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Second Annual Report
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An Investigation of Near Critical and Super-Critical Burning of Fuel Droplets

by

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Abstract

This report summarizes the work done under NASA contract NGR 39-009-007 for the period September 1, 1967 to September 1, 1968. Principal accomplishments of the report period are briefly discussed and publications arising from the research are listed.

The most significant achievement has been the verification of existing supercritical droplet combustion theories for various pressures, droplet sizes and ambient oxygen concentrations. Work was also begun on high pressure droplet gasification which included the development of a theoretical model of droplet heat-up in the presence of combustion. Preliminary experimental work in this area, to date, has included verification of evaporation models (without combustion) in gas environments at temperatures typical of combustion processes at atmospheric pressure.

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I. Introduction

This second annual report is a summary of the principal accomplishments made during the course of research performed under NASA contract NGR 39-009-007, during the period Sept. 1, 1967 to Sept. 1, 1968. The findings of this research are presented in more detail in the First Annual Report and several other technical reports and papers published during the present report period[2,3,4].

The computation of droplet life histories has become a basic step in the design of combustion chambers for liquid fuel rocket engines[5]. At moderate pressures, this involves computing the heat-up of the droplet from its injection temperature to its wet bulb temperature (the condition where all the heat reaching the droplet is utilized for the heat of vaporization of the material gasifying at the surface of the drop) and the rate of evaporation throughout the droplets lifetime. However, it was soon recognized, that at sufficiently high pressures, the droplet would approach its critical temperature during its lifetime (near critical combustion) or possibly exceed the critical temperature during heat-up (super-critical combustion). For supercritical combustion, a new burning regime must appear and for near critical combustion or heat-up to the critical temperature, many of the assumptions ordinarily made in life history computations become questionable. These problems gave rise to a need for further study of droplet evaporation and combustion at high pressures.

Therefore, the goal of the present research program is to study droplet combustion in the pressure regime where the droplet approaches or exceeds its critical temperature during combustion. In this report period, experimental work has been completed which gives a reasonable verification of previously proposed super-critical droplet combustion theories[7,8]. Work has also begun on the study of droplet gasification at high pressures. This has included extending steady state combustion theories, valid at the wet bulb state, to include gasification processes in the heat-up period of a burning droplet. Some preliminary experimental work on droplet gasification at low pressures has also been completed and found to be in good agreement with the theory. This low pressure matching has served to provide a base line which will allow the influences of high pressure phenomena to be evaluated more confidently.

II. Apparatus

The droplet is supported for the bead of a thermocouple within a high pressure reaction chamber. The droplet is ignited by a small hydrogen diffusion flame at pressures below 100 psia or by a hot wire placed near the droplet at higher pressures. The reaction chamber is fitted with windows to allow photographing the droplet. In order to prevent the droplet from falling from the thermocouple bead, due to reduced surface tension near the critical point, the experiment is conducted under zero-gravity conditions in a free fall chamber.

The basic construction of the apparatus was completed in a previous report period and a more detailed description of the experimental setup may be found in Ref. (1). In the present report period, the apparatus has undergone further development, as follows:

1. A background lighting system has been installed which allows alternate dark field and silhouette photographs of the droplet on the motion picture records. Preliminary testing has shown that droplet diameters may be measured during combustion for pressures up to 100 psia. At pressures greater than this light refraction from density gradients obscures the shadowgraph outline of the droplet. Further modification of the optical system is planned in order to attempt to extend the pressure

range of diameter measurements, but in any event overall evaporation lifetimes can be measured with the present system to yield information on evaporation rates.

2. Errors encountered in temperature measurements, particularly at pressures below 100 psia, were reduced in part by the use of the flame ignitor at these lower pressures. The source of this error was excessive radiation from the hot wire ignitor. By reducing the thermocouple wire size from .003 to .001 inch, coupled with the use of a glass shield over the wires where they pass through the combustion zone, further errors due to conduction along the wires have been minimized.
3. Other changes of a more minor nature included the installation of more accurate high pressure gages, absolute manometers for low pressure testing and repiping the gas handling system for GOX service.

