Multi Point Water Quenched Probe for Spatially Averaged Hot Gas Sampling in Industrial Combustors

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Abstract

Extracting gas samples through intrusive probes remains the most common and simple means of gas composition analysis. After extraction, the probe delivers the gas sample to an online or offline gas analysis unit; these devices operate on many different principles but ultimately measure the composition of the gas at the sampling unit. This procedure works well when the measured species are homogeneous in space and when the gas temperature is low enough to freeze any chemical reactions prior to extraction. In industrial combustors, these conditions are typically only met when the sample is taken from the exhaust stream; where heat exchangers and other devices mix the gas and remove heat prior to sampling. When these conditions are not met, such as when sampling from an industrial heater or gas turbine transition piece, special design considerations are needed to ensure reliability in the measurement. In particular, the probe must be able to quench reactions in situ to avoid subsequent oxidation and spatially average the sample. This paper describes the design procedure for a new multi point gas sampling probe that incorporates these considerations. A chemical kinetics analysis was performed to find the required cooling rate to quench the chemical reactions. With the required quenching rate known, a one-dimensional single-point probe was designed using a heat transfer model that delivered the required cooling rate. Next, a series of these single point probes were combined in a sample rake designed to spatially average the gas sample. The rake’s quenching rate was validated with a two-dimensional heat transfer model using ANSYS. The new multi point probe is shown to have sufficient spatial averaging and quenching rate characteristics suggesting that it is an appropriate design for species measurement within typical industrial combustors.

1. Introduction

1.1. Background

Despite the many advances in optical diagnostics, probe techniques still play a vital role in flow field investigations for scientific and industrial applications alike. Probing refers to the insertion of an object in the flow field to infer a characteristic of the fluid or to extract a sample of the fluid. For example, probes are commonly used to measure the pressure and temperature of a fluid or to remove a sample for gas analysis. This paper concerns the requirements and design of extractive gas sample probes. Of particular concern is the ability to accurately measure toxic gas concentrations such as nitrogen oxides (NOx), carbon monoxide (CO), organics of several types, sulfur oxides (SOx) and particulate matter [1]. There are many optical techniques to measure these pollutants including: flame emission spectroscopy, spontaneous flame radiation, chemiluminescence, laser absorption spectroscopy and various flame imaging techniques[2]. Compared to these diagnostics, probing may appear obsolete. However, all of these methods require optical access. In terms of measuring capability, gas analysis is very reliable and has the capability to measure much more species than optical methods. Also at high pressure conditions, optical methods fail. In comparison, probes can be inserted into hard to ”see” places and are very robust; all while having a well proven history of accuracy [3].

The requirements for gas sampling probes are relatively simple. The probe must extract a sample of fluid without significantly altering the flow field or composition of the fluid. Further, the probe should accurately measure the fluid at the point of mea-
measurement; i.e. the probe needs to halt, or "quench" chemical reactions as quick as possible, otherwise the composition measured does not reflect the actual composition at the sampling location. A suitable probe would, therefore, extract a small amount of fluid so as not to impair the spatial resolution of the measurement and rapidly reduce the temperature of the extracted fluid [4]. Suitable probes of several different types have been demonstrated (see Figure 1 for several common probes). These include quartz micro-probes with orifices as small as 75 µm, metallic convection-quenched probes, and gas-dynamic quenched "aeroquench" probes (i.e. probes that rapidly cool the gas via pressure drop and acceleration)[5]. If a probe extracts too much fluid or is too large, a significant disturbance of the flow field may result. So called isokinetic sampling is a probing technique where the stream velocity and sample velocity are matched so as to minimize the obstruction of the probe or swallowing of streamlines [5, 6]. Streamline divergence is a problem because it can lead to a perturbation in the concentration gradient and an error in the concentration measurement [7], especially when a probe is used to measure particulate concentrations [8]. A theoretical correction for spatial concentration gradients was proposed by Yanagi and Mimura [9].

Extractive gas sample probes have a well documented history of accuracy. For example, both uncooled quartz microprobes probes (usable up to 2000°C) and water cooled metallic probes were shown to have sufficient quenching rates to freeze the chemical reactions[2, 10]. Two main thermal quenching mechanisms exist: gas dynamic quenching via rapid temperature/pressure reduction (with associated acceleration to supersonic within the probe) and convective cooling of the sample. Quenching also occurs via radical recombination at the wall; this phenomena is discussed further below. Required quenching rates were estimated in many of the early studies by measuring the change in concentration of a trace species as the quenching rate was increased. At a critical cooling rate, the concentration would no longer change with further change in the cooling rate. The heat transfer rate was estimated for these conditions and the quenching rate derived. A quoted thermal quenching rate of $10^6 - 10^8 K/s$ was common from early flame sampling literature and this number was supported by early heat transfer analyses. For example, Colket et al. [11] showed through a gas dynamic model that aerodynamically quenched probes could achieve static temperature reductions on the order of $10^6 K/s$, while Bilger estimated his aerodynamic quench rates varied from $10^6 - 10^8 K/s$ [6]. These cooling rates were only experimentally justified; in this study a gas kinetic analysis will revisit these quenching rates.

