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Final Report

TRANSIENT HEAT TRANSFER

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I. INTRODUCTION

This final report is intended to serve as a brief summary and index to the various publications which have resulted from the subject contract. It was deemed desirable to make the treatment in this manner by virtue of the large volume of material produced and the variety of the technical areas covered. The topics are delineated below with references made to prior progress reports and technical papers as appropriate.

II. TECHNICAL AREAS COVERED

A. OPTIMIZATION OF PRESSURIZED DISCHARGE PROCESSES IN CRYOGENIC CONTAINERS (Refs. 1,2,4,5,6,33,34,35)

The theory of single fluid heat exchanger dynamics was extended to the pressurization of cryogenic containers during the period prior to the efforts described here, under Ref. 33. Results were reported in Ref. 34. The theory developed has been generalized to include the time-dependent inlet gas temperature, ambient temperature and/or ambient heat flux, in Ref. 1. This generalization has been applied to the special case of linear time-dependent transients, and plotted parametrically. Then it has been shown how a linear disturbance can be utilized to solve problems associated with disturbances of arbitrary form. These results have been reported in Refs. 2 and 35. The theory above, although involving a number of idealizations, results in the exact solution of the differential formulation of the problem, obtained on the basis of these idealizations. One assumption, the negligible heat transfer between the pressurant gas and the driven liquid, was relaxed and the solution obtained by an approximate integral method (Refs. 4, 5, and 6). The results show the validity of neglecting the axial conduction. The cases with and without heat interaction with the ambient are considered.

The theory developed has been employed in the optimization of the pressurized discharge process by evaluating the mean density of the residual pressurant. Experiments were conducted with a simulation of the full size containers. The experimental apparatus and results compared with theory are presented in Refs. 1, 2, 4, and 5.

Data on the performance in full scale containers were obtained from the George C. Marshall Space Flight Center for the purpose of reducing the data for an arbitrary pressurant inlet temperature. The results are presented in Refs. 4 and 5.

B. BOILING OF A CRYOGENIC FLUID UNDER REDUCED GRAVITY (Refs. 1-7, 10-15)

The purpose of this study was to determine the significance of body forces, such as gravitational attraction, on the various regimes of boiling heat transfer. Liquid nitrogen was selected as the fluid for the initial study. Its properties are close to those of liquid oxygen, and is much less hazardous. A drop tower having 32 ft of free fall distance was constructed, providing a near zero gravity of 1.4 sec duration. Because of this short period, steady state techniques for heat transfer measurements were not deemed desirable for surface of relatively large sizes. A transient technique was adopted, employing the heating surface as a transient calorimeter.

Initial efforts were directed at obtaining data at atmospheric pressure. Preliminary data at $a/g = 1$ was obtained with a 5/8 in. diameter aluminum sphere, and the results are reported in Ref. 1.

A sphere 1 in. diameter was constructed of copper and data obtained at $a/g = 1$ and free fall conditions ($a/g \approx 0$). These results are reported in Refs. 2 and 10. Subsequent results obtained with a 1/2 in. diameter sphere (Ref. 3) show no effect of size between 1 in. diameter and 1/2 in. diameter spheres.

The drop tower was modified to permit operation with fractional gravity, $0 \leq a/g \leq 1$. A digital computer program was developed to more accurately account for the distributed thermal behavior of the sphere at high heat flux, and to remove to some extent the subjectivity involved in determining rates of change of temperature. These are described in Ref. 4.

Results for the 1 in. diameter sphere at atmospheric pressure for the various fractional gravities are presented in Refs. 5 and 6, combined in Ref. 11 and summarized in Refs. 12 and 13. Further data were obtained with a 1/4 in. diameter sphere, and presented in Ref. 6. These showed a size effect in the film boiling regime between a 1/2 in. and 1/4 in. diameter spheres. Also presented here were additional film boiling data for the 1 in. diameter sphere where the test package had been modified to obtain gravity fields in the range $0 \leq a/g \leq .001$.