III. Super-Critical Droplet Combustion

With increasing ambient pressure, eventually a condition is reached where the droplet heats up with little evaporation and gasification occurs primarily by the droplet exceeding its critical temperature. In this regime, the combustion process is primarily controlled by the diffusion of the fuel vapor to the combustion zone. Spalding has developed a theory for combustion in this regime by modeling the fuel vapor as a point source. Rosner has modified this theory to allow for the finite dimensions of the vapor pocket[8].

Tests were conducted to check the validity of these theories employing decane as the fuel, with droplet sizes in the range 600-1200μ in oxygen nitrogen mixtures varying from air to pure oxygen. The gas pressures employed in these tests varied from 800 to 2000 psia. At these pressures, the temperature traces indicated that there was little evaporation prior to the droplet exceeding its critical temperature.

A super-critical combustion time was defined as the time between the droplet reaching its critical temperature and burnout. This parameter was compared with the theoretical results and found to be in reasonably good agreement with respect to variations in initial droplet diameter, pressure and ambient oxygen concentration[4]. At high ambient oxygen concentrations, where the greatest differences exist between the theories of Spalding and Rosner, the Rosner distributed source model was found to give a more accurate correlation of the data.

Predicted and experimental flame positions were also compared. These results were found to be in good agreement with respect to variations in all experimental variables. These results may be contrasted to the case of the low pressure quasisteady combustion theories, where theoretical and experimental flame positions were often in large disagreement[9].

IV. Droplet Gasification

Following the completion of work on super-critical droplet combustion, project effort was turned to the problem of droplet heat-up and gasification at high pressures. General observations to date on this problem have indicated the following results:

1. The pressure levels where droplet gasification occurs primarily by the droplet exceeding its critical temperature are in general agreement with Wieber's[6] calculations.
2. The rate of droplet heat-up, following ignition, increased as the ambient oxygen concentration was increased.

There are theories available to estimate droplet transport rates during heat-up for the case of droplet evaporation without combustion. However, the existing theories of droplet combustion were limited to steady burning at the wet bulb state. Therefore, it was necessary to extend these theories in order to make the model valid for combustion during heat-up. The theoretical model resulting from this allows the estimation of droplet transport rates at any time during heat-up, for any ambient temperature and for any ambient oxygen concentration assuming the existence of a diffusion flame if a combustion process is present (naturally, the role of fuel and oxidizer can be readily interchanged to consider an oxidizer droplet in a fuel rich atmosphere). Convection effects are carried in the model via a film theory approximation.

With this model completed, the experimental approach selected was first of all to obtain base line comparisons for a variety of ambient conditions at low pressures. This allows a check of the theoretical approach and the methods of computing average properties in the absence of high pressure effects. With this base line established further testing will be undertaken at increased pressures in order to evaluate the corrections needed for high pressure computations.

To date, theoretical and experimental comparisons have only been made for droplet evaporation without combustion. The theory was compared with earlier data on the zero-gravity evaporation of iso-octane droplets in air at temperatures on the order of 1000°F and pressures of one and two atmospheres[10], with good agreement respecting the temperature and diameter variations of the droplet.

A second set of comparisons were made for water and decane droplets evaporating in the gases exhausting from a flat flame burner. The burner was operated stoichiometrically on a carbon monoxide, oxygen, nitrogen mixture to yield a gas temperature of 2520°K. Under these conditions, the oxygen concentration in the burner combustion products was less than 1 1/2% due to dissociation, and combustion effects in the droplet boundary layer may be neglected with little error for decane. The comparison between theory and experiment was again very good.

V. Future Work

The accuracy of the vaporization model will be further tested by a series of runs, on the flat flame burner, with increasing ambient oxygen concentration in order to investigate the influence of active combustion in the boundary layer. With these results in hand, further comparisons will be made at low pressures in the zero-g apparatus in order to evaluate the influence of a low gas temperature (external to the flame front).

With the completion of these base line studies further testing will be undertaken at high pressures so that the high pressure corrections can be evaluated. This activity will also include theoretical comparisons of the results of the low pressure models with models making allowance for high pressure effects (vapor pressure corrections, content heat corrections, etc.).

References

A. Publications Arising from Research under the Contract.

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