mixing (inhomogeneity) in the secondary zone would also result in excessive CO formation.

In general lean combustion should be employed, if homogeneity with respect to the local fuel/air ratio can be obtained within the primary zone. However, there is no advantage of lean over rich combustion, if initial maldistribution causes inhomogeneity in the primary zone and the secondary zone improves the uniformity. For this condition, low NO_x production might make rich combustion preferable. Many conventional burners are of this type.

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Part II—Liquid Fuel Combustion

The effect of the fuel droplet vaporization rate on the production of carbon monoxide (CO) during combustion in a gas turbine has been evaluated. The temporary CO concentrations exceeding the equilibrium values, observed for premixed combustion, are reduced or eliminated by the gradual introduction of fuel via droplet vaporization. Staged fuel addition is demonstrated as a means of avoiding the excessive initial CO formation associated with premixing at low equivalence ratios.

Introduction

GAS turbines of the present generation rely upon liquid fuel as the prime energy source. This fuel is conventionally prepared for combustion by pressure or air assisted atomization. However, the fuel droplets do persist within the active combustion zone. As a result, the influence of the vaporization/mixing process is superimposed on the chemical kinetics which were the sole control of premixed combustion. The vaporization/mixing rate can under certain conditions become a significant factor in liquid fuel combustion emissions.

The preceding work[1] presented a discussion of the CO production and consumption within the primary zone of a gas turbine combustor for premixed combustion. The present effort extends this to combustion of vaporizing fuel droplets. This work is also confined to the primary zone of a gas turbine combustor. The combustor model and chemical reaction mechanism applied have been described in detail in Ref. 2. Following the arguments in Ref. 2, the liquid fuel vaporization and mixing has been simulated by a fuel availability rate process. Comparison with the results from a more complete treatment of the droplet vaporization mechanism[4] shows that the availability rate used corresponds to droplet sizes of about 20μ, 40μ, and 105μ.[2]

In reality, the primary combustion zone has fuel being sprayed into the hot combusting gas mixture. Some of the initial drops are small and vaporize immediately; others enter the hottest active zone and are at once vaporized. This part of the fuel is immediately available for combustion. The remainder of the fuel enters the recirculation zone as droplets, and vaporizes and combusts in a continuous fashion. Hence, a continuous distribution of droplet sizes may be viewed as a two part system, where smaller drops are represented by premixed combustion and larger drops as liquid fuel combustion.

In effect, there is an immediate introduction of vaporized and mixed fuel followed by a period where the remaining fuel vaporization predominates. In order to simulate this effect, a fraction of the fuel is premixed and the remainder is introduced by the aforementioned fuel vaporization mechanism. This ratio of premixed fuel to liquid fuel has to be estimated because of a lack of detailed experimental information. The condition of 25% premixed/75% liquid initial fuel has been used as a base. However, the limiting case of 100% initial liquid fuel combustion has also been investigated.

Emphasis has been given to high pressure conditions, since the carbon monoxide (CO) levels for high pressure premixed combustion[1] showed the largest excursions above equilibrium. The pressure dependency is deduced from comparison with results of low pressure combustion. For large droplets, vaporization/mixing becomes the rate determining step in the combustion process. Therefore, the early parts of rich combustion with large droplets resemble lean conditions if one adjusts for different ignition delay times. This makes the results for rich combustion more encompassing.

Results

The rate of carbon monoxide production and consumption is a function of a number of parameters such as temperature, fuel/air ratio, degree of premixedness, fuel droplet size, and pressure. For comparison, all cases are for an effective air inlet temperature of 1000°K.[1]

For the more realistic combustion type with 25% premixed/75% liquid initial fuel, the response of the temperature and CO levels to droplet size is demonstrated in Figs. 1 and 2, respectively. The case of completely premixed combustion is added in Figs. 1 and 2 for comparison. Premixed combustion can be

