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Manned Spaceflight Center

Houston, Texas

PREFACE

This report is a final draft of a literature search required as partial fulfillment of condition of NASA Contract NAS 9-5174, "Liquid Propellant Behavior under Conditions of Varying Acceleration." Every reasonable effort has been made to obtain as complete a listing of the open literature regarding low-g liquid behavior. Some items may have been missed, however. Readers are respectfully invited to offer additions during the remainder of calendar year 1966.

The work of collecting and collating literature material was accomplished by G. A. Hastings and D. W. Hill. Review of all the items and the preparation of commentary was accomplished for the most part by J. G. Seebold and, to a lesser extent, by H. M. Satterlee.

The Literature of Low-g Propellant Behavior

This report concerns publications in the fields of low-g fluid mechanics and heat transfer which appeared during and after 1959. This year was chosen because it marks the approximate beginning of development of what might be called the "modern" theory of capillary fluid mechanics. Capillary action was, of course, a subject of classical investigation. The advent of space flight has brought with it a resurgence of interest in capillary fluid mechanics, because in unpowered orbital flight, spacecraft acceleration and local gravitational acceleration are nearly balanced, and no overpowering body force is felt by contained liquid. The liquid is in an approximately "weightless" condition, and forces which are usually negligible, such as contact and surface forces, become dominating influences, just as they are in the classic capillary tube.

As a result of this similarity, there is a substantial body of classical literature which is directly applicable to present needs and fundamental in the development of the modern theory. Considerable detail regarding the results and history of development of the Theory of Capillarity, together with specific references to the literature, can be found in James Clerk Maxwell's classical article in the ninth edition of the Encyclopedia Britanica, as revised by the 3rd Baron Rayleigh in the tenth edition.

One comprehensive and useful summary of the modern theory of capillary fluid mechanics is "Capillary Hydrostatics and Hydrodynamics at Low-g" by W. C. Reynolds, M. A. Saad, and H. M. Satterlee, hereafter referred to as "Reynolds (1964)". This is an extension of an earlier publication by W. C. Reynolds which appeared in 1961; a further extension, by W. C. Reynolds and H. M. Satterlee, will shortly appear in a NASA monograph on the Dynamics of Propellant Sloshing, edited by H. N. Abramson. Other relatively comprehensive publications, many in the nature of reviews, have appeared; among them are Benedikt (1961), Berenson (1963), Clodfelter (1963), Koestel (1959), Neimer (1959), Otto (1964), Sherley (1962), Steinle(1963), Unterburg (1962), and Wood (1963). An attempt has been made in preparing the present report to select and comment on publications which seem to be of most practical importance to spacecraft designers, or which have been fundamental in the development of modern capillary fluid mechanics.

Boiling heat transfer has been the subject of vigorous experimental and some analytical investigation for a considerable period of time. Although most work has been carried out at high heating rates which are not typical of the orbital environment for tanked propellants, some pre-1959 work is still of interest. Most of the early work which has found application in low-g heat transfer, including particularly that in bubble dynamics, is summarized and referenced in M. Jakob's "Heat Transfer".

The following commentary is subdivided into 7 sections dealing with Propellant Location and Interface Shape, Interface Stability, Reorientation, Sloshing, Propellant Containment and Ullage Control, Draining, and Heat Transfer. The bibliography covers, in addition to the foregoing topics, such topics as life support, propellant gaging, phase separation, distribution of non-condensables, gyros, accelerometers, and experimental techniques. Experimental techniques are discussed in almost all of the experimental investigations mentioned in the commentary; additionally, some publications such as Kirk (1960), Cummings (1963), Kirk (1963), Lepper (1963) Vander Velde (1963), and Paynter (1965) deal almost exclusively with this subject. The bibliographic citations are grouped by calendar year, and listed alphabetically (by the last name of the senior author) in each year.

Propellant Location and Interface Shape

The problems of the equilibrium configuration of liquid in a partially filled container in a low-gravity environment were among the first to be attacked, both because of practical necessity and because some classical results and methods were found to be applicable. These are the problems of capillary hydrostatics, the most likely location of a contained mass of liquid, and the shape of the liquid-gas interface, under equilibrium conditions.

