ABSOLUTE AND CONVECTIVE INSTABILITY OF A LIQUID JET IN MICROGRAVITY

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ABSTRACT

The transition from convective to absolute instability is observed in the 2.2 second drop tower of the NASA Lewis Research Center. In convective instability the disturbance grows spatially as it is convected downstream. In absolute instability the disturbance propagates both downstream and upstream, and manifests itself as an expanding sphere. The transition Reynolds numbers are determined for two different Weber numbers by use of Glycerin and a Silicone oil. Preliminary comparisons with theory are made.

INTRODUCTION

The capillary instability of an infinitely long inviscid jet in vacuum with respect to temporally growing disturbances was investigated by Rayleigh (ref. 1). The instability of a viscous liquid jet with respect to spatially growing disturbances was investigated by Leib and Goldstein (ref. 2). They demonstrated that the disturbance in the jet may grow spatially as it is convected downstream or grow both in the upstream and downstream directions depending on the flow parameters. The former is called convective instability and the latter is called absolute instability. They determined the critical Weber number below which the flow is absolutely unstable as a function of Reynolds number. Lin and Lian (ref. 3) showed that the critical Weber number may be increased for a given Reynolds number by increasing the density of the ambient gas which was neglected by previous workers. The effect of gas viscosity was investigated by Lin and Lian (ref. 4). In the above referenced theories, gravity is neglected. Therefore, the good comparison of experiments on earth with theoretical results (ref. 5) may be fortuitous. Moreover the phenomenon of the jet absolute instability has never been observed. The observation of jet instability in the NASA Lewis drop tower facility allows us to elucidate the phenomenon of absolute instability. The comparison of experiments with theory is still in a preliminary stage, however.

THEORY

The linear stability analysis of the jet instability results in the characteristic equation (ref.6)

$$\boldsymbol{D}(\boldsymbol{k},\omega)\cdot\boldsymbol{A}(\boldsymbol{k},\omega)=\boldsymbol{S}(\boldsymbol{k},\omega)$$

where **D** is the coefficient matrix, **k** is the complex wavenumber vector, ω is the complex frequency and S is the Laplace-Fourier transform of the source vector arising from the initial condition. The eigenvector A in the physical space may be obtained from the inverse Laplace-Fourier transform (ref. 6)

$$\boldsymbol{A}(\boldsymbol{r},\tau)\int_L \frac{d\omega}{2\pi}\exp(\omega\tau)\int_F \frac{d\boldsymbol{k}}{(2\pi)^2}\exp(i\boldsymbol{k}\tau)\boldsymbol{D}^{-1}\boldsymbol{S},$$

where **r** is the position vector, τ is time, **k** is the complex wavenumber assumed to be two-dimensional, and the subscripts L and F denote suitably chosen integration paths in the Laplace and Fourier space respectively. The singularities of the integrand are given by

$$D(\boldsymbol{k},\omega)=0,$$

which is the characteristic equation for the unforced natural disturbances. When the singularity is a saddle point in the Fourier space the jet may become absolutely unstable, and the axisymmetric disturbance grow asymptotically as (ref. 6).

$$\lim_{\tau\to\infty} A \sim \exp(ik_o y)\exp(\omega_o \tau)/\tau^{1/2}$$

when k_o and ω_o denote respectively the location of the saddle point in the Fourier space and the branch point in the Laplace space, and y denote any point along the jet axis. When the singularity of the integrand is a simple zero of D=0, the jet may become convectively unstable. Then the disturbance which is convected downstream with the group velocity V_g behave asymptotically as (ref. 6)

$$\lim_{\tau\to\infty} A(V_g\tau,\tau) \sim \frac{1}{\sqrt{\tau}}\exp[k_{im}(\omega_s),V_g\tau],$$

where k_{im} is the maximum of k_i for $\omega_r=0$, and ω_s is the corresponding frequency of oscillation.

EXPERIMENTS

A series of experiments to investigate the transition between absolute and convective instability in a liquid jet were performed at the 2.2 second drop tower at NASA Lewis Research Center. A preliminary round of ten tests, performed with Glycerin, showed that it was possible to identify the transition with the existing drop rig. A second round of eighteen tests, performed with Dow Corning 200 Series 1000 cSt Silicone Oil, were completed with additional sensors to identify the transition point more accurately.

To investigate absolute and convective instabilities in liquid jets, one needs to be able to produce a liquid jet, induce a disturbance, photograph it, and record important flow parameters. Hence, the experimental drop rig consists of four main systems: a pressure delivery system to drive the liquid jet, a piezoceramic forcing system, a high speed photographic system, and a sensory and data acquisition system. From the preliminary round of tests it was found that the forcing system was not necessary for testing absolute instability as the vibrations from the start of the drop were sufficient to introduce a disturbance into the liquid jet. Compressed helium gas, controlled by a pressure regulator, was used to pressurize and drive the test fluid at a constant rate through the system to the solenoid valve and one millimeter nozzle. A high speed Milliken DBM-45 16mm motion picture camera was used in conjunction with a Quadtec 1538-A strobe light, synchronized at 200 frames per second, to photograph the jet. Pressure, velocity, and temperature in the second round of tests were measured by a Setra model C206 pressure transducer, AWCO model ZHM-01 flowmeter, and Omega type T thermocouple and model TX903 transmitter. These three channels of analog data were recorded by a 12-bit tattletail digital data acquisition system, whose sampling rate was controlled by the flowmeter.

