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DOE/ET/10660-T1

COMBUSTION STUDIES OF COAL-IN-OIL DROPLETS

Final Report, August 1, 1977—July 31, 1979

By
C. K. Law

December 1979

Work Performed Under Contract No. FG01-77ET10660

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U. S. DEPARTMENT OF ENERGY

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Distribution Category UC-90e

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ABSTRACT

The combustion characteristics of droplets of coal-oil mixtures were investigated both theoretically and experimentally. Results show that agglomeration of the coal powder occurs upon complete depletion of the volatile oil components, and therefore has serious implications regarding radiation transfer, total burning time, and particulate collection efficiency. Agglomeration is somewhat irrelevant for COM with No. 6 oil because of the small volatility-differentials between coal and No. 6 oil. As a result of agglomeration, fine-crushing the coal is unnecessary unless they can be reduced to micron-sizes such that agglomerate ignition is facilitated.

I. INTRODUCTION

As the nation's petroleum reserve steadily diminishes and the need for viable, alternate fuel sources becomes more urgent, two facts stand out prominently with regard to the utilization of fossil fuels. First, coal constitutes the most abundant fossil fuel resource in this country, with enough reserve to last several centuries. Second, most of the combustors, both stationary and mobile, utilize liquid fuels. It is therefore logical that much effort be directed at converting coal into forms suitable for utilization by liquid-fueled combustors.

An obvious solution to this need is to chemically convert coal to liquid fuel through the various liquefaction processes. However, an alternate, more direct approach is simply to inject and burn mixtures of coal powders and oil. The concept involves mixing finely crushed coal in the liquid fuel such that the resulting coal-oil-mixture (COM) still behaves like a liquid and hence can be sprayed into the conventional liquid-fueled combustors with minimum amount of combustor modifications. Whereas in this approach the coal generally serves only as a passive, secondary fuel source, it must be emphasized that even a few per cent substitution can be translated into substantial savings in the total liquid fuel consumption. Furthermore, since the production of coal-oil-mixtures requires only the physical processes of crushing and mixing rather than the energy-expensive chemical processes of liquefaction, a net saving in energy at the production stage is also realized.

In view of such incentives associated with the utilization of coal-oil-mixtures, it is then necessary to investigate in detail their combustion characteristics in typical combustor environments, particularly those within furnaces and boilers whose longer residence times allow for

more complete combustion of coal. Of particular interest is the behavior of individual droplets, which collectively determine the nature of spray combustion and therefore the performance of the combustor.

Thus the aim of the present program is to gain fundamental understanding on the combustion characteristics of multicomponent, multi-phase fuel droplets as typified by coal-oil-mixtures, with or without water addition. Theoretical bases of the problem are discussed in the next section. Two series of experiments were conducted, on suspended and free droplets respectively. Their results are presented in Sections III and IV, which are followed by conclusions and recommendations. Detailed discussions on all of the above aspects can be found in Appendixes A to C.

II. THEORETICAL DESCRIPTIONS OF COMBUSTION BEHAVIOR

The present research has identified that the possible combustion modes of COM are intimately dependent on two important factors, namely (1) the intensity of internal circulation within the droplet; and (2) the relative volatilities between coal and oil. Let us first discuss effects of internal motion.

Internal motion is generated by the shear stress acting at the droplet surface by some external gaseous motion (see Fig. 1 of Appendix B). The existence of internal motion can significantly enhance the transport processes within the droplet and therefore the relative vaporization rates of the different species at the droplet surface. Thus in the limit of rapid mixing we expect vaporization will follow the batch distillation process, with the more volatile components being depleted from the droplet first. Thus if the oil used is much more volatile than coal, then all the coal powders will be left behind as an agglomerate upon complete depletion

of oil. According to this scheme a 100 μm droplet with 1% coal particle concentration will yield a 20 μm agglomerate.

The implications of this possible agglomeration are significant. First, it implies that the sizes of the coal particles which actually undergo combustion in the form of agglomerates are determined by the initial concentrations of the coal particles and the initial droplet sizes, but not by the sizes of the individual coal particles. The only influence of the individual particle size is the possible modification of the rheological properties of the mixture, for example the viscosity coefficient, and hence the droplet size distribution of the spray. Therefore it is probably not necessary to use extremely fine coal particles in the preparation of the coal-oil-mixtures since these individual particles will eventually agglomerate anyway.

The formation of these large agglomerates is expected to intimately affect such combustion characteristics as the rate of radiative transport, which is an important heat transfer mechanism within furnaces and boilers. Furthermore, due to the non-volatile nature of coal, and the reduced residence time after the liquid is completely vaporized before coal can be burned, complete combustion of these agglomerates may not always be possible. If this is indeed the case, then not only the energy utilization aspect of coal addition cannot be fully realized, the soot emission problem will be seriously compounded. Even if complete combustion is achieved, the problem of particulate collection and emission still need to be considered because the large agglomerates will produce correspondingly large ash particles.

The above combustion mechanism, leading to coal particle agglomeration, is based on the assumption that internal circulation is of sufficient intensity

such that vaporization resembles batch distillation. The other limit occurs when internal circulation is very weak such that diffusion, rather than convection, is the dominant mode of transport within the droplet. Then because of the very slow rate of liquid-phase mass diffusion, the more volatile liquid components will be trapped in the droplet interior, being unable to reach the droplet surface to be vaporized. Thus as the droplet is being heated to very high temperatures, these volatile components will boil internally. The subsequent internal pressure build-up will be sufficiently strong to shatter the emulsion droplet, hence producing droplets of much smaller sizes which can be readily burned. Obviously agglomerates will not form with this combustion mode.

Thus we see that depending on the strength of internal motion, qualitatively different combustion characteristics can result. The difference will be greater when the volatility-differentials are larger. Therefore we expect that, for example, the difference is large for coal-in-No. 2 oil and small for coal-in-No. 6 oil.

To substantiate the theoretical results, the following series of experiments were conducted. Details of the theory can be found in Appendix A.

III. SUSPENDED-DROPLET EXPERIMENTS

In these experiments a COM droplet of the order of 1000 μm was suspended at the end of a quartz fiber and ignited through spark-discharge. The subsequent combustion sequence was observed through high-speed cine-microphotography at 1000 fps. All the experiments were conducted in ambient air. No. 2 oil and 200 to 400 mesh coal powders were used. The experimental apparatus is shown in Fig. 9 of Appendix B.

A typical combustion sequence can be qualitatively described as follows. After ignition a brief steady burning period exists before some internal disturbance is initiated as evidenced by the wrinkling of the originally smooth droplet surface. Soon small masses are seen to be intermittently ejected from the droplet. This state persists, which may or may not be accompanied by more violent fragmentations involving larger masses, until most of the liquid fuel has been vaporized, leaving behind an irregularly-shaped agglomerate of coal particles adhering to the suspension fiber. The amount of agglomerate left behind is very substantial (Fig. 11 of Appendix B). It was further found that when a small amount of water is added to COM, a violent explosion always occurred, leaving behind no agglomerate at the fiber.

To investigate the effect of internal motion, hot air was blown upward beneath the droplet. Then it was observed that all fragmentations and explosions were inhibited. All these results substantiate our theoretical predictions.

IV. FREE-DROPLET EXPERIMENTS IN FURNACES

This series of experiments (Fig. 1 of Appendix C) involved injecting a stream of monosized COM droplets into a 1000°C furnace, collecting the vaporization/combustion products, and examining them using Scanning Electron Microscope (SEM). These experiments have the advantage of using smaller droplets, of the order of 600 μm to 700 μm , and the lack of complications from the suspension fiber.

The experiments yielded the following results. In all cases studied spherical agglomerates formed (see Figs. 4 to 6 of Appendix C), which seem to consist of almost all the coal powders originally present. For COM with

No. 2 oil, almost all the oil was vaporized when the agglomerate was formed. The subsequent agglomerate heating and ignition required much time. For COM with mixtures of No. 2 and No. 6 oils, the agglomerate consists of both the coal powder as well as the No. 6 oil. Ignition of the agglomerate was much facilitated. This implies that for COM with No. 6 oil agglomeration is probably irrelevant because of the small volatility-differential between oil and coal.

Addition of water showed no effect in initiating fragmentation, probably because of the significant amount of internal motion generated within the freely-falling droplet. COM with micron-size coal particles were also used. Similar agglomeration processes were observed, although ignition was facilitated.

V. CONCLUSIONS AND RECOMMENDATIONS

From the present theoretical and experimental results, the following conclusions and recommendations can be made.

- (1) The combustion characteristics of COM droplets, with or without water addition, depend on the intensity of internal motion and the oil volatility. Rapid internal motion and high oil volatility favor agglomeration.
- (2) In realistic furnace environments agglomerates of large sizes do form. The subsequent heating and ignition of these agglomerates may require substantial time and hence may significantly prolong the total burning time.
- (3) Agglomerates also modify the radiation and emission characteristics.
- (4) Agglomeration is a serious problem for COM with No. 2 oil, but is somewhat irrelevant for COM with No. 6 oil because of the closer volatility between coal and No. 6 oil.

- (5) From (4) it can be said that any attempt in making COM more combustible through addition of some volatile oil may actually aggravate the agglomeration problem.
- (6) From combustion considerations it is unnecessary to fine-crush the coal powders since they will agglomerate anyway. The exception is for micron-size coal for which ignition is facilitated.
- (7) Addition or retention of small quantities of water in COM does not seem to either promote or inhibit agglomeration, although additional experiments with more viscous No. 6 oils are needed for further verification.

Reprinted from AIChE JOURNAL, July 1978

Internal Boiling and Superheating in Vaporizing Multicomponent Droplets

The vaporization and combustion of a miscible multicomponent droplet in a quiescent atmosphere is analyzed by assuming transient-diffusive transport within the droplet, quasi steady diffusive-convective transport in the gas phase, and ideal solution behavior for the mixture. Results on the vaporization of a binary droplet show that owing to the significant liquid phase diffusional resistance, the vaporization process approximately consists of an initial transient regime, an intermediate, diffusion limited, almost quasi steady regime, and a final volatility limited regime. It is further demonstrated that the entrapment of the volatile components within the rapidly heated droplet interior may lead to the initiation of either homogeneous or heterogeneous nucleation, which can result in the fragmentation of the parent droplet with the internal pressure buildup.