The principle of minimum surface energy was used by Li (1960) to investigate the stable configuration of liquid in a zero-g field. It was concluded that if the liquid wets the tank wall, it will cling to it, leaving a vapor bubble in the tank. A further result was that bubbles on the tank wall will pulsate until they become large enough to touch each other, then they will coalesce to form a larger bubble which will eventually join the central bubble by contact. Again, by formulating the isoperimetric variational problem associated with minimum total potential energy of a tank partially filled with liquid, Li (1962) found that the free endpoint transversality condition yields an expression for contact angle which is independent of gravitational acceleration; this relation is the familiar Dupre-Young equation. A method for series solution of the differential equation for the equilibrium shape of an axisymmetric liquid-gas interface is also given by Li (1962), and the first few coefficients are worked out.

An introduction to the theory and macroscopic description of capillary hydrostatics is presented by Berenson (1963). The minimum energy principle is also discussed by Neu (1963) and Clodfelter (1963).

The zero-g equilibrium configuration of liquid contained in cylindrical and spherical tanks is discussed by Clodfelter (1963) along with experimental observations, including transient overshoot of the zero-g surface shape. Petrash and Nelson (1963) also made an experimental investigation of the transient change in the capillary surface that results when a liquid contained in a cylindrical tank experiences sudden weightlessness.

The shape of the capillary surface in a right circular cylinder is discussed by Satterlee and Chin (1965). A derivation of the governing differential equation and the results of numerical integration are presented. Good agreement with experiment is shown, and the experimental techniques are discussed. An ellipsoid of revolution approximation to the capillary shape is also developed.

In another approach to the solution of the same problem, Yeh and Hutton (1965) make use of the series solution due to Li (1962). Some additional coefficients are developed to improve convergence, but application is still limited to nearly flat interfaces. The classic method and results of Bashforth and Adams are discussed, and numerical examples of the use of the classic tables are given.

The capillary surface in an annular tank in an axial body force field is described in Seebold, Hollister, and Satterlee (1966).

The investigation and calculation of static interface shapes for a broad range of Bond numbers are discussed by Moiseev, et al (1964); emphasis is on methods rather than results.

The shape of the equilibrium free surface in a cylindrical tank rotating at constant angular velocity about its axis in an axial body force field is discussed by Seebold and Reynolds (1965). Shape parameters of the several possible equilibrium interface configurations, obtained by numerical integration of the governing differential equation, and the supporting experimental results are presented. In an earlier study, the equilibrium shape of a bubble located on the axis of an inviscid body of liquid in solid body rotation in zero-g is described by DiMaggio (1963) in terms of elliptic integrals, and some selected zero-g bubble contours are plotted.

Blackshear and Eide (1964) derive the differential equation for the shape of a free liquid surface in a tank of square cross section in the presence of gravitational, centrifugal, and capillary forces. A closed solution is obtained by neglecting the capillary forces. The results of numerical solution of the complete problem, restricted to a two-dimensional infinite channel, are presented.

The results of an experimental study of the zero-g equilibrium interface in which cryogenic liquids were employed are reported by Siegert and Petrash (1965). It was found, not surprisingly, that cryogenic liquids behave no differently than standard and more easily handled test liquids. In an earlier experimental investigation reported by Petrash et al (1962) it was found that the equilibrium configuration of alcohol in a spherical glass tank in zero-g is a totally wetted tank wall with a vapor bubble in the interior of the liquid. In a related study, Petrash and Otto (1962) verified that knowledge of contact angle and tank geometry permits prediction of the zero-g configuration of liquid in the tank. Petrash, Nussle, and Otto (1963) report experimental verification of the fact that the shape of the equilibrium liquid-gas interface is completely determined by contact angle and Bond number. Some interesting pictures of low-g interfaces in spherical, cylindrical, and conical containers are included. In a similar study employing spherical, conical, and cylindrical containers, the same authors (1963) found that the contact angle remains unchanged in zero-g compared to its one-g value.

The results of a low-g aircraft test program in which the configurations of water, engine oil, hydraulic fluid, JP-4 fuel, and mercury were investigated is reported by Clodfelter and Lewis (1961).

The parameters which affect propellant location in coasting orbital flight are reviewed by Satterlee (1962), and it is demonstrated that propellant location can be predicted. For another discussion of propellant location problems, together with the results of experimental and analytical investigations, see Sherley (1962).

Early contributions of importance were made by Benedikt (1959) and Reynolds (1959). The former presented an estimate of the relative importance of capillary and gravitational forces acting on a liquid in low-g, while the latter demonstrated the importance of capillary forces in a free-fall photographic study.

