Two-Phase Alkali-Metal Experiments in Reduced Gravity

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Future space missions envision the use of large nuclear reactors using either a single or a two-phase alkali-metal working fluid. The design and analysis of such reactors require state-of-the-art computer codes that can properly treat alkali-metal flow and heat transfer in a reduced-gravity environment. Current single and multiphase computer codes rely on the presence of gravity—in the fluid momentum equations, in defining their flow regimes, in specific two-phase flow models, or indirectly in the form of correlations obtained from tests conducted in a 1-*g* field. New flow regime maps, models, and correlations are required if the codes are to be successfully applied to reduced-gravity flow and heat transfer. A literature search of relevant experiments in reduced gravity is reported on here and reveals a paucity of data for such correlations. The few ongoing experiments in reduced gravity are noted. General plans are put forth for the reduced-gravity experiments that will have to be performed, at NASA facilities, with benign fluids. Data from the reduced-gravity experiments with innocuous fluids are to be combined with normal gravity data from the two-phase alkali-metal experiments. Calculations and analyses undertaken here give every expectation that the correlations developed from this data base will provide a valid representation of alkali-metal heat transfer and pressure drop in reduced gravity.

Nomenclature

Bo = Bond number; (We)/(Fr) (gravity forces divided by surface tension forces)
C = heat capacity
D = hydraulic diameter
Fr = Froude number; $(\rho U^2/D)/(\rho g) = U^2/(Dg)$ (inertial forces divided by gravity forces)
G = mass flux
g = acceleration due to gravity (i.e., gravity force); fraction of normal (Earth) gravity
h = enthalpy
k = thermal conductivity
P = pressure
Pe = Peclet number; Re · Pr (bulk heat transport divided by conductive heat transport)
Pr = Prandtl number; $(C_P\mu)/k$ (momentum diffusivity divided by thermal diffusivity)
Re = Reynolds number; $(\rho U^2/D)/(\mu U/D^2) = (UD)/\nu$ (inertial forces divided by viscous forces)
T = temperature
U = velocity
We = Weber number; $(\rho U^2/D)/(\sigma/D^2) = (\rho U^2 D)/\sigma$ (inertial forces divided by surface tension forces)
x = quality
μ = dynamic viscosity
ν = kinematic viscosity ($=\mu/\rho$)
ρ = density
σ = surface tension

Subscripts

ℓ = liquid
P = pressure
v = vapor

I. Introduction

THE Pacific Northwest Laboratory (PNL) of the Department of Energy (DOE) has been assigned the role of modeling the thermal hydraulics of advanced multimegawatt (MMW) nuclear reactors. Various reactor concepts are being proposed by other DOE National Laboratories, by industry, and by universities. This document addresses the experimental requirements posed by one concept—where the reactor working fluid is a boiling alkali metal. Because neither the organizations nor the sites of projected experiments have been selected yet, the ensuing discussion is purposely kept very general in recommending approaches and plans.

Future space missions envision the need for high power levels (up to hundreds of MWe), which are orders of magnitude greater than required by spacecraft launched previously. The concept that appears to have the best potential for supplying such power is a nuclear reactor-based one, with a heat engine and alternator providing the conversion of thermal to electrical power. Stringent weight, heat transfer, and compactness criteria lead to the use of an alkali-metal heat transfer medium, with a boiling alkali-metal (BAM) system offering significant advantages over a single-phase system with an intermediate heat exchanger.

There is a crucial need for analytical tools that can simulate two-phase flows in a zero gravity (0 *g*) or variable gravity environment. Mature computer codes exist that consider single-phase liquid-metal flow and two-phase steam-water flow, both in normal gravity. To be completely useful for the design and analysis of BAM reactors, these codes will need to be modified to handle boiling alkali metals instead of water and to do it in variable gravity.

Experimental 0-*g* two-phase flow data are needed to provide new models and correlations for flow regimes, drag, and heat transfer. Data on alkali-metal two-phase forced convection in a normal gravity field are extremely limited; reduced-gravity data are practically nonexistent (only mercury condensation has been studied somewhat). However, reduced-gravity experiments with two-phase flow of more common fluids (e.g., water, air/water, halocarbons) have been more numerous. A comprehensive literature survey of these experiments has been completed. Results of this survey indicate that both the nature of boiling alkali metal and reduced-gravity experiments, and the acquired data, have been limited in various ways. Thus, the utility of these past experimental efforts to the design and analysis of a space reactor is marginal, and new experiments will have to be performed.