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SCOPE

For vaporizing multicomponent droplets without much internal circulation, the extremely slow process of liquid phase mass diffusion is rate limiting such that vaporization ceases to resemble the batch distillation process as governed by volatility differentials. The entrapment of the volatile components within the rapidly heated droplet in-

terior may subsequently lead to homogeneous or heterogeneous nucleation and hence further atomization of the liquid droplet due to the internal pressure buildup. It is also suggested that the heterogeneously induced fragmentation is a possible mechanism in preventing the formation of large coal particle agglomerates in vaporizing coal slurry droplets. The present study aims to explore and quantify the vaporization and nucleation characteristics of a multicomponent droplet in typical combustor environments.

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CONCLUSIONS AND SIGNIFICANCE

The present investigation shows that owing to the slow rate of liquid phase mass diffusion compared with that for droplet surface regression and liquid phase thermal diffusion, the vaporization process approximately consists of an initial transient regime, an intermediate, diffusion limited, almost quasi steady regime, and a final volatility limited regime which onsets when the continuously diminishing droplet size becomes comparable with the characteristic mass diffusion length. It is further demonstrated that the concept of droplet fragmentation due to the occurrence of

internal homogeneous nucleation is viable; that the attainment of the limit of superheat within the droplet interior is enhanced for increased ambient temperatures, ambient pressures, and volatility differentials among the constituents; and that this concept is most suitable for application in high pressure combustors. Droplet fragmentation due to internal boiling in the presence of heterogeneous nucleation sites has also been studied and found more attractive for application in several aspects, particularly the potential on the utilization of coal slurry fuels in atmospheric combustors.

It has recently been suggested (Ivanov and Nefedov, 1965; Dryer, 1975; Jacques et al., 1975; Law, 1977) that sprays with fine droplets can be produced by emulsifying a high boiling fuel with water such that as the emulsion droplet becomes appreciably heated in the combustor, the embedded water microdroplets can be heated to the limit of superheat and subsequently explode. The disintegration of the parent droplet essentially constitutes a secondary atomization process, producing droplets of very fine sizes which can be readily vaporized. Furthermore, the violence associated with the so-called microexplosion (Ivanov and Nefedov, 1965) also disperses the secondary droplets into a large physical volume, hence producing a more uniform charge for combustion.

The primary difficulties involved with the utilization of water-in-oil emulsions are their instability from internal phase coalescence, as well as the weight and heat sink penalties associated with water addition. Whereas these difficulties either are not serious drawbacks for certain combustors or can be surmounted for others with further technological developments, an alternate mechanism to induce microexplosion, through internal superheating of a miscible, multicomponent, evaporating fuel droplet, is also possible. The concept capitalizes on the fact that the liquid phase Lewis number Le_L , representing the ratio of thermal to mass diffusion rates, is a large number. Therefore, when internal circulation is not strong such that diffusion is the dominant transport mode within the droplet, the droplet interior will be heated at a rate much faster than that with which the more volatile compounds in the inner core can be transported to the surface where they are preferentially vaporized. It is then conceivable that the volatile mixture trapped in the inner core can be heated to the limits of superheat, homogeneously nucleates, and subsequently ruptures the parent droplet with the resultant internal pressure buildup.

Whereas several analyses (Faeth, 1970; Newbold and Amundson, 1973; Law, 1976) have been performed on multicomponent droplet vaporization by assuming the internal states are maintained perpetually uniform such that the volatility differentials among the constituents are the rate limiting factors, Landis and Mills (1974) first pointed out that in the absence of internal circulation, liquid phase mass diffusion is instead the rate limiting process. Their results for the pure vaporization of a binary droplet show that after an initial transient, the internal concentrations approach almost constant profiles which persist until complete droplet consumption, and that the droplet interior can be driven to the boiling state. Hence, with suitable heterogeneous nucleation sites, internal boiling can be initiated.

Since conventional liquid fuel blends do not contain any heterogeneous nucleation sites, internal bubbling can be initiated only when the internal states have reached the limit of superheat, which requires a steeper concentration gradient, a higher droplet temperature, and is expected to be significantly more difficult to be attained than the state of boiling. The present investigation then aims to explore, and subsequently demonstrates, that with proper optimization, the limit of superheat can indeed be reached within the droplet interior. Hence, microexplosion through internal superheating is a viable concept. By studying the phenomena of interest in greater detail, we shall also show that as the droplet size diminishes, the vaporization process becomes progressively more dominated by the volatility differentials. Therefore, contrary to the results of Landis and Mills (1974), the concentration profiles do not remain at constant values towards the end of the droplet lifetime. Finally, the formulation of Landis and Mills (1974) is also generalized herein to the case of multicomponent droplet which can undergo either pure vaporization or combustion.

FORMULATION

Problem Definition

The problem analyzed is the isobaric, spherically symmetric vaporization of a droplet, initially of radius $r_{s,0}$, temperature $T_o(r)$, and consisting of N compounds characterized by their respective molar fractions $\bar{X}_i(r)$, molecular weights W_i , specific latent heats of vaporization L_i , normal boiling temperatures T_{bi} evaluated at the normal atmospheric pressure p_b , and critical temperature T_{ci} and pressure p_{ci} , that at time $t = 0$ is introduced, and ignited in the case of combustion, in a stagnant, unbounded atmosphere. The atmosphere is characterized by its temperature T_∞ , pressure p_∞ , and mass fractions $Y_{i,\infty}$ of its $N + 2$ species consisting of the N vaporizing species, the oxidizer gas O , and a noncondensable inert species.

For pressures not close to critical, the gas phase processes can be assumed to be quasi steady since they occur at rates much faster than those of the liquid phase processes (Law, 1976; Sirignano and Law, 1978). Hence, the relevant transport mechanisms are transient diffusion in the liquid phase and diffusion and radial convection in the gas phase. Radiative transfer is neglected owing to the small droplet sizes of interest. In the case of combustion, we shall also invoke the flame-sheet approximation, which states that the outwardly diffusing multicomponent fuel vapor F reacts stoichiometrically and completely with the inwardly diffusing oxidizer gas at an infinitesimally thin flame front located at r_f . Finally, for mathematical convenience unity, gas phase Lewis

number and conventional constant transport property assumptions will also be invoked.

The formulation then consists of descriptions for the gas and liquid phase transport processes, the interfacial phase change, and the state of the limit of superheat. These will be presented in the following.

Gas Phase Description

Explicit expressions stated in terms of the states at the gas-liquid interface have been derived (Law, 1976) for the quasi steady, spherically symmetric, convective-diffusive transport of a multicomponent gas, with or without diffusional burning confined to a flame sheet. In particular, the nondimensional expressions for the total and fractional mass vaporization rates $\hat{m}$ and ϵ_i and the amount of heat utilized for droplet heating $\hat{H}$ are, respectively, given by

$$\hat{m} = \ln \left(1 + \frac{\hat{T}_s - \hat{T}_s + \tilde{Y}_{\infty} \tilde{Q}}{\tilde{L} + \hat{H}} \right) \quad (1)$$

$$\epsilon_i = Y_{is} + (1 - Y_{Fs}) \frac{(Y_{is} - Y_{if})}{(Y_{Fs} - Y_{if})} \quad (2)$$

and

$$\hat{H} = \frac{(\hat{T}_s - \hat{T}_s + \tilde{L} - \tilde{Q}) + (1 + \tilde{Y}_{\infty})[\tilde{Q} - \tilde{L}(1 - Y_{Ff})/(1 - Y_{Fs})]}{(1 + \tilde{Y}_{\infty})(1 - Y_{Ff})/(1 - Y_{Fs}) - 1} \quad (3)$$

where $\hat{m} = m/(4\pi\rho_0 D_0 r_s)$, $\epsilon_i = m_i/m$, $\tilde{L} = \Sigma \epsilon_i \hat{L}_i$, $\tilde{Q} = \Sigma \epsilon_i \hat{Q}_i$, $\tilde{Y}_{\infty} = Y_{\infty}/\Sigma \epsilon_i V_i$, $Y_{Ff} = \Sigma Y_i \hat{T}_i$, $\hat{T}_i = C_p T/L_r$, $\hat{L}_i = L_i/L_r$, $\hat{Q}_i = Q_i/L_r$, $\hat{H} = H/L_r$, L_r is a reference latent heat of vaporization, and for convenience we can assume the value of unity in the system of units adopted. The summation operation is to be performed over all of the vaporizing species. The problem has also been formulated in such a generalized manner that the results specialize to combustion by setting $Y_{if} = 0$ and to pure vaporization by setting $Y_{\infty} = 0$ and $Y_{if} = Y_{is}$.

