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An Investigation of Air Solubility in  
Jet A Fuel at High Pressures

Semi-Annual Status Report

For the Period

September 1, 1980 to February 28, 1981

by

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Semi-Annual Status Report on  
An Investigation of Air Solubility in Jet A  
Fuel at High Pressures

SUMMARY

The report discusses activities under NASA Grant No. NSG 3306 for the period September 1, 1980 to February 28, 1981. This comprises the third semi-annual reporting period under the grant.

The investigation is examining several problems concerned with the supercritical injection concept. Supercritical injection involves dissolving air into a fuel prior to injection. Upon injection the air comes out of solution forming a vapor phase within the liquid. A similar effect can be obtained by preheating the fuel so that a portion of the fuel flashes when its pressure is reduced. Flashing is known to improve atomization properties and the presence of air in the primary zone of a spray flame is known to reduce the formation of pollutants. Therefore, the approach has been proposed as a means of improving the combustion characteristics of sprays.

The investigation is divided into three phases as follows:

1. Measure the solubility and density properties of fuel/gas mixtures, including Jet A/air, at high pressures and correlate these results using basic thermodynamic theory.

2. Investigate the atomization properties of flashing liquids, including fuel/dissolved gas systems. Determine and correlate the effect of inlet properties and injector geometry on mass flow rates, Sauter mean diameters (SMD) and spray angles. The injector configuration is limited to straight-hole orifices with no swirl.

3. Examine the combustion properties of flashing injection in an open burner flame, particularly considering flame shape and soot production.

Phase 1 of the investigation has been completed and is reported in Ref. 1. Work during this report period concentrated on Phases 2 and 3. The findings are as follows:

1. Atomization. An experimental apparatus was constructed to permit measurements of injector flow rate, spray angle and SMD for Jet A fuel containing a dissolved gas with injector inlet pressures in the range 3.4-10.3 MPa. For a conventional, single-orifice injector, the presence of dissolved gases resulted in a slight (10%) increase in spray angle and reduction of SMD in comparison to non-flashing injection. Redesign of the injector to allow throttling into an expansion chamber prior to injection, however, resulted in dramatic increases in spray angles and substantial reductions in SMD (50%) in comparison to nonflashing injection. These benefits were obtained for a relatively wide range of expansion chamber pressures.

Current efforts are devoted to similar measurements for a wide range of operating conditions and geometries, employing a Universal Injector which allows orifice sizes and mixing chamber volume to be readily varied. Existing correlations for two-phase flow in orifices and for atomization in twin fluid injectors are being applied in order to correlate the measurements and provide general design information concerning flashing injectors.

2. Combustion. A test apparatus which allows observation of the combustion properties of flashing injectors was designed and is currently being fabricated. Combustion tests for flame shape and soot concentrations will be undertaken once atomization results are complete.

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## 1. INTRODUCTION

Many practical propulsion and power systems, e.g., aircraft propulsion, industrial gas turbines, Diesel engines, etc., involve combustion of fuel sprays. Liquid fuels that will be available in the future, coal derived liquids, shale oil, etc., present new difficulties with regard to their atomization and combustion properties. Supercritical injection [2],\* and the related process of flashing injection [3], are receiving attention as a means of improving atomization and combustion properties of fuels in order to reduce the impact of these problems. The objective of this investigation is to develop a better understanding of the thermodynamic, flow and combustion properties of the supercritical or flashing injector concepts.

Supercritical or flashing injection involves operation at conditions where a portion of the liquid flashes to a vapor upon injection. The distinction between the methods is that supercritical injection employs a dissolved gas [2], while flashing injection employs vaporization of the liquid itself. In either case, the fuel is prepared upstream of the injector. The flashing process occurs as the pressure of the liquid is reduced, either within the injector passage or a short distance from the injector exit within the combustion chamber.

The present investigation is considering supercritical injection by means of dissolved gases. Figure 1 is a sketch of the concept for a gas turbine combustor. In this case, air is drawn from the inlet of the combustor, compressed, mixed with the fuel, and allowed to dissolve prior to injection.

The potential effect of the supercritical injection is dependent upon the amount of air that can be dissolved in the fuel prior to injection. The first phase of this investigation involved accumulating necessary solubility data and correlating the results using thermodynamic theory [1]. Figure 2 is an illustration of the solubility of air in a typical Jet A fuel blend. Measurements and predictions of solubility are plotted as a function of pressure for two different liquid temperatures. The predictions employ the Soave equation of state for high pressure multicomponent mixtures [1]. The effect of temperature is not very significant over this test range; however, solubility increases almost linearly with pressure, reaching levels of 15-20% dissolved air (molal basis) at pressures of 10-15 MPa.

The predicted solubility of air in Jet A, over a broader range of conditions than Fig. 2, is illustrated in Fig. 3 [1]. It is evident that significant quantities of air can be dissolved in the fuel, particularly at elevated temperatures and pressures. Calculations were also completed to determine the variation of the specific volume of the flow as the dissolved gas mixture was expanded. It was found that the

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\* Numbers in brackets designate references.

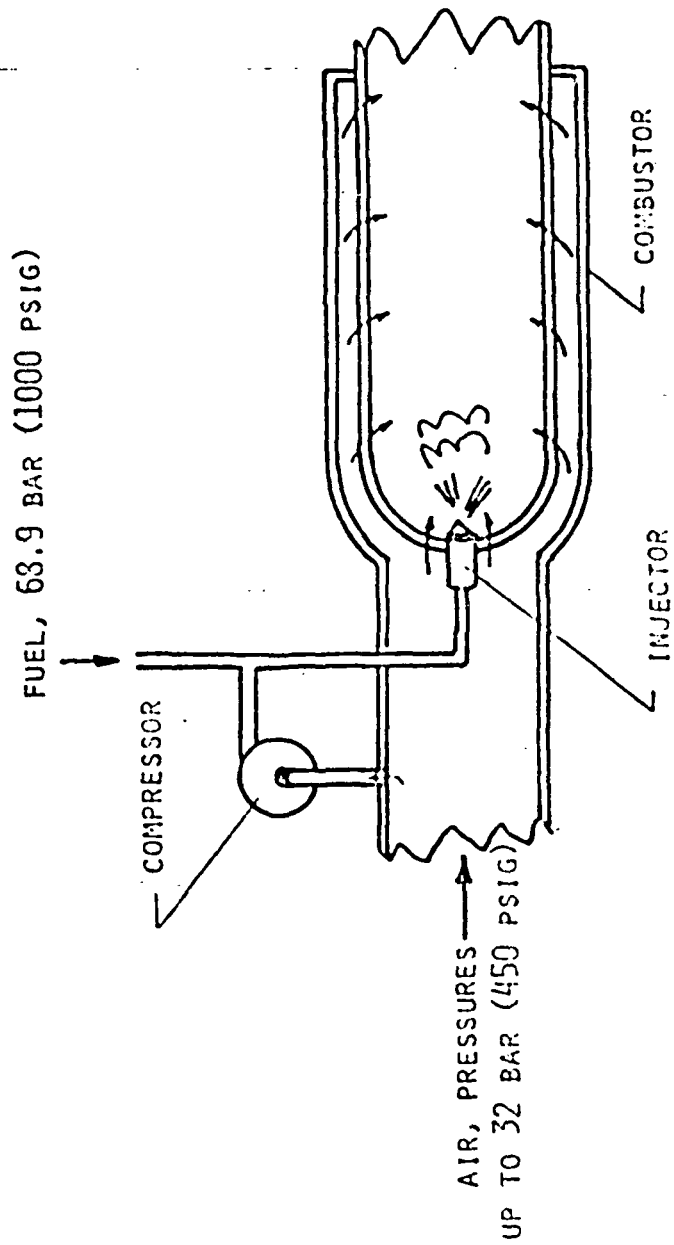


Figure 1. Supercritical injector concept.