The proper choice of probe type depends on the application. For example, quartz microprobes may be desired for accurate spatial measurement within laminar flames (even though some studies suggested that micro probes could not be aerodynamically quenched [11] due to boundary layer buildup which prevented flow acceleration to supersonic within the small probes [12]). Further, Bilger and Beck showed that the probe type had a drastic effect on the measurement of nitric oxides [13]. In addition, England et al. showed a significant difference between nitric oxide emissions measured using 5 different probes[14]. A water cooled quartz probe measured the most NO$_x$ followed by a non cooled quartz probe, water cooled gold-tipped stainless probe, an uncooled stainless probe, and a uncooled stainless tube (in descending order of measured NO$_x$ con-

![Figure 1: Example cross-sections of typical probe designs used for extractive gas sampling.](image-url)
have been no combined heat transfer-kinetics analysis, but to the author’s knowledge there have been no combined heat transfer-kinetics analysis, but to the author’s knowledge there

The required quenching rate is tied to a reaction rate analysis, but to the author’s knowledge there have been no combined heat transfer-kinetics analyses to answer this question; although there have been a number of studies that suggest their quenching rates are adequate. For example, Friedman and Cyphers [10] had good agreement with a quenching rate of \( \sim 10^7 \) for a propane-air flat flame, Dyakov et al. showed their probe measurements of ethane-air flat flames matched GRI mech 3.0 kinetics calculations within 10% using an uncooled quartz probe, [19] and Rortveit et al. showed good agreement for counter-flow flames [20]. A solid theoretical justification for the required quenching rate is needed. This study attempts to address this need and offer a simple chemical-kinetic and heat transfer analysis that can be used to design gas sampling probes for accurate CO and NO\(_x\) measurement.

1.2. Problem Description

This paper describes the design process to create a multi point sampling probe. A chemical kinetics model was created to simulate a single point gas sampling probe within an industrial combustor. The model was solved with Chemkin and GRI Mech 3.0. A constant heat transfer rate was applied to simulate cooling within the probe, and the concentration of important species are plotted versus various heat transfer rates. With this model, a theoretical basis for the required quenching rate was established. Next, a 1D finite difference heat transfer model was created and used to simulate the probe. Various geometric design parameters were varied so that the calculated quenching rate would meet the required value. Finally, a novel multi point probe was created where each sample port was designed to match the single point probe. This multi point probe was validated using a static thermal analysis in ANSYS.

2. Kinetics Model

The gas flow within the sample probe was simulated using two plug flow reactors (PFR); see Figure 2. The first PFR simulated the combustor and essentially acted as a source of CO, NO\(_x\), and temperature. The second PFR simulated the sample probe. The inlet composition was varied by applying a small heat loss to the first PFR and by changing the distance. The diameter of the first PFR was large enough to supply a low velocity, quasi-equilibrium state for the outlet gas. A constant heat loss was applied to the second PFR to simulate the convective quenching. In addition, an
An instantaneous temperature drop was applied at the entrance of the second PFR to account for fluid acceleration to $M=1$.

Surface reactions are difficult to model but would increase quenching rates due to radical recombinations at the surface. [4, 6] Fristrom suggests that radical destruction at the walls may be equal in importance to rapid temperature reduction when considering reaction inhibition inside the probe [12]. Therefore, when only including gas-gas reactions the calculated quenching rates should be considered conservative. Despite the overall increase in quenching rate (when including surface reactions), catalytic surfaces may reduce trace species concentrations under certain circumstances which can lead to erroneous concentration measurements [7]. For example, platinum catalysts are known to reduce NO to NO$_2$ or nitric acid [8]. Indeed early measurements of NO$_2$ were biased by conversion within the probe leading to erroneous conclusions in some early kinetics models [21]. Clearly, further analysis of the effect of surface reactions on gas sampling is warranted, but not included in this study.

3. Heat Transfer Model

A multi-zone model of the inner tube was solved for the sample gas temperature distribution. The tube was broken into two main zones: an entry region and a fully developed region. The sample fluid in both regions was assumed one dimensional and steady. For simplicity of calculation, the fluid was chemically frozen and constrained to the gas phase. These are good assumptions as long as the initial sample temperature and composition are such to guarantee negligible amounts of heat release (radical recombination) within the tube. Sampling from typical fuel/air flames of industrial applications meet these requirements but sampling from oxy-fuel flames may not.