Liquid Phase Description

The unsteady liquid phase heat and mass diffusion are governed by

$$\frac{\partial T}{\partial t} = \frac{\alpha_1}{r^2} \frac{\partial}{\partial r} \left(r^2 \frac{\partial T}{\partial r} \right) \quad (4)$$

$$\frac{\partial Y_i}{\partial t} = \frac{D_i}{r^2} \frac{\partial}{\partial r} \left(r^2 \frac{\partial Y_i}{\partial r} \right) \quad (5)$$

Since one of the liquid phase boundaries is continuously regressing, solutions for Equations (4) and (5) can be facilitated by fixing the droplet surface at unity and by moving the upper limit in time from a finite to an infinite value through the transformations

$$\sigma = \frac{r}{r_s(t)} \quad \text{and} \quad \tau = \int_0^t \frac{\alpha_1}{r_s^2(t')} dt' \quad (6)$$

Using Equation (6), Equations (4) and (5) are, respectively, transformed to

$$\frac{\partial T}{\partial \tau} = \frac{1}{\sigma^2} \frac{\partial}{\partial \sigma} \left(\sigma^2 \frac{\partial T}{\partial \sigma} \right) - K_1 \hat{m} \sigma \frac{\partial T}{\partial \sigma} \quad (7)$$

$$\frac{\partial Y_i}{\partial \tau} = \frac{1}{Le_i \sigma^2} \frac{\partial}{\partial \sigma} \left(\sigma^2 \frac{\partial Y_i}{\partial \sigma} \right) - K_1 \hat{m} \sigma \frac{\partial Y_i}{\partial \sigma} \quad (8)$$

which are to be solved with the initial and boundary conditions

$$T(\sigma, 0) = T_0(\sigma), \quad Y_i(\sigma, 0) = Y_{i0}(\sigma) \quad (9)$$

$$(\partial T / \partial \sigma)_{\sigma=0} = 0, \quad (\partial Y_i / \partial \sigma)_{\sigma=0} = 0 \quad (10)$$

$$(\partial T / \partial \sigma)_{\sigma=1} = K_2 \hat{m} (\hat{H} - \tilde{L}) \quad (11)$$

$$(\partial Y_i / \partial \sigma)_{\sigma=1} = Le_i K_1 \hat{m} (Y_{is} - \epsilon_i) \quad (12)$$

where $K_1 = (\lambda_g C_i) / (\lambda_l C_g)$, $K_2 = \lambda_g / \lambda_l$ and the identity

$$\hat{m} = -(\rho_l C_g / 2\lambda_g) dr_s^2 / dt \quad (13)$$

has been used. Equations (11) and (12) represent energy and species conservations at the interface.

Hence, with $\hat{m}$, ϵ_i and $\hat{H}$ given by Equations (1) to (3), and using the phase change description of Equation (16) which relates Y_{is} and Y_{is-} , $T(\sigma, \tau)$ and $Y_i(\sigma, \tau)$ can be solved from Equations (7) to (12). The instantaneous droplet size is obtained by integrating Equation (13), yielding

$$\hat{r}_s^2(\tau) = \exp \left[-2K_1 \int_0^\tau \hat{m}(\tau') d\tau' \right] \quad (14)$$

where $\hat{r}_s = r_s / r_{s0}$. Finally, when we invert Equation (6), the nondimensional physical time $\hat{t} = (\alpha_l / r_{s0}^2) t$ is

$$\hat{t} = \int_0^\tau \hat{r}_s^2(\tau') d\tau' \quad (15)$$

with $\hat{r}_s^2(\tau)$ given by Equation (14).

Phase Change Description

Since for a volatile liquid the phase change process occurs at rates much faster than the gas phase transport processes, the vapor concentration at the droplet surface can be considered to be saturated. By further assuming that the liquid behaves as an ideal mixture, Raoult's law states that

$$X_{is} = X_{is-} \left(\frac{p_b}{p_s} \right) \exp \left[\left(\frac{L_i}{R_i} \right) \left(\frac{1}{T_{bi}} - \frac{1}{T_s} \right) \right] \quad (16)$$

where the molar and mass fractions are related through

$$Y_i = \frac{X_i W_i}{\Sigma X_i W_i} \quad (17)$$

The Limit of Superheat

Skipov (1974) and Apfel (1971) have measured, for a variety of pure substances, the limits of superheat as a function of pressure, which were shown (Eberhart and Schnyder, 1973) to be approximately correlatable by a modified equation of state. This correlation, however, is somewhat inconvenient to use owing to the implicitness with which the variables are related. We have instead found that the available data can be quite satisfactorily correlated by (Figure 1)

$$(1 - T_{Li}/T_{ci}) = 0.111(1 - p/p_{ci})^{0.858} \quad (18)$$

which provides an explicit relation between the variables. The standard and maximum deviations in the fitting are 0.005651 and 0.01255, respectively.

Fig. 1. Experimental and fitted limits of superheat for pure liquids as a function of pressure.

For small values of (p/p_{ci}) , Equation (18) can be expanded, giving

$$(T_{Li}/T_{ci}) \approx 0.889 + 0.0952(p/p_{ci}) \quad (19)$$

which shows that in this limit (T_{Li}/T_{ci}) depends linearly, but very insensitively, on (p/p_{ci}) . In particular, for vanishing (p/p_{ci}) , which is approximately the case for many liquids at 1 atm, (T_{Li}/T_{ci}) is a constant equal to 0.889.

Measurements on the limit of superheat of mixtures which exhibit close ideal solution behavior show an approximate linear variation with the liquid molar fraction (Blander and Katz, 1975); namely

$$\tilde{T}_L = \sum T_{Li} X_i \quad (20)$$

Hence, combining Equations (18) and (20), we can

estimate the limit of superheat for a given mixture composition at a given pressure. It may also be noted that since the sizes of the fuel droplets of interest are typically of the order of $100 \mu\text{m}$ and hence are not small, the internal pressure is essentially the same as that of the ambience.

This completes the description of the model. If we know the instantaneous concentration distributions within the droplet, the limits of superheat $\tilde{T}_L(\sigma, \tau)$ can be computed and compared with the droplet temperature $T(\sigma, \tau)$.

The instant at which $\tilde{T}_L(\sigma, \tau) = T(\sigma, \tau)$ is satisfied somewhere within the droplet signifies the onset of internal bubbling due to homogeneous nucleation and is approximately identified as the state when microexplosion of the droplet occurs.

RESULTS AND DISCUSSIONS

Equations (7) to (12) were numerically integrated using the Crank-Nicolson technique. The radial mesh size was taken to be 0.05. Accuracy in the numerical scheme was further assured by decreasing the mesh size by at least a factor of two and noticing essentially no change in the computed results.

All the results to be presented in the following are for the pure vaporization of a binary droplet, with $T_o(\sigma) = 300^\circ\text{K}$ and $X_{io}(\sigma) = 0.5$, in a constant environment devoid of any fuel vapor. The gas phase specific heat is taken to be that of the fuel vapor at about 1500°K , $C_g = 1 \text{ cal/g}^\circ\text{K}$, since fuel vapor is the only species which is transported through convection. Further, noting that $C_l \approx C_g$, and that λ_g/λ_l is typically between 0.1 and 0.3, we have used $K_1 = K_2 = 0.2$. The liquid phase properties are representative of those of alkanes between T_o and the boiling point, whereas λ_g is that of air between 1000° to 2000°K .

Figure 2 shows the molar concentration profiles of decane in a decane-dodecane droplet which is undergoing pure vaporization in a $T_\infty = 2000^\circ\text{K}$, $p_\infty = 1 \text{ atm}$ environment. The curves are also plotted as functions of Le_l and $M = 1 - \hat{r}_s^3$, which represents the fractional amount of the original droplet mass vaporized and for the present study appears to be a more meaningful indication of the progress in the vaporization process than either the physical time $\hat{t}$ or the transformed time τ .

Fig. 2. Concentration profiles of decane for a decane-dodecane droplet vaporizing in a 2000°K , 1 atm environment.

Fig. 3. Surface and center values of decane concentration as a function of M for a decane-dodecane droplet vaporizing in a 2000°K, 1 atm environment.

Since the presence of internal circulation diminishes Le_1 owing to the increased convective transport which is equally efficient for both heat and mass, effects caused by the varying degrees of internal circulation can be simulated by decreasing Le_1 . Hence, results are presented both for $Le_1 = 30$, which is representative of typical liquid fuels, and for smaller values of Le_1 . In the limit of convection dominated transport, $Le_1 \rightarrow 1$.

Figure 2 shows that the concentration profiles are qualitatively influenced by Le_1 . When mass diffusional resistance is significant, at $Le_1 = 30$, a steep concentration gradient exists near the droplet surface, although as σ decreases, an almost uniform state is rapidly approached. Comparing the $M = 0.5$ and 0.95 cases also shows that an approximately constant profile exists for a significant portion of the droplet lifetime. These diffusion limited characteristics gradually disappear as Le_1 decreases until for $Le_1 = 1$, at which heat and mass transport are equally efficient, the concentration gradient is gentle and uniform throughout the droplet. Furthermore, since decane can now be more readily brought to the surface where it is preferentially vaporized owing to its higher volatility, its concentration within the droplet is rapidly depleted.

The above observations are further illustrated in Figure 3, where the surface and center values of the molar fraction of decane are plotted vs. M . It is of particular interest to note that for $Le_1 = 30$, the vaporization process consists of three regimes. During the initial transient regime, the decane concentration near the surface is rapidly depleted owing to its volatility, although its value in the inner core is practically undisturbed. Subsequently, an intermediate, mass diffusion limited, almost quasi steady regime exists during which the species are transported to, and exposed at, the regressing surface at approximately constant rates. For large Le_1 , this steady period persists until almost complete droplet consumption. However, towards the end of the droplet lifetime, a volatility limited regime exists during which the more volatile component becomes rapidly depleted from the entire droplet composition. The vaporization characteristics now resemble those of the rapid mixing model (Faeth, 1970; Newbold and Amundson, 1973; Law, 1976). This result is physically realistic because as the droplet vaporizes, its size will eventually become comparable with the characteristic diffusion length. Then, diffusional transport is significantly enhanced, the concentrations are almost perpetually uniformized, and hence volatility differentials limit the vaporization process.

The droplet size at which this volatility limited regime becomes important can be estimated as follows. First

Fig. 4. Surface and center values of temperature as a function of M for a decane-dodecane droplet vaporizing in a 2000°K, 1 atm environment.

note that since $\hat{m}$ does not vary significantly except during the very initial period (Law and Sirignano, 1977), the variation of the droplet size can be estimated by integrating Equation (13) with an average $\hat{m}$, $\langle \hat{m} \rangle$. This yields

$$r_s^2 = r_{s0}^2 - (2\lambda_g \langle \hat{m} \rangle / \rho_l C_g) t \quad (21)$$

Furthermore, since the characteristic diffusion length Δ_1 is

$$\Delta_1 = (D_1 t)^{1/2} \quad (22)$$

we have, after eliminating t from Equations (21) and (22)

$$(\Delta_1/r_s) = [(\hat{r}_s^{-2} - 1)/(2K_1 \langle \hat{m} \rangle Le_1)]^{1/2} \quad (23)$$

Therefore, diffusional transport is expected to be significantly enhanced when $(\Delta_1/r_s) = 1$, or

Fig. 5. Amount of droplet mass vaporized at the onset of internal bubbling as a function of ambient pressure for a heptane-hexadecane droplet vaporizing in a 2000°K environment.

