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Mixing uniformity of emissions for point-wise measurements in exhaust ducts

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Abstract

Exhaust hoods are commonly used to capture all emissions from stationary combustion systems that are open to the environment, such as residential heaters or stoves. For experimental purposes, emissions are sampled at one, or more, discrete locations downstream in the exhaust duct. Point-wise measurements in the duct are often taken with the assumption that the emissions are homogeneously distributed across the duct cross-section, because the flow is turbulent and therefore believed to be thoroughly mixed. However, the length of such systems is rarely sufficient to ensure fully-developed flow, and the actual homogeneity is seldom assessed. In the present work the mixing within the duct is investigated by simulating the emissions distribution within various hood and duct configurations. The simulations include a straight duct with and without baffles and two different exhaust hood configurations, namely at the Stove Testing Lab at Lawrence Berkeley National Laboratory (LBNL) and at the University of Adelaide that meet standard requirements. The air flow in the ducts was simulated using Reynolds-averaged (RANS) turbulence modelling, with carbon monoxide (CO) as a representative combustion product, injected at three locations in the straight duct and two locations (centre and side) in the exhaust hoods. Simulations predict that, in isolation, neither a straight duct without baffles, nor a hood with a 90° elbow followed by a straight duct without baffles, provide sufficient mixing to achieve a near uniform distribution of CO at the sampling locations. However, simulations show that adequate mixing of dilution air and CO is achieved with baffles-induced flow detachment and recirculation, not from turbulent mixing in the straight section of the duct itself. The simulations also suggest that elbows, baffles, expansions or other geometrical features are needed to induce thorough mixing. For example, in the Stove Testing Lab at LBNL, flow disturbance is induced by an expansion into a larger diameter straight duct immediately downstream of the hood and the 90° elbow. Although these two systems demonstrate sufficient mixing of CO within the exhaust, the RANS simulations in this study suggest that other systems relying solely on mixing within a specified duct length (viz. 8–12 diameters) may not be sufficient.

Introduction

The evaluation of the combustion properties and efficiency of stationary appliances, such as cookstoves, is often based on measurements of emissions. In order to provide representative measurements of these emissions, the released products typically need to be captured. In laboratory studies, exhaust hoods are often used to capture all emissions of combustion systems that do not have a flue or other exhaust system, which are then transported outside via ducting. The hood generally spans over a larger area to ensure it captures all the emissions from the appliance, which is often quite a localised source. In the region under the hood, the draft velocity is low to avoid disturbing the combustion itself. The flow velocity increases in the contraction of the hood, is turbulent within the duct and is therefore believed to be thoroughly mixed. Nevertheless, large spatial inhomogeneities of the emissions under the hood could persist throughout the duct if sufficient mixing is not ensured. Within the duct, point-wise measurements rely on homogeneous emissions distribution to determine the performance of the combustor in a representative, repeatable and affordable manner. The present study numerically investigates the mixing behaviour of a representative gaseous combustion product within different exhaust systems to evaluate the validity of measurements taken at specific locations in exhaust ducts.

An exhaust hood typically includes a contraction hood, followed by ducts, of various geometries, and a blower or fan, to create a forced air flow. The necessary requirement—as well as the challenge—is to measure representative combustion emissions within the duct. Existing designs of exhaust hoods for emissions measurements are represented in standard methods, such as AS/NSZ 4013:2014 or US EPA Title 40 §60. While both suggest two 90° elbows and a straight section before the measuring location, US EPA guidelines suggest two baffles (semi-circular obstruction) in between the 90° elbows; but also allows for alternative measurements after eight or, if not feasible, after two diameters of straight ducting. A specific test protocol for cookstoves (ISO 19867-1, 2018), stipulates one 90° elbow followed by baffles and 12 diameters (12D) of straight duct upstream of the sampling location. With these different options, and many more found in the literature for the design of exhaust hoods, it is unclear which specifications achieve comparable and representative measurements. The evaluation of the mixing behaviour of gaseous emissions through computational fluid mechanics could therefore provide insights into the necessary flow characteristics to achieve sufficient mixing.