Additional information relative to capillary hydrostatics can be found in Andes (1962), Barcatta (1963), Benedikt (1961), Brazinsky (1962), Callahan (1962), Chin (1964), Cline (1964), Driscoll (1960), Jähsman (1961), Koestel (1959), Neimer (1959), Otto (1965), Otto (1964), Povitskii (1963), Reynolds (1964), Roennau (1961), Shuleykin (1963), Stehling (1961), Steinle (1963), Swalley (1965), Unterburg (1962), Wolczek (1959), and Wood (1963).

Interface Stability

Liquid contained at the top of an inverted tank in a low-gravity environment may under certain circumstances be stable in that location. Under very special circumstances the liquid may derive support from surface and contact forces, but usually the liquid is supported by the pressure of the gas beneath the liquid-gas interface, while the interface itself is stabilized by surface tension. The stability of an inverted meniscus to small disturbances is a dynamic problem that can, under certain circumstances, be investigated by simpler methods treating the static problem.

By analyzing the liquid-gas interface in an inverted rectangular channel, Concus (1963) showed that the static variational method and the dynamic small vibration method yield identical stability limits for an inviscid liquid. In an extension of these results, Concus (1964) showed that while solutions to the free surface differential equation exist which represent inflected surfaces, such surfaces are unstable.

The work of Bretherton (1961) has important implications regarding the stability of an axisymmetric liquid-gas interface which exhibits zero contact angle. It is shown that under the action of gravity a bubble will not rise in a tube unless the Bond number exceeds 0.842; this must also be the critical Bond number for an inverted axisymmetric meniscus of zero contact angle. The inviscid motion of the bubble in effectively gravity-free and gravity-dominated environments is also discussed.

The comprehensive results of Reynolds, et al (1964), make possible the investigation of the stability of almost any axisymmetric meniscus contained in a tank of arbitrary wall curvature. The capillary stability of an axisymmetric liquid-gas interface in an annular tank is determined in Seebold, Hollister, and Satterlee (1966).

Seebold and Reynolds (1965) discuss the stability of the capillary surface in a cylindrical tank rotating at constant angular velocity about its axis. Rotation is found to be destabilizing in the case of wetting liquids in an adverse acceleration environment, and to introduce an instability which can occur at zero- or even positive-g. A parametric stability map governing the existence of stable menisci, and supporting experimental results, are presented.

In an experimental investigation, Jetter (1963) found that square or rectangular passages are not effective in stabilizing liquids which exhibit vanishingly small contact angle because of corner effects.

The effect of boundary elasticity on interfacial stability has been investigated analytically by Smith (1965) and Tong and Fung (1965). The former considered a flat surface contained in a two-dimensional channel having flexible walls or floor, while the latter studied a cylindrical domain with a flexible bottom. In practical situations at low-g, sloshing frequencies and elastic frequencies are vastly mis-matched, so that no important interaction should be observed.

It is shown in Koval and Bhuta (1966) that the addition of an electrical body force changes the natural sloshing frequency of a capillary surface, thereby altering the capillary stability characteristics. This would be true of any superimposed body force, of course.

The stability of the accelerated interface between a liquid and air was investigated experimentally by Emmons, Chang, and Watson (1960). In this study, a third-order theory was also developed for the unstable growth of disturbances on the free surface. Bellman and Pennington (1961) extended the analysis of Taylor instability to include surface tension and viscosity. Surface tension has a stabilizing influence, and viscosity reduces the rate of growth of disturbances.

Additional information relative to capillary stability can be found in Anliker (1963), Beam (1961), Bell (1963), Berenson (1963), Cline (1964), Li (1963), Masica (1964), Masica (1964), Otto (1964), Otto (1965), Sherley (1963), Sternling (1959), Swalley (1965), and Wood (1963).

Reorientation

The stability theory referred to in the last section says nothing about what happens after the critical Bond number is exceeded, except that the inverted meniscus becomes unstable. One naturally expects that a liquid will somehow flow to the other end of its container. It is this flow, and the reverse flows that develop when the liquid impinges on the other end of the tank, that are the subjects of reorientation studies.