II. Facilities Available for Reduced-Gravity Experiments

Space-based research facilities are very limited. Ideally, a manned, orbiting space station would be available with exten-

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sive laboratory facilities for reduced-gravity research. Also, launch costs, as well as the costs of developing space-qualified test hardware, would be reasonable in terms of the resulting data. Neither criterion is met currently. Small, low-power experiments can be performed on the shuttle, albeit with nonhazardous fluids. The competition for the scheduled shuttle flights is keen, and tests must be planned years in advance of actual flight. Sometime in the 1990's a permanent manned orbiting laboratory may become available.[1] At this time it is not clear if any alkali-metal experiments would be permitted there; hazardous materials are taboo on the shuttle. Regarding launch and test development costs, no appreciable cost reduction is foreseen in the near future.

Given the situation described, at best only a few shuttle experiments will be performed within the time frame allotted for two-phase, reduced-gravity experiments. For the majority of the experiments, ground-based facilities will have to be employed. These present various limitations—the chief ones being the duration and steadiness of the reduced-gravity environment.

Drop Towers and Tubes

Drop towers and tubes are structures purposely built for studying reduced-gravity effects. They use a controlled environment and a difference in elevation to produce "free-fall." That is, an object freely falling in a gravitational field (consisting of body forces) has no net forces acting within it (e.g., pressure gradient) and therefore replicates the phenomena one would observe if that selfsame object had no external forces whatsoever acting on it. In the towers/tubes, the experimental package is released from an elevated position and subsequently arrested at a lower one. The intervening free-fall period is the experimental phase, during which a reduced-gravity environment is present within the experimental module.

Several deficiencies are associated with these facilities. Because the freely falling experiment is constantly accelerating at 9.8 m/s^2, there is an evident limit to a reasonably sized tower or tube. This severely constrains the duration of the experiment. Aerodynamic drag imposes a net force on the experiment. Low g-levels† (on the order of 10^{-6}) can be achieved by evacuating the air from the drop tower before an experiment. Alternately, drag shields are of some benefit in nonevacuated towers.

While various organizations besides NASA possess drop towers (e.g., the University of Michigan), these towers are generally small. The most accessible facilities are at the NASA Lewis Research Center (LeRC). At LeRC, a 2.2-s nonevacuated drop tower, and a 5.2-s evacuated drop tube[2] are available for experiments[3] (the times refer to the duration of the free-fall period). The nonevacuated tower offers quick turnaround so that many experiments (≤ 9) can be performed each day. Its drawback is the short free-fall time. The 5.2-s tube provides additional time, but, because the entire tube must be pumped out (to $\sim 10^{-2}$ Torr) between tests, only several experiments are feasible per day. Furthermore, each facility has unique requirements that preclude construction of a single test vehicle acceptable to both the drop tower and tube. It is therefore recommended that experiments be performed in the 5.2-s drop tube.

Aircraft

An aircraft flying a parabolic trajectory can attain low g-levels. These levels can be sustained considerably longer than those in drop towers because the elevation change during free-fall is much greater. The aircraft also offers significantly more room for an experiment, and power can be drawn from onboard generators, obviating the need for batteries. An additional advantage is that the experimenter can fly along with the experiment and is able to both observe and control the test while it is in progress.

There are disadvantages associated with this mode of reaching reduced gravity. The magnitude and uniformity of the g-level produced is dependent on many factors, the chief one being the skill of the pilot. Note that before the free-fall maneuvers an acceleration of about $2\frac{1}{2}g$ is experienced. This acceleration may perturb flow in the test loop, increasing the time required to establish steady state once reduced gravity is achieved. If so, the period for taking valid data may be much shorter than the free-fall time.

NASA owns two aircraft dedicated to reduced-gravity research. A Learjet at LeRC is available[2] that is capable of operating for 15 to 20 s in a free-fall mode. It can fly up to six free-fall trajectories per mission. A much larger aircraft, the KC-135, is similarly maintained by the Johnson Space Center (JSC).[4,5] Somewhat longer free-fall conditions—about 25 s—can be held.[6] It is therefore recommended that both aircraft be considered if aircraft missions become necessary.

Rocket

A rocket can perform essentially the same function as the aircraft described above. Recently, a SPAR VIII rocket was used in a fluids experiment.[7] This rocket provided over 4 minutes of an "average acceleration near zero" (actual g-level was not reported). Because of the hard landing, it appears that only the film record survived intact.

