Ignition of a Fuel Spray by a Hot Surface

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An experimental study of the ignition of Jet-A fuel sprays by an isothermal hot surface was conducted in a vertical axisymmetric duct. The ranges of flow conditions under which ignition was investigated were: 1) freestream velocity, 1–5 m/s; 2) boundary-layer momentum thickness, 3–20 mm; 3) freestream air temperature, 40–250°C; 4) fuel concentration, ignitability limits; and 5) droplet size (SMD), 20–200 μm. In addition to measurements of the wall temperature necessary for ignition under the above conditions, local measurements of velocity, "turbulence" intensity, fuel concentration, and the fraction of fuel vaporized were measured in the boundary layer at surface temperatures just below that required for ignition. The results exhibited vapor ignition trends for most of the flow conditions, with some exceptions where single-droplet ignition appeared to be present. The experimental data are compared with existing vapor ignition theory.

Nomenclature

A = $[(4PrkL_c\rho_\infty c_\infty)/u_\infty](c_\infty h_r/c_p T_\infty)$, parameter used by Toong
c_p = specific heat at constant pressure
c_∞ = c_p associated with the freestream flow
h_r = enthalpy of combustion per unit mass
k = rate constant in an Arrhenius expression for the global reaction rate
L = length of heated surface
L_c = characteristic length in Toong's A parameter
PHI = bulk equivalence ratio in the flow
Pr = Prandtl number
Re_x = freestream Reynolds number based on x
SMD = Sauter mean diameter of the droplets in the spray
T = temperature
T_{ign} = spontaneous ignition temperature of the mixture
T_w = wall temperature at ignition
T_∞ = freestream temperature
u = gas velocity in the boundary layer
u_∞ = freestream velocity
u^* = $20.45\ Lv/y^{*2}Pr^{2/3}$
x = streamwise distance from the start of the momentum boundary layer
x_0 = streamwise distance from the start of the momentum boundary layer to the start of the heated section
y = distance normal to the wall
y^* = distance from the wall to the isotherm corresponding to the spontaneous ignition temperature
δ_t = thermal boundary-layer thickness
θ = $(T_w - T)/(T_w - T_\infty)$
ν = kinematic viscosity
ρ_∞ = mass density in the freestream flow

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Introduction

THIS experimental investigation was undertaken to explore the nature of fuel spray/air ignition by hot surfaces.[1-4] Referring to Fig. 1, the problem considered may be viewed as that of a uniform fuel spray/air mixture in a prepared momentum boundary layer encountering a step change in the wall temperature. The thermal boundary layer grows along the heated surface and preignition reactions occur in a region near the wall. Ignition of the fuel vapor in the boundary layer will occur if conditions are such as to support the growth of a suitable ignition kernel. For fuel spray/air mixtures, ignition can also occur in the fuel vapor/air mixture surrounding an individual droplet in the boundary-layer flow. In that case, the burning mixture can be transported with the droplet, which may or may not remain in the boundary layer. The experiments were conducted with Jet-A fuel and also with gaseous propane. Propane was selected to make a connection between the data obtained with the new apparatus and data in the literature and because propane and kerosine exhibit similar ignition behavior.

Apparatus and Procedure

The experimental apparatus designed for the study[4] had provisions for creating suitable flow conditions and for making measurements in the boundary layer under conditions approaching ignition. The ranges of flow conditions under which ignition was investigated were: freestream velocity, 1–5 m/s; momentum thickness of the boundary layer, 3–20 mm; freestream air temperature, 40–250°C; fuel concentration, ignitability limits; and droplet size (SMD), 20–200 μm.

The design of the system was such that those parameters could be varied independently. The temperature of the isothermal wall when ignition events occurred was determined for the range of conditions given. Local measurements of velocity, "turbulence" intensity, fuel concentration, and the fraction of fuel vaporized were made in the boundary layer at surface temperatures just below that required for ignition.

Referring to Fig. 2, the hot surface in the experimental apparatus was the inner wall of an axisymmetric duct oriented vertically with the flow upward. The fuel spray was injected into a suitably prepared airflow in a manner such that the airflow was not greatly disturbed. In determining the temperature of the heated wall at which ignition occurred, the flow conditions were first established and the temperature of the heated wall was raised slowly (0.5°C/s) until ignition was

observed. Ignition events were detected both by means of a photodiode and by visual observations. Except for some remarks on observations of single-droplet ignition, all ignition data reported here correspond to events leading to the development of a flame consuming the entire conbustible mixture. Ignition results were not found to be sensitive to the precise rate of heating of the wall. Following ignition, the rate of the airflow was increased to blow off the flame.

It is useful to note at the outset that, for virtually all of the runs made in this investigation, the fuel in the boundary layer was in the form of vapor. Under some conditions, however, a few large droplets evidently penetrated the boundary layer and impacted on the wall, as could be detected by a diminution of the local luminosity of the wall. And for conditions near the lean limit, ignition of the combustible mixture in the vicinity of individual droplets was observed. Except for the effects of the spray in cooling the outer portions of the boundary layer by evaporation and in contributing to the range of equivalence ratio present in the boundary layer, the situation would be expected to bear a close resemblance to the ignition of gaseous fuel/air mixtures.

The surface materials employed in the study were stainless steel and pure nickel. Sections of 2 in. Schedule 40 pipe (5.08 cm i.d., 4.75 mm wall, 15.25 cm long) were utilized. The relatively thick wall served both to help minimize streamwise variations of the wall temperature and to reduce the coupling of gas-phase thermal transients in the growth of an ignition kernel with local thermal transients in the wall properties. Seven thermocouples situated close to the inner surface at positions distributed along the duct served to monitor the wall temperature. The duct was heated by means of two Calrod units (2 kW) wrapped on its outer surface and the entire assembly was insulated. As noted in Ref. 4, the nickel surface exhibited serious oxidation under fuel-rich conditions and it was accordingly difficult to obtain data representative of a clean nickel surface. The oxide coating generally tended to increase the wall temperature at ignition and also tended to render erratic results for similar run conditions. While no intensive effort was made to determine contributions of heterogeneous reactions to those results, those observations seemed to be attributable to the insulating effect of the oxide flakes formed. The stainless steel also oxidized, but with a less severe effect on the ignition results.