The experimental apparatus was then modified to obtain boiling data at elevated pressures and with subcooling. The results for spheres with saturated liquid nitrogen at various pressures and gravity levels are presented in Ref. 14. The data in film boiling are compared with existing correlations in both Refs. 6 and 14.

A flat heating surface (disc) was constructed to make use of the transient technique to determine the effect of heater surface orientation on the various boiling regimes, using pressure, subcooling and gravity level as independent parameters. To date these parameters have been varied only in the film boiling region, and the results are presented in Ref. 7.

A technical report is under preparation to bring together all of the results obtained with liquid nitrogen for the parameters of heater surface configuration, orientation, pressure, subcooling and gravity.

Modification and relocation of the drop tower was initiated to obtain heat transfer data with liquid hydrogen under reduced gravity fields. Some data had been obtained with nucleate boiling at low values of heat flux (Ref. 15), and showed relatively small effect of gravity for the time periods covered. In the present work the various regimes of boiling will be covered, including incipient, nucleate, maximum and film boiling. These are possible by virtue of use of the transient technique. Also anticipated to be included are effects of pressure and subcooling. This is being continued under contract NAS-8-20228.

C. HEAT TRANSFER TO A CRYOGENIC FLUID IN AN ACCELERATING SYSTEM (Refs. 2,4, 5,6,8,9,12,16)

This study was initiated to determine the influence of high gravity fields, up to a/g = 20, on nucleate boiling of liquid nitrogen, with the gravity direction directed toward the flat heating surface. Prior studies with water (Ref. 16) indicated that at lower values of heat flux, ΔT_{sat} decreased with increasing acceleration, due to the increasing contribution of natural convection. At higher levels of heat flux, however, this trend reversed itself and ΔT_{sat} increased with increasing acceleration. This was attributed, tentatively, to the premature or earlier departure of the vapor bubbles, thereby reducing the "agitation" of the boundary layer. It was desired to observe if similar behavior occurred with a cryogenic fluid. Liquid nitrogen at atmospheric pressure was used, and the liquid was essentially saturated at all conditions.

Preliminary results at a/g = 1 are presented in Ref. 2. Based on these results the heater configuration was modified to reduce losses from the sides and bottom. Partial results with operation at various levels of heat flux and gravity are given in Refs. 4, 5, and 6, and the composite results are given in Figs. 30 and 31 of Ref. 6 and also in Ref. 12. These indicate behavior similar to that observed with water.

Efforts were initiated to obtain corresponding data at higher levels of acceleration, up to a/g = 100, and also to include the effects of subcooling and pressure. The apparatus was to be designed to utilize the transient technique, thereby providing a convenient means for obtaining data at the maximum heat flux region, and in the film boiling region. These initial efforts are described in Refs. 8 and 9.

D. INJECTION COOLING (Refs. 2-9, 17-20, 22)

The cooling of a volatile liquid, such as the liquid propellant LOX may be accomplished by injecting a gas of low solubility, for example helium, into the liquid. The cooling effect arises from the evaporation of a small part of the liquid into the bubbles which thereby grow to attain a thermodynamic equilibrium size determined by the saturated gas-vapor mixture state corresponding to the prevailing pressure and temperature of the liquid. When the gas is soluble the bubble may initially grow or collapse depending on the prevailing conditions.

The analytical and experimental study undertaken consists of three parts:

1. lumped system analysis for injection cooling of a liquid column.

2. the dynamics of a single stationary gas-vapor bubble.

3. the dynamics of a single moving gas-vapor bubble.

In the first part the injected gas is assumed to attain the equilibrium composition instantaneously at the moment of injection. The limitations of this assumption is explored in Part 2 and Part 3 by considering the dynamics of the discrete process of growth or collapse of a single injected gas bubble, first ignoring then including its translatory motion.

1. Lumped System Analysis

Ref. 2 states the problem of the cooling of a liquid column by the continuous injection of a gas and outlines the scope of the investigation. Solutions obtained for the limiting conditions of zero solubility and heat capacity of the injected gas and uniform (lumped) conditions throughout the liquid at all times show good agreement with experimental results made available by the sponsor from full scale mock-up test of the injection cooling of the Saturn LOX suction lines (Ref. 17). The lumped analysis, extended to include the effects of gas solubility and heat capacity and the effect of displaced liquid volume, is reported in Refs. 3 and 4, and a summary of the work including comparison with experiment is given in Ref. 18.