The reorientation flow of liquid in a cylindrical tank was studied experimentally by Hollister and Satterlee (1965). Reorientation acceleration was imposed during free fall after establishment of the typically highly-curved low-g liquid-gas interface. Reorientation Bond numbers of order 10 and 200 were employed. Similar studies with zero-g initial shapes are reported by Masica and Petrash (1965), and Masica and Salzman (1965). In the latter it is demonstrated that baffles can be helpful in alleviating the recirculation ("geysering") problem associated with reorientation flow, thus promoting better liquid collection.

Bowman (1965) presents an experimental study of reorientation flow in which the typical low-g interface is not allowed to develop; instead, the surface is initially quite flat. As a result, some interesting flow patterns, not expected to be observed in most practical settling situations, were observed. The results of a linearized analysis presented in Bowman (1966) successfully reproduced many of these features. In an experimental investigation of reorientation under non-axial acceleration, Bowman (1966) found that when a settling Bond number of 72 is applied to a cylindrical tank inclined at 1°, the unsymmetric flow characteristic is not very repeatable, whereas when the cylinder is inclined at 10°, a definite tendency of the liquid to flow up one side of the container is always observed. This is not surprising, since the transverse component of the settling acceleration results in transverse Bond numbers of 1.26 for 1° inclination and 12.7 for 10° inclination. The critical transverse Bond number is about 1 for liquid-solid combinations which exhibit contact angles near zero degrees (as used in the experiments); therefore uncertain transverse unstability behavior would be expected at 1° inclination, while an inclination of 10° should produce definite transverse instability.

Another discussion of propellant settling, with particular emphasis on orbital transfer of propellants, is presented by Gluck and Gille (1965). A description of the flow, together with an estimate of the settling time, is based on scaled experiments conducted at one-g.

The structural significance of the impingement of reorientation flow on the end of a propellant tank was the subject of an experimental investigation reported by Stephens (1965). While a preliminary analysis is alleged to have indicated that damaging stress levels could result, no structurally significant impact loads were observed.

Problems of liquid reorientation and associated phenomena as found in the Centaur vehicle, together with experimental and analytical results, are discussed by Sherley (1962). Additional information can be found in Otto (1964), Otto (1965), Reynolds (1964), Steinle (1963), Swalley (1965), and Wood (1963).

Sloshing

The sloshing characteristics of propellants contained in rocket tanks are of considerable practical importance because of the possibilities of unstable interaction with attitude control system oscillations, immersing vent lines, developing excessive forces and moments due to liquid motion, and so forth. For the purpose of this report, this subdivision includes linear and non-linear sloshing, transient response to sudden weightlessness, and the effect of anti-slosh baffles.

The analytical and experimental study of Satterlee and Reynolds (1964) treats linearized sloshing about an axisymmetric equilibrium meniscus in a cylindrical container. Complete analytical and experimental results are presented for linearized low-g sloshing in the fundamental mode.

Two approaches to the analysis of symmetric liquid sloshing in an infinite channel of rectangular section are presented by Hung, et al (1964). In the first, the velocity potential, free surface shape, pressure, and vibration frequency are expanded in the ratio of the maximum amplitude of free surface vibration to tank radius. A first-order velocity potential is obtained (the zero-order potential is zero). In the second approach to the same problem, a harmonic function expansion and Fourier time-series analysis are employed. Numerical computation was carried out in a single case and the results are presented.

A linearized analysis of axisymmetric sloshing during draining under low-g conditions is presented by Saad and Oliver (1964). The results indicate a slight reduction in the critical Bond number for draining an inverted tank.

Series solution of the linearized sloshing problem is carried out by Koval and Bhuta (1965). The velocity potential is obtained as an infinite series of eigenfunctions. An approximate explicit expression can be obtained by truncating the series, and this approximation could be used to estimate pressures exerted by the sloshing liquid on the containing tank. In another paper, Bhuta and Koval (1965) discuss the problem of linearized sloshing in a draining or filling tank in low-g. The possibility of vapor blowthrough during draining is indicated, as is the need for baffles to damp the free surface motion during filling. The latter results are questionable because flow during filling is much farther from ideal than flow during draining.

The linearized approach to the study of zero-g motion of liquids was investigated by Randolph (1963). The author contends that such an approach yields no useful information on the dynamics of liquids which suddenly experience weightlessness, and that the idea of incipient dynamics should be abandoned. In spite of this, successful linearized analysis has been reported.

