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Non-Coalescence Effects in Microgravity

(NAG 3-1894)

Performance Report for the period

17 June 1997 - 16 June 1998

Submitted to:

Dr. Ray Skarda

Microgravity Fluids Branch, Mail Stop 500/102
NASA Lewis Research Center
21000 Brookpark Road
Cleveland, OH 44135

by

Prof. G. Paul Neitzel, Principal Investigator

The George W. Woodruff School of Mechanical Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0405

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I. Summary

Non-coalescence of two bodies of the same liquid and the suppression of contact between liquid drops and solid surfaces is being studied through a pair of parallel investigations being conducted at the Georgia Institute of Technology and the Microgravity Research and Support (MARS) Center in Naples, Italy. Both non-coalescence and contact suppression are achieved by exploiting the mechanism of thermocapillary convection to drive a lubricating film of surrounding gas (air) into the space between the two liquid free surfaces (non-coalescence) or between the drop free surface and the solid (contact suppression). Earlier experiments performed included flow-visualization experiments in both axisymmetric and (nearly) two-dimensional geometries and quantitative measurements of film thickness in the contact-suppression case in both geometries. Work done in the second year has focused on obtaining quantitative results relating to the effects of variable air pressure, development of analytical and numerical models of non-coalescing droplets and to pursuing potential applications of these self-lubricated systems.

II. Discussion of Research

Non-coalescence, as defined for the purposes of the present research grant, is the ability of two liquid masses to refrain from coalescing (joining) when brought into apparent contact under the proper conditions. Non-wetting, refers to the inhibition of contact between a liquid mass and a solid surface normally wetted by this liquid. Both of these phenomena are due to the separation of the liquid masses and/or the liquid and solid by the presence of a thin, lubricating film of the gas in which the systems are immersed. In the case of non-coalescence, this film may be provided by driving relative motion between the two liquid surfaces, either through the action of thermocapillarity or through the forced motion of one of the surfaces (see Dell'Aversana, Banavar & Koplik, 1996); for non-wetting, thermocapillarity is employed to drive the film by cooling the solid surface sufficiently below the temperature of the liquid droplet.

The research done in the second year of this project has been divided between experimental, numerical and theoretical work. The theoretical portion of the research has been carried on at Georgia Tech in collaboration with a new graduate student, Ms. Shelley Chen. Ms. Chen is engaged in the theoretical development of a lubrication model to describe the droplet motion and film flow. In addition, she will be continuing with the experiments of Mr. John Nalevanko, a former M.S. student, who designed and built an apparatus for studying non-coalescence between two threads of the same liquid and non-wetting between a thread and a solid surface..

Numerical computations have been underway at the MARS Center with the aim of simulating the flows in both the liquid and gas phases associated with two-dimensional, non-coalescing droplets. This problem is a difficult one since droplets are of order millimeters in size while the film thickness is known to be (see Dell'Aversana, Tontodonato & Carotenuto, 1997) of the order of microns. Hence, there are three orders of magnitude difference in the relevant length scales. Work has focused on the use of grid-transformation schemes to account for the length-scale disparity. Early results appear promising, but the problem of allowing the free surface to move, being determined as part of the solution, still needs to be tackled.

Experimental efforts have been aimed at gathering further quantitative results of the effect of surrounding gas pressure and at exploring possible uses for "self-lubricated" systems. We are now able to enclose a pair of non-coalescing droplets in a sealed vessel which can be evacuated to precisely controlled pressures. For a given liquid, droplet size and relative displacement, we then measure the pressure at which coalescence occurs. Results to date have been surprising with respect to the magnitudes of these threshold pressures, which are so low as to bring into question the validity of the continuum hypothesis for the gas in the film. This subject will receive further attention in the upcoming project year.

With respect to possible applications of non-coalescing systems, one type of experiment has been performed in which we were able to levitate a small device containing a magnetized needle above a bath of silicone oil. The levitation was accomplished by attaching a number of droplets to the bottom of the device and heating these radiantly. The magnetized needle permitted to device to rotate in response to nearby ferromagnetic materials and also, in the absence of these substances to align with the earth's magnetic field. This experiment confirms our earlier hypothesis that it may be possible to use such non-coalescing systems as bearings in low-load situations such as might be experienced in a microgravity environment. We have also conducted very preliminary experiments using acoustic excitation to suppress coalescence of a droplet with a bath of the same liquid. A potential use for this mechanism might be to use acoustic forcing to inhibit coalescence within clouds of droplets, which could be beneficial in a combustion application. This is likewise being explored further in the coming year.