2. The Dynamics of a Single, Stationary Gas-Vapor Bubble

The transient growth and/or collapse of a single stationary spherical bubble suddenly introduced into a quiescent liquid was investigated analytically and experimentally for a binary system in this part of the study. A detailed description of the work is given in Ref. 19, while the major findings are summarized in Ref. 20. Two cases were studied. For the case of a nonsoluble gas, nitrogen and helium bubbles injected into water displayed growth rates obtained from high-speed film recordings that were in agreement with those predicted by the analysis. The valid extrapolation of these results to cryogenic systems is discussed in Ref. 6. For the case of a soluble gas, ammonia bubbles were injected into water and the effect of solubility on collapse rates was demonstrated experimentally (Ref. 19). Preliminary work on this phase of the study includes the problem statement and discussion (Ref. 2) and the application of source theory to bubble growth in single component and binary boiling systems (Ref. 3) and to the growth of the nonsoluble gas bubble (Ref. 4).

3. The Dynamics of a Single Moving Gas-Vapor Bubble

The transient growth or collapse of a single bubble having a time dependent translatory motion through a quiescent liquid determined by its time dependent size is investigated for a binary system in this part of the study.

A forthcoming technical report will summarize in detail the complete work. A preliminary simplified analysis of the effect of steady translatory motion on the growth of a nonsoluble gas bubble (Ref. 5) was based on the assumption of internal circulation of the gas-vapor mixture considered to be lumped and basing

the heat transfer in the liquid phase on a quasisteady falling film analysis.

The detailed development of the analysis accounting for both heat and mass transfer by diffusion and convection and including the effect of size change on the translatory bubble motion has been reported as follows. For the case where bubble growth is controlled by heat transport in the liquid phase such that the interface temperature remains constant a power series solution was developed for the liquid temperature field neglecting the effect of radial convection (Ref. 7). Based on this analysis solutions for the time dependent bubble size were obtained for the cases of small and large accelerations of the translatory bubble motion. The effect of radial convection was considered in Ref. 8 and agreement between analysis and experiment is noted. In Ref. 9 the potential flow velocity field resulting from translatory motion and bubble growth are included in the perturbation analysis for the liquid temperature field. Study is being continued of the heat transfer and skin friction near the front stagnation point of a spherical and an ellipsoidal bubble and will be reported in a forthcoming technical report and in Ref. 22, as will the effect of mass transport in the liquid phase by considering the growth of a moving vapor bubble in a binary mixture. The composition of the gas phase is assumed to be uniform but time dependent. Asymptotic solutions valid for large times will be presented. This is being continued under contract NAS-8-20228.

E. INTERFACE HEAT AND MASS TRANSFER IN A SUDDENLY PRESSURIZED LIQUID-VAPOR SYSTEM (Refs. 5,6,21)

When a container partially filled with a liquid and initially in phase equilibrium is suddenly pressurized a new phase equilibrium state is approached under the processes of heat and mass transfer associated with condensation or evaporation at the interface. For the case of multicomponent system in two semi-infinite phases (gas and liquid) separated by a plane interface exact solutions have been obtained for the transient temperature and concentration distributions and for the resulting interface heat and mass transfer (Refs. 5,21). Approximate solutions obtained for the same problem by use of the source theory (Ref. 6) are of considerably simpler form and compare favorably with the exact solutions. Numerical results are presented for single component systems and binary systems of helium-nitrogen.

F. TRANSIENT LAMINAR FREE CONVECTION HEAT AND MASS TRANSFER IN CLOSED, PARTIALLY-FILLED LIQUID CONTAINERS (Refs. 23-29)

The two-dimensional, laminar transient natural convection heat and mass transfer in a closed rectangular container having a liquid-vapor interface has been studied. Several cases with different boundary conditions, including constant wall heat flux, change in wall temperature and pressurization have been treated. This study represented the initial stages of a program being conducted to study the transient velocity profiles, temperature stratification and pressure histories in such containers.