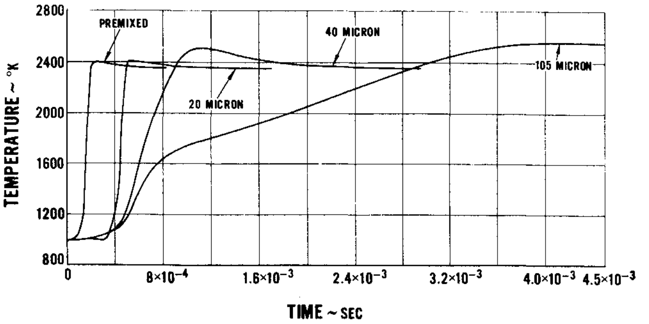

Fig. 1 Combustion temperature vs elapsed time for rich premixed combustion and for rich liquid fuel combustion (25% premixed/75% liquid fuel) with 20μ, 40μ, and 105μ drop sizes, $\phi = 1.5$, $T_{\text{inlet}} = 1000°\text{K}$, $P_{\text{inlet}} = 23$ atm.

viewed as the limit where the droplet size is zero and vaporization/mixing occurs instantaneously. The contrasting limit has the liquid portion of the fuel in one single droplet and essentially only the combustion of the premixed portion of the initial fuel occurs. These results, as in all following cases, indicate that the CO overshoots are retarded with increasing droplet size and subsequently with increasing delay in the combustion process.

Though combustion of 100% initial liquid fuel is a less realistic extreme case, the response of its CO levels to drop size is shown in Fig. 3 for an equivalence ratio of 1.5 and in Fig. 4 for an equivalence ratio of 0.8. A comparison of the results in Fig. 3 with the ones in Fig. 4 demonstrates the dependency of the CO production and consumption on fuel/air ratio.

Figure 5 presents an example of the influence of the degree of premixedness ranging from 100% to 0%. Again, retarding of the fuel availability because of vaporization/mixing diminishes the peaking of the CO concentrations. While Figs. 1–5 consider high pressure combustion, Fig. 6 shows the results for low pressure combustion at an equivalence ratio of 0.8, with 25% of the initial fuel being premixed.

Discussion

The initial sequence of breakdown reactions of the original fuel molecule leading to intermediates with one or two carbon atoms can be rate determining for the over-all combustion process. As a result, these intermediates maintain a comparatively low concentration level. For liquid fuel combustion, the liquid fuel acts as a heat sink. The resulting temperature drop causes a slowdown of the initial breakdown reactions. Combustion of liquid fuel or with staged fuel addition can be viewed as premixed combustion with a small initial fuel concentration and continuous or discrete fuel additions. The over-all result is a slowdown of the entire combustion process including the formation of CO. All carbon of the original fuel molecule except for that retained in unburned hydrocarbons passes through the state of CO. The relation between the CO formation rate and the fuel breakdown rate is discussed in Ref. 1. The latter rate is directly proportional to the available vaporized/mixed fuel concentration. The actual CO level results from the balance of the CO production and the CO consumption by $CO + OH \rightleftarrows CO_2 + H$ (Ref. 1).

Generally, the slowed down CO production caused by liquid fuel vaporization/mixing causes the resulting transient CO levels to decrease. This trend is assisted by the fact that the OH radical overshoot, above its equilibrium value, occurs during a much longer time span than for premixed combustion.[2] The result is a higher CO consumption rate.

The limiting cases of 100% premixed combustion and of 100% liquid fuel combustion are least complex. Premixed combustion, which can also be viewed as 100% liquid fuel combustion with zero droplet size, has been discussed in Ref. 1. 100% liquid fuel combustions with finite droplet sizes generally show a relatively long ignition delay time part of which is caused by the fuel vaporization/mixing producing a combustible gas mixture. With increasing drop size, the transient CO peaks are retarded and reduced as shown in Figs. 3 and 4. For lean combustion with large drop sizes, the transient CO peaks can be completely eliminated. Generally, these peaks occur after a combustible mixture has been reached and has subsequently reacted causing the abrupt temperature rise.