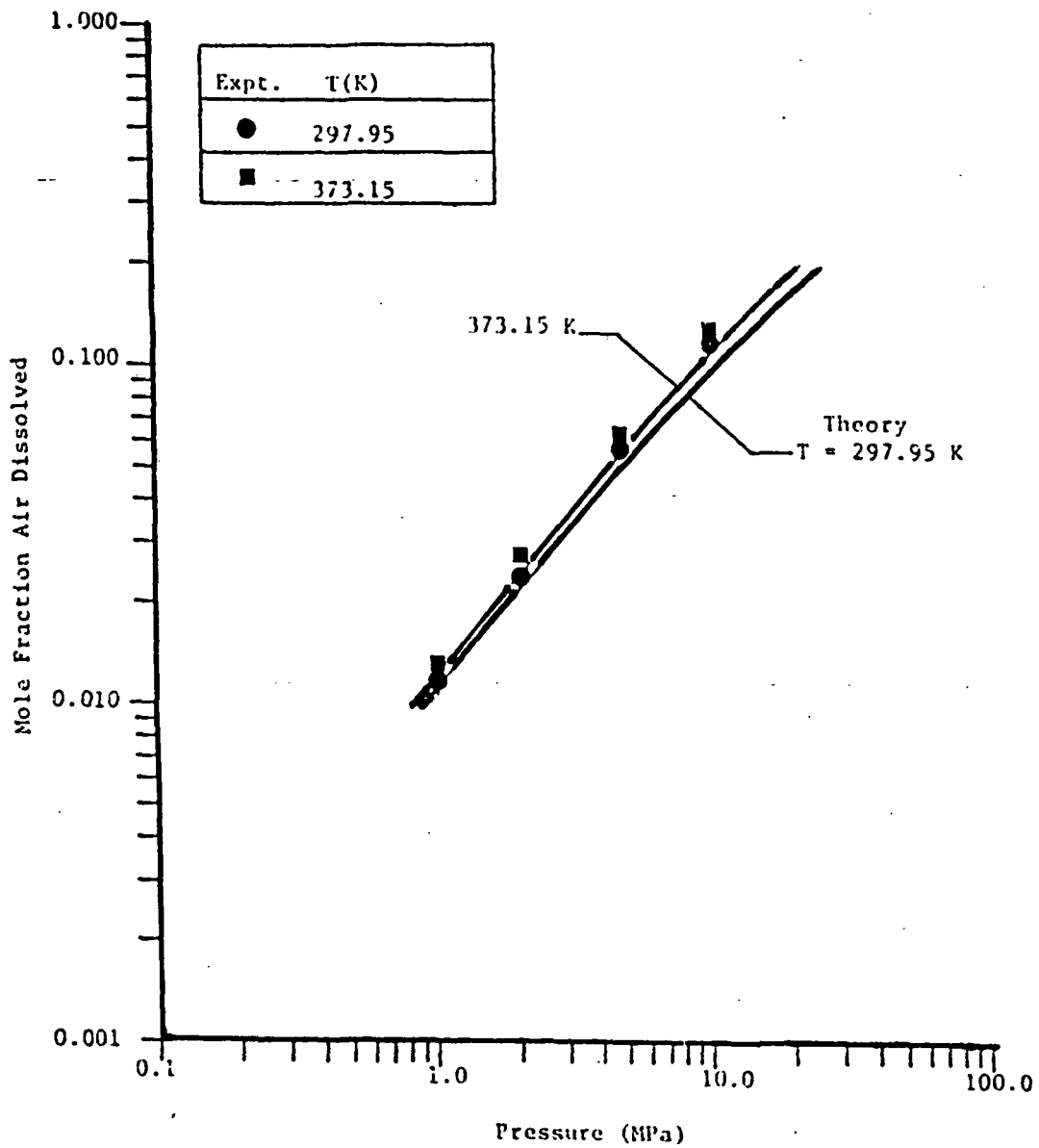


Figure 2. Predicted and measured air solubility in Jet A.



