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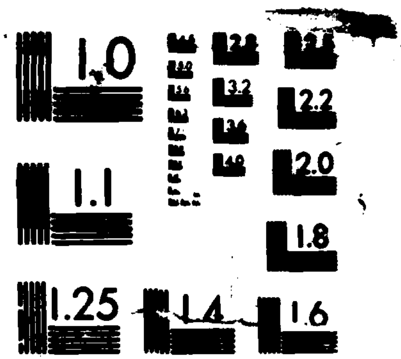

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The objective of the work was the investigation of fluid dynamic and surface tension instabilities that affect the breakup of fuel jets in the atomization process. Computational and analytical methods were used. Initial work involved the evaluation of numerical methods for flows with density discontinuities. It was discovered that many commonly used methods are poorly suited to predicting two phase flows. However, a suitable method was found, and it was programmed in a Navier-Stokes prediction code. The code has passed some accuracy tests, and others are ongoing. Predictions of simple one and two phase flows were conducted as part of these tests. A method for computing surface tension effects was included in the prediction algorithm, but further work is ongoing to make the method more robust. An inviscid stability analysis of an expanding-radius liquid tubular jet was performed. It was found that no new instability mechanisms are introduced by the rate of change of radius. A viscous stability analysis of a shear layer with a discontinuity in density was initiated and will be continued.

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Spray Formation: Three Dimensional Liquid Jet Breakup Due to Surface Tension

In spray combustion, a liquid fuel is atomized and distributed in the combustion chamber to enhance the combustion process. Atomization is achieved by forcing a jet of liquid fuel through a fuel injector and into a gas whereby it is broken up into a large number of minute drops. The atomization process is critical to the combustor's performance. The focus of this study is the initial region of the liquid fuel jet, as it begins to break up under the influence of fluid dynamic and surface tension forces. Liquid jet breakup is difficult to study experimentally due to the small spatial and temporal scales involved. However, the flow is governed by a well-defined set of equations, and thus, it can be studied by mathematical means.

The present work involves analysis and numerical simulation of the initial stage of liquid jet breakup which is a precursor to atomization. The objectives of the present work are to improve the understanding of the instability mechanisms in the initial region of the liquid jet and to explore possible methods for exploiting surface instabilities to improve the atomization characteristics of the fuel injection process. In this first year of a two year study, the numerical methods needed to investigate the liquid jet breakup have been evaluated and assembled. Initial calculations of two phase flows have been made. Also, mathematical analysis has been performed on one aspect of jet breakup and is in progress on another aspect. These topics are discussed below.

Numerical simulation of the liquid jet is performed by integrating numerically the discretized Navier-Stokes equations for an incompressible, variable density fluid. The simulation is done on a fixed grid in two or three space dimensions and time. As originally planned, the numerical algorithm used to integrate the equations is a finite volume, fractional steps method. However, the discrete density jump imposes restrictions on specific details of the method, and a significant amount of time was invested in a study of Navier-Stokes integration methods.

For a fundamental study of liquid jet dynamics, it was felt that the algorithm must have good accuracy and must guarantee mass and momentum conservation at the sharp density discontinuity at the liquid/gas interface. Aerodynamics research has shown that nonconservative methods will give incorrect motion of discontinuities, which would be intolerable in the present work. This dictates that the true momenta, ρU_i, rather than the velocities, U_i, be conserved variables. For flows with large density differences between liquid and gas phases, it then becomes essential that the density implicitly associated with the momenta must be consistent with the density computed by the mass conservation equations, since small inconsistencies could produce large fluctuations in computed velocities. The only discretization scheme which could be devised that would satisfy the conservation and consistency requirements was a cell centered scheme. The widely used staggered grid discretization scheme uses different cells within the grid for conserving mass and the momenta, and as a result, is essentially incompatible with the consistency requirement. A decision to develop a new algorithm was made after a thorough assessment of existing Eulerian methods revealed that none of the methods appropriate for the work (as described in the literature) satisfied momentum conservation in the presence of density discontinuities.

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Thus, a method which uses a nonstaggered grid was developed. The density and momenta are stored at cell centers, and the pressure is stored at cell corners. Otherwise, it is similar to the methods envisioned in the original proposal. The present method is second order in time and second order in space with optional fourth order accuracy on convective terms. It uses the fractional steps concept to satisfy the divergence-free constraint while maintaining good efficiency.

