5/15220

FINAL REPORT

September 2001

NASA Project Nag 3-1891

ABSOLUTE AND CONVECTIVE INSTABILITY AND SPLITTING OF A LIQUID JET AT MICROGRAVITY

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1. Task Objective

The objective is to establish a definitive role of the capillary, viscous, and inertial forces at a liquid-gas interface in the absence of gravity by using the fluid dynamics problem of the stability of a liquid jet as a vehicle. The objective is achieved by reexamining known theories and new theories that can be verified completely only in microgravity. The experiments performed in the microgravity facility at NASA Glenn Research Center enable the verification of the theory with experimental data. Of particular interest are (1) to capture for the first time the image of absolute instability, (2) to elucidate the fundamental difference in the physical mechanism of the drop and spray formation from a liquid jet, and (3) to find the origin of the newly discovered phenomenon of jet splitting on earth and in space.

2. Task Description

To achieve the stated objective, the research effort was divided into two major fronts: theoretical and experimental works. On the experimental side, a test rig was designed and fabricated to be used in the NASA Glenn 2.2 second drop tower facilities.

The experimental method is described briefly as follow. A test liquid is stored in a compressed liquid and is driven by pressurized helium through a regulator. The test fluid passes through a series of sensors which measure temperature, pressure, and flow rates before reaching the nozzle through which the liquid jet emanates. The time evolution of the liquid jet is photographed with a high speed motion picture camera. The nozzle itself is vibrated at a controlled frequency so as to promote disturbances at a particular mode. Various fluids were tested at various flow rates and frequencies of external forcing. The recorded images were digitized and analyzed to determine the wavelength, wave speed, and other morphological properties. The results were compared with theoretical prediction.

On the theoretical side, a unified theory is developed to predict the onset of absolute and convective instability in various parameter spaces. The mathematical method used was the Chebyshev collocation method which provides the required accurate numerical results.

Both experiments and theories are described in detail in the published works.

3. Task Accomplishments

The images of the absolute instability at small and large Reynolds numbers have been captured for the first time. The quantitative effects of interfacial shear relative to interfacial pressure, interfacial viscous normal stress and other physical force have been elucidated for the first time. Favorable comparisons between theories and experiments have been accomplished. The results have been published in professional journals as cited in section 6.

4. Task Significance

The research results provide a sound scientific basis for rational design of many industrial processes. These processes include fuel spray formation, fire suppression, film coatings, formation of various chemical sprays, jet cutting, ink jet printing, powder metallurgy and many others. These results are not only useful for space applications, they are equally useful on earth. Improvements of the efficiency of these processes will also bring about a drastic reduction in environmental pollution (e.g., removal of toxic material), and in waste of material, energy and money.

5. Personnel Involved

Dr. S.P. Lin is the Principal Investigator. Mr. Brian Connery and Mr. Brian O'Donnell completed their M.S. thesis based on their drop tower experiments. Mr. Connery is currently working for Pioneer Aerospace Co, and Mr. O'Donnell is pursuing a Ph.D. program at Georgia State University. Mr. J.N. Chen has passed his Ph.D. Qualifying examination and his Ph.D. thesis proposal defense and, is expected to complete his Ph.D. degree program in the near future. He is devoted to the theoretical side of the work. The NASA manager of the project is Mr. Myron Hill of NASA Glenn Research Center. Mr. Wayne Braun worked as an Undergraduate Research Participant. He is currently working for Boeing Aerospace Co. Other recent graduate students include Andrew Honohan, M.S. Clarkson Univ., currently a Ph.D. Student at Georgia Tech. Illari Vihinen, M.S. Clarkson Univ, currently at G.E., and Vincent Cook, M.S. Clarkson Univ. Currently at Lockheed Martin.

6. Publications

1. O'Donnell, B., Chen, J.N. and Lin, S.P., 'Transition from convective to absolute instability in a liquid jet," Physics of Fluids, **13**, 2732-2734.