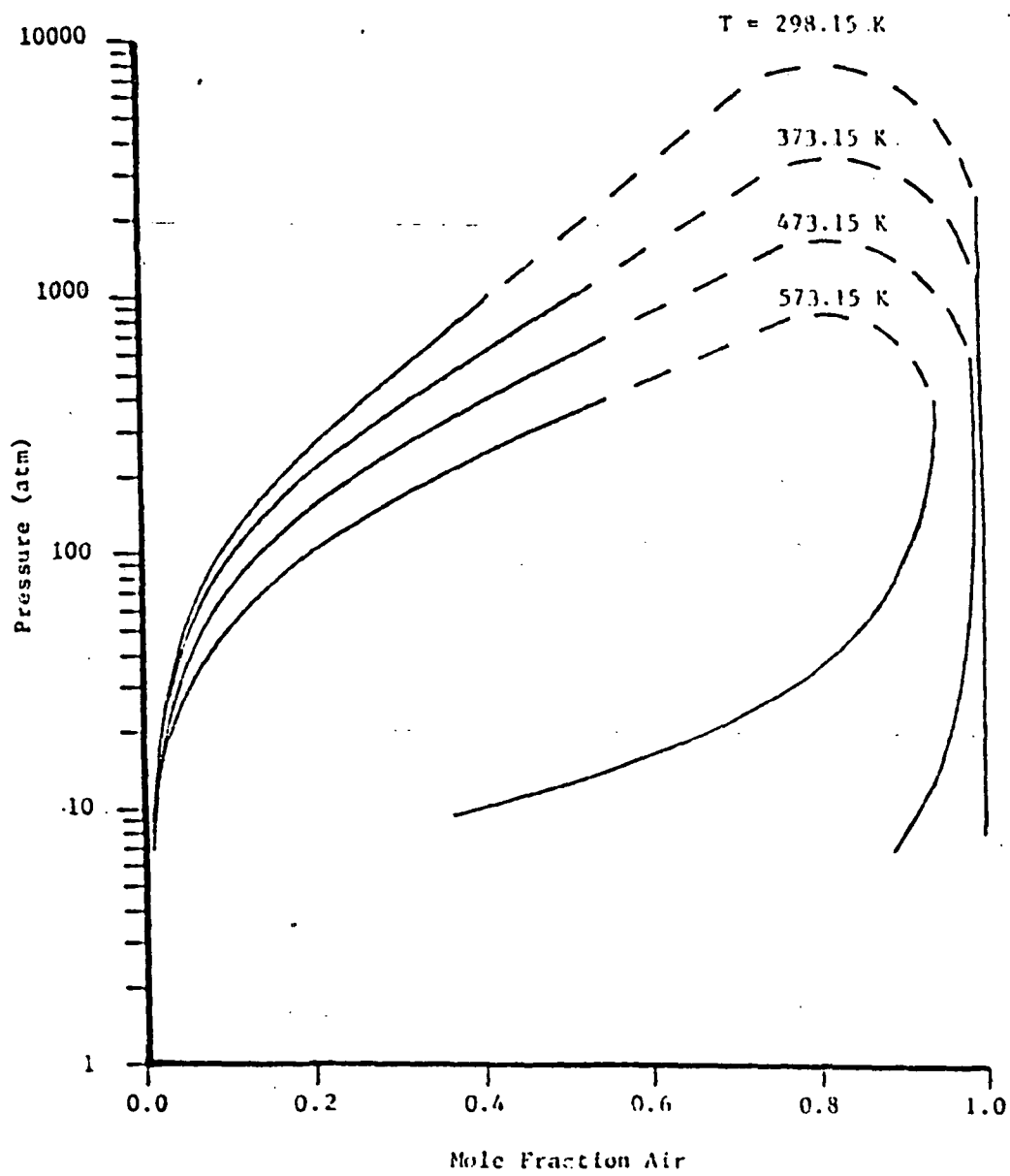


Figure 3. Predicted properties of Jet A/air.

presence of dissolved gas resulted in volume increases of as much as twenty times that of the neat liquid (inlet pressure and temperature 6.9 MPa and 473 K with an outlet pressure of 0.1 MPa). Both dissolved gas and vapor flashing contributed to the volume increase, particularly at higher fluid temperatures [1]. A volume change of this magnitude has the potential of substantially influencing atomization.

Commercial spray cans for paint, deodorants, etc., provide common examples of the effect of flashing dissolved gases for a liquid injection process. In view of this application, several studies of flashing atomization have been reported [4-6]. It is generally agreed that flashing provides a significant reduction of drop sizes in the spray, when compared with conventional liquid injection, improving atomization. Whether similar improvements can be realized with fuel/air mixtures, however, has not been demonstrated. Recent work on the spray angles observed when flashing liquid fuels indicates relatively poor comparison with existing empirical correlations for other liquids [7]; therefore, there is substantial uncertainty concerning the application of available results to fuel/dissolved gas systems.

Aside from the effect of dissolved gases on atomization, the presence of air in the primary zone of a spray flame is known to influence the production of pollutants--particularly soot. Twin-fluid injectors (air blast or air assist) are finding increasing application in gas turbine and aircraft propulsion systems due to this beneficial effect [8]. Dissolved air concentrations illustrated in Figs. 2 and 3 are generally lower than those employed for conventional twin fluid injectors. However, the intimate contact between fuel and air in a dissolved gas system has the potential for better utilization of the air in the injector flow. Whether this is the case, however, must be established.

Having determined the quantities of air that can be dissolved in a typical fuel (Jet A) [1], activities during the current investigation are devoted to determining the influence of dissolved gases on the atomization and combustion of the fuel. The specific objectives of the current phase of the investigation are:

1. Investigate the atomization properties of flashing liquids, including fuel/dissolved gas (air) systems. Determine and correlate the effect of inlet properties and injector geometry on mass flow rates, Sauter mean diameters (SMD) and spray angles. The injector configuration is limited to straight-hole orifices with no swirl.
2. Examine the combustion properties of flashing injection in an open burner flame. Determine the effect of dissolved air on flame shape and soot production.

This report summarizes progress on the investigation for the period September 1, 1980 to February 28, 1981. During this period, the bulk of project effort was devoted to the atomization study. Apparatus development was also undertaken for the combustion investigation. The results for each phase of the study are discussed in the following.

## 2. ATOMIZATION STUDY

### 2.1 Introduction

Atomization properties of dissolved gas systems are being examined for injector inlet conditions considered during the earlier investigation of solubility and density properties of dissolved gas mixtures [1]. This includes pressures up to 10.4 MPa, with Jet A-air mixtures. While swirl is employed for many injector designs, it was felt to be premature to consider this complication at this time. Therefore, testing was limited to straight-hole orifices with no swirl. Measurements of mass flow rates, SMD and spray angle were undertaken using various injector geometries. Models of the injection process are being considered in order to assist the correlation of this data.

During the course of the research, it was found that the flashing injection process could be significantly influenced by the internal geometry of the injector. In particular, the use of an expansion chamber upstream of the injector exit passage was found to substantially improve atomization properties, similar to results obtained by earlier investigators [9-11].

The effect of an expansion chamber is qualitatively indicated in Fig. 4. The top figure indicates conventional pressure atomized injection with no dissolved gas present. In this case, drops are formed by interaction of the flow with gas outside the injector. The second sketch illustrates the process when flashing of vapor or dissolved gas occurs, using a conventional injector. Here, bubbles form within the liquid as it is depressurized, and grow similar to bubble growth in homogeneous boiling processes [4-6,12-14]. The radial expansion of the bubbles tends to increase the spray angle, while the formation of relatively thin liquid layers between bubbles reduces SMD. Bubble growth velocities, however, are low; therefore, this approach requires relatively large amounts of vapor production and low flow velocities in order to have a significant impact on spray properties.

The third sketch in Fig. 4 illustrates flashing injection when an expansion chamber is present upstream of the injector orifice. The flow is partially flashed as it passes through the orifice at the inlet of the expansion chamber. There is a two-phase flow within the expansion chamber which can exhibit a variety of flow regimes (bubbly, slug, churn, annular, annular-mist, etc.) depending upon the mass quality, momentum, passage diameter, and state of flow development [15]. The condition illustrated is an annular-mist flow which would be representative of high momentum conditions with a large volume fraction of gas or vapor. This flow expands through the injector orifice and since it is compressible, choking and external expansion can occur, similar to single-phase flows in nozzles. The liquid in the annulus is drawn into a thin film in the orifice and subjected to a high shear rate by the gas flow, similar to the action of twin-fluid injectors [8]. External expansion and large shear rates tend to increase the jet angle and reduce drop sizes, thus the use of an expansion chamber improves injector performance in some circumstances. The liquid continues to flash as it passes through the injector orifice, which probably also influences the process.