Fig. 6. Location within droplet where internal bubbling initiates as a function of ambient pressure for a heptane-hexadecane droplet vaporizing in a 2000°K environment.

$$M = 1 - (1 + 2K_1 \langle \hat{m} \rangle Le_l)^{-3/2} \quad (24)$$

Since $2K_1 = O(1)$, Equation (24) shows that efficient diffusional transport onsets early in the droplet lifetime for $\langle \hat{m} \rangle Le_l = O(1)$ or less but occurs only towards the end for $\langle \hat{m} \rangle Le_l \gg 1$. For the present case $\langle \hat{m} \rangle = O(1)$, Figure 3 shows that for $Le_l = 30$, this volatility limited regime is distinct and occurs when $M \rightarrow 1$.

Figure 3 further shows that the three regimes identified for $Le_l = 30$ become less distinct as Le_l decreases. Hence, for $Le_l = 10$, the quasi steady regime ceases to be distinct, whereas, for $Le_l = 1$, the entire vaporization process is transient and volatility limited.

Fig. 7. Amount of droplet mass vaporized at the onset of internal bubbling as a function of ambient temperature for a heptane-hexadecane droplet vaporizing in a 10 atm environment.

Figure 4 shows the temporal variations of the surface and center values of the droplet temperature. Since liquid phase heat conduction is an efficient process regardless of the existence of internal circulation (Law and Sirignano, 1977), Figure 4 shows that the temperature histories are qualitatively similar for both the high and low Le_l values, except for the existence of the final, volatility limited regime at $Le_l = 30$, during which the droplet temperature rapidly increases to approach the wet-bulb value of the less volatile component.

We next present results on the possible attainment of the limit of superheat within the droplet interior as a function of the ambient temperature and pressure, with $Le_l = 30$. The binary components selected for study are heptane and hexadecane, whose volatilities are respectively representative of gasoline, a volatile fuel, and diesel, a nonvolatile fuel. These are selected because the attainment of superheating can be facilitated by utilizing components with large volatility differentials. The less volatile component, which has a larger concentration at the droplet surface and a higher boiling point, is needed to achieve a higher droplet temperature, whereas the more volatile component, which is more concentrated in the interior and also has a lower limit of superheat, is used to suppress the concentration-weighted limit of superheat, $\tilde{T}_L$.

The two important parameters characterizing the phenomenon are the time and location the limit of superheat is first attained. Obviously, to maximize the benefits of microexplosion caused by internal bubbling, this event should occur deep within the droplet and early in the droplet lifetime.

Denoting the state at which internal bubbling initiates by the superscript "o", Figure 5 shows M^o as a function of p_∞ with $T_\infty = 2000^\circ\text{K}$. It is seen that increasing p_∞ enhances the occurrence of internal bubbling. This is because as p_∞ increases, the boiling point of the fuel, and hence the droplet temperature, increases at a much faster rate than that for the limit of superheat. Figure 5 also shows that a minimum p_∞ exists below which internal bubbling cannot occur. For pressures higher than those in this critical regime, internal bubbling occurs when about 30 to 40% of the droplet mass has been vaporized. The above observations suggest that the concept of microexplosion induced by internal superheating is more suitable for application in high pressure combustors, for example, the diesel engine.

Figure 6 shows the location σ^o , where the limit of superheat is first reached within the droplet. It is seen that except in the critical regime of 3 to 4 atm, σ^o is between 0.6 to 0.7, and hence $(r^o)^3$ is between 0.2 to 0.35. Therefore, from a mass point of view, bubbling can be considered to occur quite deep within the droplet. It is also significant to note that although the onset of bubbling is relatively delayed in the critical regime, it occurs deep within the droplet such that the microexplosive effects are maximized.

Figure 7 shows M^o as a function of T_∞ with $p_\infty = 10$ atm. As expected, M^o decreases with increasing T_∞ . A minimum T_∞ also exists below which internal bubbling is not possible.

It is also of interest to investigate the characteristics of internal bubbling caused by heterogeneous nucleation, assuming that some heterogeneous nucleation sites are present within the droplet. This scheme appears to be more attractive than microexplosion through internal superheating in several aspects. Since heterogeneous nucleation can be attained much more readily than homogeneous nucleation, the concept of microexplosion can now be applied to fuel blends with smaller volatility

differentials and to combustor environments with lower temperatures and pressures. In fact, Figure 5 shows that M^* actually slightly decreases with decreasing p_* , hence making its utilization particularly attractive in atmospheric combustors, for example, the industrial and domestic furnaces. Furthermore, with internal boiling, the droplet interior temperature is limited to the local boiling point of the fuel mixture; hence the intensity of liquid phase pyrolysis, and subsequently the extent of soot formation, may be substantially lessened. Finally, since a less steep concentration gradient is required, some degree of internal circulation, which is usually unavoidable in realistic situations, can also be tolerated.

Figures 5 and 7 also show that internal bubbling can be initiated early in the droplet lifetime, which is beneficial for enhanced atomization effects; although due to the smaller internal vapor pressure buildup and the fact that nucleation now occurs closer to the surface (Figure 6), the microexplosive event is expected to be less violent and hence less effective. The primary drawback of this scheme, however, is the need to introduce heterogeneous nucleation sites. Since these sites are naturally present in droplets of coal-dust-in-oil slurries, the potential of their utilization in boilers and furnaces as a measure to conserve fuel oil appears more attractive. It is also of significance to note that without the postulated heterogeneously induced internal bubbling and hence droplet fragmentation, it is conceivable that the coal particles within the slurry droplet will become progressively more concentrated as the much more volatile liquid components are vaporized. Eventually, a large coal particle agglomerate will be formed, and, depending on the remaining residence time in the combustor, incomplete combustion of this agglomerate may occur. Then not only are the chemical energy of the coal particles not utilized, but a large amount of smoke is also exhausted. Even if complete combustion is possible, the sizes of the ash particles produced may also be larger than desired. Fortunately, the present study indicates that this is not likely to be the case.

ACKNOWLEDGMENT

This research was sponsored by the Division of Fossil Energy Research, Department of Energy under Grant EF-77-G-01-2741. The author also wishes to express his sincere appreciation to H. K. Law for her able assistance with the numerical work.

NOTATION

C	= specific heat at constant pressure
D	= mass diffusivity
H	= energy used for droplet heating per unit mass of fuel vaporized
K_1, K_2	= $(\lambda_g C_1) / (\lambda_l C_g), \lambda_g / \lambda_l$
L_i	= specific latent heat of vaporization
Le	= Lewis number
m_i	= mass evaporation rate of i
$\langle \hat{m} \rangle$	= average nondimensional mass evaporation rate
M	= fraction of mass vaporized, $1 - \hat{r}_s^3$
p	= pressure
Q_i	= heat of reaction per unit mass of i reacted
r	= radial distance
$\hat{r}$	= r_s / r_{s0}
R_i	= gas constant of i
t	= time
T	= temperature
T_{Li}	= limit of superheat of i

W_i = molecular weight of i
 X, Y = molar and mass fraction, respectively

Greek Letters

α	= thermal diffusivity
ϵ_i	= fractional mass vaporization rate, m_i/m
λ	= thermal conductivity
Λ	= characteristic length for mass diffusion
τ	= transformed time, Equation (6)
ν_i	= stoichiometric mass ratio of oxidizer to i
ρ	= density
σ	= transformed radial distance, $r/r_s(t)$

Subscripts

b	= boiling state
c	= critical state
f	= flame
F	= all of the fuel species
g	= gas phase
i	= index for fuel species
l	= liquid phase
o	= initial state
O	= oxidizer
s	= droplet surface
s^+, s^-	= gas and liquid side of droplet surface
∞	= ambience

Superscripts

$\sim$	= species weighted quantity
$\wedge$	= nondimensionalized quantity
$\circ$	= state of internal bubbling

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Manuscript received November 9, 1977; revision received March 8, and accepted March 27, 1978.

COMBUSTION CHARACTERISTICS OF DROPLETS OF COAL/OIL AND COAL/OIL/WATER MIXTURES†

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(Received 7 November, 1978)

Abstract—The utilization of coal/oil mixtures in furnaces and boilers appears to be a viable short-to-medium range solution to partially alleviate the demand on petroleum supply with minimum combustor modifications. The present investigation first demonstrates that the combustion characteristics of the coal/oil mixture droplets depend intimately on the intensity of internal circulation. Rapid internal motion favors batch-distillation-type vaporization which causes the coal particles to agglomerate. On the other hand, slow internal motion traps the volatile components in the inner core of the rapidly-heated droplet and may eventually lead to internal boiling and subsequently fragmentation of the droplet. Experimental results reveal a mixed behavior, although the degree of agglomeration is significant even at moderate levels of coal loading. It is subsequently shown that the addition of small quantities of water significantly enhances the potential and intensity of droplet explosion. Practical implications of the present results are also discussed.

1. INTRODUCTION

As the nation's petroleum reserve steadily diminishes and the need for viable, alternate fuel sources becomes more urgent, two facts stand out prominently with regard to the utilization of fossil fuels. First, coal constitutes the most abundant fossil fuel resource in this country, with enough reserve to last several centuries. Second, most of the combustors, both stationary and mobile, utilize liquid fuels. It is therefore logical that much effort be directed at converting coal into forms suitable for utilization by liquid-fueled combustors.

