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16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

This report provides a brief summary of experimental and theoretical work carried out at Princeton University on flame spreading across liquid fuels. The importance of surface tension driven flows ahead of the flame front in controlling flame spread across liquids at temperatures below the flash point was demonstrated experimentally. Buoyancy and radiation effects were also present but were of lesser importance. Variations in the temperature of the liquid surface are attributed to eddies in the gas phase ahead of the flame front. These eddies may also play a role in flame propagation across solid combustibles. It is proposed to investigate these eddies by means of laser doppler velocimetry. A two-dimensional, steady-state computer program is under development for use as a tool in studying flame propagation above liquid and solid fuels.

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Aerospace & Mechanical Sciences Report #1308

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Aerospace & Mechanical Sciences Report #1308

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I. INTRODUCTION

Princeton University has had a continuing effort on fire safety-related research. The program began as a result of our interest in problems related to aircraft firesafety with particular concern for understanding the mechanism(s) responsible for flame spreading over fuel spills. Past research had been supported by the Army Ballistics Research Laboratory and the National Science Foundation Office of Research Applied to National Need. During the past year this effort was supported by the National Fire Protection and Control Administration and monitored by the Fire Research Center of the National Bureau of Standards. This document is the final report required under the NFPCA grant.

II. HISTORY, GOALS AND ACHIEVEMENTS

The Princeton program in fuel fire safety was initiated in late 1968 with respect to aircraft fire safety questions. Examination of literature at that time revealed that insufficient experimental research had been performed to verify the mechanism of flame propagation assumed in the theoretical developments which existed.[1,2,3] Indeed, the theories assumed that the same physical mechanisms prevailed for solids and liquids.

Our first early attempt at physical modelling suggested that the mechanism of flame propagation across liquid fuels depended upon the flash point of the fuel. When the bulk temperature of the fuel was greater than the flash point, it was realized that a flammable mixture existed everywhere above the fuel surface. When initiated, a flame would propagate across this liquid surface very much like a premixed laminar flame. However, if the bulk temperature of the liquid was below the flash point, it was postulated that the initiated flame must somehow preheat the liquid ahead of it to the proximity of the flash point in order to create a combustible mixture into which the flame could propagate. It was then postulated and stressed for the first time[4,5] that propagation across high flash point liquids and solids was essentially a lean flammability limit problem and the rate of flame spread was much slower than propagation across low flash-point materials. A schematic of the variation of the flame propagation rate as a function of bulk temperature was then conceptually sketched. We were later to learn that Roberts[6] in England had undergone the same thinking process much earlier, but his work was not to appear in the open literature until much later.[7]

While developing the model for flame propagation, experimental efforts were undertaken to establish the mechanism of heat transfer for propagation across high-flash-point fuels. Tarifa[1] had proposed that heat was convected from behind the flame to the liquid and conducted through the liquid ahead of the flame. Our efforts to verify this postulate by artificially varying the thermal diffusity of the liquid by experiments with liquid-saturated porous-materials and free liquids in pans, revealed the existence and importance of convection in the liquid.[8] We then postulated that these convection currents in the liquid were established by surface tension gradients at the liquid surface and induced by the presence of the flame.[8,9] We believe that this has been one of the more important concepts in flame spreading across liquids and have showed[4] that it had ramifications with respect to ignition and mass burning of liquids as well.

Roberts[6,7] had also observed convection currents in his liquid studies, but failed to advance reasons for the currents or to make appropriate analytical calculations of the liquid flows. Roberts' thesis revealed another fascinating point. In his measurements with low flash point liquids he found that the propagation rates were about 200 cm/sec. - a value about five times the normal stoichiometric laminar flame speed for a hydrocarbon fuel! At this point the experimental research at Princeton took two directions: 1) to verify that the convective liquid motion controlled the rate of flame propagation in high flash-point fuels and that these motions were induced by surface tension gradients and 2) to attempt to explain the abnormal, high values of flame spread across low flash point liquids.