Except for regions close to the ends of the heated duct, the temperature of the central portion of the duct was measured to be uniform to within about 5% for the runs reported. A plot of the streamwise distribution of the wall temperature is shown in Fig. 3. In correlating and reporting the data, the "wall temperature at ignition" was a simple average of the innermost five temperatures, covering a length of 12.7 cm.

Several velocity profiles were employed in the investigations reported here. A "uniform" profile was established for most of the run conditions with propane, such that the velocity variation across the flow was within a few percent of being constant to within a few millimeters from the wall of the duct; the boundary-layer thickness at the exit plane of the test section was about 5 mm. To represent thicker boundary layers at the start of the heated section, the flow conditioning was arranged to provide a flow with a radial distribution peaked at the center, termed here a "developed" profile. Representative measured profiles are shown in Fig. 4. The ratio of the peak velocity to the bulk velocity for the developed profile increased roughly linearly with bulk velocity, to a maximum value of about 1.6 at a bulk velocity of 3.3 m/s. The boundary-layer thickness measured for the developed profiles at the exit of the test section, however, remained nearly the same for the ranges of bulk velocity considered.

The LDA data included measurements of the velocity fluctuations in the flow and those results are reported here in the form of "turbulence" intensities. These fluctuations must be interpreted in terms of the nature of the experimental apparatus and the flow conditions. There was a modest level of screen-generated turbulence in the flow attributable to the fine-mesh, flow-conditioning screens employed in the study, which decayed predictably with downstream distance. But most of the fluctuations observed could be more correctly related to turbulence in the wakes of the injector elements and to the presence of droplets and the fine injector air jets in those flows involving fuel sprays. The boundary layers studied here, then, are predominantly laminar ones, subject to some level of turbulence in the freestream core of the flow.

For runs with the developed velocity profile in the investigations involving Jet-A fuel sprays, a "diffusion" section (a 15.24 cm length of screen-lined duct), was positioned between the injection station and the upstream measurement station. The outer ring of injector elements was removed for those runs to improve the spray characteristics of the injectors at the lowest fuel flow rates of interest in those runs. The diffusion section served to permit the fuel spray to disperse throughout the gas flow prior to encountering the test section. That section was not employed for runs with the "uniform" profile nor were the injector elements removed for those runs.

Experimental Results

The results presented here comprise only a portion of the evidence collected in the course of the investigation and represent thoroughly repeatable ignition conditions free of spurious effects that could arise in the operation of the facility. Over

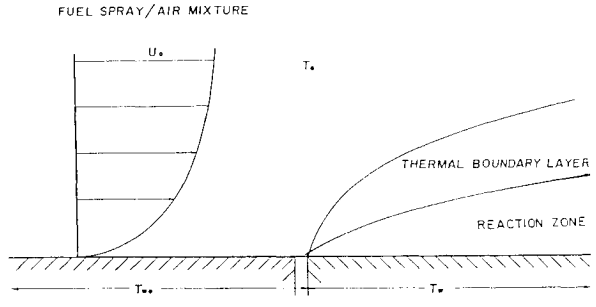

Fig. 1 Fuel spray ignition in a boundary-layer flow over a heated surface.

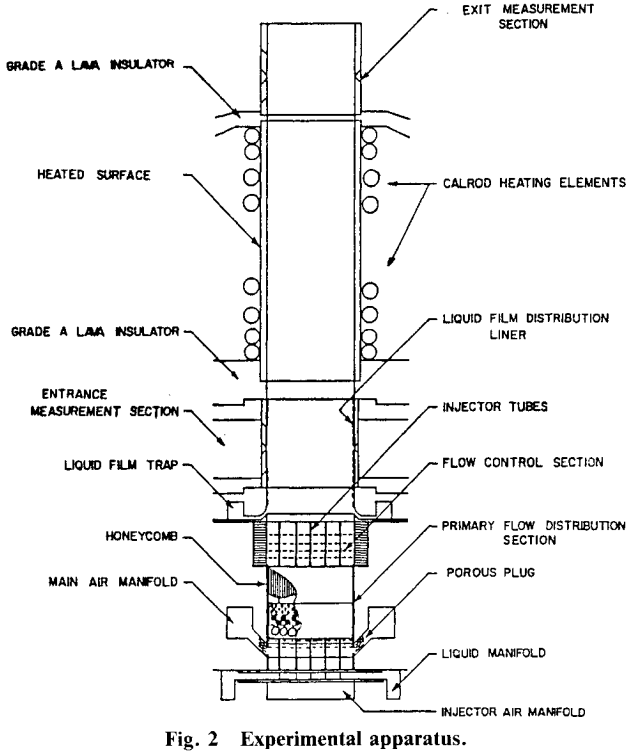

Fig. 2 Experimental apparatus.

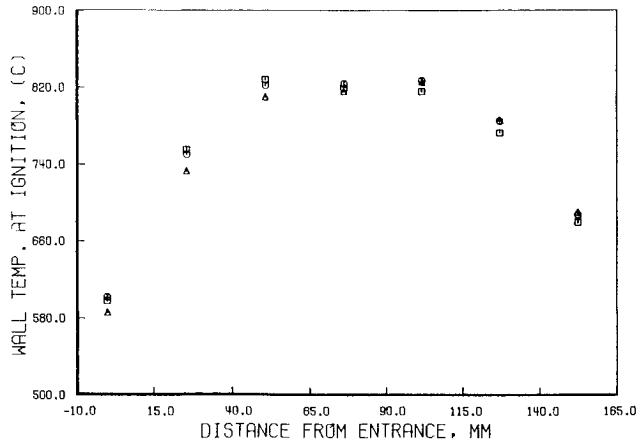

Fig. 3 Wall temperature distribution near ignition.