An obvious solution to this need is to chemically convert coal to liquid fuel through the various liquefaction processes. However, an alternate, more direct approach is simply to inject and burn mixtures of coal powders and oil. The concept involves mixing finely crushed coal in the liquid fuel such that the resulting coal-oil-mixture still behaves like a liquid and hence can be sprayed into the conventional liquid-fueled combustors with minimum amount of combustor modifications. Whereas in this approach the coal generally serves only as a passive, secondary fuel source, it must be emphasized that even a few per cent substitution can be translated into substantial savings in the total liquid fuel consumption. Furthermore, since the production of coal-oil-mixtures requires only the physical processes of crushing and mixing rather than the energy-expensive chemical processes of liquefaction, a net saving in energy at the production stage is also realized.

In view of such incentives associated with the utilization of coal-oil-mixtures, it is then necessary to investigate in detail their combustion characteristics in typical combustor environments, particularly those within furnaces and boilers whose longer residence times allow for more complete combustion of coal. In the next Section we shall discuss the various combustion mechanisms of a coal-oil mixture droplet which may also contain some water. Particular emphases will be placed on the possible formation of large coal particle agglomerates as well as their possible dispersion through droplet fragmentation induced by internal boiling of either water or the more volatile oil components. The above concepts are substantiated in Section 3, in which theoretical results on multicomponent droplet combustion are presented. Experimental results are discussed in Section 4.

2. POSSIBLE COMBUSTION MODES OF COAL/OIL AND COAL/OIL/WATER DROPLETS

Relevance of studying single droplet combustion

In liquid-fueled combustors utilizing spray injection techniques, the spray jet is formed at a short distance downstream of the atomizing nozzle. The jet subsequently penetrates into the

†This paper was presented at the 1978 *Midwest Energy Conference*, Chicago, Illinois, 19-21 November, 1978.

combustor interior, entrains the surrounding hot oxidizing air, and thereby enhances the vaporization and combustion of the fuel. Since reaction between fuel and oxygen is possible only when the fuel is in the vapor state, the vaporization of the droplet ensemble is obviously an important process in determining the combustor performance. Furthermore, since the fuel droplets are sufficiently far apart from each other, effects due to their interference are expected to be small. It is then physically realistic to estimate the behavior of the droplet ensemble through statistical summation of those of the individual droplets, and therefore an understanding of the vaporization and combustion of a single droplet in environments simulating the spray interior is of fundamental importance.

Fundamental processes governing droplet combustion

The fundamental physico-chemical processes during the combustion of a single droplet are shown in Figs. 1 and 2. In Fig. 1 there is no relative motion between the droplet and the environment such that spherical symmetry prevails. Stable combustion is maintained with the outwardly-diffusing fuel vapor reacting in approximate stoichiometric proportion with the inwardly-diffusing oxidizer gas at a thin flame surrounding the droplet. Part of the chemical heat release at the flame is transported inward to sustain further vaporization at the droplet surface. Within the droplet interior the transport of heat and mass is strictly through diffusion, with the transport rates being proportional to the respective diffusion coefficients and the temperature or concentration gradients.

In Fig. 2 a relative motion exists between the droplet and the environment. The primary difference between the present case and the stationary droplet is the existence of some recirculatory motion within the droplet interior induced by the shearing stress acting at the droplet surface. Heat and mass transport within the droplet interior is now effected through

Fig. 1. Flow configuration for spherically symmetric droplet combustion.

Fig. 2. Flow configuration for droplet combustion in the presence of external convection.

both diffusion and convection. As will be elaborated in the following, qualitatively different combustion characteristics may result depending on the intensity of the additional convective transport.

Finally, we note in passing that the present discussions are completely applicable to the case of pure vaporization simply by identifying the flame as the ambience.

Quiescent combustion of coal/oil droplets

Two limiting behavior can be identified for the combustion of coal/oil droplets, depending on the intensity of internal circulation.

In the so-called rapid-mixing limit,²⁻⁴ internal circulation is of sufficient intensity such that the temperature and concentration profiles within the droplet interior are maintained perpetually uniform. Since the concentration of the various components are continuously being replenished at the droplet surface, the vaporization process is similar to that of batch distillation. Hence the more volatile components are always being preferentially vaporized, causing the droplet to become progressively more concentrated with the less volatile ones. Since the dispersed coal particles can be considered to be essentially non-volatile compared with the liquid components, and hence will not participate in the vaporization process, they will eventually form a large coal particle agglomerate as the liquid fraction is completely vaporized. According to this scheme a 100 μm droplet with 1% coal particle concentration will yield a 20 μm agglomerate.

The implications of this possible agglomeration are significant. First, it implies that the sizes of the coal particles which actually undergo combustion in the form of agglomerates are determined by the initial concentrations of the coal particles and the initial droplet sizes, but not by the sizes of the individual coal particles. The only influence of the individual particle size is the possible modification of the rheological properties of the mixture, for example the viscosity coefficient, and hence the droplet size distribution of the spray. Therefore it is probably not necessary to use extremely fine coal particles in the preparation of the coal-oil-mixtures since these individual particles will eventually agglomerate anyway.

The formation of these large agglomerates is expected to intimately affect such combustion characteristics as the rate of radiative transport, which is an important heat transfer mechanism within furnaces and boilers. Furthermore, due to the non-volatile nature of coal, and the reduced residence time after the liquid is completely vaporized before coal can be burned, complete combustion of these agglomerates may not always be possible. If this is indeed the case, then not only the energy utilization aspect of coal addition cannot be fully realized, the soot emission problem will be seriously compounded. Even if complete combustion is achieved, the problem of particulate collection and emission still need to be considered because the large agglomerates will produce correspondingly large ash particles.

Disruptive combustion of coal/oil droplets

The above combustion mechanism, leading to coal particle agglomeration, is based on the assumption that internal circulation is of sufficient intensity such that vaporization resembles batch distillation. The other limit occurs when internal circulation is very weak such that diffusion, rather than convection, is the dominant mode of transport within the droplet. Then qualitatively different combustion behavior will result,^{5,6} as will be discussed in the following.

Consider for simplicity a droplet consisting of two miscible liquid components with vastly different volatilities. When diffusion is the dominant transport mechanism, and since liquid-phase heat diffusion rate is one to two orders of magnitude faster than the corresponding mass diffusion rate, the droplet interior will be heated much faster than the rate with which the more volatile compound in the inner core can diffuse outward so as to reach the surface where it can be vaporized. Therefore under this situation liquid-phase mass diffusion rather than the volatility-differential is the rate-limiting factor. Eventually the volatile inner core can be heated beyond its local boiling point. Subsequently, with the presence of coal particles to serve as heterogeneous nucleation sites, internal boiling can be initiated. The resultant internal pressure build-up may then induce either partial or complete fragmentation of the parent droplet.

It is also reasonable to expect that this explosive event will continuously repeat itself with the secondary droplets produced. These repeated explosions then essentially constitute very

efficient secondary atomization schemes, producing droplets of fine sizes which can be readily vaporized. Furthermore, the violence associated with these explosions also disperses the smaller droplets into a large physical volume, hence producing a more uniform charge for combustion. Finally, since the maximum droplet temperature is now limited to the lowest value of the local boiling points, the possibility of soot formation due to high temperature liquid-phase pyrolysis is also expected to be significantly reduced. It can therefore be concluded that the occurrence of droplet explosion generally tends to diminish the heterogeneous nature of spray combustion.

It must, however, also be emphasized that this explosive combustion mode occurs only under certain favorable situations. Firstly, the internal motion should be minimal such that a steep concentration gradient can be established. This would require, for example, that the droplet be small so as to minimize the shear at the interface, and that the fuel be viscous. The fuel composition is also important because high-boiling point components are needed for the droplet to sustain high temperatures whereas low-boiling point components are needed for the ease of initiating internal boiling. Therefore the potential for explosion requires certain optimum composition.

Disruptive combustion of coal/oil/water droplets

An alternate scheme to induce explosion is to add small amount of water in the coal-oil-mixture. Since water does not mix with oil, boiling will initiate when the droplet temperature reaches the boiling point of water, which can be achieved quite easily because the boiling-point ranges of most liquid fuels are higher than the boiling point of water. It is also obvious that the initiation of the boiling of water is insensitive to either the fuel composition or the internal motion.

In addition to facilitating the occurrence of explosion, the utilization of coal/oil/water mixtures also has other inherent advantages. First one notes that since small amount of water is usually present within coal powder, special process is not required for water addition. In fact if disruptive combustion does have beneficial effects on the combustor performance and the presence of water enhances them, then the practice of drying the coal powder before using not only is unnecessary and costly, but may in fact be detrimental. Finally, it has also been found that the presence of water significantly enhances the stability of coal-oil-mixtures.

We shall analyze in the following the combustion characteristics of a multicomponent fuel droplet in the diffusion limit, and shall subsequently demonstrate that the above concepts are viable.

3. THEORETICAL RESULTS ON MULTICOMPONENT DROPLET COMBUSTION

Problem definition

The problem analyzed is the isobaric, spherically symmetric, liquid-phase diffusion-limited vaporization history of a multicomponent droplet after it is introduced, and ignited in the case of combustion, into a stagnant, unbounded atmosphere. The model has no explicit allowance for the presence and participation of water and coal particles in the combustion process; therefore it is implicitly assumed that they exist in trace amounts and their only function is in initiating boiling.

For pressures not close to critical, the gas-phase processes can be assumed to be quasi-steady since they occur at rates much faster than those of the liquid-phase processes.¹ Hence the relevant transport mechanisms are transient diffusion in the liquid phase, and diffusion and radial convection in the gas phase. Radiative transfer is neglected due to the small droplet sizes of interest. In the case of combustion we shall also invoke the flame-sheet approximation, which states that the outwardly-diffusing multicomponent fuel vapor reacts stoichiometrically and completely with the inwardly-diffusing oxidizer gas at an infinitesimally thin flame front. Finally, for mathematical convenience unity gas-phase Lewis number and conventional constant transport property assumptions will also be invoked.

The theoretical model then consists of descriptions for the gas- and liquid-phase transport processes, the phase change at the droplet surface, and the state of internal boiling. The formulations are briefly outlined in the following; detailed discussions can be found in Ref. 6.