Additional difficulties are encountered in the use of a rocket for reduced-gravity experiments. Survival and recovery of the experimental module is certainly an issue. The size of this module is quite restricted by the rocket itself. The transition from high to reduced gravity, noted under aircraft, is accentuated here. It is not clear how low and steady a g-level is within rocket capabilities. And finally, the number of rockets that would have to be expended in any realistic test series could run into the hundreds, or even thousands—a daunting prospect.

Because of all these negative attributes, rockets are dropped from further consideration at this point. In the future, the option of using a rocket to fly an alkali-metal experiment may have to be reconsidered.

Shuttle

The advent of the shuttle presents new opportunities for reduced-gravity and other space-related experiments.[8] Instruments and small experiments can be housed in small storage containers or in the crew's storage lockers. Larger, more complex test apparatus can be rack-mounted at the aft flight deck or hard-mounted to the shuttle structure within the payload bay. With the Remote Articulator System a payload can be maneuvered outward to distances of 15 m.

These features are merely embellishments to the shuttle's unique capability to maintain a reduced-gravity environment for a long time. Thus, shuttle-based fluids experiments can be run until steady-state conditions prevail, and the low unvarying g-level ensures the absence of gravity-dominated phenomena. Yet another advantage of the shuttle over most other facilities is the possibility of involving crew members in operating or controlling the tests.

A full description of shuttle capabilities and requirements must encompass the less attractive features as well. These requirements for an experimental package are rather onerous in terms of development costs, safety considerations, and, of course, the expense of the shuttle flight itself. Any and every experimenter is faced with clearing these time-consuming hurdles. And the extremely conservative safety criteria, meant to guarantee the safety of the crew, preclude the presence of any hazardous materials or conditions in an onboard experiment. These rules may be relaxed somewhat in the future as more experience is accumulated and perspective is gained on experimental hazards as opposed to launch and flight dangers. It is highly unlikely that any alkali-metal experiments will be permitted onboard the shuttle. Perhaps a free-flying test package,

†g is defined as the fraction of normal (Earth) gravity, and is the resultant (net) force within the body due to the Earth's gravity field. Use of these terms is consistent with engineering terminology.

launched from the shuttle, would be acceptable for alkali-metal flow and heat transfer tests.

Although it represents a significant improvement over the other facilities, the shuttle environment is by no means ideal. The g-level typically present during orbit is 10^{-3} to 10^{-4}; jitter can degrade it to 10^{-2}. A true microgravity condition ($g = 10^{-6}$) is achieved only at the shuttle's center of gravity.[9] In comparison, the space station of the 1990's has a 10^{-5} to 10^{-6} g-level requirement. This space station, which is still being designed, will represent the first true in-space laboratory with extensive power, instrumentation, data acquisition, and computational capabilities. But until its debut, experimenters must look to the shuttle for the best reduced-gravity environment.

Magnetic Field

Keeping in mind that the ultimate goal of this experimental series (i.e., for MMW purposes) is to obtain data on alkali-metal two-phase behavior in reduced gravity, use of the facilities described represents an arduous and complex approach. If possible, one would like to work directly with the alkali metals, on Earth—and still obtain valid data. One potential means for doing so is to investigate behavior in high-g (>1-g) fields created mechanically by, for example, a centrifuge. Given data points at 1 g, and various higher g-levels, one is tempted to extrapolate to a 0-g condition. But extrapolation is never a reliable technique and can lead to serious error. Extrapolation in this manner to the singularity of a 0-g situation is not justifiable; there is simply no way to evaluate the results so achieved.

One alternative exists. The fact that alkali metals are excellent conductors of electricity can be used to advantage. A magnetic field can be employed to "levitate" the alkali metal. By proper orientation, the magnetic field can cancel the gravitational body force, producing essentially 0-g conditions. Of course, the uniformity of this field must be ensured, and Joule heating of the alkali metal must be minimized.

There exists a well-known relationship between a magnetic field, an electric current, and a moving conductor. The geometrical relationship among these three parameters is illustrated by the familiar right-hand rule.[10] An electric motor is a typical example of the motion induced in the conductor (armature) by an electric current in a magnetic field.[11] A less-familiar but more apropos example is the electromagnetic pump, specifically developed for pumping electrically conductive fluids such as alkali metals.[12]

For a test section, one can envision a vertical length of pipe entirely within a horizontal magnetic field of the requisite strength to cancel gravity and provide adequate mass flow. Two complications come to mind: 1) assuming heating in the test section, the temperature, and properties, of the alkali metal will vary over the length of the section; and 2) the generation of vapor may introduce anomalies. These effects, and the manner in which they influence the desired cancellation of the gravitational body force, need to be examined in detail to assess the feasibility of this approach.