An interface tracking method is used in conjunction with the conservation equations to insure that the density discontinuity is resolved sharply. This approach is second order accurate, which is felt to be the minimum required for studying stability. The Simple Line Interface Calculation (SLIC) method originally envisioned for this work is first order, and computed results reveal certain characteristics (e.g., the truncation of small waves on an interface nearly parallel with grid lines) that would hamper a study of interface instability mechanisms. Surface tension is included via the interface tracking method and the momentum equations. In general the surface tension method gives good results. However, there was a problem in the surface tension procedure for some shallow-angle waves which caused the method to become unstable. The problem was traced to an approximation in the fractional steps procedure, and it has been partially corrected. Some further work is required, but this is believed to be straightforward. The results given below avoid this problem.

A computer code which employs the above described methods was written and is being evaluated on some sample problems. Single phase flow in a cavity with a driven lid was computed, as this is a 'standard' test case for Navier-Stokes methods. Accurate results at several Reynolds numbers have been computed. Two- and three-dimensional cavity flow calculations have been performed successfully. The remaining calculations are of two-dimensional axisymmetric flows.

In a uniform flow without gravity or surface tension, a surface wave should convect indefinitely without distortion. The ability to simulate this distortion-free convection is critical to the ability to predict accurately the growth rates of waves on the liquid surface. The density jump is used to identify the interface. (The density contours show a smeared interface, but this is an artifice of the plotting package.) Figure 1(a) shows the initial condition of the wave. Figures 1(b,c) show the wave after it has traveled one half and two wavelengths, respectively, and the fidelity of convection prediction can be seen. Although this test case is physically uninteresting, it is a challenging numerical test because there is a 10 to 1 jump in density and momentum across the interface which must be convected through all cells between the trough and crest of the wave. The present method gives good results for this flow, and it shows none of the 'truncation' problems associated with the SLIC method.

The Rayleigh instability, which causes a liquid cylinder with surface tension to break up into drops, has also been simulated. The liquid cylinder is initially at rest, but its surface is given a small sinusoidal displacement. Surface tension induces a pressure disturbance which causes long waves to be amplified and short ones to decay. As above, there is a 10 to 1 jump in density across the interface. Figures 2(a,b) show the density contours and velocity vectors for a long wave, and the velocities indicate that the disturbance is growing. The decay of a short wave is shown in Figures 3(a,b). Quantitative evaluation of the method's accuracy for this problem has not yet been performed, but it is planned for the near future.

The above test cases have done nothing to increase our understanding of the physics of the problem. However, they do show that the numerical method can treat the sharp density jump and surface tension at the interface, even for short wavelengths. Since the object of the work is to investigate the physics, it is felt that the use of an accurate method is essential. These test cases indicate that the desired accuracy has been achieved.

At present, the work is directed at completing the evaluation of the computer code and making any needed modification. The ability to simulate the conical liquid jet should be achieved early in the second year, at which time the work will focus on the instability mechanisms of fuel sprays.

Other aspects of interface flows have also been investigated. These are being pursued at a low level of effort and are intended to complement the main computational thrust of the work. Inviscid stability analysis of the cylindrical liquid sheet (of constant mean radius) has been used by previous researchers to explain some conical fuel spray phenomena. In the present work this analysis was extended to a liquid sheet with a radius which increases in time. The analysis should more closely approximate the physics of conical sprays than the constant radius case. However, it was found that the stability mechanisms which are present in the constant radius case are unaffected by the rate of change of radius. Inviscid Lagrangian computational methods were also investigated. These methods are well suited to two-dimensional simulations and are being considered as a means of checking the Navier-Stokes simulations. An Orr-Sommerfeld analysis of a shear layer with variable density and viscosity has been started but not completed. If successful, this work will provide guidance on viscous instability mechanisms, and it may help explain Reynolds number effects on atomization.

Progress this year has been slightly slower than planned due to difficulties with the Navier-Stokes integration algorithm. The fundamental shortcomings of previous methods for flows with discontinuous density were not fully anticipated. It is believed that the time spent to resolve the difficulties which were uncovered will yield more accurate results for spray flows. This delay should not prevent the research from achieving its stated goals.