To find the transition point in each round of tests, a trial and error procedure was used. Although the transitional Reynolds and Weber numbers can be obtained from theory and used to determine starting velocities and pressures, determining whether or not the instability will be visible in the test section during the 2.2 seconds of microgravity is not as trivial. Consequently, the first few tests were conducted over a broad range of pressures to get a general idea of our operating range, followed by a second set of tests to pinpoint the transition from absolute to convective instability.

Analysis of our 16mm films was performed with the TRACKER software and digital object tracking system at NASA Lewis Research Center. This tracking system included a Mekel 16mm film transport system, a Kodak Megaplus digitizing camera, a Matrox Image series framegrabber, two high resolution monitors, and a Pentium PC, among other devices for other input media. Representative images at one g and microgravity were also digitized and archived for future study.

The classification of a test as absolute or convective was determined by observing the microgravity images. In all tests, the basic state is a quiescent liquid jet at one g, the disturbance is the vibration introduced at the start of the drop, and the perturbed state is the result which exists in microgravity. In convective instability, the disturbance would be rapidly convected downstream, leaving behind a quiescent, constant diameter jet, as shown in Figure 1. In absolute instability, the disturbance would cause the liquid jet to bifurcate into an upstream and downstream section. The upstream section would snap back towards the nozzle and achieve a new dynamic equilibrium which resembled an expanding sphere, as shown in Figure 2. The sphere remains connected to the nozzle by a neck, which grows in diameter in the downstream axial direction. The downstream portion would either disappear from view or float back and coalesce with the upstream portion. At the transition, the jet breaks into two parts, but the neck grows significantly in length and can be observed as a jet whose diameter increases in the downstream direction, as shown in Figure 3.

Absolute and convective instability can also be qualitatively thought of as a balance between surface tension and inertial forces. Looking at a balance of forces in the axial flow direction for absolute instability, the inertial force acts in the downstream direction while the net force of surface tension acts in the upstream direction. In absolute instability, surface tension is stronger, enabling the disturbance to break the jet into two and containing the upstream section so that it remains local to the nozzle. Fluid particles exit the nozzle and decelerate as they enter the expanding sphere, increasing the size of this section. In the transitional case, the downstream inertial force has grown such that it balances with the upstream surface tension force. The surface tension force is still able to break the jet into two parts, but the increased inertial force has lengthened the neck between the nozzle and the sphere, signifying that the transition is about to occur, much like an elastic metal in a uniaxial tension test at its yield stress undergoing plastic deformation just before failure. For convective instability, the inertial force completely overpowers the surface tension force. The upstream surface tension force is effectively reduced to zero so that surface tension now acts solely to maintain the diameter of the jet. Fluid particles travel freely downstream as if they were still contained by the walls of the nozzle.

Figure 4 shows the experimental versus theoretical transition points. Glycerin with surface tension 63.3 dynes/cm, viscosity 1182 cSt, specific gravity 1.26 and Dow Corning 200 Series Silicone oil with surface tension 21.2 dynes/cm, viscosity 1000 cSt, and specific gravity 0.972 were used as test fluids. Due to the limited dimension of the test section and short test time of 2.2 seconds, some uncertainty as to the precise transition point remains. More refinement of our experiments is being planned.

CONCLUDING REMARKS

The transition from convective to absolute instability in a liquid jet is demonstrated experimentally for the first time. The comparison between theory and experiments is far from complete.

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Figure 1. Convective Instability, (Re=0.233, We=0.215)

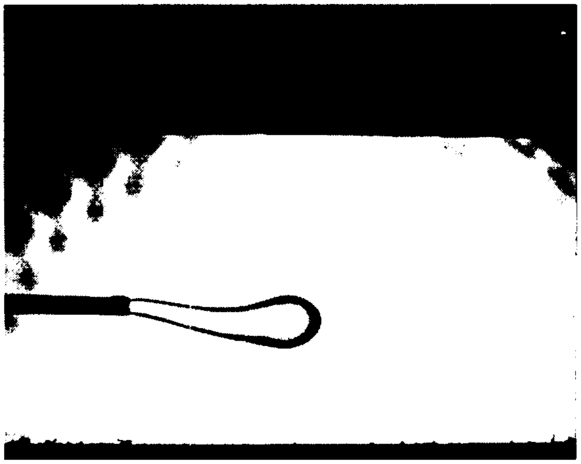

Figure 2. Absolute Instability, (Re=0.070, We=2.365)