We note with pride the appearance of an article in *Physics Today*, the monthly publication of the American Physical Society, which resulted from an invited talk given at the APS March Meeting last year. In addition to the article itself, a photograph from our research graced the cover of the January, 1998 issue in which it appeared, giving welcome visibility to our work.

III. References

Dell'Aversana, P., Banavar, J. R. & Koplik, J. 1996 Suppression of coalescence by shear and temperature gradients. *Physics of Fluids* **8**, 15.

Dell'Aversana, P.; Tontodonato, V.; Carotenuto, L., 1997 Suppression of coalescence and of wetting: the shape of the interstitial film. *Physics of Fluids* **9**, 2475.

IV. Project Personnel

at Georgia Tech:

G. Paul Neitzel, Professor, Principal Investigator

Shelley Chen, Graduate Research Assistant

at the MARS Center:

Luigi Carotenuto, Researcher

Dario Castagnolo, Researcher

Pasquale Dell'Aversana, Researcher

V. Publications and Presentations

Dell'Aversana, P., Tontodonato, V. & Carotenuto, L. 1997 Suppression of coalescence and wetting: the shape of the interstitial film, *Physics of Fluid* **9**, 2475-85.

Neitzel, G. P. & Dell'Aversana, P. 1998 When liquids stay dry, *Physics Today* **51**, 38-41.

Neitzel, G. P. 1997 Thermocapillary convection in microgravity," *invited* talk presented at JASMAC-13 (proceedings, pp. 17-20), Meeting of the Japan Society of Microgravity Application, Fukuoka, Japan, October 30-31.

Dell'Aversana, P., Neitzel, G. P., Castagnolo, D. & Tontodonato, V. 1997 Non-coalescence and wetting suppression via thermocapillarity," presented at the Fiftieth Meeting of the Division of Fluid Dynamics of the American Physical Society, San Francisco, CA, November 23-25.

Appendix

MARS Center Performance Report

(Exhibits not included)

Microgravity Advanced Research and Support Center

Non-Coalescence Effects in Microgravity

Performance Report

for the period

June 17, 1997 through April 16, 1998

(Year 2)

Subgrantee's part

Subgrant number:	**E-25-L43-G1**
Subgrantee:	**Microgravity Advanced Research and Support Center (MARS)**
Subgrantee address:	**Via Comunale Tavernola, 80144, Napoli, Italy Phone: +39-81-234-4580 Fax: +39-81-234-7100**
Principal Investigator:	**Dr. Luigi Carotenuto**
Prime grant number:	**NAG3-1894**
Grantee:	**Georgia Institute of Technology**
Principal Investigator:	**Prof. G. P. Neitzel**

Date: **30 April 1998**

Luigi Carotenuto

Francesco Laccetti
(General Manager)

Non-Coalescence Effects in Microgravity
Performance Report
Year 2

The present document reports on the Subgrantee's activities being performed for the second year of a study concerning the phenomenon of stable non-coalescence between liquids[1]. The work is being executed jointly with the Georgia Institute of Technology and will be carried out over a four-year period. The activities of the second year are expected to be completed by June 16, 1998, as scheduled. They are now being performed according to what announced in the statement of work [Exhibit A] and completed to about 70%.

The mechanism at the basis of the permanent inhibition of coalescence and of wetting has been basically understood and illustrated in the course of the first year of the project. Nevertheless, part of the present activities continue to pursue the investigation of the scientific aspects of non-coalescence. In fact, the experiments are expected to yield new elements to complete the analytical description of the phenomenon. However, with respect to the previous year, a larger effort is being spent today to investigate the mechanical features of non-coalescing and non-wetting systems in view of possible applications. In the following, we shall occasionally refer to such systems as "self-lubricated" in line with the usage of this phrase in a previous publication[2].