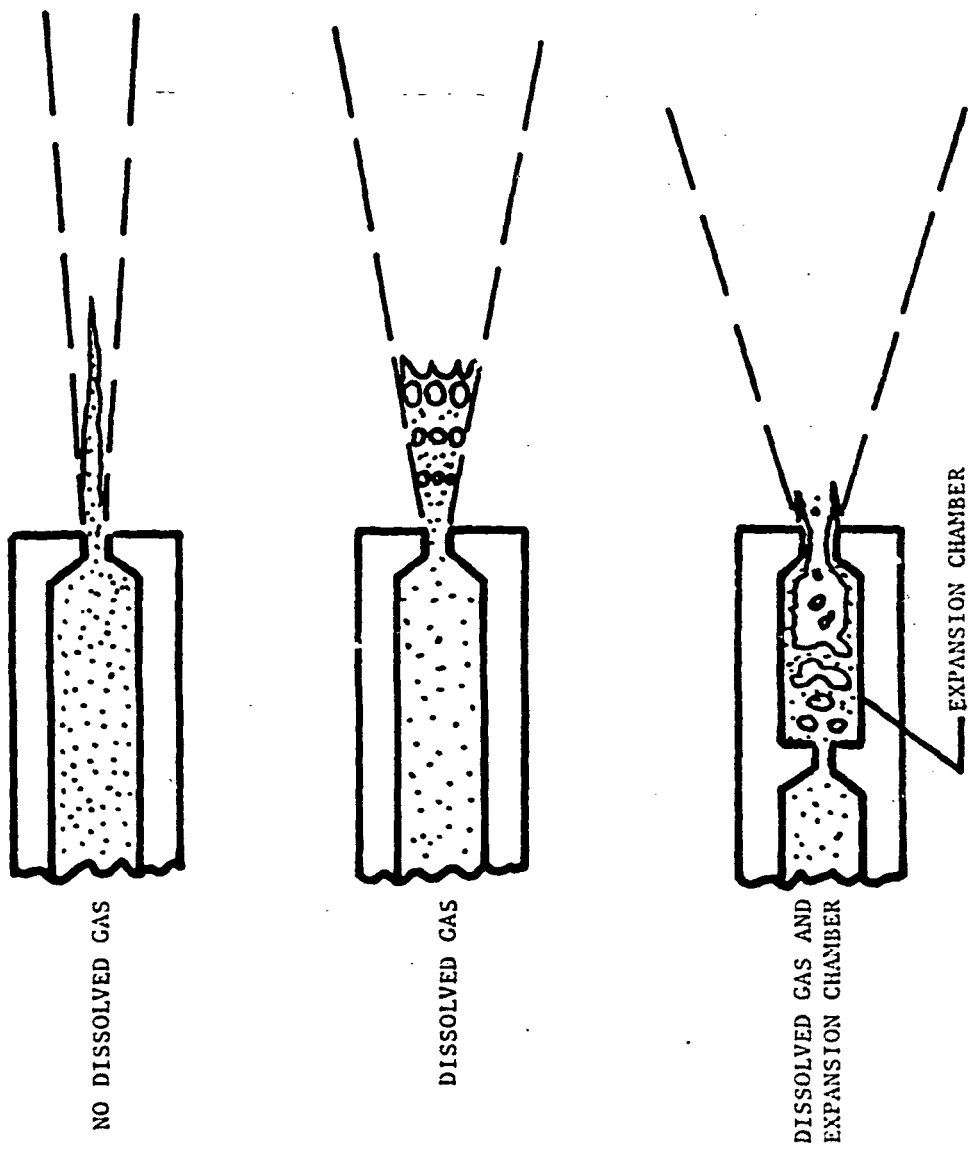


Figure 4. Flashing injection process.

It became evident as the research proceeded that greatest benefits for the flashing injection process were obtained with an expansion chamber for present test conditions. Therefore, project effort has largely been devoted to this concept.

In the following, the arrangement of the apparatus and the instrumentation used is described first. This is followed by a description of the experimental results obtained to date and a discussion of the theoretical methods being considered in order to help correlate the measurements. This section of the report concludes with an outline of plans for the next report period of the project.

## 2.2 Experimental Methods

### 2.2.1 Apparatus

The preceding considerations suggest that properties of the expansion chamber (diameter, length, pressure and flow mass quality) are likely to influence flashing injector performance, since these parameters are known to influence the flow regime of two-phase flows in tubes [15]. Therefore, a Universal injector design, where expansion chamber geometry can be changed relatively easily, was employed for the tests during this exploratory stage.

A sketch of the Universal test injector appears in Fig. 5. The injector orifice is replaceable, work to date has employed a 0.2 mm diameter orifice with a length to diameter ratio of two. The upstream orifice is variable--consisting of a bank of ten orifices constructed from watch jewels. The orifices have diameters in the range 0.07-0.46 mm. The expansion chamber is built into a center plate. Several different lengths are used with diameters which can be varied by installing collars. A pressure tap is provided in each expansion chamber.

The arrangement of the test apparatus is illustrated in Fig. 6. Downward injection is used with the injector flow being removed through an exhaust vent. Ambient velocities near the injector are very low (less than 1 m/s) thus the injector is essentially operating in a stagnant atmosphere.

The fuel is saturated with air directly in the fuel tank, similar to the earlier solubility study [1]. The air pressure within the tank provides the driving pressure for the flow through the injector. Samples are drawn directly from the fuel tank to measure the amount of gas dissolved in the liquid prior to operating the injector. Flow is initiated by opening a shut-off valve at the exit of the fuel tank.

### 2.2.2 Instrumentation

Pressures are measured in the fuel tank, upstream of the injector and in the expansion chamber. Injector mass flow rate is measured by timing the period required to pass a measured quantity of fuel through the injector.

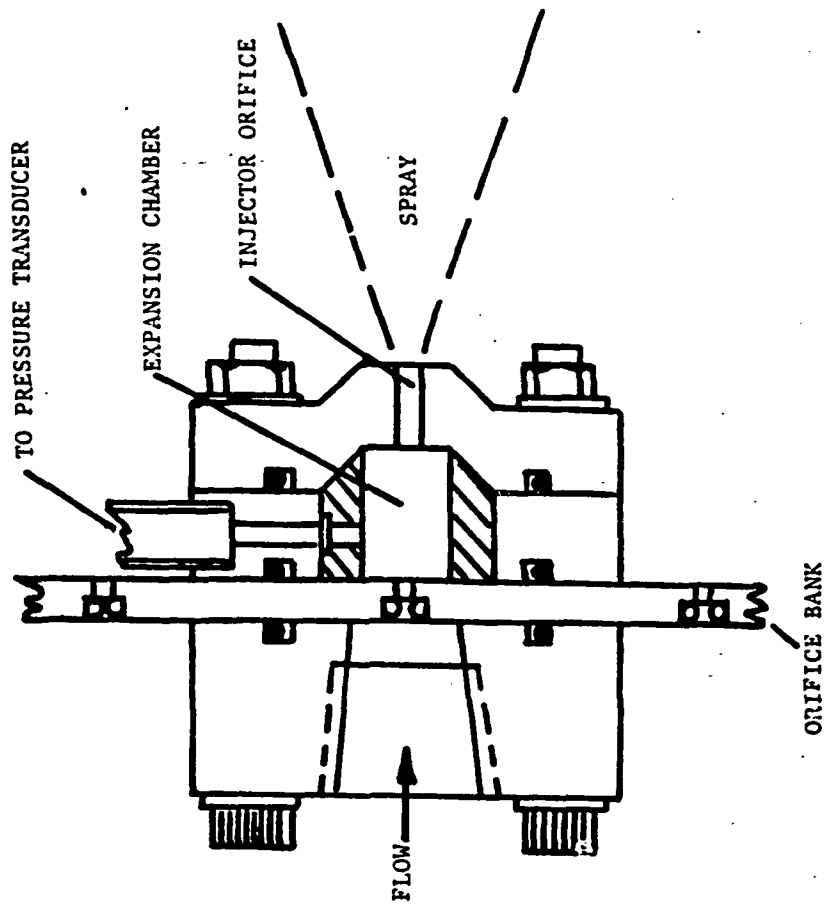


Figure 5. Experimental flashing injector.