For the gas phase the spherically-symmetric governing equations are the conservation relations for energy and species concentrations, each of which consists of terms representing diffusion, (radial) convection, and source/sink. The thin-flame approximation assumes infinitely fast chemical reactions such that the flame is simply a sink for the reactants and a source of heat and combustion products; the magnitude of which are determined from stoichiometry. These gas-phase equations yield analytical solutions expressible in terms of the temperature and heat fluxes at the droplet surface. These, together with the equilibrium vapor pressure condition valid at the droplet surface, serve as coupling relations with the liquid-phase transport processes, which are governed by the classical heat conduction equation for both heat and mass conservation, but allowing for the steadily changing droplet surface temperature, heat flux, and location. The liquid-phase transient-diffusive equations are then solved numerically. Therefore by continuously tracing the temperature and species profiles within the droplet as vaporization/combustion is initiated, the hypothetical vapor pressure of either water or the multi-component oil can be calculated for a given time and at a given location within the droplet. The state at which the vapor pressure reaches the ambient pressure would indicate that boiling is possible.

Results

Results shown in Figs. 3–5 are for the pure vaporization of equal-molar decane–dodecane droplet in a 2000°K, 1 atm, fuel-free environment. The initial droplet temperature is 300°K.

Fig. 3. Concentration profiles of decane for a decane–dodecane droplet vaporizing in a 2000°K, 1 atm environment.

Fig. 4. Surface and center values of decane concentration as a function of the fractional amount of droplet mass vaporized, M , for a decane–dodecane droplet vaporizing in a 2000°K, 1 atm environment.

Fig. 5. Surface and center values of temperature as a function of M for a decane-dodecane droplet vaporizing in a 2000°K, 1 atm environment.

Figure 3 shows the molar fraction of decane as functions of the liquid-phase Lewis number, Le_l , defined as the ratio of thermal diffusivity to mass diffusivity, and the fractional droplet mass vaporized, $M = 1 - (r_s/r_{s0})^3$, where r_s and r_{s0} are respectively the instantaneous and initial droplet radii.

Since the presence of internal circulation diminishes Le_l due to the increased convective transport which is equally efficient for both heat and mass, effects caused by the varying degrees of internal circulation can be simulated by decreasing Le_l . Therefore results are presented for both $Le_l = 30$, which is representative of typical liquid fuels, and for smaller values of Le_l . In the limit of convection-dominated transport, $Le_l \rightarrow 1$.

Figure 3 shows that the concentration profiles are qualitatively influenced by Le_l . When mass diffusional resistance is significant at $Le_l = 30$, a steep concentration gradient exists near the droplet surface, although as σ decreases an almost uniform state is rapidly approached, where $\sigma = r/r_s$ is the normalized radial distance. Comparing the $M = 0.5$ and 0.95 cases also shows that an approximately constant profile exists for a significant portion of the droplet lifetime. These diffusion-limited characteristics gradually disappear as Le_l decreases until for $Le_l = 1$, at which heat and mass transport are equally efficient, the concentration gradient is gentle and uniform throughout the droplet. Furthermore since decane can now be more readily brought to the surface where it is preferentially vaporized due to its higher volatility, its concentration within the droplet is rapidly depleted.

The above observations are further illustrated in Fig. 4, where the surface and center values of the molar fraction of decane are plotted vs M . It is of particular interest to note that, for $Le_l = 30$, the vaporization process consists of three regimes. During the initial, transient, regime the decane concentration near the surface is rapidly depleted due to its volatility, although its value in the inner core is practically undisturbed. Subsequently an intermediate, mass-diffusion-limited, almost quasi-steady regime exists during which the species are transported to, and exposed at, the regressing surface at approximately constant rates. For large Le_l , this steady period persists until almost complete droplet consumption. However, towards the end of the droplet lifetime a volatility-limited regime exists during which the more volatile component becomes rapidly depleted from the entire droplet composition. The vaporization characteristics now resemble those of the rapid-mixing model.²⁻⁴ This result is physically realistic because as the droplet vaporizes its size will eventually become comparable with the characteristic diffusion length. Then diffusional transport is significantly enhanced, the concentrations are almost perpetually uniformized, and hence volatility-differentials limit the vaporization process.

Figure 4 further shows that the three regimes identified for $Le_l = 30$ become less distinct as Le_l decreases. Hence for $Le_l = 10$ the quasi-steady regime ceases to be distinct, whereas for $Le_l = 1$ the entire vaporization process is transient and volatility-limited.

Figure 5 shows the temporal variations of the surface and center values of the droplet temperature. Since liquid-phase heat conduction is an efficient process regardless of the

existence of internal circulation,⁷ Fig. 5 shows that the temperature histories are qualitatively similar for both the high and low Le_l values, except for the existence of the final, volatility-limited regime at $Le_l = 30$, during which the droplet temperature rapidly increases to approach the wet-bulb value of the less volatile component.

We next present results on the state when internal boiling first becomes possible as a function of the initial fuel composition. Denoting this state by the superscript "*", Figs. 6 and 7 show M^* and σ^* due to boiling of oil for a heptane-decane mixture and a heptane-dodecane mixture. Obviously in order to maximize the effect of micro-explosion, internal boiling should initiate early in the droplet lifetime and deep within the droplet interior. These imply small values of M^* and σ^* .

Fig. 6.

Fig. 7.

Fig. 6. Amount of droplet mass vaporized at the onset of internal boiling of oil for various initial compositions.

Fig. 7. Location within the droplet where internal boiling of oil initiates for various initial compositions.

Figure 6 shows that an optimum composition exists for the early initiation of internal boiling, and that it cannot be achieved for fuel compositions which are excessively rich in either the high- or the low-boiling-point components. These are in agreement with our earlier discussions that to enhance internal boiling high-boiling-point components are needed to raise the droplet temperature whereas low-boiling-point components are needed to increase the vapor pressure.

Figure 7 shows that for situations under which internal boiling is initiated early, it occurs close to the droplet surface. On the other hand for situations with delayed initiation, the droplet interior has become substantially heated such that boiling occurs deep within the droplet and therefore is expected to induce a more violent explosion.

Figure 8 shows M^* as induced by the boiling of embedded water. As expected, with higher concentrations of the low-boiling-point fuel, heptane, the attainable droplet temperature is lower and M^* occurs late in the droplet lifetime. As the concentration of the high-boiling-point component increases, M^* is correspondingly advanced. For the present disruptive mechanism boiling is always initiated at the droplet surface which has the highest temperature.

The result that $M^* = 1$ at $X_{\text{heptane}} = 1$ as shown in Fig. 8 is strictly coincidental because for the present system the boiling points of water and heptane are almost identical (at 1 atm). Had we used a compound with a higher boiling point than that of heptane M^* will be less than one for all compositions, implying that internal boiling can always be achieved.

The trend as shown in Fig. 8 is also expected to be insensitive to the intensity of internal motion. For example in the opposite limit of rapid internal mixing, since heptane is initially preferentially vaporized, boiling will not initiate until heptane has essentially been depleted. This implies that for initial higher concentrations of heptane the delay will be correspondingly longer.

Fig. 8. Amount of droplet mass vaporized at the onset of internal boiling of water for various initial compositions.

4. EXPERIMENTAL RESULTS

Coal/oil droplet combustion

Previous discussions illustrate that in the limits of vanishing or intense internal circulation, either complete dispersion or agglomeration of the original coal particles in the coal/oil droplet may occur. In realistic situations an intermediate behavior is expected and has been experimentally investigated.

In the experiments a coal/oil droplet of the order of $1000\ \mu\text{m}$ is suspended at the end of a quartz fiber and ignited through spark discharge (Fig. 9). The subsequent combustion sequence is studied through high speed cine-microphotography with framing rates of 1000 fps. All the combustion sequence reported herein took place in the ambient air. The coal powder used are first dried at low temperatures to eliminate the moisture content. It may also be noted that the suspension fiber is not expected to interfere with combustion, particularly the agglomeration process, owing to the fact that its thickness ($\sim 75\ \mu\text{m}$) is of the same order as the sizes of the larger coal particles.

A typical combustion sequence (Fig. 10a) can be qualitatively described as follows. After ignition a brief steady burning period exists before some internal disturbance is initiated as evidenced by the wrinkling of the originally smooth droplet surface. Soon small masses are

Fig. 9. Schematic diagram of the suspended droplet apparatus.

Fig. 10. Abstracts of typical combustion sequence of (a) a coal/oil mixture droplet, and (b) a coal/oil/water mixture droplet.

seen to be intermittently ejected from the droplet. This state persists, which may or may not be accompanied by more violent fragmentations involving larger masses, until most of the liquid fuel has been vaporized, leaving behind an irregularly-shaped agglomerate of coal particles adhering to the suspension fiber. The subsequent burning is probably maintained by the remaining amount of liquid fuel being vaporized off from the coal particle surfaces and crevices, although the intensity is very weak. Soon complete extinction occurs, leaving behind the agglomerate.

To further quantify the relative amounts of the coal particles dispersed through fragmentation or left behind through agglomeration, the weight of the agglomerate has been measured as a function of the initial coal concentrations and droplet sizes. The agglomerates are separated from the suspension fiber ultrasonically and subsequently collected through filtering. For each condition tested fifty runs were conducted so that a large sample can be collected for weighing. It is of course also more statistically significant.

Figure 11 shows the fractional amount of the coal particles agglomerated as a function of the initial coal concentrations (by mass) in the droplet. The liquid fuel is Number 2 heating oil whereas the coal powders are 200 mesh Pittsburgh seam coal. The initial droplet sizes are $900 \pm 50 \mu\text{m}$ and $1200 \pm 50 \mu\text{m}$.

It is seen that for low levels of coal addition the amount of agglomeration varies linearly with the initial concentration, although it becomes almost a constant at moderate to high levels of loading. The change-over is quite sharp, indicating the possible existence of a narrow transition region separating different regimes of rheological or combustion behavior. It may be emphasized that the amount of agglomeration is significant even at moderate levels of loading, implying that the concern expressed previously on the modification of the combustion processes by these large agglomerates is real and needs to be further investigated.