Drs. Robert E. Childs and Nagi N. Mansour have worked on this project. No degrees have been awarded in conjunction with this work. No publications have yet resulted from this work, but it is planned that an abstract will be submitted to the 26th AIAA Aerospace Sciences Meeting, to be held in January 1988. Mr. Dan Bulzan of the NASA Lewis Research Center has been contacted regarding this work. General objectives were covered. No new discoveries or patents have resulted from this work.

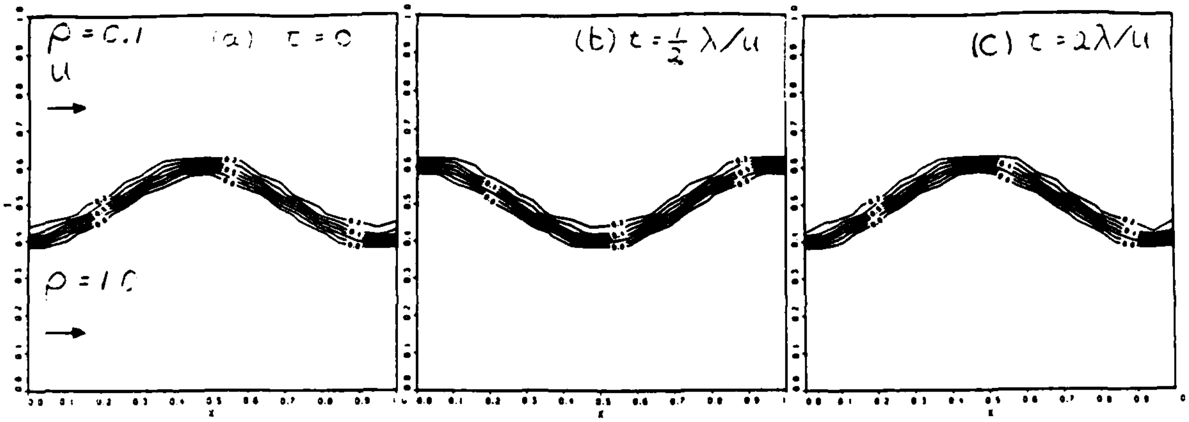

Figure 1. Density contours show essentially distortion-free convection of a simple sinusiodal wave in a uniform flow field.