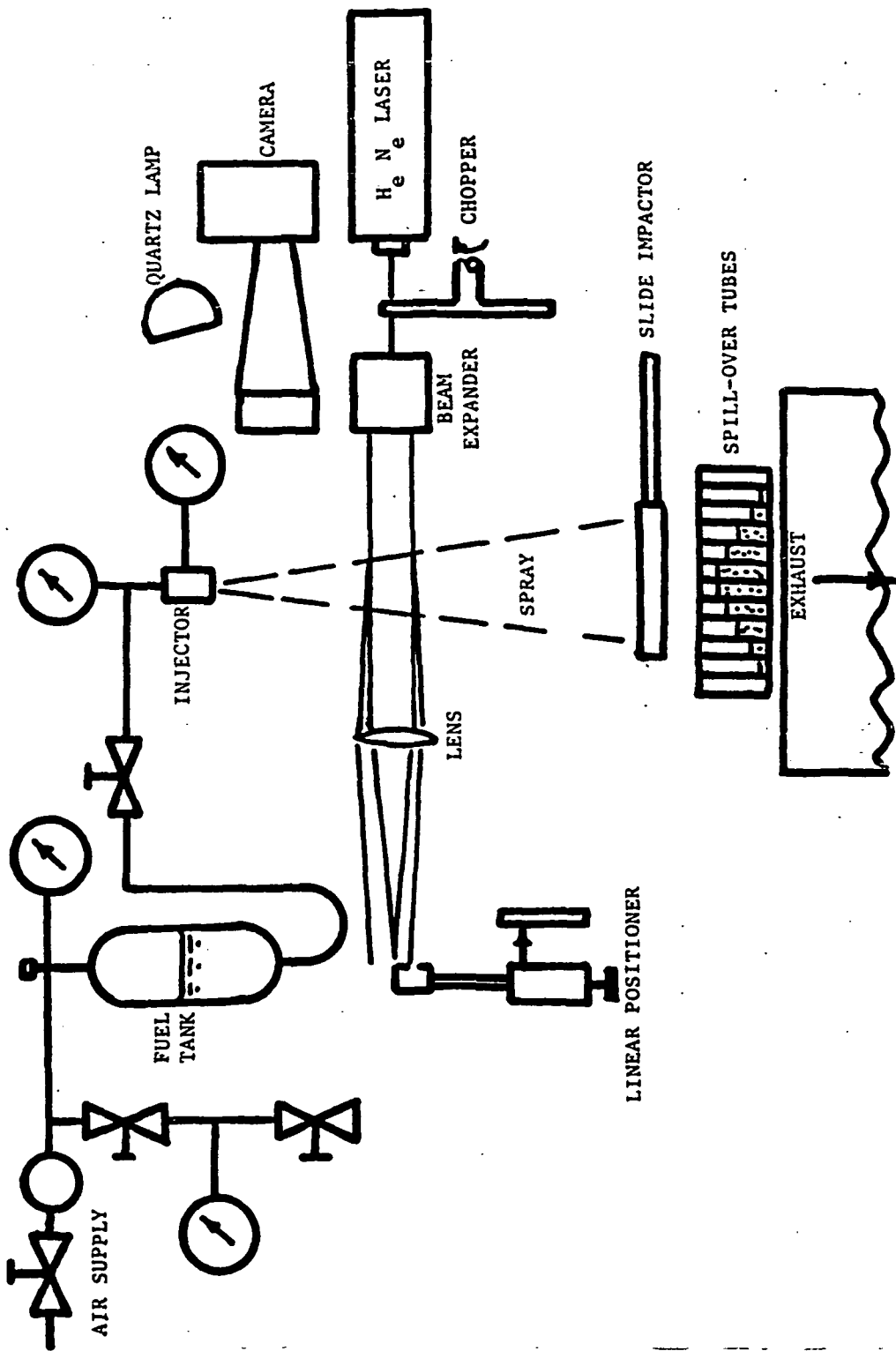


Figure 6. Flashing injector apparatus.

The spray is photographed using a Graphlex 4 x 5 still camera with Polaroid Type 52 film at a shutter speed of 1/50 s. The camera lens (f/7.5, 203 mm focal length) is located to provide a 7.5:1 primary magnification of the spray. The spray is illuminated from the front using two 650W quartz lamps.

The spill-over technique is used to measure the distribution of liquid flux in the spray [16]. This involves twelve glass tubes, 8 mm ID x 10 mm OD, closed at the bottom and ground with a taper at the top, which are placed in a rack within the spray. When the entrained air in the spray passes over each tube, the bulk of the liquid is captured (except for the smallest drops) and collects in the bottom of the tube. Sample collection for a fixed period of time allows the liquid flux to be measured volumetrically. The performance of this system is influenced by the capture efficiency of the tubes. Comparison of total liquid flow rates measured at the fuel tank and computed from the liquid flux measurements of the spill-over tubes, indicated a collection efficiency of 70-90% for present test conditions.

Two methods are being employed to measure drop sizes: the droplet impaction technique and laser scattering. The droplet impactor system was developed during earlier research on sprays in this laboratory [17,18]. A sketch of the system appears in Fig. 7. Glass slides having a width of 5 mm are coated with magnesium oxide and placed in the holder illustrated in Fig. 7. The shutter mechanism provides a means of exposing the slide to the spray for a short time interval. The shutter consists of a 6.35 mm hole drilled in a pneumatically driven slider. When the slide is exposed to the spray, the drops leave an impression in the magnesium oxide coating proportional to their size. After exposure, the slide is placed in a microscope where the impressions are sized and counted. Several thousand drops are counted in order to provide a statistically significant indication of the spray size distribution. The collection efficiency of the system varies with drop size and velocity, with the smallest drops passing around the impactor [18]. The present measurements were not corrected for this effect, however, since local gas velocities were not measured. It is estimated that the collection efficiency is greater than 85% for drops larger than 15  $\mu\text{m}$ .

The second method of drop size measurements involved the Dobbins, et al., [19] light scattering approach which yields SMD. The light source is a 5 mW He-Ne laser. The laser beam is passed through a spatial filter and expanded to 7.5 mm diameter. The larger beam passes through the spray and is collected using an 85 mm diameter, 600 mm focal length lens. Scattered light distribution is measured at the focal point of the lens with a photomultiplier having an 0.2 mm diameter aperture. The photomultiplier is mounted on a linear positioner to yield the intensity of scattered light as a function of radial position. The signal to noise ratio of the system is improved by chopping the laser beam while employing a high pass filter on the detector output. The variation in scattered light intensity yields the SMD as described in Ref. 19.