Bowman suggests that typical water cooled probes barely achieve quenching rates on the order of $10^6 K/s$ [7]. Further increase in the quenching rate requires the combination of an aeroquench and convective cooling probe such as Figure 1 (c). With this type of probe, quenching rates up to $10^8 K/s$ are achievable [7]. Our probe design accomplishes this in a passive way. A large pressure drop forces a rapid acceleration to choked sonic conditions with a corresponding decrease in static temperature. The momentum equation can be removed from the calculation by assuming that the fluid is choked at the entrance and that friction within the tube is negligible. Finally, mass and energy are numerically solved at each node for the local temperature.

4. Probe Design

The heat transfer and kinetics models were designed to simulate a stainless steel convective-quench probe such as that depicted in Figure 1 (a). The probe had three concentric tubes; the sample entered the inner tube and cooling water traveled around the outer two tubes. The sample tube diameter and length were adjusted to optimize the heat transfer rate. Once optimized, the single point probe was used as the design basis for the multi-point probe. The multi-point probe utilized a sample tube surrounded by a finned water channel to maximize the quench rate. Figure 3 shows a cross-sectional view of the probe design. The sample enters the small tube on the left side of the probe where it is rapidly cooled by two finned water channels. The sample then enters a relatively large sample plenum where it mixed with the other tubes for spatial averaging. Two additional water channels at the right side of the probe return the water to the outlet tube.

The multi-point probe was designed to spatially average one dimension of hot gas across a combustor outlet, such as a gas turbine’s transition piece. The cross sectional view depicted in Figure 3 was stacked vertically producing many different sample probes all connected to the sampling plenum.
The large pressure drop from combustor to sample plenum guarantees choked flow within each individual sample tube; which in turn guarantees an equal distribution between all tubes. Additional design measures would be needed to guarantee uniform sampling from a non-pressurized environment. An example of the probe design is shown in Figure 4. Two end caps are removed in these images to show the internal design of the probe.

Figure 4: Images of the multi-point emissions sampling probe. Probe length is approximately 150 mm.

5. Results and Discussion

5.1. Single Point Probe

The first PFR was supplied with a stoichiometric mixture of methane and air at a preheat temperature that was large enough for autoignition to occur. Figure 5 shows a sample output from this reactor. With this setup, the flame occurs at approximately 2.75 cm. Here CO attains a super-equilibrium value in the flame and quickly reduces to a quasi-equilibrium state of approximately 3% (mole fraction) after the flame. The NO\textsubscript{x} (sum of NO and NO\textsubscript{2} in the output) reaches approximately 5000 ppm through the flame. The heat loss rate and velocity were tuned to ensure that the output products were in a quasi-equilibrium state. The input to the "sample probe" or second PFR was varied by adjusting the length of the first PFR. In the following, two cases are discussed: the first with \(~1.2\%\) CO and the second with \(~500\ ppm\) CO.

These cases correspond to 1. sampling immediately after the flame, and 2. well downstream or after a heat exchanger respectively. The former is interesting for analyzing burner performance while the latter is necessary because environmental attainment regulations are concerned mainly with toxic gas concentrations within exhaust streams.

The second PFR used a substantially smaller diameter than the first to capture the acceleration into the sample tube. A 17% reduction in static temperature was applied manually to simulate the acceleration to sonic conditions. A constant heat loss was applied to simulate the convective-quench process. The heat loss rate was varied to simulate different quench rates within the probe. Figure 6 shows the static temperature within the probe for a low, medium, and high quench rate. The quench rate in K/s was formed by converting the spatial coordinate to time using an average velocity and then taking the derivative close to \(x=0\) cm. As expected, the temperature approaches 300 K sooner for higher quench rates. It should be noted that these simulations were run out to very large spatial distances to show the effect of lower quench rates on final "quenched" concentration but that these spatial distances are unrealistically large for a sample probe. For example, in Figure 6 it takes approximately 200 cm for quenching to occur at \(\sim 1*10^6\) K/s, but a typical probe would be limited to less than 10 cm. Under these conditions, the sample is effectively unquenched at 10 cm meaning additional conversion could occur inside the sample delivery system.

If the quenching rate is low enough, gas phase reactions within the probe will lead to chemical conversion/reduction. An example of this phenomena is shown in Figure 7 for the case of 1.2% initial CO.
concentration (the initial CO concentration is the same for all three quenching rates). An increase in quenching rate leads to a reduction in the CO lost to conversion. Obviously a quench rate of $10^6$ K/s (which was suggested by many of the original studies[6, 7]) is not adequate to quench the CO-\text{CO}_2 reaction; as much as 65% of the CO species is lost at this quench rate. Even at $\sim 2*10^7$ K/s there is roughly 20% lost. At a quench rate of $\sim 9*10^8$ K/s, the reactions are essentially quenched, with a concentration reduction of less than 5% (it’s impossible to reach 0% because some conversion is always necessary due to radical recombination). These are very serious requirements for sample probes but including surface reactions may improve the situation. If sampling must be done at a slow quenching rate, then kinetic data of this type may be used correct the measurement.