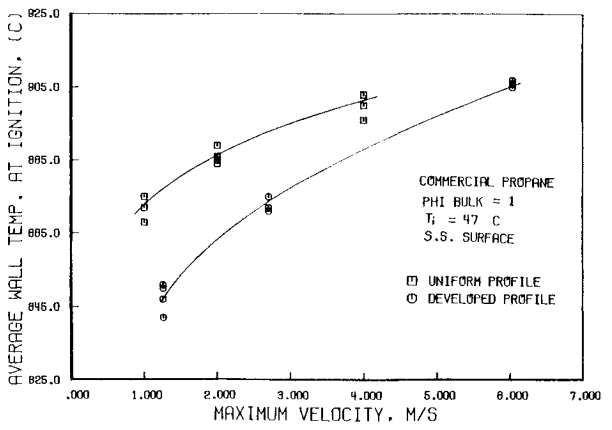

Fig. 5 Effect of velocity on wall temperature at ignition for commercial propane gas.

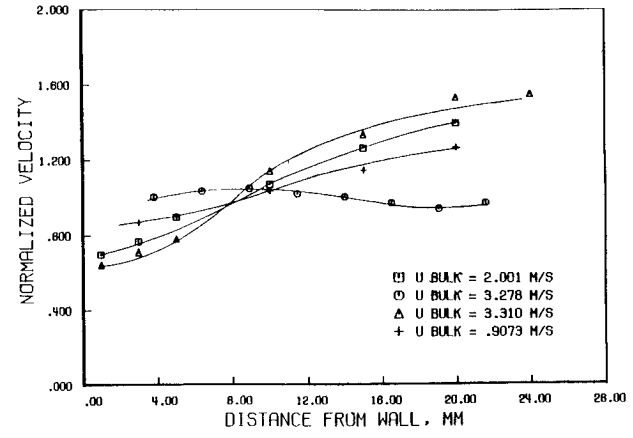

Fig. 4 Velocity distributions for "developed flow."

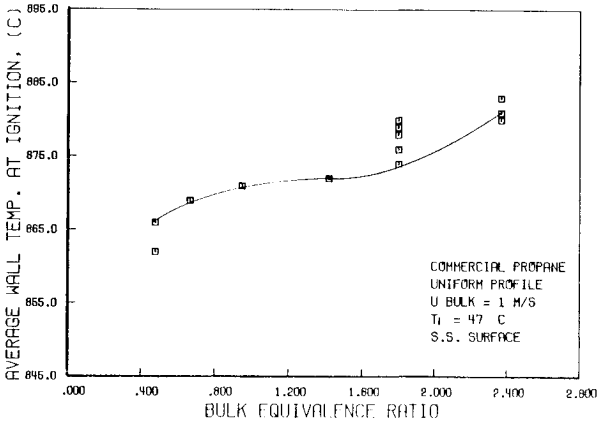

Fig. 6 Effect of equivalence ratio on wall temperature at ignition for commercial propane gas.

the course of the study, it was observed that many conditions could arise that would tend to compromise the results in some way. The oxidation of the surface, "malfunctions" in one or more of the individual injector elements, asymmetries in the flowfield, small gaps in the hot seals, and improper operation of the instrumentation all contributed to the difficulties experienced in acquiring data considered reliable. The oxidation of the nickel surface, for example, appeared to preclude obtaining data for that surface over a sufficiently wide range of operating conditions to be presentable here, although a considerable effort was made to obtain such data. It seems reasonable to say that few, if any, of the measurements and operating conditions could be regarded casually without in some way jeopardizing the results. Most of the research effort, then, was devoted to uncovering those factors and providing procedural or hardware modifications to improve the merit of the results.

Propane Ignition

While the principal objective in this work was to examine the ignition of a fuel spray by a hot surface, runs were also made with gaseous commercial propane (85% propane, 13% ethane, 0.8% methane, balance aromatic hydrocarbons). It was far simpler to use a gaseous fuel for the purposes of testing measurements and the operating procedures for the facility. Moreover, ignition data could be compared with available ignition data for nonflowing systems. Since the chemistry of propane ignition bears a close relation to that of kerosine, the data also could be taken to be at least comparable to that for pure kerosine vapor. The runs with propane were all made with carefully prepared propane/air mixtures of uniform composition.

Three broad groups of ignition runs were made with premixed commercial propane. They comprised a group of runs at a constant bulk velocity of 1 m/s with a "uniform" velocity profile in which the equivalence ratio was varied; a group of runs at a nominal equivalence ratio of 1.0, wherein the bulk velocity was varied at 1–8 m/s for both uniform and developed velocity profiles; and a group of runs made under stoichiometric conditions with a "uniform" velocity profile and a bulk velocity of 1 m/s, wherein the inlet air temperature was varied. Velocity measurements were made in the boundary layer for flows with the developed velocity in profile at bulk velocities of 1–3 m/s and for the uniform velocity profile. Fuel concentration measurements were made in the boundary layer for flow with a uniform velocity profile and a bulk velocity of 1 m/s.

The propane ignition results are summarized in Figs. 5–7. Figure 5 is a plot of the wall temperature at ignition for a stoichiometric mixture as a function of the maximum velocity in the flow for both uniform and developed velocity profiles. The results show that the wall temperature at ignition was consistently higher by perhaps 20–30°C for the uniform velocity profile as compared with values for the developed profile. Both exhibited similar trends. Figure 6 illustrates the effects of equivalence ratio on the wall temperature at ignition for flows with uniform velocity profiles and a bulk velocity of 1 m/s. The data extend over the normal range of flammability limits for propane. It might be noted that in the course of examining the methods for preparing the mixture, some runs were initially made for poorly mixed flows. In those runs, ignition could be observed at equivalence ratios as high as 6.2, whereas the published rich limit is 2.5 for propane/air mixtures. The fuel/air mixture for the data of Fig. 6 was uniform to at least

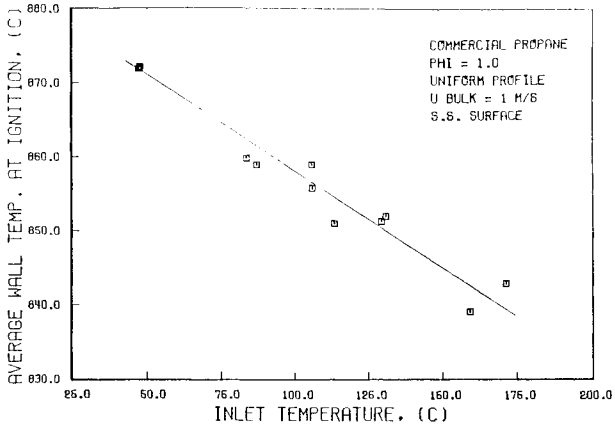

Fig. 7 Effect of inlet air temperature on the wall temperature at ignition for commercial propane gas.