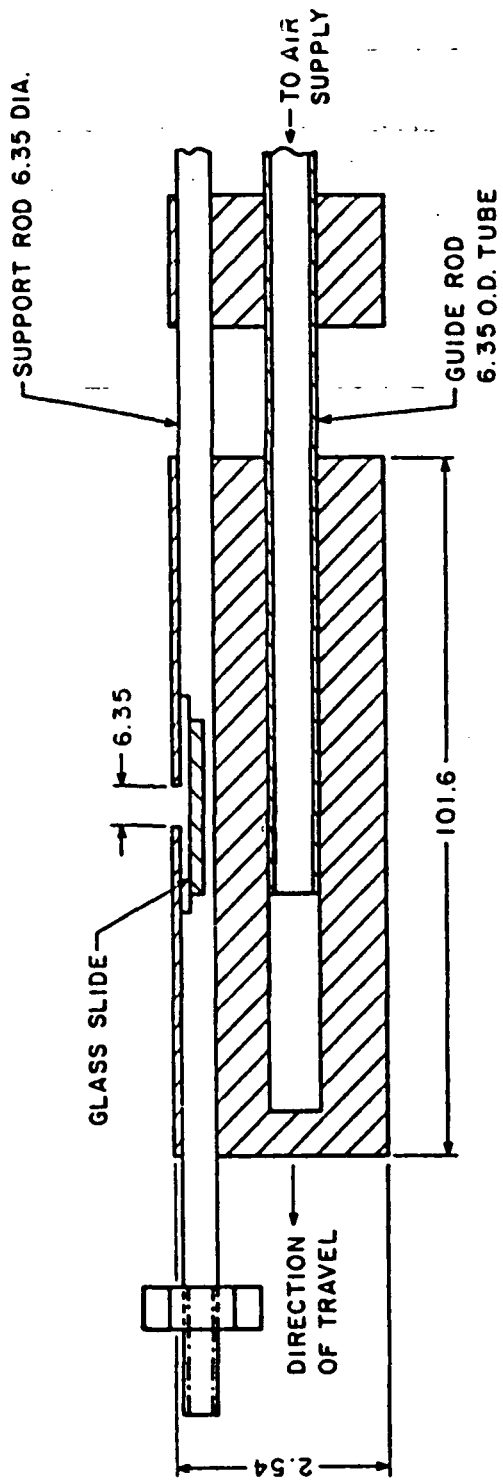


Figure 7. Sketch of the droplet impactor.

### 2.3 Experimental Results

We have not proceeded sufficiently far with theory to obtain an efficient correlation of the measurements. Therefore, only a sample of the findings obtained thus far will be described in the following, in order to indicate the general nature of the results.

The mass flow rate of the injector is plotted as a function of the ratio of expansion chamber and injector inlet pressure in Fig. 8. Two different inlet pressures are considered, 6.89 and 10.34 MPa, for Jet A fuel saturated with air. Also plotted on the figure are predicted flow rate variations, assuming that the fluid passing through the injector was an incompressible liquid with a constant flow coefficient. The measured flow rates decrease much more rapidly than the predictions with decreasing values of expansion chamber pressure. This is a clear indication of the development of a two-phase flow upstream of the injector orifice with increased flow resistance due to the larger specific volume of the mixture.

The variation of SMD and spray angle with expansion chamber pressure is illustrated in Fig. 9. The SMD measurements were obtained by the light scattering method, except that slide impaction was also employed for the results with no dissolved gas present (in this case, slide impaction yielded  $55 \mu\text{m}$  while light scattering yielded  $53 \mu\text{m}$ ). With the expansion chamber pressure equal to the upstream pressure, the presence of dissolved gases results in a slight reduction in SMD (about 10%). As the pressure of the expansion chamber is reduced, however, the SMD decreases continuously, at least for expansion chamber pressures greater than 20% of the upstream pressure. Therefore, use of an expansion chamber results in improved atomization for flashing injection.

The results in Fig. 8 indicate that the presence of the expansion chamber yields a dramatic increase of spray angle, particularly for higher injector inlet pressures. As the pressure within the expansion chamber is decreased, the spray angle increases at first, reaching a broad maximum, and then decreases again. The somewhat unusual jumps in these plots are probably due to flow regime transitions in the expansion chamber, although further study will be required to show that this is the case. For high upstream pressures, spray angles reach values on the order of  $40^\circ$ . In comparison, an incompressible single-phase axisymmetric jet has an angle of spread of  $18-24^\circ$ . Greater angles are attained for underexpanded compressible jets, where the flow in the passage is choked and the pressure at the exit of the passage is greater than the ambient pressure. Similar choking phenomena for the two-phase flow through the injector passage probably accounts for the large spray angles observed during the present measurements. The expansion chamber pressures for the results pictured in Fig. 8 are high enough so that choked flow behavior would not be unexpected--even for a two-phase flow.

Measurements of liquid flux distribution were completed for some of the operating conditions of the flashing injector. The sprays were found to be full-cone, with a Gaussian decrease in liquid flux with radial distance from the centerline.

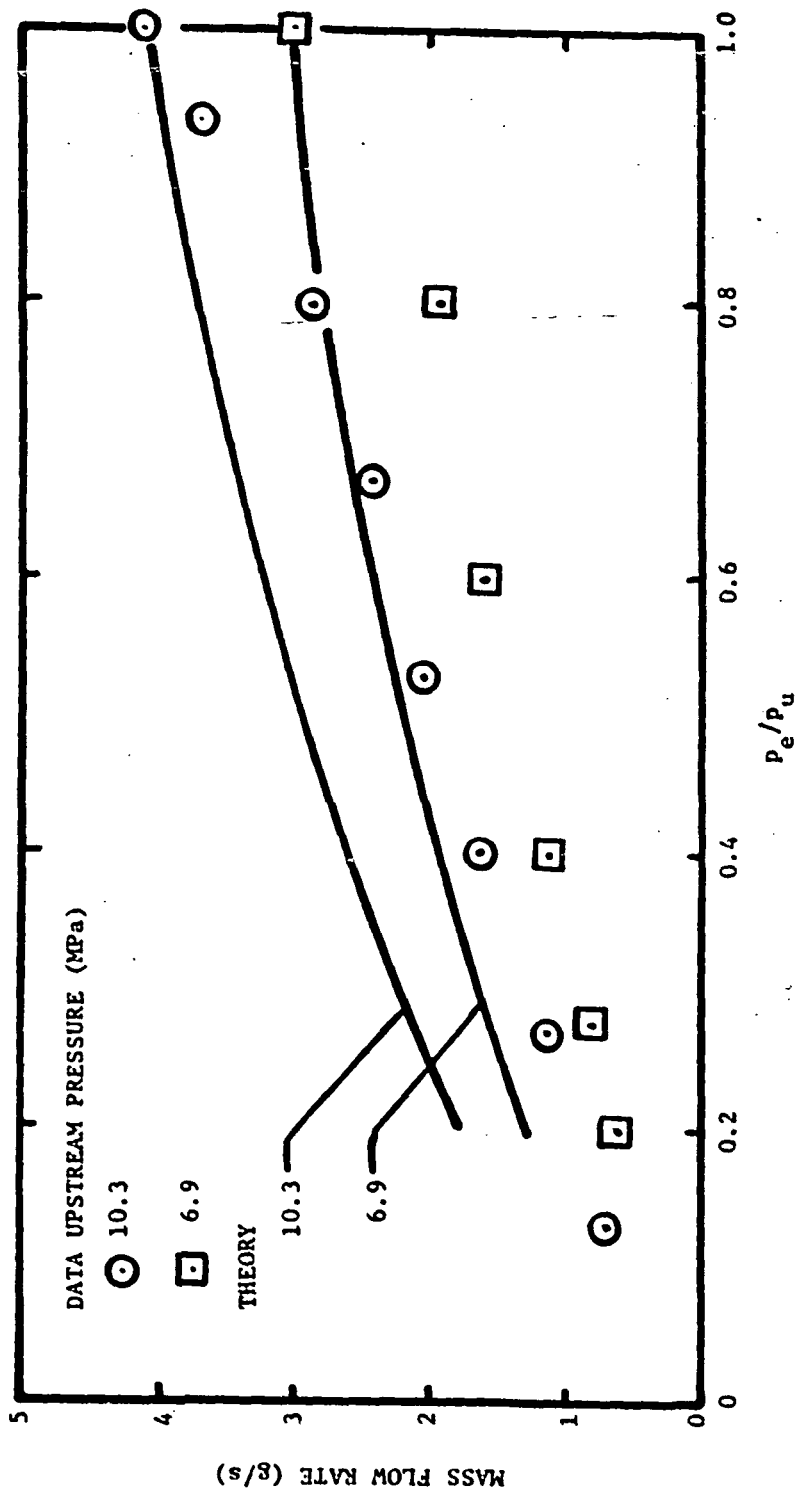


Figure 8. Injector mass flow rate as a function of expansion chamber pressure.