Coal/oil/water droplet combustion

Figure 10(b) shows the explosion event of a typical burning sequence of a coal/oil/water droplet. The water content is about 5% by volume. It is found that whereas the pre-explosion combustion behavior is generally more quiescent than that of the coal/oil droplet, the explosion in the present case occurs earlier and is catastrophic. It completely shatters the droplet, leaving behind practically no remnants on the fiber. The advantage of water addition to induce explosion and enhance its intensity is obvious.

Fig. 11. Fractional amount of coal particles agglomerated as a function of the initial content of coal for coal/diesel mixtures.

5. CONCLUSIONS

In the present investigation we have demonstrated that the combustion characteristics of coal/oil droplets depend intimately on the intensity of the internal recirculatory motion. In the limits of zero and infinite rates of internal circulation, complete agglomeration and dispersion of the coal particles may occur. In realistic situations it is found that both mechanisms occur, although the degree of agglomeration is significant even at moderate levels of coal loading. However, it is also shown that with water addition the droplet explosion mechanism is greatly intensified and therefore minimizes the degree of agglomeration.

The practical implications of the present study are as follows. First of all it needs to be determined, from both efficiency and emission considerations, whether it is desirable to have large or small coal particles in such combustors as furnaces and boilers. Larger particles would enhance radiative transfer and also produce larger ash particles which probably can be collected more easily. On the other hand smaller particles would lead to more homogeneous and complete burning.

Therefore if large particles are desired, then efforts should be made to remove water from the coal powders so that agglomeration is favored. On the other hand much processing energy can be saved by not requiring excessively fine coal powders since they will agglomerate anyway.

Conversely if small particles are desired, then it may not be necessary to remove the water present in the coal powders provided, of course, its amount is not excessive. However, in this case it is probably also not necessary to have very fine coal powders because the secondary or tertiary droplets produced through explosion may still be large enough to contain numerous coal particles.

The above considerations then lead to the following concrete conclusion. In deciding the sizes of coal particles used for coal/oil mixture combustion, the factors to be accounted for are the rheological and stability characteristics of the mixture, the atomization and droplet-explosion efficiencies of the spray, and the burning time of the coal particle agglomerates. The factor that does not need to be considered is the burning time of the individual coal particles.

Acknowledgement—This research was sponsored by the Division of Fossil Energy Research, Department of Energy under Grant EF-77-G-01-2741.

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APPENDIX C

COMBUSTION AND AGGLOMERATION OF COAL-OIL MIXTURES IN FURNACE ENVIRONMENTS

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ABSTRACT

The combustion characteristics of freely-falling mono-sized coal-oil mixture (COM) droplets in heated air were investigated by studying the quenched samples using scanning electron microscope. Parameters varied include the volatility of the oil, the concentration and size of the coal particles, the residence time, and the effects of water and surfactant addition. Results substantiate the formation of coal particle agglomerates upon depletion of the volatile oil components, and emphasize the importance of oil volatility on COM combustion. In particular the combustion of coal in No. 6 oil is not expected to differ much from that of the neat No. 6 oil, although addition of oils with higher volatility may aggravate the agglomerate formation, heating, and ignition processes, and thereby significantly prolong the total burning time. Addition of water may cause droplet swelling and fragmentation due to internal bubbling which, however, can be inhibited by moderate amount of internal circulation induced by the external convective motion.

I. INTRODUCTION

A promising technology for coal utilization is to mix finely-crushed coal in oil and then directly burn the coal-oil mixture (COM) in such stationary combustors as furnaces and boilers. The concept is attractive in that it enables the direct substitution of oil by coal as an energy source, that the crushing and mixing processes involved in its preparation are far more economical than the energy-expensive coal-liquefaction and gasification processes, and that the mixture is still pumpable and hence can be readily used in the conventional oil-fired combustors with minimum hardware modification. Mixtures with high coal contents have been burned and preliminary results from demonstration plant studies are encouraging.

One of the primary concerns with COM utilization is the possible formation of large coal particle agglomerates after the volatile oil components in the COM droplets have been preferentially vaporized off (Law et al., 1979). These agglomerates obviously will take longer to burn and will also influence the radiative transfer as well as the ash characteristics. Furthermore, one may also question the need to fine-crush the coal if these particles will eventually agglomerate anyway.

On the other hand it has also been suggested (Law et al., 1979) that agglomeration may be either prevented or minimized through the bubbling of some volatile components trapped within the droplet interior. The resultant internal pressure build-up will shatter the agglomerate into much smaller pieces. Indeed this so-called "micro-explosion" event has been theoretically predicted (Law, 1977, 1978) and experimentally verified (Lasheras et al., 1978, 1979a, 1979b) for miscible and immiscible

liquid mixtures consisting of oil, water, and alcohol. For these liquid mixtures internal bubbling is initiated through homogeneous nucleation, which requires a high droplet temperature and hence can occur only under special combustion situations and for particular mixture compositions. On the other hand, for COM combustion the coal particles may serve as sites of the relatively easier process of heterogeneous nucleation, implying micro-explosion may occur more readily. The intensity of explosion, however, would be milder because of the less superheat available.

A preliminary experiment was conducted (Law et al., 1979) in room temperature on the burning of a single COM droplet suspended at the end of a quartz fiber. A mixed behavior was observed, showing mild ejaculations of small masses from the droplet and the eventual formation of an irregularly-shaped coal-particle agglomerate when burning was terminated upon complete depletion of the oil component. Addition of small quantities of water intensified the fragmentation.

The present experiment extends the previous investigation to situations involving freely-falling droplets in a hot environment simulating the furnace interior. Thus we are able to establish conclusively the formation of agglomerates without any uncertain implications due to the presence of the suspension fiber. The furnace environment also allows the characterization of the further heating and subsequently the ignition and combustion of the agglomerates after they are formed. Finally, the present study has also identified the effects of coal particle sizes, oil volatility, water addition, and surfactant addition. The experimental procedure is outlined in the next section and the results are presented

in Section III.

II. EXPERIMENTAL PROCEDURE

The experiment involves generating a horizontal stream of monosized droplets, letting them fall through an electrically heated furnace after torch-ignition, collecting the samples at the bottom of the furnace, and analyzing them using scanning electron microscope (SEM). The schematic of the apparatus is shown in Fig. 1.

The droplet generation technique is a slight modification of the conventional one (see, for example, Sangiovanni and Kestin, 1977) in which the liquid fuel is fed through a capillary tubing vibrating at the Rayleigh instability frequency, which causes the liquid jet to break up into closely spaced mono-sized droplets upon leaving the nozzle. A straightforward application of this technique, however, requires tubings with large bores in order to prevent clogging and to achieve monodispersity. This results in correspondingly large droplets with diameters in excess of 2 mm. In the present experiment a frequency slightly off the critical value is located at which a satellite stream of much smaller droplets is produced at an angle to the main stream. Depending on the COM composition droplets with diameters around 600 μm to 700 μm can be generated and are the ones used in the present study. The initial droplet diameter is measured photographically.

The furnace is a 3.81 cm-diameter ceramic tubing electrically-heated from outside. It has two sections, each 53.3 cm long. Experiments were conducted using either one or both sections so as to provide some

variations in the residence time of the COM droplet within the furnace. The furnace is open at both ends, hence inducing an upward buoyant flow with velocity about 8 m/sec estimated using particle-track method. The temperature within the furnace is quite uniform, varying between 950°C and 1000°C. The samples were impact-collected at about 5 cm below the bottom of the furnace.

The COM was prepared in a domestic blender at about 9000 rpm. Before mixing the coal powder was first dried at low temperatures to eliminate the 3 to 4% moisture content. Examination by SEM showed that drying has no effect on the coal particles. During experimentation the mixture in the reservoir was continuously stirred using a magnetic stirrer to prevent settling.

Other experimental details will be presented whenever appropriate.

III. EXPERIMENTAL RESULTS

Most of the COM tested consisted of either 200 mesh or 400 mesh Pittsburgh seam coal. Since there is no difference in their observed behavior, the following discussions are based on the 400 mesh samples. It may also be noted that since the SEM photographs shown in the following are only for the purpose of illustration, successive magnifications need not correspond to the same sample.

Figure 2 shows the unburned coal samples with their characteristic irregular shapes and sharp edges. Figure 3 shows the coal particles that have undergone burning in the full-length furnace. Here the buoyancy effects were sufficiently strong such that the samples were actually

collected at the top of the furnace. Obviously much devolatilization, swelling, and outgasing of the original coal particles have occurred. The near-spherical particles were shown, using X-ray microprobe on SEM, to be primarily ash in content.

Figures 4 to 8 show the collected samples of COM consisting of 30% coal and 70% No. 2 oil by weight. The samples shown in Figs. 4 to 7 were collected using the half-length furnace. The formation of coal particle agglomerate, after vaporization of No. 2 oil, is clearly demonstrated. Figure 4 is an overall view of an agglomerate on the collection plate which is covered with a transfertape both to soften the impact and to adhere the sample. In general, the agglomerates collected are quite uniform in size, and there are also very few particles of much smaller sizes. Furthermore we also did not observe any particles leaving the furnace from the top for this particular series of experiments. All these then imply that the amount of masses ejaculated from the COM droplet before impact must be small and few, and therefore the agglomerate consists of the bulk of the original coal powder in the COM droplet.

Assuming all of the original coal powders form the agglomerate, the porosity of the agglomerates can be calculated by measuring the diameters of the COM droplet and the agglomerate. Thus it is found that the porosities are about 74% for 30% coal content and 84% for 10% coal content. There does not appear to be much variation with 200 mesh or 400 mesh coal. This is probably due to the fact that most of the coal particles in the 200 mesh sample are already quite small.

Figures 5 and 6 show the front and plane views of the agglomerate.

These clearly demonstrate the rigidity of the agglomerate, hence again emphasizing the likelihood that almost all the oil have been depleted before the agglomerate is formed. This is further confirmed when the impact of COM droplets with higher oil contents resulted in splashes on the collection plate.