To assess the mixing behaviour in an exhaust system, initially an understanding of mixing in a straight pipe is required. Previously, it has been suggested that in turbulent straight pipes, fully developed flow can be achieved at 100–130 diameters downstream of any disturbance [1]. While the turbulence properties of fully-developed flow are not a necessity for a well-mixed gas flow, turbulence is the dominant mixing mechanism in a straight pipe. A shorter length could be insufficient to achieve homogeneous distribution of constituents in ducts. Furthermore, it has been shown that tracer gas measurements in a straight duct at 9D downstream of a 90° elbow deviate approximately 20% from the mean and obstructions or mixing elements need to be introduced to reduce this value [2]. The lack of certainty in the mixing of various systems may render any data erroneous or misleading. Simulations enable a deeper understanding of the influence of the length of the straight pipe section, as well as geometrical specifications on gaseous mixing in the duct to ensure reliable point-wise measurements.

A numerical study of mixing of emissions from stationary combustion systems with dilution air in exhaust hoods is provided to investigate the validity of point-wise measurements within ducts. Point-release of a tracer gas is used to investigate the impact of non-homogenous release of pollutants across the duct inlet, to assess the mixing homogeneity and to identify a reliable sampling measure at a single point downstream in the duct. Specifically, the influence of flow obstructing baffles, in a straight pipe and a representative exhaust hood, as well as geometrical specifications, elbows and expansions, in two representative exhaust hoods are addressed. While the focus of the present study is the mixing behaviour in exhaust hoods, the results might also be relevant for direct emissions measurements within flues or exhaust pipes.

Methods

Modelling

Three exhaust systems were modelled, specifically; the gas flow in a straight pipe with and without baffles; the facilities at the Stove Testing Lab at Lawrence Berkeley National Laboratories (LBNL); and those used at the University of Adelaide (UofA) with and without baffles. Model specifications and boundary conditions for all five variations are presented in Table 1.

The steady Reynolds-averaged Navier-Stokes (RANS) simulations were conducted with ANSYS CFX 17.2, using the shear-stress transport (SST) turbulence model [3]. All simulations employ a second-order coupled solver for turbulent flows and convergence was better than 10^{-4}. The inlet turbulence intensity was 5%. Smooth, no slip walls were employed. For the more complex hood structures, transitional turbulence using the Gamma Theta model [5] with reattachment modification was used. In the region of the elbow and baffles the boundary layer was resolved, while in the straight duct of all models, a low 0.0002–0.0007 mm first inflation layer thickness and a subsequent growth of 1.2 was employed. A structured, quadrilateral, computational mesh, was created in the straight duct while the enclosures and duct intersection in the UofA cases were unstructured, based on mesh independence studies. In the duct $y^+<5$ was widely achieved. The wall-treatment switched between resolving the boundary layer for sufficiently low y^+, and standard k–ω wall functions. Transport of CO is modelled using binary Fickian diffusion and a turbulent Schmidt number of 0.9, which has previously been validated [6].

Table 1: Model specifications of the geometries the straight pipe with (SP-B) and without (SP-N) baffles, the LBNL, and the UofA with (-B) and without (-N) baffles.

	Outlet $kg{\cdot}s^{-1}$	Tracer flow L/min	Elements $\cdot 10^6$	Re $\cdot 10^3$
SP-N	0.112	Isokinetic	7.45	30
SP-B	0.112	Isokinetic	1.37	30
LBNL	0.112	100 L/min	2.83	30
UofA-N	0.078	Isokinetic	4.30	35
UofA-B	0.078	Isokinetic	4.81	35

Straight pipe

The straight pipe model has an inner diameter of 250 mm and 30 m length. CO is introduced separately in three locations (L1–L3) in a 10° wedge, spanning from 100 mm<r<250 mm, as presented in Figure 1(c). The entrance plane is defined as an opening to ensure isokinetic flow, while the mass flow through the pipe is specified at the outlet. Simulations were also performed with baffles, 300 mm and 600 mm downstream of the inlet, oriented such that the first baffle obstructs half the flow path (B1), while the second obstructs the opposite half (B2). The three cell thick baffles were removed from the geometry.