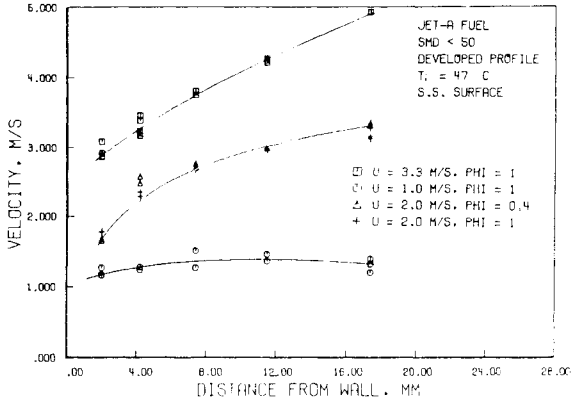

Fig. 8 Upstream velocity profiles.

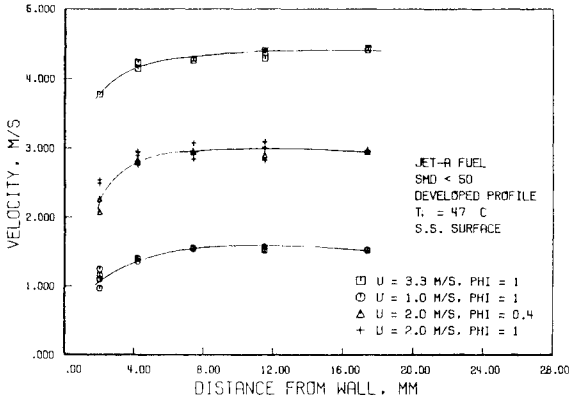

Fig. 9 Downstream velocity profiles.

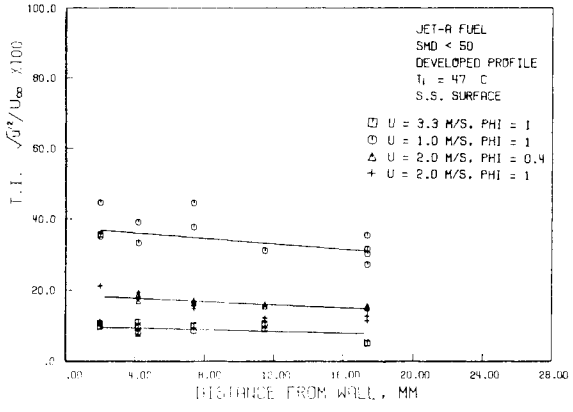

Fig. 10 Upstream "turbulence" intensity profiles.

2%. At the lean end of the range, it should be pointed out that the flame established changes markedly as the equivalence ratio becomes smaller. Extremely faint but visible regions could be observed under those conditions and the low end of the range in Fig. 6 should not be taken to be a lower ignition if the appearance of any evidence of a flame is to be regarded as an ignition event. The effect of the inlet temperature of the air on the wall temperature at ignition is shown in Fig. 7 for stoichiometric mixtures at a bulk flow velocity of 1 m/s. It can be seen that the effect is a linear one resulting in a decrease of the wall temperature at ignition by an amount (30°C) substantially less than the corresponding increase in inlet air temperature (115°C).

Kerosine Spray Ignition

Ignition determinations for the runs with kerosine sprays were made on the basis that the entire spray would be observed to ignite following a local ignition event. Such a distinction is necessary since the combustible mixture around an individual fuel droplet may ignite on occasion without resulting in propagation of the flame to the remainder of the mixture. While the observation of such ignition events may be noted here, they are not regarded as ignition for the purposes of the presentation of the data.

The ignition runs with kerosine (Jet-A) may be arranged into four groups, all but one of which were conducted with a developed velocity profile, with the "diffusion" section of duct in place and with the outermost ring of injector elements removed. Most of those runs were for sprays determined to have SMD values on the order of 50 μm. The first group of runs involved ignition measurements for a stoichiometric mixture for several values of bulk velocity ranging 1-3.4 m/s. The second group involved ignition measurements for bulk velocities of 1 m/s, wherein the equivalence ratio was varied over the range of flammability for the fuel. The third group of runs was made for stoichiometric conditions with a uniform velocity profile and bulk velocities ranging 1-3 m/s. The last group of runs was made to examine the effect of droplet size on the ignition behavior. Those runs were made with stoichiometric mixtures at 1 m/s bulk velocity (developed profile) and with SMD values ranging from below 10 μm to hundreds of micrometers.

Velocity distributions in the boundary layer under conditions approaching ignition were measured primarily for the developed velocity profile, for stoichiometric flows with spray SMD values on the order of 50 μm, and for bulk velocities of 1-3.3 m/s. Similar measurements for the uniform velocity profile were made only at the higher end of the bulk velocity range. Sampling measurements were made for runs with kerosine, again for the developed velocity profile, for stoichiometric conditions (except for one run with an equivalence ratio of 0.4), and for bulk flow velocities of 1-3.3 m/s.

The local velocity measurements are presented in Figs. 8-11. Figures 8 and 9 illustrate the developed velocity profiles for the upstream and downstream measurement stations, respectively. Corresponding profiles show a "flattening" in passing through the heated duct. Referring to Fig. 9, the thickness of the boundary layer at the exit station does not exhibit the significant dependence on bulk velocity that the inlet profiles exhibit. Figures 10 and 11 show the turbulence intensities for the same flow conditions. Values at the upstream end (Fig. 10) are relatively high and presumably reflect the proximity of the measurement station to the disturbances caused by the fuel injection process. Those at the downstream end (Fig. 11) show that a significant decay in flow perturbations has occurred.