Figure 7 is a detailed view of the agglomerate surface. It is seen that the coal particles remain in their original form, implying they have not undergone any devolatilization or chemical reaction before impact. This is reasonable because during the burning of COM droplets the coal particles are at the same temperature as that of the droplet, which is limited by the boiling point of No. 2 oil and therefore may be too low for devolatilization. Furthermore even after the agglomerate is formed a period of heating is still needed before the coal particles are hot enough to react.

To investigate the effect of further heating of the agglomerate, Fig. 8 shows a sample collected using the full-length furnace. The surface is now very rugged, with blow-holes of various sizes which are obviously produced by outgasing. However, closer examination of the coal particles at the surface and within the interior shows the same characteristics as those in Fig. 7, implying the lack of devolatilization or reaction. Thus the outgasing is likely to be caused by vaporization of some small quantities of oil trapped in the agglomerate interior. It is worth emphasizing at this point the significant amount of time needed to heat the agglomerate after it is formed. This period is even longer than that of oil burning leading to agglomeration. Finally, we

note that the agglomerate at this stage is quite loose; some of them break up upon impacting the plate.

Next we investigated the effects of water addition in amounts of 5 to 10%. Two methods of preparation were adopted. In the first method water was first mixed with coal before the coal-water mixture was blended with oil. To mix coal powder uniformly with a given amount of water, the coal powder was first thoroughly wetted and then dried to retain the amount of water desired. The agglomerate characteristics showed no difference from the case without water addition. Compared with the previous suspended-droplet results, there are three possible explanations for the lack of violent explosion in the present situation. Firstly it is possible that although both the suspension fiber and the coal particles offer sites of heterogeneous nucleation, the quartz fiber is more effective than the coal powders in initiating nucleation. Secondly, the significant amount of natural and forced convection experienced by the free droplets here could have caused combustion to occur in the wake region rather than as an envelop flame surrounding the droplet. Thus the droplet might have subjected to less heating and hence attained a lower temperature. Finally, the external convection also could have generated much internal circulation which tended to uniformize the concentration gradients and therefore diminished the likelihood of internal bubbling (Law, 1978; Law et al., 1979).

To identify the most probable cause for the lack of fragmentation

for the present freely-falling droplets, with or without water addition, we repeated the suspended-droplet experiments except now the burning droplet was also subjected to increased intensity of external convection achieved by blowing hot air from below. The blowing was not strong such that the droplet still burned in the envelop flame mode. It was thus found that without external blowing combustion was disruptive, but with increasing blowing intensity disruption was eliminated and the combustion was quiescent, resembling that of a pure fuel droplet. Since in this experiment both the quartz fiber and the coal powders were present to initiate nucleation, and since the droplet was surrounded by the flame, implying that the droplet temperature was high and therefore favoring internal bubbling, the lack of disruption can only be explained on the basis of enhanced internal circulation. It is worth noting that similar results were also observed for water/oil emulsion droplets (Law et al., 1980). The importance of internal motion on the combustion characteristics of multicomponent, multi-phase droplets can hardly be over-emphasized.

Returning to our discussion of the results of water addition, in the second preparation method water was first mixed with oil before the coal powder was blended in. In order to make a stable water/oil emulsion, a 1% surfactant consisting of a mixture of Span 80 and Tween 80 was added. Figure 9 shows that the surface characteristics of the agglomerate are quite different from those shown in, say, Fig. 7. Further investigation showed similar samples were also obtained for CUM

with only surfactant addition. Therefore the smooth surface as shown in Fig. 9 is a coating by the surfactant which is quite nonvolatile. This coating may inhibit outgasing when the internal pressure is low. However, with continuous internal pressure build-up the outgasing event will be intensified when it eventually occurs.

The effects of fuel volatility was investigated with a mixture of 10% coal, 30% No. 6 oil, and 60% No. 2 oil. Mixtures with higher contents of No. 6 oil were not pumpable with the present set-up. Figure 10 shows that the agglomerate was already formed using the half-length furnace; for a 10% coal and 90% No. 2 oil the full-length furnace was required for agglomeration. Figure 11 shows a smooth and thick crust which upon dissection revealed a thick and tar-like shell. This is to be contrasted with agglomerates of coal and No. 2 oil, which when pressed would crumble into coal particles. It is then reasonable to expect that most of the relatively non-volatile No. 6 oil actually formed the agglomerate rather than having been vaporized off. This also explains the much shorter time needed to form the agglomerate; only the No. 2 oil component of the original COM droplet needed to be vaporized. Finally, with the samples investigated, the agglomerates are hollow inside with the diameter of the hollow space about half of that of the agglomerate. This indicates the existence of internal bubbling, which is characteristic of the burning of No. 6 oil.

When these agglomerates were allowed further heating by adding on the second furnace section, burning occurred and the samples were now collected at the top of the furnace because of buoyancy. Figures 12 and

13 show a quenched sample, illustrating that it is likely that most of the No. 6 oil and the smaller coal particles were burnt by this stage. The agglomerate, however, still retains its original size. It is also significant to recall that agglomerates of 30% coal in No. 2 oil failed to burn under similar situations (Fig. 7). Therefore it is believed that agglomerates consisting of some No. 6 oil can ignite and burn easier, probably for the following reasons. Firstly, the agglomerate has a higher initial temperature because the COM droplet can sustain a higher temperature due to the elevated boiling point. Second, it is also obvious that the No. 6 oil in the agglomerate can gasify easier than coal and hence facilitates ignition.

Extending the above results to COM consisting of coal and only No. 6 oil, it can be anticipated that agglomeration occurs rapidly, to be followed by ignition and active burning. Therefore the total burning time of such a COM droplet is probably of the same order as that of a neat No. 6 oil droplet. On the other hand COM consisting of some volatile components, say No. 2 oil, will suffer a much longer burning time because of the delays in agglomeration and agglomerate heating. This may explain the recent field testing results, conducted at Pittsburgh Energy Technology Center (Demeter, 1979) using coal in No. 6 oil, showing complete burnout of the COM. On the other hand results from combustor testings (Sangiovanni, 1979) and spray combustion (Gollahalli and Rasmussen, 1979) using coal in No. 2 oil studies produced substantial unburned coal.

Finally, we have also tested a COM consisting of micron-size coal in No. 2 oil. The results are qualitatively similar to those obtained

with larger particles in No. 2 oil as previously discussed, except now because of the much smaller coal sizes the agglomerate is more compact and can be ignited relatively more easily.

IV. CONCLUSIONS

The present investigation offers the following conclusions. It is very likely that agglomerates form during the burning of COM droplets, implying that coal burns in the form of agglomerates instead of individual particles. Thus COM may not be suitable for application in combustors with short residence times (e.g. small diesel engine). From combustion considerations it is also unnecessary to fine-crush the coal unless they can be reduced to micron-size. Then ignition and combustion can be facilitated.

The oil volatility has a dominant influence on COM combustion. Thus with No. 6 oil agglomeration is probably irrelevant because the original COM droplet behaves somewhat like an agglomerate anyway. The burning will be similar to that of the neat No. 6 oil. However, with more volatile oils agglomeration is important and delays involved in agglomerate heat-up and ignition can be substantial. Thus attempts to make COM more volatile in the hope of facilitating combustion may in fact prolong the total burning time. This again implies the undesirability of forming COM with diesel oil.

The present experiments show that addition of small quantities of water does not seem to affect agglomeration, although Lasheras et al. (1978) observed micro-explosion of water/oil emulsion droplets. This can be due to the difference in the intensities of internal circulation,

which tends to suppress internal bubbling (Law et al., 1980). At any rate, for COM with No. 6 oil, since their combustion characteristics are expected to be somewhat similar to those of neat No. 6 oil, some degree of droplet description should occur with water addition as demonstrated by Gollahalli (1979) for freely falling neat No. 6 oil droplets.

Finally, it has also been shown that surfactant addition produces a crust at the agglomerate surface, although its influence on the overall combustion behavior may be minor.

Acknowledgement

This research was sponsored by Pittsburgh Energy Technology Center, Department of Energy under Grant No. FG01-77ET10660. Mr. C. H. Wang assisted with some of the initial experimentations. J. Demeter and J. Ekman of the Pittsburgh Energy Technology Center, and A. Kestin and J. Sangiovanni of the United Technologies Research Center, kindly provided us with most of the samples tested.

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Figure Captions

- Figure 1. Schematic of the experimental set-up.
- Figure 2. Unburned coal samples, 1500X.
- Figure 3. Burned coal samples, 1500X, full-length furnace.
- Figure 4. Overall view of an agglomerate of 30% coal and 70% No. 2 oil, 20.9X, half-length furnace.
- Figure 5. Front view of an agglomerate of 30% coal and 70% No. 2 oil, 109X, half-length furnace.
- Figure 6. Plane view of an agglomerate of 30% coal and 70% No. 2 oil, 100X, half-length furnace.
- Figure 7. Detailed view of the agglomerate surface showing coal particles remain unburned, 30% coal and 70% No. 2 oil, 1500X, half-length furnace.
- Figure 8. Formation of blow-holes after further heating of the agglomerate, 30% coal and 70% No. 2 oil, 150X, full-length furnace.
- Figure 9. Surface crust formed by 1% surfactant addition, 1500X.
- Figure 10. Agglomerate from burning 10% coal, 30% No. 6 oil, 60% No. 2 oil, 150X, half-length furnace.
- Figure 11. Crust of the agglomerate from burning 10% coal, 30% No. 6 oil, 60% No. 2 oil, 1500X, half-length furnace.
- Figure 12. Quenched sample of the burning agglomerate, 10% coal, 30% No. 6 oil, 60% No. 2 oil, 150X, full-length furnace.
- Figure 13. Quenched sample of the burning agglomerate, 10% coal, 30% No. 6 oil, 60% No. 2 oil, 1500X, full-length furnace.

Figure 1

C-17

20 μm

Figure 2

C-18

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

C-25

Figure 10

C-26

Figure 11

Figure 12

Figure 13