2. Chen, J.N. and Lin, S.P., "Absolute and convective instability of an annular liquid jet," J. Fluid Mech. (To appear).

3. Lin, S.P. and Reitz, R.D. 1998, Ann. Rev. Fluid Mech. **30**, 85.

4. Lin, S.P. and Chen, J.N. 1998, J. Fluid Mech. **376**, 37

5. Teng, C.H., Lin, S.P. and Chen, J.N., J. Fluid Mech., **332**, 105 (1997).

6. Vihinen, I., Honohan, A. And Lin, S.P. 1997, Phys. Fluids **9**, 3117.

7. Lin, S.P. and Webb, R.D. 1994, Phys. Fluids **6**, 2545.

7. Industry Affiliation

Eastman Kodak Company, Dr. S.J. Weinstein.
Catterpillar Co. Ms. K.M. Sun

8. Innovative Technology

Controlled external forcing at the liquid jet nozzle with a piezoelectric crystal enables one to produce nearly monodispersed droplets. This technique will find applications in advanced material processing (including hairline - crack - free ceramics and complex alloys). It will also find applications in tailored spray formation for efficient fuel combustion and fire suppression.

9. Related Future Work

An annular liquid jet is a circular cylindrical liquid sheet emanating from an annular slot of a nozzle. It encloses one core fluid and is surrounded by another fluid. Annular jets are encountered in many industrial processes. In some applications such as ink jet printing their stability is essential, but in some other applications such as encapsulation and fuel spray formation their instability must be promoted but properly controlled. The stability of annular jets has been studied in the contexts of ink jet printing [1,2], optical fiber spinning [3], encapsulation [4,5], gas absorption [6], and atomization [7,8,9].

Recent advances in biological science and material science have stimulated the interest in forming microcapsules and nonocompound particles for applications in controlled release of pharmaceutical formulation [10], direct delivery of biodegradable microspheres [11], focused nanoparticulate dosage application [12], and gene transfer [13] with minimal damage. There are many other applications, for example, in the current effort to achieve inertial confinement nuclear fusion one needs completely spherical shells of precisely uniform thickness in order to have a successful laser induced implosion of the fuel target [14].

The existing theoretical analysis of the stability of annular liquid jets either neglects the viscosities of the core fluids and the fluids surrounding the annulus or approximates the basic flows which do not satisfy the governing equations exactly. Consequently, it is difficult to ascertain which part of the results extracted from the theory is attributable to the approximation, and which part of the results is genuinely physical. Moreover the experimental conditions do not match with theory completely, and thus the extraction of fundamental knowledge from comparisons of theory and experiments becomes very difficult. To overcome this difficulty and to establish definitive scientific knowledge on the fluid physics of flows with two distinctive curved fluid-fluid interfaces subjected to different shear, capillary and inertial forces under variable gravitational conditions, we have obtained a basic flow representing a liquid annular jet which satisfies the governing equation exactly. The onset of instability in this basic flow with respect to temporal as well as spatio-temporal disturbances is analyzed by the proposer [37]. The results have been obtained by extending the proposer's method which has led to the results described in the last paragraph of this section. These results enable one to propose experiments at microgravity as well as at 1g-condition to achieve successful microencapsulation processes. Modification of the macroscopic theory which can be applied to microencapsulation to the case of nano-encapsulation is also proposed. Nanonozzles will be used in experiments to verify the theory of absolute and convective instabilities and demonstrate its applications to the process of nanoencapsulation.