Only a few experiments have been performed with a boiling liquid metal (mercury) in a magnetic field.[13] These experiments were not intended to investigate a 0-g condition, so their results are hardly applicable here.

It is recommended that the use of magnetic fields be investigated further. Enormous benefits would result from Earth-based potassium experiments that replicated the conditions in space.

Summary and Conclusions

The facilities and techniques for generating reduced-gravity environments are summarized in Table 1. It is concluded that several of them would be suitable for future experiments. A study of magnetic field utilization to attain 0-g is under way at Princeton University and is funded by PNL.

Additional constraints on the types of fluid, size of the experimental package, power available to run the experiment, and instrumentation and data acquisition equipment have exerted a negative influence on the nature of the experiment. As a result, the operable mechanisms in reduced-gravity two-phase convection have not been elucidated, nor have quantitative heat transfer and hydrodynamic correlations been developed. The data are generally more qualitative than quantitative and suggestive of the improvements needed to obtain valid results. No criticism of these past efforts is implied, as they were the first research steps taken in charting an unknown field. These efforts will now be discussed in some detail.

Table 1 Experimental facilities and techniques for attaining a reduced-gravity environment

Type	Features	Special conditions	Lowest g-level attainable[a]	Reduced gravity duration, s	Comment
Drop	Various towers/ tubes (13.2 to 145 m high)	Vacuum/drag shield; cryogenic	$\leq 1 \times 10^{-5}$	5.15 (10, if accel. from bottom)	Time is severe constraint. High deceleration rate (approx. 30 g) to stop.
Magnetic,[b] viscous, sonic, inertial	"Levitate" sample	—	Unknown	Days	Techniques may generate secondary effects, disturbing or distorting sample.
Aircraft	Repeated parabolic trajectories between two altitudes	Can accommodate large payloads	≤ 0.01	Approx. 20	Relatively high g-field level; difficult to maintain at steady value.
Rocket	Free-fall mode	—	Unknown	Approx. 250	No details provided in literature.
Spacelab (shuttle)	Limited size of experimental package	Stringent safety requirements	1×10^{-2} -1×10^{-6} (jitter-free, on center of gravity)	Days	Long scheduling lead time. Crew members can be used to "run" experiments.

[a]Fraction of Earth gravity.

[b]While these techniques generally do not provide truly 0-g conditions, they may be of some utility here and are included for completeness. Gravity fields > 1 can be attained by inertial techniques, while near 0-g conditions are possible through use of magnetic fields.

Classification of Tests by Facility

Drop Tests

Recently, growth of single bubbles in microgravity (10^{-4} to 4×10^{-2} g) has been studied by Cooper et al.[14] Water, toluene, and hexane have been separately examined, under no-flow conditions. With the liquid in a saturated state, a single bubble was initiated at the wall by electrical means, and its growth recorded with a high-speed camera. From the record, a simple expression was developed, governing the growth of diffusion-controlled bubbles. No sudden departure of the bubbles from the wall was observed; the lack of large temperature gradients was presumably responsible. The shapes of bubbles were found to be functions of surface tension, rate of growth, time, and the microgravity field. A relationship was also found between the maximum bubble diameter at departure from the wall and the gravitational field. Surface tension was observed to aid bubble departure by rounding-off bubbles.

Another experimental study[15] examined the proportion of vapor generated at the surface of saturated Refrigerant 11, and in the bulk liquid (i.e., bubbles), upon venting to vacuum. The 5-s drop-test facility was used with a photographic record plus some instrumentation such as pressure transducers and a thermistor. No bulk vapor was generated at 0 g (i.e., all of the vapor was generated at the surface); small amounts of bulk vapor (boiling) were generated at measurable gravity levels. The vent rate, the percentage of vapor by volume, and the Bond number (defined as the ratio of acceleration to capillary forces) strongly influenced the amount of bulk vapor generated.

An earlier experimental program[16] studied force-convection boiling at low heat flux and low velocities in microgravity. The liquid used was slightly subcooled (0.4 to 1.5°C) distilled water, heated from below with a flat Chromel strip. Temperature was measured by a thermistor, and a 900-frame-per-second camera recorded the dynamics during the 2.2-s free-fall. Bubble growth exhibited a cyclical trend; it is not clear if steady-state conditions prevailed. The majority (85%) of the bubbles remained attached to the heater surface, essentially forming a bubble boundary layer. The bubble diameter was found to correlate well with saturation layer thickness. The relevance of this work is probably restricted to storage tanks containing cryogenic fluids.