Combustion cases with 25% premixed/75% liquid fuel display CO levels similar to the characteristics for premixed combustion during the early part of the combustion process, while later the effects of liquid fuel combustion dominate. The effect of liquid fuel combustion has been eliminated, as shown in Fig. 2. This extreme case is best simulated by having the liquid portion of the fuel concentrated in one single droplet. For larger droplets, the separation of premixed and liquid fuel combustion characteristics becomes more pronounced. Since the abrupt temperature rise for 25% premixed/75% liquid fuel

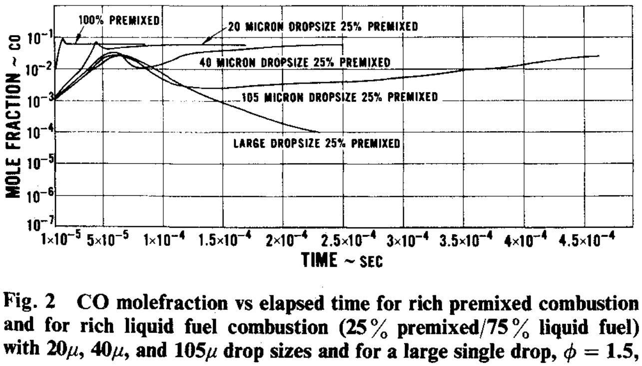

Fig. 2 CO molefraction vs elapsed time for rich premixed combustion and for rich liquid fuel combustion (25% premixed/75% liquid fuel) with 20μ, 40μ, and 105μ drop sizes and for a large single drop, $\phi = 1.5$, $T_{\text{inlet}} = 1000°\text{K}$, $P_{\text{inlet}} = 23$ atm.

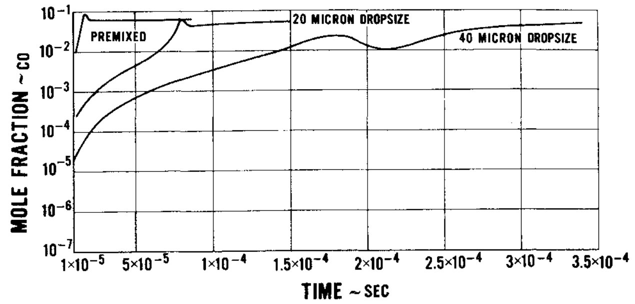

Fig. 3 CO molefraction vs elapsed time for rich premixed combustion and for rich liquid fuel combustion (0% premixed/100% liquid fuel) with 20μ and 40μ drop sizes, $\phi = 1.5$, $T_{\text{inlet}} = 1000°\text{K}$, $P_{\text{inlet}} = 23$ atm.

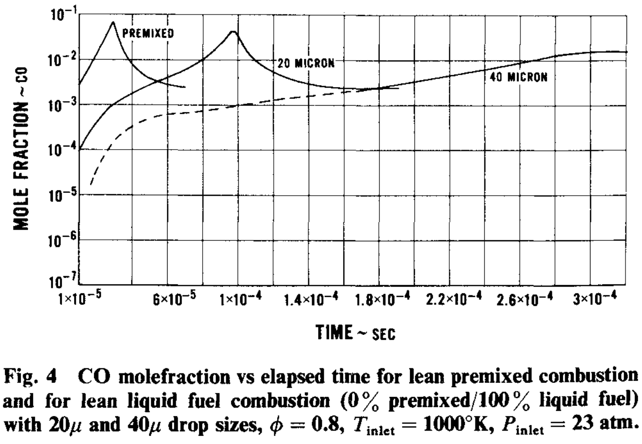

Fig. 4 CO molefraction vs elapsed time for lean premixed combustion and for lean liquid fuel combustion (0% premixed/100% liquid fuel) with 20μ and 40μ drop sizes, $\phi = 0.8$, $T_{\text{inlet}} = 1000°\text{K}$, $P_{\text{inlet}} = 23$ atm.

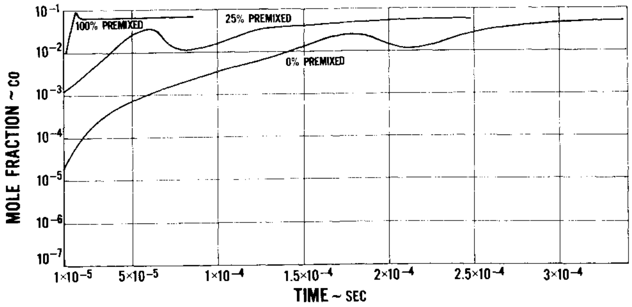

Fig. 5 CO molefraction vs elapsed time for rich premixed combustion and rich liquid fuel combustion (25% premixed/75% liquid fuel and 0% premixed/100% liquid fuel) 40μ drop size, $\phi = 1.5$, $T_{\text{inlet}} = 1000°\text{K}$, $P_{\text{inlet}} = 23$ atm.

combustion can be caused by the combustion of the premixed portion of the fuel alone, the transient CO peaks occur rather early, where the combustion of the premixed fuel dominates.