The present proposed future work gorws out of the current project the accomplishment of which is described below to provide necessary information. Neglecting gravity and the ambient gas, Leib and Goldstein [15, 16] showed theoretically that the formation of drops from a circular cylindrical liquid jet issued from a nozzle is caused by convective instability which forces the growing disturbance to propagate in the downstream direction. However, when the Weber number defined as $We \equiv \rho U^2 a/S$ (ρ, U, a and S being respectively the density, the jet velocity, the jet radius, and the surface tension) is reduced to below a critical value the convectively unstable jet becomes absolutely unstable at a given Reynolds number. In contrast to convective instability, the unstable disturbances propagate in both the upstream and downstream directions. The authors were able to predict the onset of absolute instability, because they allow the disturbance to grow both temporally and spatially which is more realistic. The Reynolds number is defined by $Re \equiv aU\rho/\mu$, where μ is the liquid viscosity. They also obtained the critical transition Weber number as a function of Re. As $Re \to \infty$, the critical Weber number approaches the inviscid limit of π [15,16]. Lin and Lian [17] and Lin and Chen [20] showed that absolute instability still exists in the presence of ambient gas. As the gas to liquid density ratio Q is increased the transition Weber number is increased at a given Re as shown in Fig. 1. As the gas to liquid viscosity ratio N is increased, the transition Weber number is reduced slightly [18]. The transition from convective to absolute instability has been observed for the first time in the 2.2 - sec drop tower at the NASA Glenn Research Center. Figure 2 is a photograph of a convectively unstable jet in air at We = 17.6, Re = 5.4 . The radius of the drop formed by convective instability is of the same order as the jet radius, as can be seen in this figure. Figures 3(a) and 3(b) are photographs of an absolutely unstable jet. They are taken at 0.2 sec and 0.4 sec after the test rig was dropped in the tower. The upstream propagating disturbance suddenly rushed toward the nozzle tip to form an expanding pendant while the downstream propagating disturbance grows along the thin thread of liquid downstream of the growing pendant. The transitions from convective to absolute instability at relatively small Reynolds numbers have been observed by Vihnen, Honohan and Lin [19], and by O'Donnell [35,38] at relatively large Reynolds number. The latter experimental points are shown in Fig. 1. The comparisons between experiments and theories are very good. The evidence and concept of absolute instability is now established. As one moves away from the transition curve toward a higher Weber number region at a given Re, the amplification rate of the disturbances becomes larger and the wavelength above which the disturbances can be amplified becomes shorter. Rayleigh's original stability analysis of an inviscid liquid jet in vacuum indicates that the temporal disturbance amplification rate is independent of the Weber number. This led many experimentalists to obtain the temporal amplification rates of disturbances at various frequencies at different Reynolds numbers. Unfortunately they did not record the corresponding Weber numbers, despite of the fact that Chandrasekhar [36] has shown that the breakup of an inviscid jet is the consequence of the competition between the surface force and the inertial force. Our theories and experiments clearly show the dependence of the amplification rates on the Weber number, Reynolds number, density and viscosity ratios. An example is given in Fig. 4. When $We \gg \rho_g/\rho$ a spray with droplet diameter of $O\,(S/\rho_g U^2 a)$ which is much smaller than the jet diameter, is formed, where ρ_g is the gas density. It is shown theoretically that a spray cannot be formed without ρ_g. By use of the energy equation Lin and Chen [20] showed that mechanism of the drop formation is mainly due to capillary pinching but that of atomization (spray formation) is mainly due to the interfacial shear, and pressure fluctuation. The relative importance of pressure and shear fluctuations on the spray formation depends on the flow parameters. Generally speaking, larger droplets in a spray are generated by interfacial shear, and the smaller ones are produced by pressure fluctuation. In contrast to the Rayleigh mode of jet breakup which produces large drops by capillary pinching, the capillary force acts against formation of sprays. The disturbance which causes the drop or spray formation can be amplified at a rate k_i only in a range of frequency depending on the flow parameters. An example is shown in Fig. 5. When an external forcing of a given frequency within the range of amplification frequency is imparted on a jet, a particular Fourier mode can be selectively amplified, and the motion of the drop can be frozen in space by use of a Stroboscope. When the amplitude of external forcing exceeds a limit, however a jet will fork. A forking jet can be observed if twice of the forcing frequency is smaller than the cut off frequency. Examples are given in Figs. 5 and 6 (Web and Lin [21]). The major results obtained and their applications are discussed in an article in Annual Review of Fluid Mechanics [22].