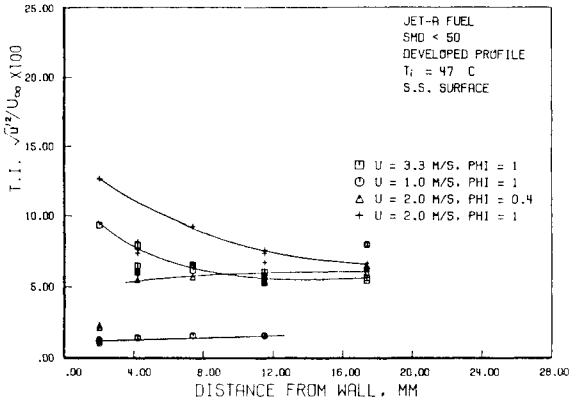

Fig. 11 Downstream "turbulence" intensity profiles.

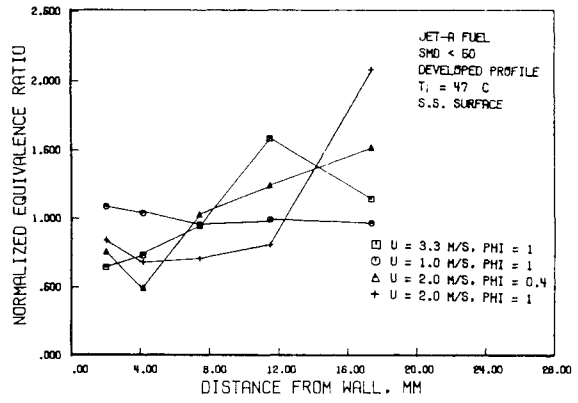

Fig. 12 Upstream distribution of equivalence ratio.

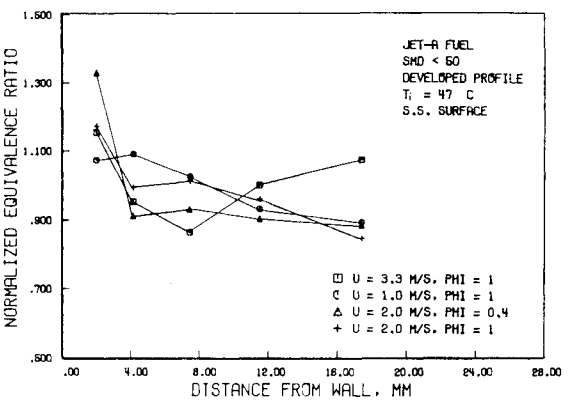

Fig. 13 Downstream distribution of equivalence ratio.

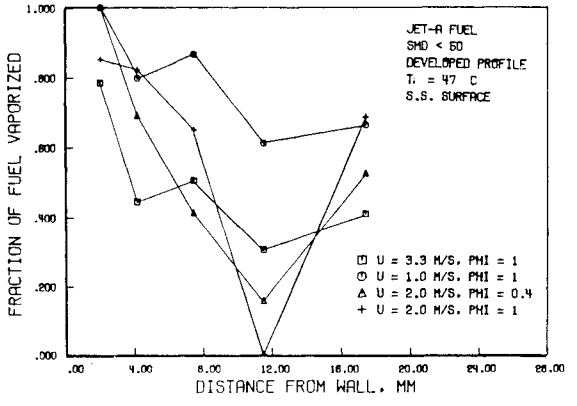

Fig. 14 Fraction of fuel vaporized in the exit flow.

The measurements of the local equivalence ratio are shown in Figs. 12 and 13. The profiles are normalized with respect to the measured bulk equivalence ratio *PHI*. The data for the upstream measurement station in Fig. 12 show a measure of irregularity, again presumably due to the proximity of the injection station. The data show a generally higher concentration of fuel in the center of the duct, as would be anticipated since the outer ring of injectors was removed for those measurements with the developed profile. Comparison with the profiles at the downstream measurement station in Fig. 13 shows that there had been considerable transport of fuel toward the wall, the equivalence ratio in the vicinity of the wall being materially higher than that at the center of the duct. The boundary layer near the exit plane was well into the fuel-rich region. Moreover, LDA measurements there showed a definite paucity of droplets in the boundary layer, as evidenced by low counting rates. The sampling measurements were found to be accurate to about 5% when measuring pure vapor/air mixtures. With liquid droplets the measurements appeared to be sensitive to flow disturbance (turbulence) levels. Estimates of the accuracy at the downstream station were about 10% and those for the upstream station were on the order of 25%.

The measurements of the fraction of fuel vaporized at the downstream measurement station are shown in Fig. 14. These data certainly reflect the difficulty experienced in applying the spillover method of Foster and Ingebo (see Ref. 4 for details) to obtain reliable results. Those measurements are probably the least accurate of those made in this investigation. Nonetheless, the data show at least reasonable trends.

Some measurements were made with a special thermocouple probe in the boundary layer at the downstream measurement station. That probe comprised a shielded thermocouple vented to the flow in such a manner as to avoid droplet impingement.

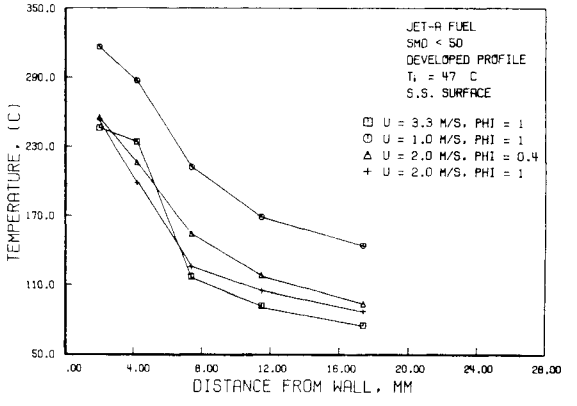

Fig. 15 Temperature distribution in the exit flow.