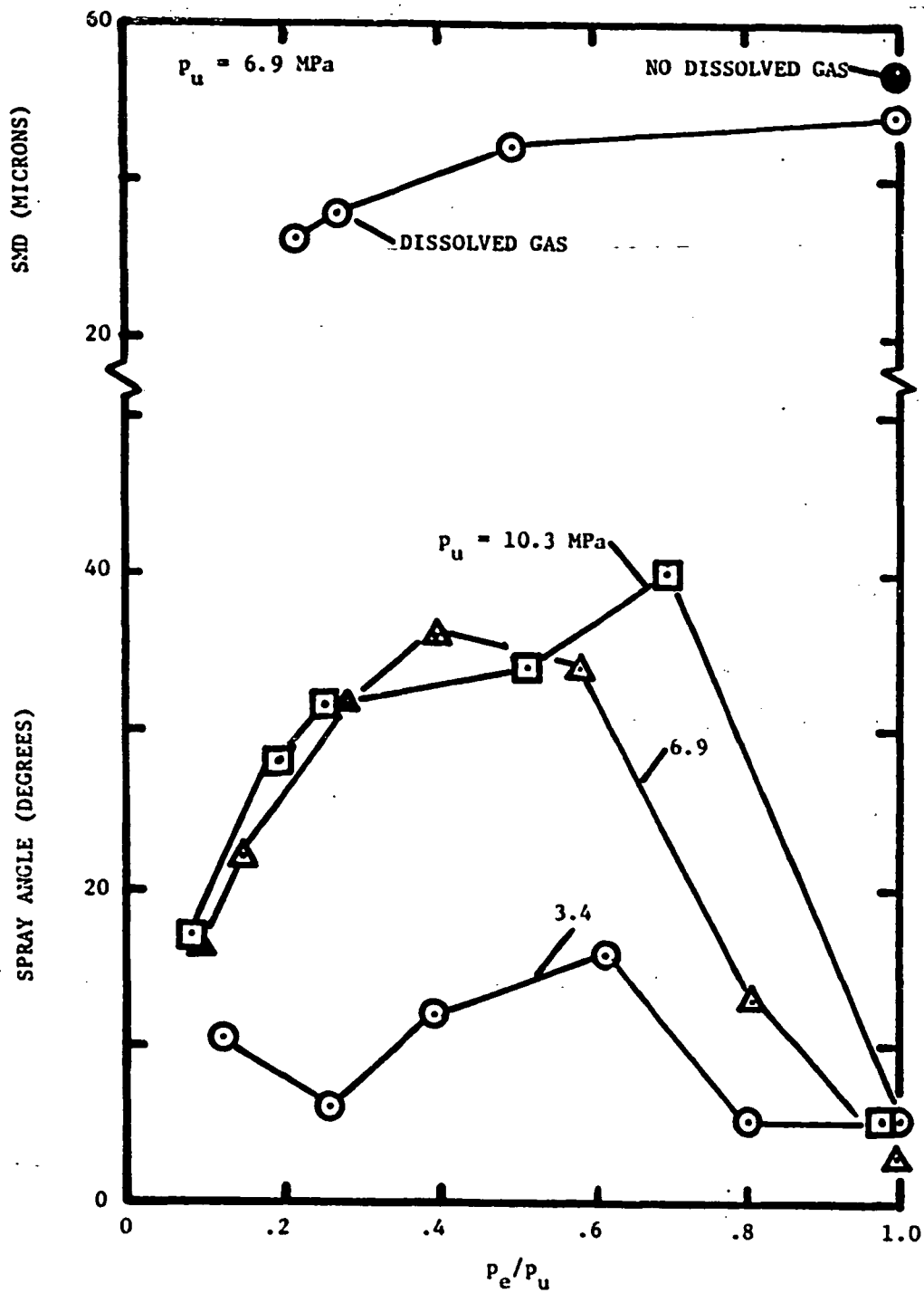


Figure 9. Spray angle and SMD as a function of expansion chamber pressure.

Some testing has been completed concerning the effect of changes in the volume of the expansion chamber. Findings thus far indicate that the influence of the expansion chamber volume on spray angle is not large. Behavior can be influenced, however, in certain regimes due to flow transitions. For example, some expansion chamber pressures yield slug flow if the volume is sufficiently large. This results in a pulsating spray and oscillations in expansion chamber pressure, which has been observed in some circumstances.

#### 2.4 Theory

In order to properly summarize the measurements, analysis is being undertaken for injector flow characteristics, SMD, and spray angle. Evidence is mounting that the flow regime in the expansion chamber also has an important influence on spray properties and this is being examined as well.

For a given injector geometry, upstream conditions and ambient pressure, it is necessary to make predictions of injector flow rate and expansion chamber pressure. Analysis for these quantities is being undertaken under the following assumptions: negligible flashing in the orifices; constant expansion chamber pressure; thermodynamic equilibrium in the expansion chamber; and adiabatic flow. For these assumptions, the flow through the upstream orifice can be modeled as an incompressible flow with densities known from our earlier investigation [1]. Properties within the expansion chamber can also be determined for a given pressure (mass quality and temperature). Subsequent expansion of the flow through the injector orifice can be treated using conventional two-phase flow analysis [15]. In particular, the relationships between flow rate and pressure drop developed by Chisholm [15] for two-phase flows are widely accepted and we will consider this approach first.

The expansion chambers are relatively small, therefore, existing correlations to predict flow regimes are not likely to be accurate. Nevertheless, they will be employed due to the absence of another alternative. As crude as this approach is, the results should still be helpful for interpreting unusual shifts in injector performance.

The flow through the downstream orifice roughly corresponds to the flow in an internally mixed twin-fluid injector. Lefebvre [8] has recently reviewed available correlations for SMD for such injectors. If the flow regime is annular, the flow most closely resembles the prefilming air blast atomizer. Therefore, dimensionless parameters and correlations for this injector configuration will be employed during initial attempts to correlate the data.

The correlation of spray angle represents the greatest uncertainty at this time. The approach used by Leinhard [13,14] is appropriate for external flashing processes, but is not applicable to the present arrangement. Therefore, the literature is being examined further in an attempt to find more background material in this area.