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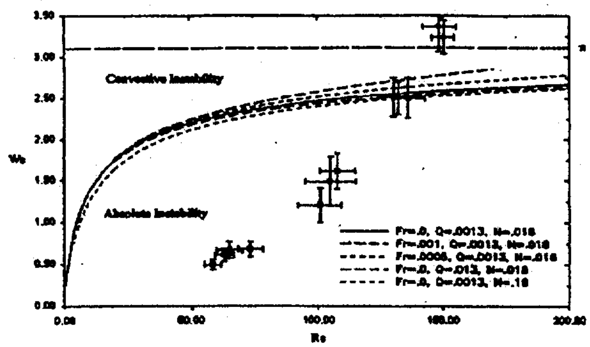


Figure 1: Critical Weber Number of Transition to Absolute Instability

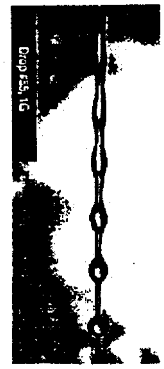
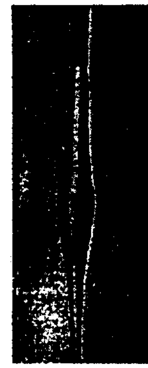


Figure 2



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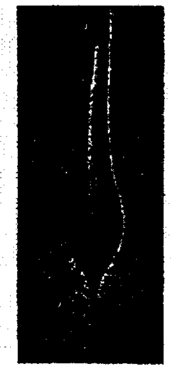

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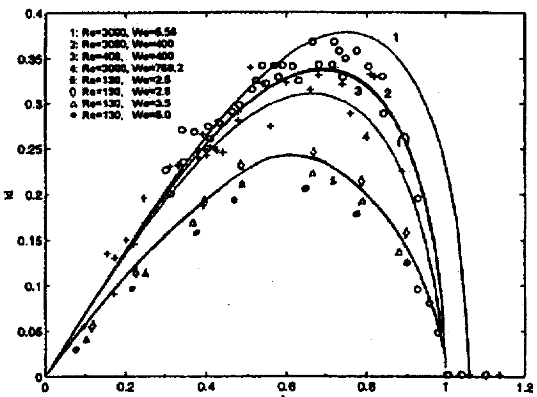

Figure 4: Amplification curves for the Rayleigh mode. Q=0.0013, N=0.018, Fr=0.0, l=10.

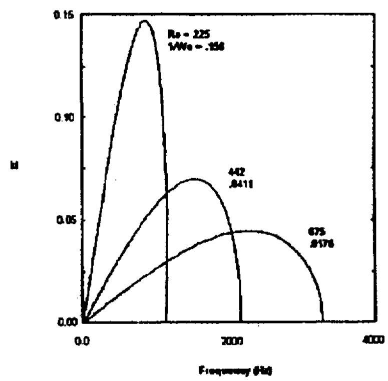

Figure 5

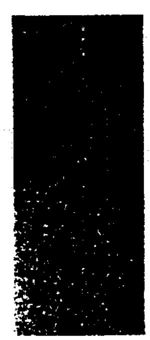

Figure 6

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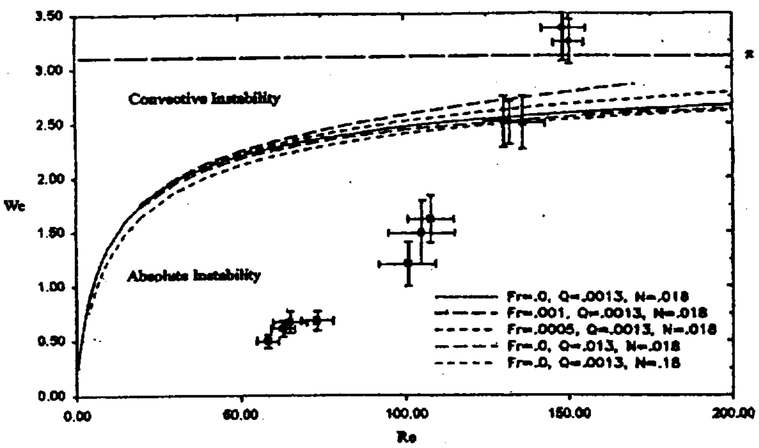