Initial species concentration and temperature have important influences on the reaction rate within the probe. The 1-D kinetics model was used to estimate the required quenching rate within the probe considering only gas phase reactions. Figure 9 shows the amount of initial CO or NO\textsubscript{x} lost versus quenching rate for a sample measured close to the flame. NO\textsubscript{x} is not as sensitive to quenching requirements as CO; over 80% of the CO converts to CO\textsubscript{2} at quenching rates thought to be sufficient (i.e. $\sim 1*10^6$ K/s). This discrepancy between calculations and experiment may be due to neglecting surface reactions in these calculations or to errors in the previously estimated heat transfer rates. Figure 10 shows a similar plot for a lower initial concentration and temperature, such as measured well downstream of the flame or after a heat exchanger. For this case, the required quenching rate to freeze the initial concentration is much lower; i.e. the design requirements for probes in these conditions are much less stringent.

The geometry fed into heat transfer model was varied to meet the required quenching rates established by the kinetics evaluation. Figure 11 shows the gas sample temperature versus probe distance for a stainless probe with a diameter of 762 \textmu m and 8 cm length. The rapid drop in temperature over the first data point corresponds to the forced acceleration to sonic conditions at the probe entrance. Overall, the gas sample was cooled by ap-
proximately 1,200 K within the probe. There was a trade off between probe size and heat transfer efficiency. In a smaller probe, the temperature penetrates into the core flow more easily because there is less gas to cool. However, smaller probes limit the turbulent motion within the probe; the obvious limit being very small Reynolds number and possibly laminar flow. In this limit heat transfer rates are much smaller. The ideal orifice size for these sonic convective-quench probes is therefore neither too large or too small. The maximum quenching rate achieved with this type of probe was \( 1 \times 10^7 \) K/s which corresponded to the probe geometry used in Figure 11. This quenching rate was sufficient to quench gas samples with medium levels of temperature and trace species concentration but will result in an error if used to measure within or close to the flame. Further improvement of the measurement requires use of an aero-convective quench probe. Such a geometry was difficult to incorporate into the multi-point probe, so the sampling limitations were accepted and will be taken into account in future measurements.

5.2. Multi Point Probe

The primary concern in applying single point data to the multi-point design is the change in the metal geometry of the probe. The sample tube is no longer surrounded completely by a water cooling tube. Rather, many sample tubes are cut into a thin bar of finned metal. This change of geometry could affect the quenching rate. To verify that the gas quenching rate was not altered, a three-dimensional heat transfer calculation was conducted. Figure 12 shows the results of a static thermal ANSYS analysis. The probe was loaded with external combustor temperature and internal water cooling. Compared to the single point probe, the surface temperature of the inner sample tube was slightly higher near the entrance region but quickly reached a similar value within the tube. Therefore, it should be expected that the quenching rate for each individual tube within the multi-point probe should roughly match that in the single point probe analysis.

6. Conclusions and Future Work

A gas phase kinetics model was developed and solved to quantify the required quenching rate to freeze chemical reactions within an extractive sample probe. It was shown that quenching rates up to \( 1 \times 10^6 \) K/s were needed to rapidly quench a gas sample with a flame; at lower quenching rates an error in the sampled gas concentration should be expected. This number is high compared to classical gas sampling literature which concluded through
measurements that $1 \times 10^6 - 1 \times 10^8$ K/s would suffice. The difference was suggested to be due to a neglect of surface reactions within these calculations or errors in estimated heat transfer rates in previous studies. The required quenching rate was shown to depend on the sample temperature and species. Hence, designing sample probes for low temperature exhaust streams is relatively simple.

Using a 1D heat transfer analysis, a single point sonic convective-quench probe was designed with sufficient size to achieve a quenching rate of $1 \times 10^7$ K/s. This value was shown to be sufficient to quench gases sampled from medium temperature environments (up to ~1,800 K which is typical of post combustion gases in many processes) but requires a correction for sampling much above those temperatures. A multi-point probe design, which consisted of a collection of single sonic convective-quench tubes, was offered. This probe has excellent spatial averaging characteristics when used to sample from pressured environments while maintaining similar quenching characteristics to the single point probe.

These analyses should be expanded upon in future experimental studies. The multi-point probe’s spatial averaging characteristics should be evaluated experimentally. In addition, probe measurements from a model combustor should be compared to an optical technique to analyze the quenching performance of the probe. Finally, the effect of additional quenching due to surface reactions should be included in future gas kinetics models.

**References**

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