## 2.5 Plans for the Next Report Period

Tests with the flashing injector will be completed, considering saturated Jet A/air mixtures at inlet pressures up to 10.3 MPa. We also plan to supplement these measurements with various air-fuel mixtures flowing directly into the expansion chamber so that a broader range of operating conditions can be simulated.

Experimental methods similar to those described in this report will be employed during these tests, with the exception of SMD. In the case of SMD measurements, the present light scattering approach will be supplemented using a Malvern drop size analyzer. The Malvern unit that will be used employs a model independent data processor which yields histograms of drop size directly. This data can be processed to obtain SMD, etc.

The theory will be applied to the measurements in order to help correlate the results.

## 3. COMBUSTION STUDY

### 3.1 Introduction

Optimum flashing injection results in much larger spray angles and smaller drop sizes than is encountered for injection of neat liquid fuel. It seems obvious that this will result in substantial changes in flame shape and pollutant production. Nevertheless, the use of flashing injection represents a complication of the combustion system and some indication of its potential benefit is needed. Therefore, testing of the combustion properties of flashing injectors is planned, with particular emphasis on measuring flame shape and soot production.

### 3.2 Apparatus

A sketch of the spray combustion apparatus appears in Fig. 10. The major features of the apparatus are similar to that used during earlier studies of spray modeling in this laboratory [20,21]. The main difference involves the modification of the fuel injection system needed for flashing injection.

The fuel injector is mounted on a three-dimensional traversing mechanism--injecting vertically upward. The spray flame is stabilized at the injector exit by means of an array of small hydrogen capillary flames. The injector configuration will be similar to that illustrated in Fig. 5.

Fuel will be delivered from storage using a variable displacement Whitey laboratory pump. Mass flow rate will be determined by weighing for a timed interval. The fuel then passes through a heater and saturator in the inlet of the injector (although it is not planned to preheat the fuel for this series of tests a heater has been installed for future work using flashing injection with no dissolved gases present).

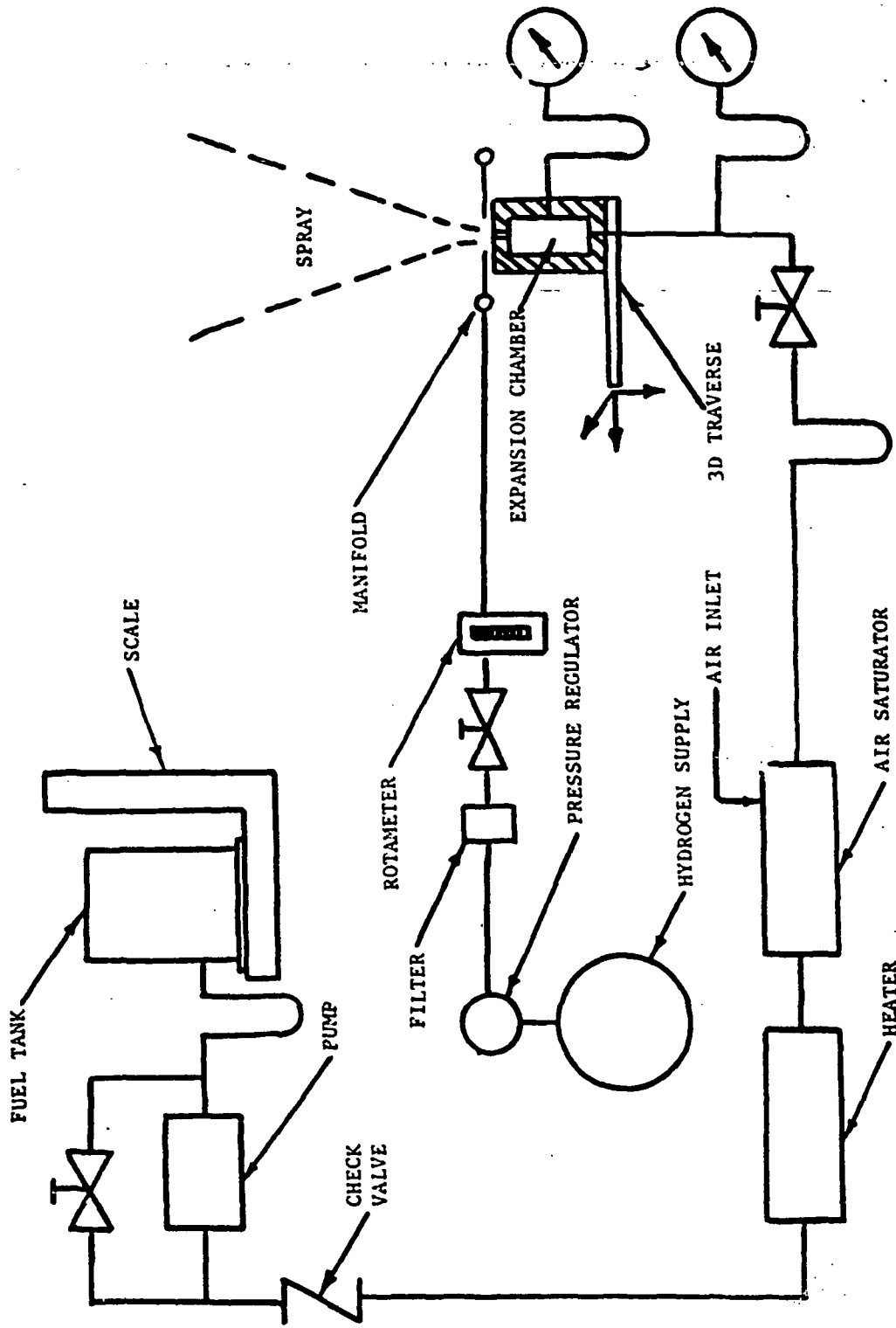


Figure 10. Spray evaporation and combustion apparatus.

The saturator consists of a packed bed within a pressure vessel. The vessel is pressurized with air which saturates the fuel as it trickles through the bed. The saturated fuel is collected at the bottom of the chamber, where the liquid level is monitored using a sight glass. The concentration of dissolved gas is determined by withdrawing samples from the saturator, similar to earlier work [1].

A gross indication of combustion properties for various operating conditions will be obtained by photographing the flames. Poor atomization and greater soot production yields a longer, more luminous flame for a fixed fuel flow rate in this apparatus.

A few test conditions will be probed in greater detail in order to obtain a quantitative indication of the effect of supercritical injection. The measurements will largely be limited to mean temperatures, velocities and soot concentrations along the centerline of the spray. Mean temperatures will be measured using a fine-wire thermocouple, shielded from drop impacts, similar to earlier work [21]. Mean velocities will be measured using a laser-Doppler anemometer, also identical to earlier work. Soot concentrations will be measured using isokinetic sampling with a quenching probe as described by Hiroyasu, et al., [22]. This involves quenching and diluting the flow prior to collecting the soot on a filter. The filter is then dried and weighed in order to obtain the soot concentration.

### 3.3 Theory

No new development of theory is planned for this phase of the investigation. However, it is planned to exercise our existing spray model [21] using the results of these measurements.

### 3.4 Plans for the Next Report Period

The spray combustion test apparatus has been assembled. At the present time, the soot collection probe and sampling system are being fabricated.

The combustion tests and their analysis will be completed during the next report period.



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