The transient response to sudden weightlessness of the free surface of a liquid in two-dimensional and cylindrical containers is subjected to a linearized treatment by Fung (1965). The predicted vertex motion compares favorably with experiment. Particularly significant is the fact that the initial vertex motion opposite to later time motion which is observed experimentally for a short time after entry into sudden weightlessness is reproduced by the analysis. A similar approach is used by Bowman (1966) to investigate the response of an initially flat interface to sudden axial acceleration. The results of an experimental study of the transient response of a liquid-gas interface to sudden weightlessness in spherical, cylindrical, and annular tanks are presented by Siegert, et al (1964).

The problem of non-linear oscillations of an inviscid, incompressible liquid having a free surface is formulated by applying Hamilton's principle at constant volume by Petrov (1964). It is demonstrated that this integral representation is equivalent to the classic boundary value problem statement. Several specific classes of extremizing functions are briefly mentioned. No applications or numerical results are presented.

A numerical scheme for computing the non-linear axially symmetric oscillations of a capillary surface in a cylindrical container is discussed by Concus, et al (1965). The numerical results presented show that the method has considerable promise and should be applicable to reorientation flow, as well.

Moiseev, et al (1964), discuss methods of solving capillary hydrodynamic problems. Of particular interest is the discussion of methods for investigating the effect of viscosity. Randolph (1965) considers the problem of non-linear axisymmetric motion of a viscous liquid in a cylindrical container. The difficulty of applying an appropriate macroscopic viscous boundary condition where the free surface contacts the solid wall is pointed out. While an approach to numerical solution is suggested, no computational or numerical results are reported.

In a study of elastic interaction of tank structure with sloshing liquid, Tong and Fung (1965) find that increased flexibility leads to reduced natural frequency. In the flat interface, square tank, analysis of Koval and Bhuta (1966), it is shown that superimposing an electrical body force alters the natural frequency of oscillation of the capillary surface. This result would be expected for any body force, of course.

In an experimental study of high-g sloshing motions, Cooper (1959) obtained good agreement with first mode small amplitude slosh theory. The "spill-over" of liquid that occurs when a large amplitude slosh wave reaches the hemispherical tank top results in considerable energy dissipation and a sharp increase in damping. Of experimental interest is the fact that while wave amplitudes were found hard to measure or define at times, the lateral force produced by slosh wave motion was readily obtained.

Miles and Troesch (1960) studied the gravity-free oscillations of the cylindrical free surface of an inviscid liquid in axial solid-body rotation contained in a cylindrical tank. This is not a problem in which surface forces are important because the centrifugal body force dominates. Comprehensive results for the natural modes of centrifugal oscillation were presented.

Further information on sloshing and related topics can be found in Brazinsky (1962), Chernous'ko (1964), Chernous'ko (1965), Chu (1964), Cline (1964), Hwang (1965), Koestel (1959), Moore (1965), Neimer (1959), Otto (1964), Otto (1965), Paynter (1964), Reynolds (1964), Scriven (1960), Shuleikin (1962), Shuleikin (1962), Siegel (1961),Smith (1965), Swalley (1965), and Unterburg (1962).

Propellant Containment and Ullage Control

In this section methods for preferential positioning of contained liquids in a low-gravity environment, such as at the tank drain for restart, and away from vents are reviewed. Included are passive methods, such as surface tension devices; active methods, such as dielectrophoretic devices; and methods of venting. Positive expulsion devices, being independent of body forces due to acceleration fields or the lack of them, are disregarded.

In an investigation carried out in a drop-tower, Petrash and Otto (1962) found internal tank baffling to be an effective means of positioning liquid for venting and restart in low-g. The effect of screens on the configuration of liquid in low-g was investigated by Clodfelter and Lewis (1961), and no important alteration in configuration was observed.

Conical baffles were found by Neu and Good (1963) to be useful for orienting liquids in zero-g. The use of a standpipe for locating liquid is discussed by Porter and Clayton (1965) in an interesting introduction to zero-g research at the Royal Aircraft Establishment, Farnborough, England.

The results of analytical studies and one-g tests of the use of surface and dielectrophroetic forces in liquid containment are presented in a report by Bell Aerospace (1963). Experimental data and general design information for proposed propellant containers are included.

Some simple experiments with capillary retention devices in axial and transverse body force fields are described by Jetter (1963). Corners in square or rectangular passages were found to promote instability.