The problem is formulated from the complete Navier-Stokes equations coupled with those from the first law of thermodynamics and the conservation of mass. Boundary-layer approximations are not made since the geometry and boundary conditions invalidate complete boundary layer flow and require additional momentum considerations not usually found in boundary layer calculations. The x-momentum, the y-momentum and the continuity equations were coupled to obtain the vorticity transport equation. The solution of the governing partial differential equations, namely, the energy equation and the vorticity transport equation, was carried out numerically using the finite-difference approximation. Special attention is given to the problem of convergence and stability of the numerical solution.

Calculations have been carried on for different levels of heat flux and different values of interfacial temperature. The calculated temperature profiles show clearly thermal stratification of the liquid layer near the liquid-vapor interface. The obtained flow patterns indicated that for small time periods, the flow is of the boundary-layer type, except near the bottom and the liquid-vapor interface.

The full study of this phase is reported in Ref. 23, giving the details of the analytical work and a complete discussion of the results. These results are also reported in Ref. 24.

The corresponding case of rectangular two-dimensional container having a distributed heat source was solved and reported in Refs. 25 and 26. An explicit-finite difference approximation procedure which is unconditionally stable for the solution of the general multi-dimensional, nonhomogeneous diffusion equation was presented in Ref. 27.

The numerical methods have been used to determine the transient velocity, as well as temperature distribution inside a two-dimensional cylindrical tank during the pressurized discharge process, and take into account the post-shutoff velocity transients and decay of flow currents established by shut-off. These will be presented in a future technical report. This is being continued under contract NAS-8-20228.

G. TRANSIENT INTERFACIAL PHENOMENA (Refs. 6,30,31,32)

Transient condensation of pressurant gas on insulating substrates was studied in Ref. 30. The variables and physical properties which govern the residence time of the condensate layer were examined. Analyses of transient boiling, both nucleate and film, on insulating substrates are presented in Ref. 6.

The source theory was applied to the bubble growth in superheated pure liquids and binary mixtures (Ref. 31). The resulting approximate solutions compare favorably with existing exact solutions and are of a considerably

simpler form. This theory is furthermore applied to predict the rates of growth and collapse of a noncondensing, nonsoluble-gas bubble in liquids. This latter application has current importance in the Saturn booster where helium gas is bubbled into the liquid oxygen lines leading to the main pumps to provide subcooling in the liquid and thus prevent initial cavitation at ignition.

In Ref. 32, the source theory was applied to predict the phase change across the interface of suddenly pressurized, one-component and multicomponent liquid-vapor systems. Numerical calculations were performed for the phase change of one- and two-component cryogenic systems of nitrogen-nitrogen, helium-nitrogen, and oxygen-nitrogen.

H. INCIPIENT BOILING OF LIQUID HYDROGEN (Refs. 8,9)

A study was initiated of the problem of the inception of boiling of liquid hydrogen. It is desired to determine with precision the conditions under which nucleation will occur, involving the parameters of surface conditions, heat flux, maximum heater surface superheat level and gravity forces.

Two approaches are being made: (1) using the transient calorimeter technique at $a/g = 1$ previously used for zero gravity liquid nitrogen boiling studies, in order to provide an indication of the point of cessation of nucleate boiling, and (2) using a steady-state electrically heated surface with precision measurements of power and temperature to determine the point of initiation or onset of nucleate boiling. It is anticipated that nonboiling convection will have a significant effect on the heat flux corresponding to the inception of nucleation, and as a first step it is desired to minimize or eliminate free convection. To broaden this study, however, the influence of free convection on the point of incipient boiling will also be determined.

Provision is being made in the test apparatus for a simultaneous visual study in order that correlation may be made between the physical measurements of temperature and heat flux and the visual identification of the first vapor bubble.

Description of the experimental apparatus is given in Refs. 8 and 9. Work on this phase is continuing, and the results will be the subject of a future technical report. This is being continued under contract NAS-8-20228.

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