Exhaust system at Lawrence Berkeley National Laboratories

The exhaust system used at LBNL consists of a hood with vertical walls, of different height, and a door at the front [7, 8]. The front is of 460 mm height, partially covered by 300 mm high doors, while the back wall extends to 760 mm below the hood. As the back wall extends further than the front from the hood, the sides are of trapezoidal shape, with the diagonal side extending from front wall corner to the back wall corner. Air can enter into the hood from all sides from below the walls. The 1,370 mm by 860 mm hood contracts into a 152.4 mm (6 in) diameter duct. The hood is followed by a 90° elbow and a stepwise expansion to 254 mm (10 in) duct. To assess the uniformity of the mixing, the tracer gas, CO, is introduced in two different locations, (1) coaxial (along the centre line of the duct connected to the hood), and (2) circumferential (off the centre line, on the side of the hood). The tracer gas inlet is modelled as a square opening with an equivalent area to the 6 mm hose used in validation experiments previously published by LBNL [4].

Exhaust system at The University of Adelaide

The UofA hood covers a square enclosure of 600 mm by 600 mm with a height of 1800 mm. Three sides of the enclosure are sealed, while the front consists of a door spanning from 600 mm above the floor to the top. Thus a 600 mm by 600 mm opening below the door allows air to enter. The hood has a 45° inclination leading into a 150 mm diameter duct at its centre. At the top of the square contraction, a 90° elbow into a straight vertical duct with an inlet for dilution flow (which is considered closed in all simulations). The straight duct extends 40 diameters (6 m). When baffles are introduced, the first baffle is located downstream of the elbow, obstructing the top half of the duct, and the second baffle is located 300 mm downstream of the first, obstructing the bottom half of the duct. CO is introduced along the centre of the enclosure at a height of 700 mm from the floor.

Results

Straight pipe

In Figure 1 the normalised CO mass concentration (the local mass fraction divided by the mean mass fraction across the duct cross-section) profile is presented across cross sectional slices of the pipe at certain locations. Pipe cross sectional planes at 12 and 100 diameter (D) length downstream of the inlet are presented in Figures 1(a) and 1(b), respectively. Three configurations of the straight pipe with baffles at 12 D downstream of the second baffle are also shown. In the configuration with baffles, three separate injection locations (L1–L3) were simulated, with respect to the baffle locations, as shown in the profile in Figure 1(c). The three locations at the circumference of the inlet are L1 at the centre of the first baffle (B1), L2 at the centre of the second baffle (B2), and L3 at the edge of the baffles, with the results presented in Figures 1(d), 1(e) and 1(f), respectively.

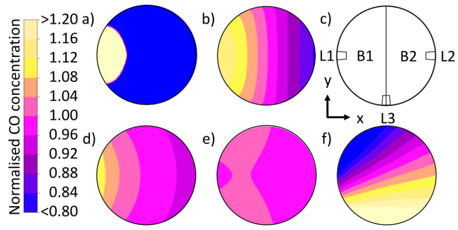

Figure 1: Normalised CO profiles at in the straight pipe: (a) no baffles, 12D; (b) no baffles, 100D; (c) profile indicating baffle and tracer locations; (d) baffles, tracer L1, 12D; (e) baffles, tracer L2, 12D; (f) baffles, tracer L3, 12D.

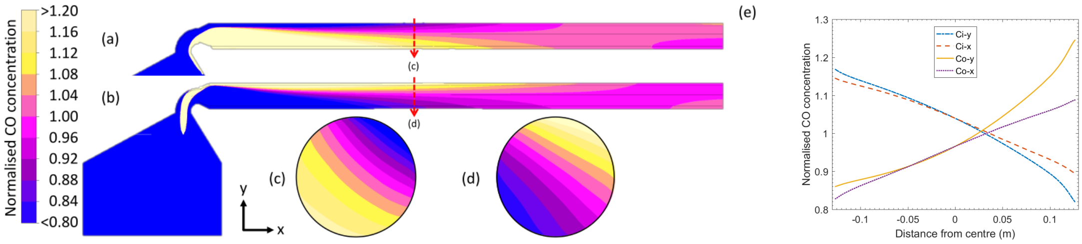

Figure 2: The normalised CO profiles along the centre plane, (a) and (b), and at the measuring location 8 diameters downstream of the expansion, (c) and (d), for circumferential (Ci) and coaxial (Co) tracer injection respectively LBNL facilities. The graph (e) shows the simulated normalised CO value along the x- and y-axes at the measuring location.