Figure 1: Critical Weber Number of Transition to Absolute Instability

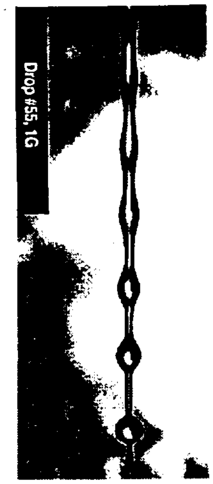


Figure 2

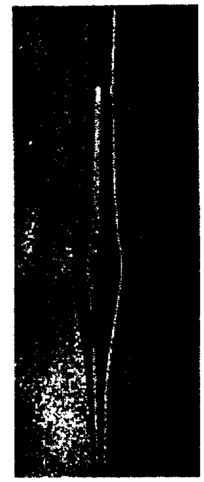
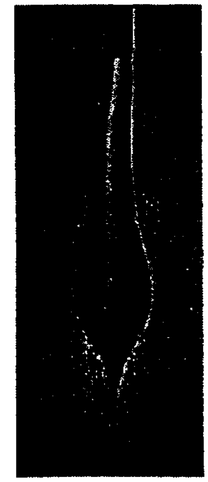


Figure 3(a)



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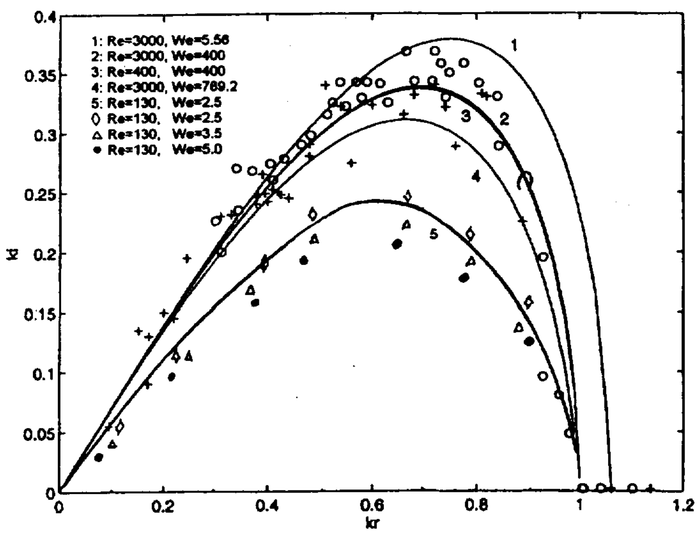

Figure 4: Amplification curves for the Rayleigh mode. Q=0.0013, N=0.018, Fr=0.0, l=10.

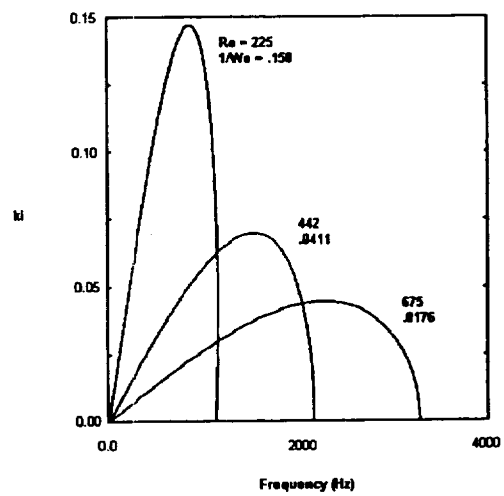

Figure 5

Figure 6

LETTER OF TRANSMITTAL

SEPTEMBER 28, 2001

FROM:		TO:	
	CLARKSON UNIVERSITY DIVISION OF RESEARCH PO BOX 5630 POTSDAM, NY 13699-5630		NASA Glenn Research Center Attn: Myron Hill, MS 500-102 21000 Brookpark Road Cleveland, OH 44135-3191

GRANT#: NAG3-1891

NUMBER	ITEM	QUANTITY
1	Summary of Research	1
2	Subject Inventions Final Report	1
	September 2001	
	PI: Dr. S. P. Lin	

xc: Grants Office, NASA GRC
Admin. Grants Officer, ONR
Industrial Property Officer, NASA GRC (original DD882)
[redacted]
375-564
Dr. S. P. Lin

APPROVED FOR TRANSMITTAL:

Constance M. Tyner

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Grant & Contract Administrator