The influence of fuel/air ratio is complex. Basically, lean combustion shows proportionately larger CO overshoots above equilibrium levels as demonstrated for premixed combustion.[1] The relative reduction of these CO overshoots is more pronounced for rich combustion, whereas for droplets, the CO overshoots are reduced to transient CO peaks below equilibrium level (see Figs. 2 and 3). The combustion process of liquid fuel is accompanied by overshoots of radicals like OH, O, H, etc., above their equilibrium values, as long as active combustion is going on as discussed in Ref. 2. Since the relative OH overshoot is larger for rich conditions, the CO consumption reaction is accelerated for rich combustion.

Generally, the low pressure combustion shows smaller temporary CO overshoots or peaks for both the premixed and the liquid fuel conditions (Fig. 6). The corresponding OH mole fractions are higher for the low pressure combustion which contributes directly to the higher CO consumption rate.

The applicable experimental data[5] indicate that measured levels of CO at low pressure are in excess of those based on local equilibrium. However, at the lean condition ($\phi = 0.8$), the CO concentrations are proportionately much greater than those of the rich levels ($\phi = 1.5$). The results for this range of stoichiometry are consistent with the presented predictions. This analysis indicates no overshoot for the rich, and an overshoot of one order of magnitude for the lean combustion.

Conclusions

The transient carbon monoxide concentrations are directly influenced by the availability of vaporized/mixed fuel. The more gradual the introduction of vaporized/mixed fuel is made, such as produced by larger initial fuel droplets, the larger are the reduction and retardation of the transient CO peaks. Poor mixing can also lower the effective fuel availability. In extreme cases, as caused by staged fuel addition, these peaks can be eliminated resulting in a monotonic CO production rate. Recent experience has shown that reductions in unburned hydrocarbons can be achieved by approaching either the premixed or small droplet liquid fuel combustion at lean stoichiometry. However, the additional air introduced to the primary zone and the peak transient CO levels for lean being only slightly lower than those for rich combustion, creates the potential for quenching, which would result in higher exit CO levels.

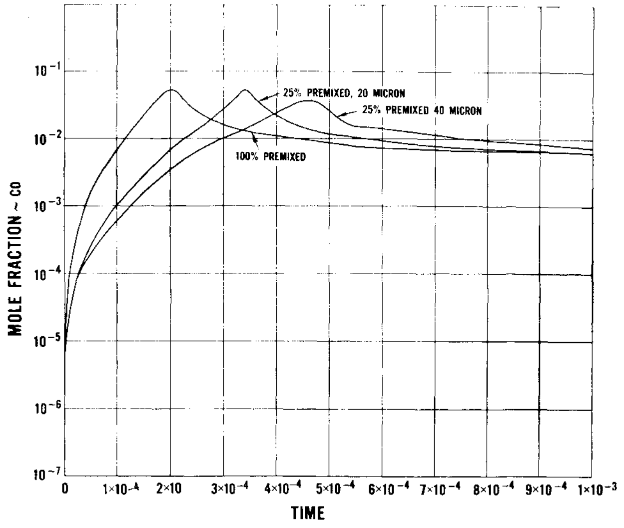

Fig. 6 CO molefraction vs elapsed time for lean premixed combustion and for lean liquid fuel combustion (25% premixed/75% liquid fuel) 20μ and 40μ drop sizes, $\phi = 0.8$, $T_{\text{inlet}} = 1000°\text{K}$, $P_{\text{inlet}} = 2$ atm.

A comparison of NO and CO levels found in the primary combustion zone in gas turbine combustors leads to the general conclusion that the CO concentration is always at or above its equilibrium value for the high primary zone temperature while the NO concentration is always below its equilibrium. The lowest NO levels are obtained in fuel rich premixed combustion while the lowest CO levels occur in lean liquid fuel combustions with slow vaporization/mixing rates.

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