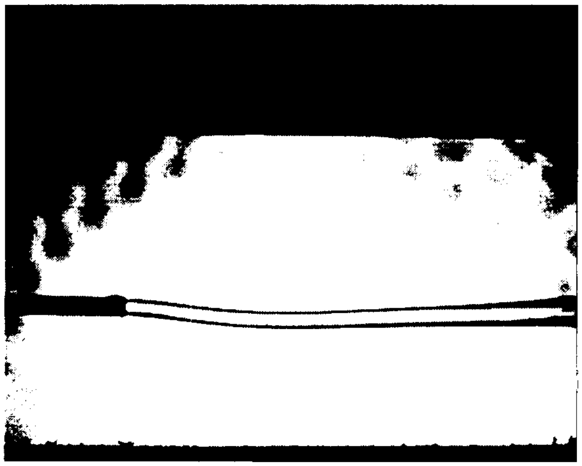

Figure 3. Transition Regime, (Re=0.158, We=0.466)

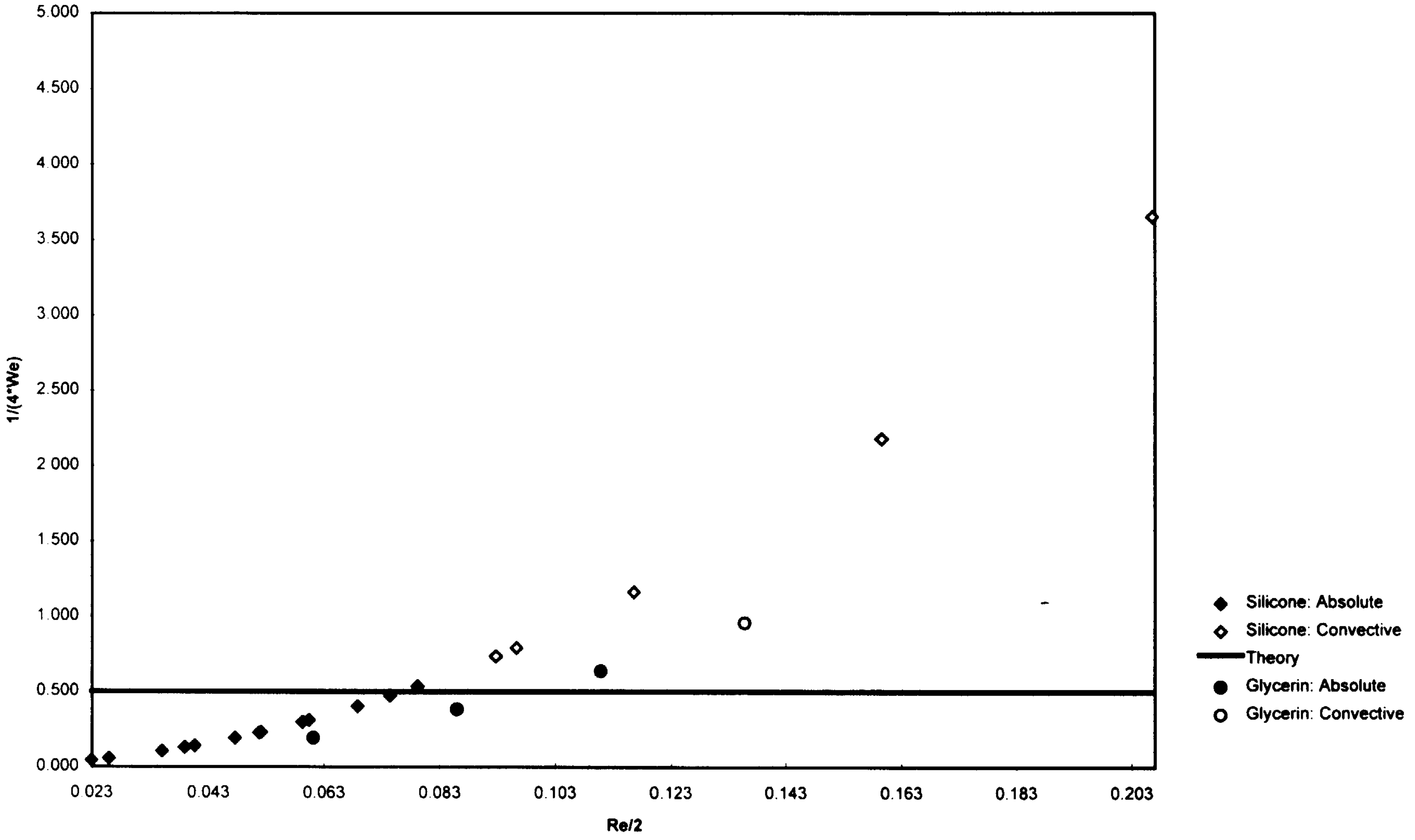

Figure 4. Absolute and Convective Instability