The results of an analytical and experimental study of propellant containment and venting in zero or small adverse gravity environments are reported by Boraas, et al (1965). Systems of coaxial cones are investigated for containment. Critical stability conditions are determined by equating buoyancy and surface tension forces. While the relations developed in this unusual way do not seem to check with standard results in the limiting cases, the experiments reported seem to be in agreement with the analysis. Screens and a central standpipe are utilized in a combined containment and venting device.

The principle of dielectrophoresis is discussed by Blackmon and Crocker (1963), together with a description of some experiments and a discussion of the application of dielectrophoretic body forces in positioning liquids in zero-gravity. In similar papers, Blackmon (1962, 1963), describes the collection of liquids using electrical forces. Calculated collection forces and times compare favorably with experiment.

An investigation of dielectrophoretic separation and orientation of liquid hydrogen in low-g is reported by Hurwitz, et al (1964). Good agreement was obtained between theory, laboratory analog tests, and zero-g aircraft tests.

A variety of venting (in this case, residual propellant dumping) methods and their relative usefulness are discussed by Satterlee (1962). Similar problems, and experimental and analytical results, are discussed by Sherley (1962). Plans for a full-scale orbital fluid mechanics experiment aboard an S-IVB stage are discussed by Cline (1964), and Swalley (1965).

Additional information on propellant containment and ullage control can be found in Abdalla (1964), Allingham (1964), Bell (1962), Blackmon (1965), Heald (1965), Hunter (1962), Krivetsky (1962), Otto (1964), Otto (1965), Paynter (1964), Porter (1965), Reynolds (1964), Rod (1962), Steinle (1963), Unterburg (1962), and Wood (1963).

Draining

Extracting liquid from a tank in a low-gravity environment can present serious problems. As the depth of liquid in a draining tank is reduced, eventually a dip will appear in the surface above the drain. In low-g, this is a severe problem because the dip is much more pronounced. When the dip is "sucked" into the drain, a direct gas path is provided to the pump suction. The propellant volume remaining in the tank when this occurs is trapped and unusable. This effect is independent of and additional to vorticity effects. Additionally, draining dynamics can adversely interact with sloshing motions.

A linearized analysis of sloshing during tank draining under low-g conditions is presented by Saad and Oliver (1964). Bhuta and Koval (1965) present a similar treatment. The formulation is generalized to account for variable axial acceleration, but the solutions presented are for constant acceleration.

The possibility of vapor blowthrough during zero-g draining is indicated.

A photographic study of zero-g draining of liquid from a cylindrical tank is presented by Nussle, et al (1965). Diffusing the incoming pressurizing gas and baffling the tank outlet were found to be helpful in alleviating the effects of suction dip, thus delaying vapor blowthrough.

An experimental study of tank draining under one-g is reported by Gluck, et al (1965). The point at which gas ingestion occurred was found to depend only on Froude number for Bond numbers of order 100 and larger; for Bond numbers of order 10, the critical condition was found to depend on Bond number as well.

Some additional information on tank draining under low-g conditions can be found in O'Loughlin (1965), Otto (1964), Otto (1965), Povitskii (1963), Reynolds (1964), Sherley (1962), Steinle (1962), Swalley (1965), and Unterburg (1962).

Heat Transfer

Heat transfer in a low-gravity environment can be expected to be somewhat different than at one-g because the equilibrium configuration of contained liquids is different, and because the natural convective transport of energy and mass, generally dominant at one-g, is much less vigorous.

In an analytical investigation of low-gravity transport processes, Gebhart (1963) finds that random disturbances normally present in the motion of space vehicles can result in relatively effective convective transport.

The heat transfer problem in a partially filled propellant tank in low-g is discussed in a report prepared by Dynamic Science Corp. (1963). A lumped-capacity formulation intended for solution on an analog computer was obtained. The heat transfer mechanisms considered were internal radiation, phase change due to evaporation and condensation, conduction, free convection, and convection in liquid layers due to differential surface tension.

The thermally-induced motion of liquid in a full two-dimensional container heated on one side and insulated on the other three is considered in the report of Hung, et al (1964). The problem is solved for a triangular heating function and the temperature, pressure, and velocity distributions are plotted.

A survey of available literature on the influence of gravity on nucleate boiling is most recently presented by Adelberg (1963), together with rationalization of the observations in terms of the pertinent force ratios. It is pointed out that since the mechanics of bubbles are strongly influenced by gravitational forces, nucleate boiling can be strongly influenced by such forces. Note is taken of the difficulty in sorting out steady-state and transient phenomena in relatively short-lived drop tower experiments. Force ratio arguments are used by Adelberg and Forster (1961) to estimate one-g test parameter values which may yield useful information on zero-g boiling heat transfer. Similar results are presented in Adelberg and Schwartz (1966).