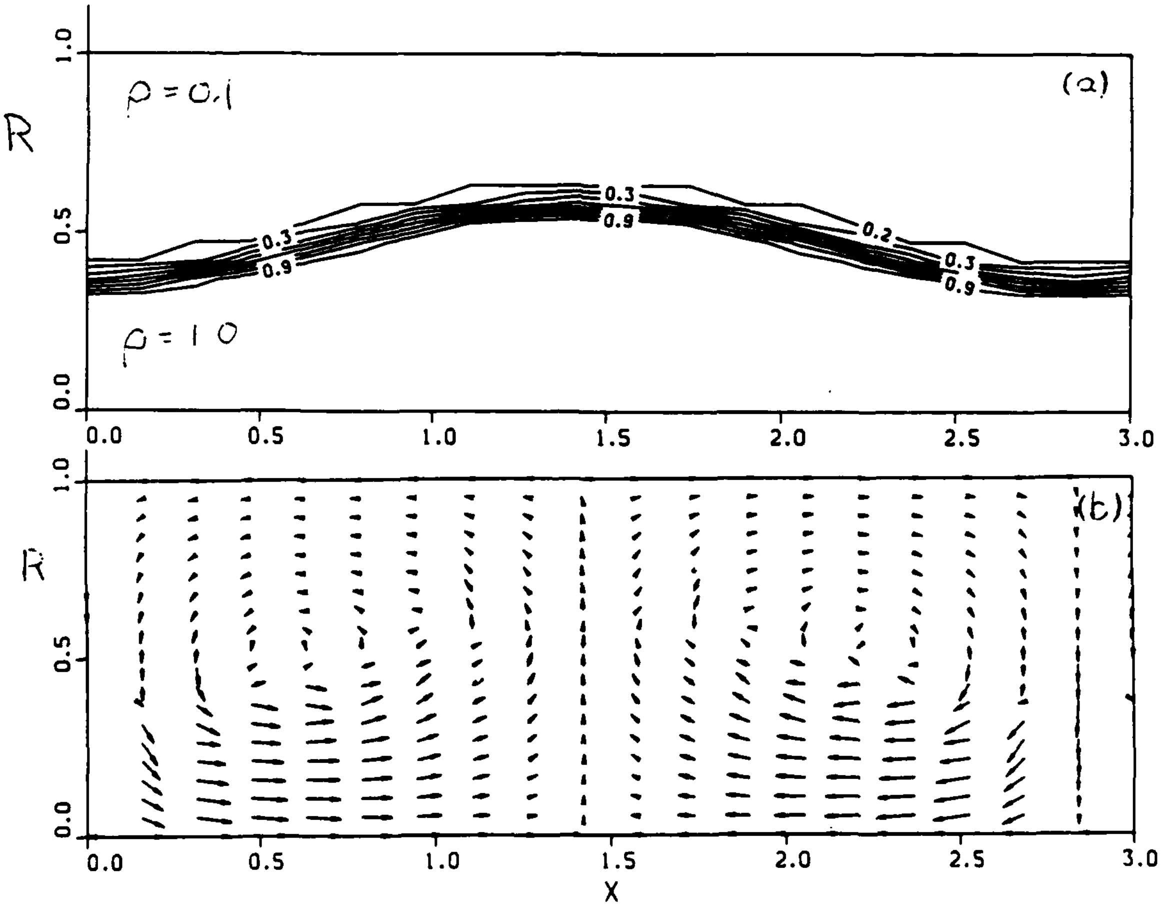

Figure 2. Density contours and velocity vectors for a growing wave on a liquid cylinder with surface tension.

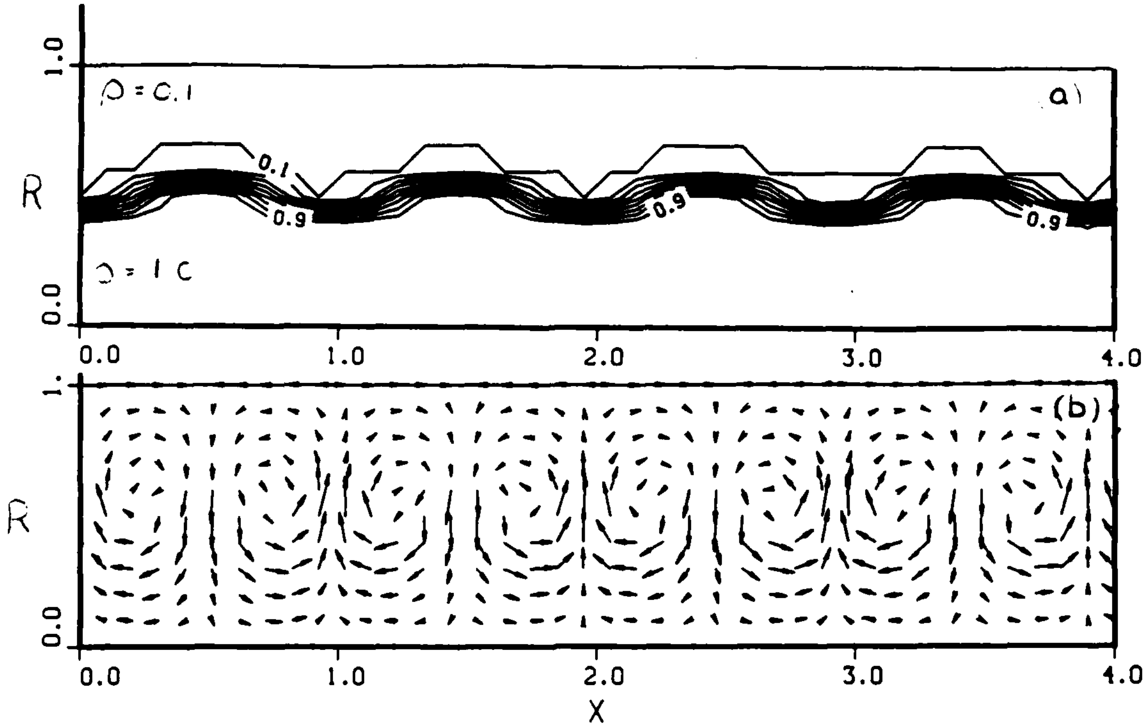

Figure 3. Density contours and velocity vectors for a decaying wave on a liquid cylinder with surface tension.

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