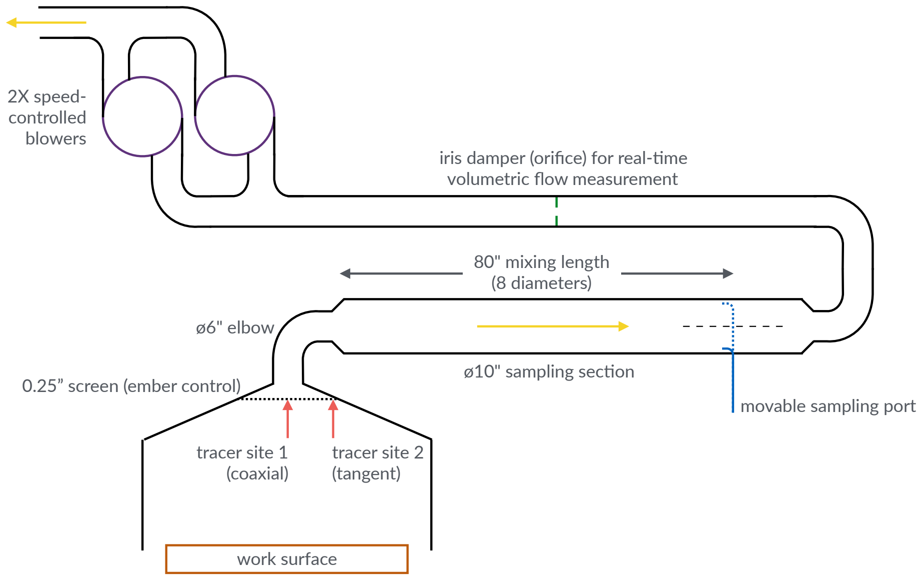

Figure 3.1: Ducting setup at LBNL Cookstove Research Lab.

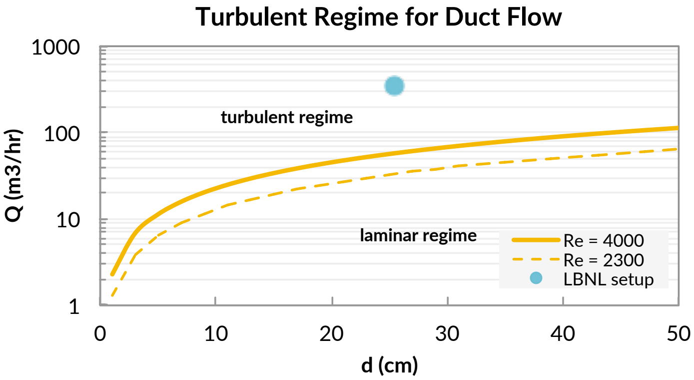

Figure 3.2: Laminar and turbulent regimes for duct flow.

3.1 Pulsing a Tracer Gas

To test empirically if we had achieved good mixing, we performed two experiments. In the first experiment, we sampled at the axis (center) of the sampling duct and pulsed a

Table 3.1: Summary data for Experiment 1

n	20
average error ($\frac{CO_{meas.}-CO_{calc.}}{CO_{calc.}}$)	-1.4%
st. dev. error	1.2%
concentration st. dev. tracer off	0.063 ppm
concentration st. dev. tracer on	0.065 ppm

tracer gas on and off ten times. The tracer gas for this experiment was introduced into the duct coaxially at tracer site 1 (see Figure 3.1) through a plastic hose with a 6.5 mm internal diameter. The tracer gas used was 350 ppm carbon monoxide mixed in nitrogen gas, and the tracer was blown into the duct at 100 liters per minute. The Reynolds number for the tracer gas exiting the tube was roughly $Re = 2.0\text{E}+4$. We compared the expected concentration of CO in the duct to the empirically measured concentration of CO and calculated the error for $n = 20$ times across the 10 pulses (once for adding tracer, once for removing tracer). Figure 3.3 illustrates the duct concentration of CO as a function of time before addition and after removal of the tracer flow to the duct, and Table 3.1 summarizes the findings. In the first experiment, we found good mixing, accuracy, and repeatability with no indication of heterogeneous mixing in the flow at the time scale of seconds or the length scale of the diameter of the sampling port.