No special effort was made to properly calibrate the instrument with respect to the two-phase flow properties or for heat transfer. The design and the flowfield in which the measurements were made were such that flow velocities over the thermocouple bead were very low. While the error sources due to radiation and conduction were competitive, it was estimated that the readings would be on the high side by as much as 30°C. Data from that probe situated at the downstream measurement station are shown in Fig. 15. They show a consistent pattern, indicating that there is measurable heating of the flow outside the thermal boundary-layer region, possibly from radiative exchanges between the droplets and the wall.

The ignition results for Jet-A fuel are shown in Figs. 16 and 17. The dependence of the wall temperature required for ignition on equivalence ratio for the developed profile and at the lowest bulk velocity (1 m/s) is shown in Fig. 16. The usual

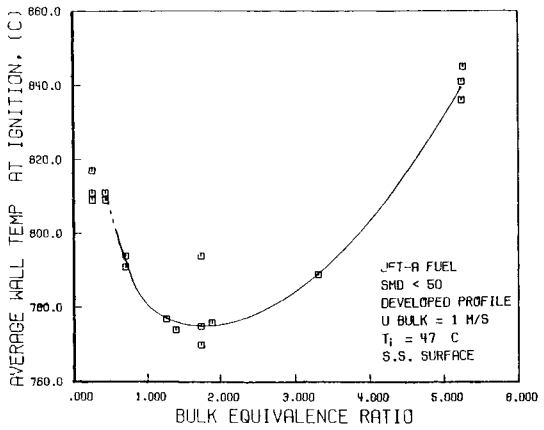

Fig. 16 Wall temperature at ignition as a function of bulk equivalence ratio for Jet-A fuel.

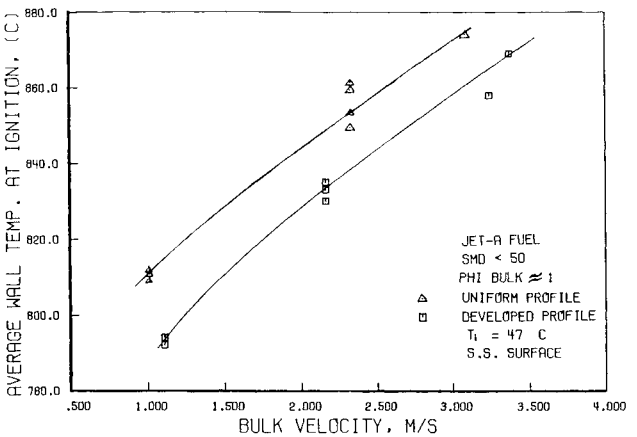

Fig. 17 Wall temperature at ignition as a function of bulk flow velocity.

minimum in the vicinity of unity equivalence ratio is exhibited, the wall temperature required for ignition increasing for other equivalence ratios and extending over a wide range, well beyond that for premixed propane. Both lean and rich limits were found. Those limits appeared to depend on droplet size. At the lean limit, ignition of individual droplets appeared to be prominent. Data for the velocity dependence of the wall temperature required for ignition are shown in Fig. 17. As for the propane results, there is a marked dependence on the boundary-layer properties, the temperatures for the developed profile being lower than those for the uniform profile by about 20°C.

The runs where the SMD of the spray was varied were made under stoichiometric conditions, with a developed velocity profile and with a bulk velocity of 2 m/s. The droplet size was varied by varying the supply pressure for the injector air, while maintaining the liquid flow rate constant. Increases in the injector airflow rate reduced the SMD of the droplets in the spray. The wall temperature required for ignition failed to vary significantly over a range of SMD values from below 10 μm to several hundred micrometers. The increase in the injector airflow rate and its momentum flux did increase the velocity in the central portion of the duct slightly, but that effect was evidently not of paramount importance. Supplemental observations made in a run when an injector malfunctioned, producing a wide range of droplet sizes throughout the run also showed that the droplet sizes had little effect on the wall temperature at ignition. In that run, there was no change in the injector airflow rate.

Evidence with respect to the oxidized condition of the surface showed that the oxide film increased the wall temperature necessary for ignition of fuel sprays as well as for gaseous fuel and that fuel-rich conditions in both cases increased the extent of oxidation. Another effect observed was that of pitting of the surface in the course of a run sequence. The pitting did not measurably influence the wall temperatures required for ignition.

Discussion

The propane ignition data were generally in agreement with published results for spontaneous ignition, except that the wall temperatures at ignition were somewhat higher than the corresponding spontaneous ignition temperatures, of course. An apparent difference from corresponding data for spontaneous ignition may be noted in the dependence on the equivalence ratio near the lean limit, where the evidence here shows a continued lowering of the wall temperature required for ignition as the equivalence ratio was reduced below unity. The observations made in the experiments as to the changing nature of the flames observed near the lean limit suggests that it might be necessary to qualify the definition of "ignition" employed to account for the appearance of those "cool" flames. The appearance of any flame was taken as evidence for ignition here, despite the fact that under some conditions the flames were barely luminous and appeared to be open at the center of the duct for equivalence ratios below 0.5.

Perhaps the most prominent aspect of the evidence obtained in the fuel spray experiments was that the fuel in the boundary layer was in the vapor state. Exceptions to that situation were found only near the lean ignition limit where ignition of the vapor/air mixture associated with single droplets was observed. The ignition process, then, was predominantly that of the boundary-layer flow of a combustible gaseous mixture. This suggests that the transport of fuel by droplet motion toward the wall was of primary importance in setting the stage for ignition, insofar as that mechanism governed the composition of the fuel/air mixture in the boundary layer, and also was influential in establishing the thermal properties of the boundary layer by virtue of evaporation of the droplets in the outer portions of the boundary layer. In these experiments, the rate of transport of the spray toward the wall could be attributed to the small measure of radial momentum imparted to the droplets in the atomization process. That was not a controlled variable in the study. While the radial velocity component in the sprays produced was nonzero, it was relatively small, evidently on the order of the radial velocity associated with a free jet. The measurements taken do provide evidence regarding the rate of transport of the fuel toward the wall. The measurements of the flow rate of the liquid dispersed by the wall screens upstream of the test section and the measurements of the distribution of fuel concentration both supply that information.