The problem of forced-convection heat transfer to a liquid contained in a rotating tank during spin-up from rest in a low-gravity environment is discussed by Fendell (1966).

Low-g heat transfer to liquid propane contained in a spherical steel tank is discussed by Rex and Knight (1964). The experiment was conducted in a sounding rocket. While the heat flux was about three times as great as the solar flux, it was still representative of orbital heating rates. Most low-g heat transfer experiments reported to date have been conducted at high heating rates which are not typical of orbital conditions. Nucleate boiling evidently persisted throughout the experiment, and a reduced heat transfer rate of about 1/3 the one-g value was observed.

The results of an experimental investigation of boiling heat transfer to liquid nitrogen in a near zero-g environment are reported by Clark and Merte (1963). The heat flux range was high, 10^3 to 2.5×10^4 Btu/hr-ft^2. A similar experimental study by Merte and Clark (1963) indicates that gravity reduction has little effect on boiling heat transfer at high heat transfer rates.

In an experimental investigation of the effect of reduced gravity on pool-boiling, Usiskin and Siegel (1961) found that the critical heat flux varies approximately with the ¼-power of gravity. It was also found that the velocity of freely rising bubbles decreases with reduced gravity, and that bubble diameters at separation from the heated surface vary inversely with gravity to the 1/3.5 power. In similar experiments conducted at high-g, Costello and Tuthill (1961) also obtained a ¼-power variation of burnout heat flux with gravity.

In an order of magnitude analysis based on experimental data, Keshock and Siegel (1964) found that when bubble growth rate is large, nucleate boiling is essentially gravity independent, and bubble departure from the heated surface is governed by inertial and surface forces. For slowly growing bubbles, the authors found that departure is governed by buoyant and surface forces. Viscous forces appeared to be unimportant.

Siegel and Howell (1965) report an experimental determination of the peak nucleate boiling heat flux in water, ethyl alcohol, and an aqueous sucrose solution in low-g. Vertical orientation of the heated wire resulted in a lower peak heat flux than did horizontal orientation. The peak or burnout flux was found to be roughly proportional to the ¼-power of g.

Qualitative information regarding nucleate pool boiling of water in low-g is presented in a report of a photographic investigation carried out by Hedgepeth and Zara (1963).

Qualitative descriptions of boiling and condensing phenomena based on visual observation of low and zero-g aircraft tests are given by Hedgepeth (1960). Both mercury and distilled water were used in a boiler-condenser test loop. In a report of a similar study in which mercury was the test liquid, Reitz (1960) reports no difference in the mode of condensation in zero-g as compared with one-g conditions.

Correlations for two-phase flow in horizontal capillary tubes are presented in a report by Suo and Griffith (1963). The correlations should be applicable to low-g flow. Similar flow visualization tests, conducted both at one-g and zero-g, are reported by Evans (1963).

The results of an experimental investigation of boiling heat transfer to subcooled distilled water flowing through a resistance-heated tube in a low-gravity environment are reported by Papell (1962). The onset of slug flow and a substantial increase in local heat transfer coefficients under low-g conditions were observed.

A scheme for simulating zero-g flow by means of vertical or parabolic ducts is described by Congelliere, et al (1963). Suggestions are made as to how two-phase isothermal flow, boiling, and condensing might be investigated. It is reported that such a system has yet to be built and tested.

Such heat transfer problems as nucleate boiling, impingement of liquid on a warm unwetted surface, and heat transfer between fuel and oxidizer tanks are discussed by Sherley (1962). A discussion of the thermodynamics of passive orbital temperature control of propellants is given by Satterlee (1962).

Information on low-g heat transfer and related topics can also be found in Abdalla (1964), Abdalla (1965), Adelberg (1965), Albers (1965), Aydelott (1964), Bell (1964), Benton (1964), Brady (1963), Clark (1964), Cline (1964), Clodfelter (1964), Ginwala (1961), Heath (1964), Henchley

(1962), Kirk (1960), Kirk (1963), Lancet (1965), Manson (1964), McGrew (1964), Merte (1961), Polk (1962), Regetz (1964), Schwartz (1965), Siegel (1959), Steinle (1960), and Trusela (1960).

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