During the first year of the project, a sealed cell was built in which it was possible to decrease the air pressure to determine the minimum pressure capable of sustaining a non-coalescing state between two droplets. Such a critical pressure was found to depend on the drop reciprocal squeezing, for any fixed temperature difference ΔT imposed between the droplets. In this second year, these measurements have been repeated to enhance the statistics and additional measurements have been performed at three different ΔT's to examine the temperature dependence of the pressure threshold for the coalescence occurrence. These measurements are intrinsically interesting (because they promise to yield new data to better describe the phenomenon analytically) and difficult to perform (because even a small dust particle or a vibration may affect the results). Therefore, in order to perform new and more accurate measurements of coalescence between droplets under conditions of controlled temperature and pressure, a new sealed cell has been obtained. With respect to the old one, the new sealed cell has several improved features including a quick access door to speed up operations, a more precise micrometer to displace the sample drop, sensors and electrical feed-throughs located on removable blank windows to permit a more flexible design. It also has the capability to accept a replacement bottom of transparent glass. This will permit us to perform observations of wetting inhibition as well, at a defined air pressure. Such observations can be performed by means of an interferometer which has been improved with respect to the one used previously to reduce its overall dimensions. In addition, to achieve a better control of all the important parameters, the pressure- and temperature-control software has been perfected. Today, with the new hardware and software system it is possible to displace a sample drop with 1 μm precision, to control the temperature within 10^{-2} K and to control the pressure inside the cell within 0.2 mbar or one-thousandth of the set point.

In the matter of using self-lubricated systems as bearings, some measurements have been executed to test the load capacity of a drop pressed either against a bath of the same liquid or against a flat glass surface. An apparatus has been set up where the drop is suspended from a precision balance and heated by radiation so as to not affect the force measurement. The bath (or the glass surface), which is at a lower temperature, has been raised beneath the drop by a DC motor to contact the drop and push it up. Forces as large as 20 dynes or more have been measured both with the bath and the glass when a 5 μl droplet of 3 mm diameter was used.

Such measurements led us to the conclusion that a small, yet useful payload could be carried by a self-lubricated system even in a terrestrial environment and that it was worthwhile to construct a working to illustrate this fact. Such a device has been built: it is a small compass hovering upon a silicone oil bath, sustained by 19 non-coalescing droplets of the same liquid working as bearings. The total mass, droplets included, is not much more than 0.2 g and, when it is made to deviate from its equilibrium position, it realigns itself with the terrestrial magnetic field, showing a considerable sensitivity to any magnetic disturbances.

In order to expand the set of the explored self-lubricated systems, several new non-coalescing configurations have been observed where more than two liquid bodies are involved. Some of these cases are illustrated in the photographs of the article here attached as Exhibit B and other configurations exist where a non-coalescing drop is not attached to a rod and is radiantly heated from above. In some of these cases a large non-coalescing drop is in "contact" with a bath and a smaller satellite drop is formed close to it. From the video from which fig. 3 in the enclosed article was taken, it is possible to observe that the motion existing within the satellite droplet is rotating in a single direction, rather than being of a multicellular nature. Owing to the smallness of the involved friction, a gyroscopic effect due to such a convection could be observable and exploited for some application, provided that all the other environmental disturbances are removed.

As far as the theoretical and numerical part of the research is concerned, new ideas regarding the relevance of the Knudsen-number variation in the low-pressure range have been suggested to explain the occurrence of coalescence at a certain critical pressure. Such a variation, to be confirmed by future experiments, could affect the persistence of a sufficient no-slip at the liquid/gas interfaces to ensure the formation of the air lubricating film. A new grid generation algorithm has been implemented to perform numerical calculations that, in the future, could help to understand also this point.

The budget allotted for travel has been used to allow one person from MARS to attend the 50th American Physical Society Division of Fluid Dynamics conference, held in San Francisco on 23 - 25 November 1997. At the meeting Dr. Dell'Aversana presented the talk "*Non-Coalescence and Wetting Suppression via Thermocapillarity* " prepared in collaboration with Prof. Neitzel *et al.*

In conclusion, we wish to point out that, besides of the publication of the article, "When Liquids Stay Dry", attached to this document as Exhibit B, the editors of *Physics Today* decided to dedicate the cover of the January 1998 issue of the magazine to the topic of this research.

Following the publication of this article, the authors have received many comments and requests for reprints from the readers, and invitations to write on about non-coalescence from the editors of Philosophical Magazine B, and the World Scientific Publishing Co.

References

[1]P. Dell'Aversana, J. R. Banavar and J. Koplik: "Suppression of coalescence by shear and temperature gradients," Phys. Fluids **8**, 15-28, (1996).

[2]P. Dell'Aversana, V. Tontodonato and L. Carotenuto: "*Suppression of Coalescence and of Wetting: the Shape of the Interstitial Film* " Phys. Fluids, **9**, 2475-2485 (1997).