The ignition data for Jet-A fuel sprays were generally comparable with those for gaseous propane, including the dependence of the data on bulk velocity and the effect of the boundary-layer profile on the wall temperature on ignition. The dependence of the wall temperature at ignition on bulk velocity was somewhat greater for the fuel sprays as compared with the propane results, probably attributable to the larger effective specific heat of the two-phase flow, accounting for evaporation of the fuel droplets.

The analysis of Toong[5] for the ignition of combustible boundary-layer flows on an isothermal hot surface yielded a principal parameter, identified by the symbol A in the original paper (and defined here in the nomenclature), in terms of which the results could be represented. It was shown that as the parameter A decreased, the ratio $(T_w - T_\infty)/T_\infty$ necessary for ignition increased. Toong's theory predicted an increase in wall temperature at ignition with increasing velocity in a plot that is concave downward, as observed here. The slope of the curve of wall temperature at ignition vs velocity would be larger for smaller values of the parameter A. The corresponding curves for propane and Jet-A fuel sprays show a larger

slope for the Jet-A data. It might be argued that, if the chemistry of kerosine vapor ignition is similar to that of propane, the Toong theory is at least consistent with the observations made here for fuel sprays in the sense that the effective specific heat of the mixture in the boundary layer would be larger for the sprays by virtue of evaporation phenomena, thereby reducing the value of the parameter A. The predictions of the Toong theory also show a decrease in wall temperature at ignition with increasing freestream temperature, as observed in these experiments.

It appears to be generally accepted that ignition of a flowing combustible gas mixture by a hot surface results from the formation and growth of an ignition "kernel" in the boundary layer above the surface. The formation and growth of the ignition kernel depends on the local composition of the mixture, its temperature, and the thermal conditions in the vicinity of the kernel, including its proximity to the wall. If the thermal losses from the kernel exceed its energy release rate, the kernel is quenched and ignition fails to occur. In the boundary-layer flows of interest here, the thermal losses depend, in part, on the local state of the thermal boundary layer and the position of the kernel within the boundary layer. To some extent, at least, preignition chemistry near the wall may be expected to alter the composition of the mixture in the boundary layer. For near-stoichiometric mixtures, the adiabatic flame temperature is well above the wall temperature required for ignition and so the wall itself may be regarded as a heat sink with respect to the thermal transients involved in the final growth of the kernel. Of course, the wall serves as the primary heat source in earlier stages of the kernel formation. An ignition event is often taken to correspond with reversal of the heat flux at the wall, i.e., transition of the temperature gradient at the wall through zero.

The evidence obtained here is not inconsistent with that view and appears to be consistent with an even simpler model. In an effort to show how far one can go in constructing a stripped-down "model" that will represent most of the evidence acquired, the chemistry and physics involved was highly simplified. Fully recognizing that, at the wall temperatures required for ignition, preignition chemistry must take place in the region adjacent to the wall, which will be neglected altogether in the stripped-down model. The model presumes the chemical kinetics to be essentially those of spontaneous ignition and neglects the influence of the preignition chemistry closest to the wall on both the chemistry and the development of the thermal boundary layer. That is, the effects of diffusion of reaction products from the region closest to the wall over the length of the heated section up to the site of the ignition kernel is not regarded as important, either with respect to the composition of the mixture in that region of the boundary layer where the ignition kernel forms or with respect to the potential influence of the production and diffusion of intermediate chemical species that could influence the ignition kinetics. The energetics of reactions in the immediate vicinity of the wall are ignored with respect to the development of the momentum and thermal boundary layers. Any effects of those reactions on the thermophysical properties in the boudnary layer are also ignored. The reader is reminded that the simple model outlined above clearly ignores many physical processes which must take place in such flows, but that a complete accounting of all such processes is simply not the point of the discussion. At the same time, it must also be stated that the experimental evidence was not of such a character that subtle effects of those phenomena would be revealed.

On the basis of that "model" of the ignition process, an ignition kernel may be expected to grow only when the local temperature is at least comparable with that required for spontaneous ignition and when the temperature gradient in the boundary layer at that location is sufficiently small. The temperature necessary to produce the formation of an ignition kernel could be anticipated to be somewhat higher than those found in spontaneous ignition experiments by virtue of the higher local heat loss rates in this situation. The consequences of this model are that, for a particular gas-phase composition in the boundary layer and for wall and freestream temperatures bounding the spontaneous ignition temperature of the mixture, the remaining factors governing the occurence of ignition in the boundary layer have to do with the thermal boundary-layer thickness and its profile. For a given profile, the thickness of the thermal boundary layer must reach a certain minimum value before ignition events are observed.

It is useful to examine the consequences of such a heuristic view of the ignition process for the experimental arrangement of interest here: ignition of a combustible gas mixture by an isothermal surface of fixed length. This will be done by considering a dimensionless temperature profile depending only on y/δ_t and making use of laminar boundary-layer results for nonreacting flow. The particular temperature profile chosen has no special significance, other than it leads to simple algebraic results that can be assessed at a glance. More precise temperature profiles would indicate the same general properties illustrated, but would result in less transparent results. As will be shown, the results of the model are in all respects in qualitative agreement with the experimental evidence.