The suggestion that surface tension gradients could create sufficient convective currents in fuels to control the rate of flame spread stimulated the interest of theoreticians at both Princeton and Cornell. The initial Princeton[10] effort in this regard was simply to determine whether surface tension induced flows were of the proper magnitude to account for the observed flame spread rates. These calculations were most encouraging. Another, more fundamental question was whether buoyancy forces could equally as well have established the convection noticed in the experimental measurements. Within the assumptions of their analytical developments, both groups[11,12] predicted that surface tension forces were dominant and should control. We then proceeded to develop more complex theoretical models with the intent of predicting the flame spread rate over practical, high flash-point materials. (See Section III).

The initial experimental goal of establishing that the convective currents controlled the rate of flame was achieved by artificially varying the viscosity of a given fuel without altering its vapor pressure and by the use of barriers in the fuel pan. In this study[9] the effects of fuel temperature variation, ambient air conditions, pan size and radiation effects were all evaluated. Radiant effects played a role, but were not a dominant factor even in large scale spread tests.[9,22] The fact that physical properties of the fuel control the rate of flame spread was indeed a most unusual finding. This realization of the importance of the convection motions had some very practical ramifications. It led to an understanding as to why the Torrey Canyon oil spill could not be burned and to a recommendation as to how oil spills could be burned.[13] In order to protect from serious fires due to aircraft fuel spills, it was recommended that runways and loading areas should be constructed of porous materials. Further it was discovered that high viscosity fuels may not have fast flame spread, but they were easier to ignite simply because heat was not convected away from the ignition source. This observation showed that gelled aircraft-fuels could in some cases do as much harm as good.

Shadowgram motion picture films of flames propagating across low flash-point fuels verified that the flames were indeed laminar.[14,15] We were then able to achieve our second goal by establishing that the abnormal laminar propagation rate was due to the stratification of the air-fuel mixture that is generated by the presence of a liquid fuel.[14,15] In fact, we were also able to establish[14,15] that this problem is similar to the one that occurs in coal mines due to stratification of the marsh gas on the roof of the mine shaft.[16]

With regard to high flash-point liquids, although the importance of convection currents was established experimentally, it was not possible to firmly establish experimentally that these currents were induced by surface tension gradients. The reason for the experimental difficulty was that for hydrocarbon fuels, no agent could be found that would alter this surface tension gradient with respect to the temperature. Thus the only other means to verify this most important point was to experimentally measure the velocity and temperature gradients in the liquid and compare them with the results predicted by the theories based on surface tension.[11,12]

This new goal was then challenged and was a formidable task. In order to accomplish this objective it was necessary to modify a hydrogen bubble technique developed in hydraulic studies.[17] Extensive and very tedious and important measurements[17,18] of velocities and temperatures in a water-alcohol fuel were recently completed under the subject NFPCA support. Briefly, these results (discussed in Section III) are only in qualitative agreement with the theories and show some buoyancy effects. More importantly, however, they show the existence of eddies in the vicinity of the travelling flame front and an unusual variation of the temperature at the liquid surface that can only be caused by an eddy in the gas phase ahead of the flame front.

We are now convinced that these eddies play a role in the flame propagation mechanism and our thinking has been stimulated to the point that we believe there is a strong likelihood they exist in the gas phase ahead of flame propagating across solid combustibles. If so, recently published theories[19,20] with respect to flame propagation mechanisms across solid combustibles may not be valid. Eddies have been observed under some spatial orientations.[21] Some investigators[19] claim they could observe no eddies in front of their propagating flame. However, estimating from our liquid results it is quite possible that their simple gas-phase seeding technique is not sufficient to identify the small eddies we believe could exist. The only means to properly identify such fluid mechanical motions is by laser doppler velocimetry (LDV). A large part of our NFPCA effort was directed at adapting an LDV system to our various flame propagating apparatus (See Section IV).

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