In case of the unobstructed spatially developing flow, it can be seen in Figure 1(a) that the CO distribution is biased towards the tracer injection location at 12D, with notable CO concentrations extending approximately 0.4D from the circumference. Previously, approximately 100 D have been suggested to ensure fully developed pipe flow [1], which is often believed to be sufficient to ensure homogeneous mixing of gas phase constituents. In Figure 1(b) it can be seen that even at 100D downstream of the inlet the CO mass fraction displays a bias toward the side of the tracer injection: with a variation of over $\pm 35\%$ across the duct in x-direction. Therefore, although fully developed pipe flow can be assumed after 100D of a straight pipe, this does not mean that all gaseous constituents are homogeneously mixed.

Adding baffles to the pipe enhances mixing, but the effects are dependent on the tracer injection location. The most homogeneous CO profile can be noted when injecting in location L2, while the greatest bias results from location L3 where the impact of the baffles is lower, because of less path obstruction.

It is evident that to achieve sufficient mixing, extremely large pipe length or specific flow disturbing elements are necessary to promote mixing. In the straight pipe at 100D downstream of the inlet, there is still a substantial bias in the tracer gas concentration, which demonstrates that under turbulent flow conditions, homogeneous constituent distribution cannot be assumed, even if the flow is fully developed.

Exhaust system at Lawrence Berkeley National Laboratories

Figure 2 presents the system at LBNL that has been extensively used for cookstove emissions testing [4, 7, 8]. The cross-sectional plane along the length of the system, for the two different injection strategies: circumferential injection and coaxial injection, are shown in Figures 2(a) and 2(b), respectively. Additionally, the normalised CO profiles in the duct cross sectional area at the measuring locations (viz. 8D downstream of the elbow) are shown in Figures 2(c) and 2(d). Figure 2(e) presents the simulated normalised CO mass fraction at the measuring location 8D downstream of the expansion, across the x- and y-axes (refer to 2(c) and 2(d)).

In Figure 2(a) and 2(b) it can be seen that flow detachment and a large recirculation zone is induced by the expansion downstream of the elbow. Flow detachment, especially at the bottom of the duct, leads to the formation of a substantial recirculation zone. While in 2(a) the coaxial release of CO leads to recirculation of low CO concentration gas, the opposite is the case for the circumferential CO release. Downstream of the flow disturbance, low and high concentration gases mix more rapidly.

At the measuring location shown in Figures 2(c) and 2(d), a low bias of the normalised CO mass fraction can be noted for both cases. A more uniform profile is achieved for coaxial tracer injection compared with circumferential injection. This shows the dependence of the mixing outcome on the source location, as also noted in the straight pipe simulations. It is evident that in both cases, the CO mass fraction is especially close to the mean value around the centre of the duct, where samples are generally extracted. A comparison with previously performed experiments [4] and the numerical results show qualitatively similarity, supporting the validity of the presented results and underlining that sufficient mixing is achieved.

Exhaust system at the University of Adelaide

Figure 3 shows the normalised CO mass fraction along the central cross-sectional plane of the UofA exhaust system (Figures 3(a) and 3(b)) and across the measuring plane within the duct at 12D downstream of the elbow or second baffle in Figures 3(c) and 3(d), respectively. Additionally, the values of the normalised CO mass fraction along the x- and y-axes at the measuring location are presented in 3(e).

When considering the configuration without baffles in Figures 3(a), 3(c) and 3(e) a largely inhomogeneous profile can be seen. Values of the normalised CO concentration along the x-axis range from 0.67 to 1.52 and a value of 0.76 can be noted at the centre of the duct, the typical location of sample extraction. It can be seen that the combination of the vertical front opening with the 90° elbow of the duct leads to a substantial bias of the CO concentration towards the front and top side of the duct. In this geometry, no zone of intensive mixing is created. Extending the measuring location further downstream, better mixing can be seen at 20D and 30D but with diminishing returns. A bias is still notable at 40D, which marks the boundary of the simulated domain. This shows that a 90° elbow followed by a straight duct, without flow disturbing elements, does not achieve sufficient mixing of gaseous constituents in this exhaust duct.