With those objectives in mind, then, the nondimensional temperature in the boundary layer is approximated by a relation of the form.

$$\theta = 1 - \exp(-y/\delta_t) \tag{1}$$

where

$$\theta = (T_w - T)/(T_w - T_\infty) \tag{2}$$

If y^*/δ_t denotes the nondimensional distance from the wall corresponding to the isotherm T_{ign}, then the wall temperature at ignition can be expressed as

$$T_w = \{T_{\text{ign}} - [1 - \exp(-y^*/\delta_t)]\, T_\infty\} \exp(y^*/\delta_t) \tag{3}$$

Now, making use of an expression for δ_t corresponding to the growth of a thermal boundary layer on a length of heated wall subject to a (laminar) momentum boundary layer starting a distance x_0 upstream from the start of the heated surface,[6]

$$\delta_t = 4.52\, Re_x^{-1/2} Pr^{-1/3} \times [1 - (x_0/x)^{3/4}]^{1/3} \tag{4}$$

Taking the case where both the thermal and momentum boundary layers start at the beginning of the length of heated surface and where the length of the surface is L, then

$$T_w = (T_{\text{ign}} - T_\infty) \exp(u_\infty/u^*)^{1/2} + T_\infty \tag{5}$$

where u^* is a characteristic velocity defined in terms of the properties of the gas, the length of the heated wall, and y^*, the distance from the wall to the T_{ign} isotherm at the ignition site. The slope dT_w/du_∞ for a given composition (given T_{ign}) and inlet temperature depends on the variation of y^*/δ_t with u_∞. Whereas the distance of the ignition kernel from the wall will depend on a number of factors having to do with the nature of the energy loss mechanisms and the ignition kinetics, it might at first be suspected that it is governed rather more by diffusion processes near the wall (anticipating that its distance from the wall will be quite small). As a first approximation, suppose that y^* does not depend on u_∞. Then,

$$d\ell n(T_w - T_\infty)/d\ell n u_\infty = 0.5(u_\infty/u^*)^{1/2} \tag{6}$$

With all other conditions fixed, the dependence of the wall temperature on the inlet temperature dT_w/dT_∞ is given by

$$dT_w/dT_\infty = -[\exp(y^*/\delta_t) - 1] \tag{7}$$

Any dependence of y^* on T_∞ is ignored in this equation. Equation (6) shows the wall temperature at ignition to grow with increasing freestream velocity, the curve being concave downward, and Eq. (7) shows a decrease in the wall temperature at ignition with increasing inlet temperature. The influence of the ignition chemistry and the thermophysical properties of the mixture arise through their effect on the spontaneous ignition temperature T_{ign}, and through the term u^* in this simple paradigm. Computations based on various combinations of the experimental data appear to be surprisingly consistent with this simple model, yielding qualitative results in agreement with virtually all the experimental data. That is, one can determine y^*/δ_t and u^* from Eq. (7) using the dependence of the wall temperature required for ignition on the inlet gas temperature for a given bulk velocity u_∞. Then making use of one value of T_w at ignition, T_{ign} can be obtained from Eq. (5). Conversely, one might evaluate T_{ign} and u^* from a pair of points on one of the curves giving the velocity dependence of T_w.

Equation (4) can be employed to evaluate the effects of initial boundary-layer thickness by selecting nonzero values for x_0. If the paradigm suggested is a valid one, a combination of both the temperature and the temperature gradient must be established to favor the growth of an ignition kernel. The temperature gradient at the point where $T = T_{ign}$ in this analysis can be expressed in the form

$$\left(\frac{\partial T}{\partial y}\right)^* = -\left(\frac{T_{ign} - T_\infty}{\delta_t}\right) \tag{8}$$

This expression infers that, if specific values of both the temperature and its gradient are necessary for the establishment of a viable ignition kernel, then they will occur at some particular value of δ_t for given mixture conditions. That is, the thermal boundary layer serves as a traditional "characteristic ignition length" in this problem. That is consistent with the results showing the influence of the initial boundary-layer thickness on the wall temperature required for ignition. The thermal boundary layer grows more rapidly on a wall with a thicker initial boundary layer and so, for a particular bulk flow velocity, the wall temperature required for ignition will be lower for the flow with the thicker initial boundary layer, as found in the experimental results. For comparable wall temperatures required for ignition, the flow with the thicker initial boundary layer will yield the critical boundary-layer thickness at a higher bulk velocity.

While it was shown that two elementary models of the flow serve to highlight the principal factors involved in the problem, refinements of the models for the purposes of elucidating more of the details of the physics taking place is a laudable goal and a number of such studies have been conducted for gas-phase ignition. For those who may be content with a correlation of data of the type acquired in these experiments, the rudimentary model illustrated above will be quantitatively adequate with the addition of perhaps one constant factor to render the temperature gradient at the wall in accord with results for a laminar thermal boundary layer. For further study of the mechanics and kinetics of this problem, it seems likely that numerical computations will be an essential tool, particularly with regard to the influence of the spray transport processes. The embodiment of all of the ignition kinetics in an ignition temperature and a critical temperature gradient, while evidently adequate for the purposes at hand, obviously oversimplifies the details of the physics involved.

Conclusions

The principal evidence yielded by the experiments may be summarized as follows:

1) The surface temperature necessary for ignition decreased with increasing thickness of the momentum boundary layer at the start of the heated surface.

2) The surface temperature necessary for ignition increased with increasing freestream velocity.

3) The surface temperature for ignition was lowest under stoichiometric bulk mixture conditions and increased for off-stoichiometric bulk compositions, as has been observed in ordinary fuel ignition studies.

4) Wide ranges of droplet sizes had little effect on fuel ignition; this could be attributed partly to the fact that under the flow conditions of interest here, virtually all of the fuel in the boundary layer was vaporized.

5) Increasing the temperature of the bulk mixture lowered the wall temperature required for ignition.

6) Both qualitative and quantitative evidence supported the inference that the thermal effect of vaporization of the fuel in the boundary layer was a significant factor in the ignition of a fuel spray, apart from the role of vaporization in merely establishing a combustible fuel/air spray.

7) A qualitative argument describing the ignition process in terms of the spontaneous ignition temperature of the fuel vapor and the thermal boundary-layer thickness can adequately represent the general behavior of the ignition process for virtually all of the runs made in this study, supporting the conclusion that the thermal boundary-layer thickness plays a dominant role in the problem.

While the experimental evidence is qualitatively consistent with simplified models of vapor ignition in a boundary-layer flow, the influence of the transport of fuel to the boundary-layer region via droplet motion remains to be investigated analytically, but can be expected to be of prominent importance in the problem. The evidence gathered in these experiments will be employed to make some assessment of those effects by means of a modified version of the CONCHAS-SPRAY code[7] in continuation of this study.

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