Telephone: 315-268-3765 Email: Constance.Tyner@clarkson.edu Fax: 315-268-6515

REPORT OF INVENTIONS AND SUBCONTRACTS

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Expires Aug 31, 2001

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1.a. NAME OF CONTRACTOR/SUBCONTRACTOR	c. CONTRACT NUMBER	2.a. NAME OF GOVERNMENT PRIME CONTRACTOR	c. CONTRACT NUMBER	3. TYPE OF REPORT *(X one)*
Clarkson University	Same	Same	NAG3-1891	a. INTERIM / X b. FINAL

b. ADDRESS *(Include ZIP Code)*	d. AWARD DATE *(YYYYMMDD)*	b. ADDRESS *(Include ZIP Code)*	d. AWARD DATE *(YYYYMMDD)*	4. REPORTING PERIOD *(YYYYMMDD)*
Division of Research, PO Box 5630, Clarkson University, Potsdam, NY 13699-5630	960601	Same	960601	a. FROM 960601 b. TO 010531

SECTION I - SUBJECT INVENTIONS

5. "SUBJECT INVENTIONS" REQUIRED TO BE REPORTED BY CONTRACTOR/SUBCONTRACTOR *(If "None," so state)*

NAME(S) OF INVENTOR(S) *(Last, First, Middle Initial)* a.	TITLE OF INVENTION(S) b.	DISCLOSURE NUMBER, PATENT APPLICATION SERIAL NUMBER OR PATENT NUMBER c.	ELECTION TO FILE PATENT APPLICATIONS (X) d. (1) UNITED STATES (a) YES	(1) UNITED STATES (b) NO	(2) FOREIGN (a) YES	(2) FOREIGN (b) NO	CONFIRMATORY INSTRUMENT OR ASSIGNMENT FORWARDED TO CONTRACTING OFFICER (X) e. (a) YES	e. (b) NO
NONE								

f. EMPLOYER OF INVENTOR(S) NOT EMPLOYED BY CONTRACTOR/SUBCONTRACTOR

(1) (a) NAME OF INVENTOR *(Last, First, Middle Initial)*	(2) (a) NAME OF INVENTOR *(Last, First, Middle Initial)*
(b) NAME OF EMPLOYER	(b) NAME OF EMPLOYER
(c) ADDRESS OF EMPLOYER *(Include ZIP Code)*	(c) ADDRESS OF EMPLOYER *(Include ZIP Code)*

g. ELECTED FOREIGN COUNTRIES IN WHICH A PATENT APPLICATION WILL BE FILED

(1) TITLE OF INVENTION	(2) FOREIGN COUNTRIES OF PATENT APPLICATION

SECTION II - SUBCONTRACTS *(Containing a "Patent Rights" clause)*

6. SUBCONTRACTS AWARDED BY CONTRACTOR/SUBCONTRACTOR *(If "None," so state)*

NAME OF SUBCONTRACTOR(S) a.	ADDRESS *(Include ZIP Code)* b.	SUBCONTRACT NUMBER(S) c.	FAR "PATENT RIGHTS" d. (1) CLAUSE NUMBER	d. (2) DATE *(YYYYMM)*	DESCRIPTION OF WORK TO BE PERFORMED UNDER SUBCONTRACT(S) e.	SUBCONTRACT DATES *(YYYYMMDD)* f. (1) AWARD	f. (2) ESTIMATED COMPLETION
None							

SECTION III - CERTIFICATION

7. CERTIFICATION OF REPORT BY CONTRACTOR/SUBCONTRACTOR *(Not required if: (X as appropriate))* ☐ SMALL BUSINESS or X NONPROFIT ORGANIZATION

I certify that the reporting party has procedures for prompt identification and timely disclosure of "Subject Inventions," that such procedures have been followed and that all "Subject Inventions" have been reported.

a. NAME OF AUTHORIZED CONTRACTOR/SUBCONTRACTOR OFFICIAL *(Last, First, Middle Initial)*	b. TITLE	c. SIGNATURE	d. DATE SIGNED
Tyner, Constance M.	Grant & Contract Administrator	Constance M. Tyner	09/27/01