When baffles are incorporated into the duct, the first baffle, constricting the top section of the duct, leads to build up of high CO concentration flow and mixing as this flow is directed towards the low CO concentration flow at the bottom of the duct (see Figure 3(b)). The second baffle then leads to build up of the remaining low CO concentration flow. Flow detachment and recirculation in the wake of both baffles causes further mixing of CO within the flow. With baffles, a discrepancy between opposite sides of duct of less than 5% is achieved, as shown in Figure 3(d) and 3(e). Especially at the centre of the duct, values are particularly close to the expected mean concentration. Therefore, sufficient mixing at the measuring location is achieved when baffles are introduced into the system.

Discussion

In all simulations, the tracer gas is introduced in small concentrations and specific locations into the system and must therefore be considered "worst case" scenarios. In application, a combustion appliance is a much more dispersed source and

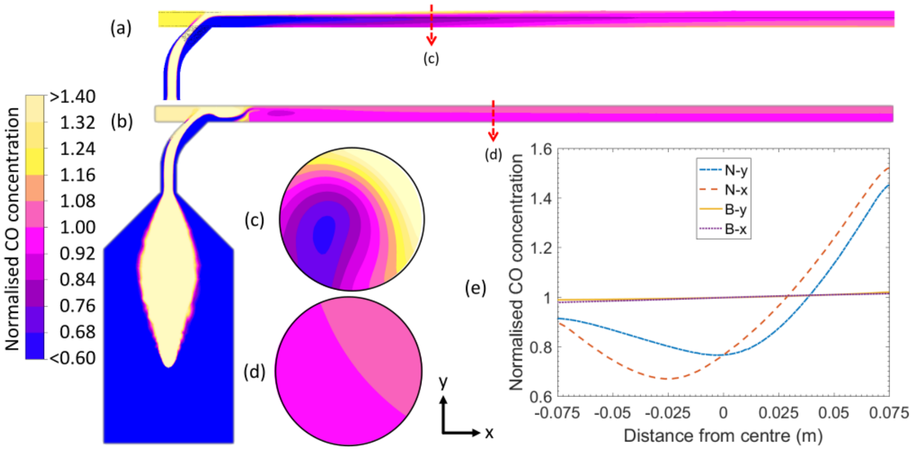

Figure 3: The normalised CO profiles of the UofA system along the centre plane, (a) and (b), and at the measuring location 12D downstream, (c) and (d) for the cases without and with baffles, respectively. In (e) the values along the x- and y-axes of the measuring location are presented.

more homogeneous mixing can be expected.

The influence of flow disturbing elements on multi-phase flows (combustion appliance exhaust gases generally contain substantial amounts of particulate matter) have not been considered in the simulations. For example, the Stokes number of < 10 μm diameter particles (density ≈ 2250 kg·m^{-3}), in the UofA system, is < 0.1. Particles with a Stokes numbers of < 1 are considered to respond and follow flow. Therefore, valid particle measurements are expected, as most particles from cookstoves are of sub-micron size [9]. However, this considers neither the influence of the dilution air on particle morphology and size distribution [10] nor the Stokes number dependence of particle size distribution within the duct [11]. Furthermore, when baffles are introduced, the large surface area of impaction might have a more substantial influence on the particle size distribution and reduce measured concentrations. Further research regarding the influence of dilution air and flow disturbing elements on particulate measurements is required.

Conclusions

Simulations of multiple exhaust geometries and the exhaust systems used at the Stove Testing Lab at the Lawerence Berkeley National Laboratories (LBNL) and the University of Adelaide (UofA) were performed to evaluate the mixing behaviour within ducts. Large spatial inhomogeneities between localised emissions sources and the surrounding area underneath exhaust hoods could propagate throughout the duct if sufficient mixing is not ensured. Sufficient mixing is required to enable valid point-wise measurements within the ducting. Results show that a straight duct or a 90° elbow followed by a straight duct achieve insufficient mixing of combustion products and dilution air within reasonable duct length. To enhance mixing, specific flow disturbances need to be introduced into the exhaust system. Sufficient mixing is achieved through a duct expansion after an elbow and the introduction of baffles into the straight duct section, in the LBNL and UofA systems respectively. These results highlight the necessity to verify the mixing patterns within a specific hood geometry when being used for exhaust sampling.

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