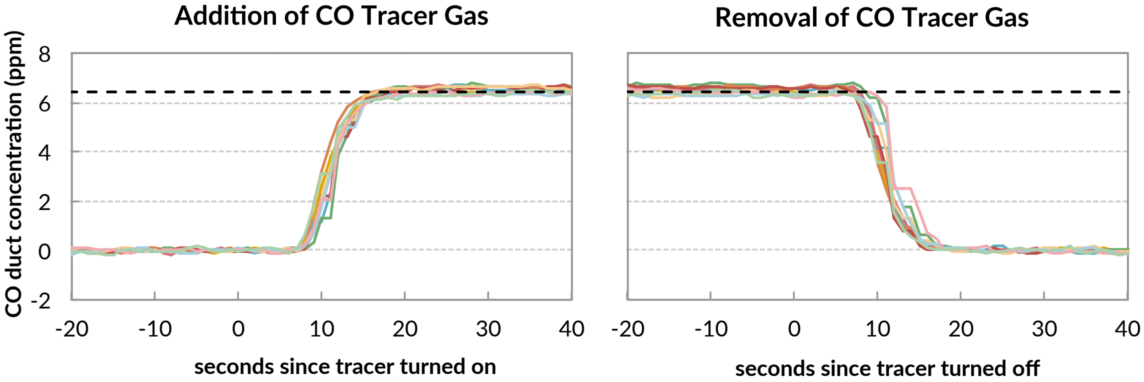

Figure 3.3: Tracer concentration at the axis of the duct for 10 pulses. Black dashed line indicates the calculated (expected) tracer concentration.

3.2 Traversing the Duct

In the second experiment, we injected tracer into site 1 (coaxial) and later into site 2 (tangent) to the duct's circumference as shown in Figure 3.1. We chose these two sites to simulate what we believed would be a worst-case mixing scenarios for a high concentration pollutant entering the duct. For each tracer injection site, we injected tracer gas at the same volumetric flow rate as the first experiment, but we kept the tracer gas at a constant flow rate. We then used our movable sampling port to transverse the entire diameter of the duct. Figure 3.4 shows the results of this experiment.

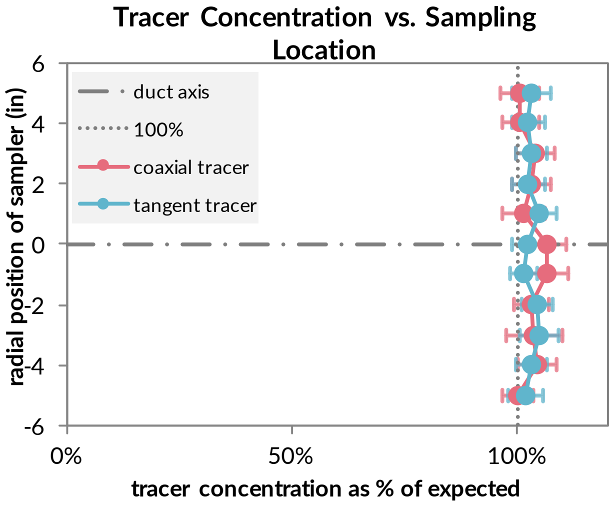

Figure 3.4: Sampling location versus tracer concentration for 1-minute averages sampled at 1 Hz.

In this experiment, we again found no evidence of heterogeneous mixing at the time scale of seconds or the length scale of the diameter of the sampling port. It is interesting to note that the pulsing experiment had negative bias while the traversing experiment had positive bias. These experiments were performed on different days, so we believe this bias may be due to sensitivity limits of the gas analyzer; ideally, we would use a CO tracer closer to 3500 ppm to increase the signal to noise ratio.

4 Conclusion

Mixing baffles have several drawbacks including flow restriction, nuisance cleaning, and potential loss of $PM_{2.5}$. We have demonstrated that a cookstove setup can be compact, simple, and well-mixed without introducing the potential frustrations and errors that can be caused by mixing baffles. After 8 duct diameters (plus a 15 cm diameter 90^o elbow) LBNL's setup was proven to be highly accurate, precise, and well-mixed at the sampling port. We only see drawbacks with no compelling reason include mixing baffles in any cookstove emissions monitoring system if the duct flow is turbulent and the sampling port is 7-10 duct diameters from the duct's mouth. The duct-only system is simple and elegant, and we believe its use will lead to higher quality data from testing centers.

References

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