A very similar series of experiments by Cochran, Aydelott, and Spuckler[17] considered several fluids, but with no forced convection. The amount of subcooling was varied, as was the heat transfer rate; the effects on bubble size and lifetime with gravity field were noted. The basic physical principles governing bubble dynamics were used in obtaining simple expressions for the dominant forces acting on the bubbles. These forces were calculated and plotted versus time.

Bubble size and lifetime in water were found to be nearly independent of the gravity field at high subcooling. For low subcooling, larger bubbles developed in 0 g than in 1 g. An ethanol/water solution, with a surface tension about 30% that of water, showed little influence of either g-field or subcooling. The results are attributed to the more nearly spherical shape of the solution bubbles, compared to water. The pressure force therefore dominated solution bubble dynamics. A variation in heat transfer rate (from 24,800 to 114,000 Btu/h-ft^2) for this solution also exhibited no trends with g-field on bubble radii and lifetimes. These findings may prove significant when the choice of a fluid for the boiling reactor is made. Tests with a sugar/water solution having a viscosity ten times that of water gave results similar to water regarding gravity and subcooling effects on bubble radii and lifetimes. But the force histories for water and the sucrose solution are vastly different, with a significant drag force in the latter.

Oker and Merte[18] performed an elaborate series of pool boiling tests using liquid N_2 and Freon 113 and heat flux from 1×10^3 to 1×10^5 W/m^2. A rather short drop tower was used, which gave <1.4 s of free-fall; it is uncertain if steady-state conditions ever prevailed during the test. The g-level was fairly high, up to 4×10^{-3}. The data indicate that surface superheat at boiling inception is a function of gravity, and it is claimed to be less at 0 g than in normal gravity. But an examination of the data shows that generally the ΔT increased significantly in the transition from normal to 0 g—which is what one would expect, as the buoyancy force driving natural convection heat transfer vanishes at 0 g. This study also shows a summary table, listing earlier nucleate pool-boiling reduced-gravity experiments and heat transfer trends. These trends appear to be somewhat contradictory.

A review article by Siegel[19] discusses and summarizes data on pre-1967 reduced-gravity experiments. Most experiments used the drop tower facilities, although some also used aircraft. For pool boiling, the critical heat flux between 0.01 and 1 g was found to correlate well with $g^{1/4}$. Whether this flux goes to zero at 0 g could not be determined from the level and duration of the g-field achievable then. Short-duration saturated pool nucleate boiling seems independent of gravity but requires substantiation. Insufficient data existed for drawing any conclusions regarding forced convection heat transfer. Some condensation results are also reported.

The early work, while important in initiating this study area, addressed only a fraction of the issues presented by 0-g boiling. This early work cannot be relied upon to provide definitive models or results.

Aircraft Tests

A fairly recent experiment delved into the topics of flow regimes and pressure drop.[20] Two-phase flow of air and water in a circular channel was examined first on Earth, then in an aircraft simulating 0 g for about 20 s per trajectory. Analysis indicated a downward shift of regime boundaries at reduced gravity; i.e., at a given quality, the transition from distributed → segregated → segregated + intermittent flow ought to occur at a lower total mass flow rate in reduced gravity.‡ Initial testing confirmed this trend but not its magnitude. However, a repeat test inexplicably nearly agreed with the analytical predictions. As for ΔP, the 0-g pressure drop is significantly higher than that for 1 g and is ascribed to the change in flow regime noted earlier—which itself was a consequence of increased turbulence in 0 g. If generally true, the added ΔP could have a considerable impact on a space reactor and needs to be investigated much more rigorously.

A similar experimental effort was devoted to condensation of Freon-12.[6,21,22] Although the test section was well-instrumented, only qualitative results are reported. It appears that the flow regimes observed (photographic record) conform reasonably well to Baker-chart predictions.[23] The flow at 0 g was notably less irregular than at 1 g, which is somewhat at variance with the trend noted above. Based on little discernible difference in condensation lengths, it was also hypothesized that heat transfer was unaffected by g-level.

Some preliminary studies used mercury in reduced-gravity condensation experiments. Albers and Macosko[24] reported practically the same pressure losses at 1 g and 0 g, in a constant-diameter tube. Both losses were greater than predicted by the Lockhart-Martinelli correlation[23] at low vapor qualities, but, in the high-quality region of the condensing tube, the pressure drop from the Lockhart-Martinelli correlation agreed within $\pm 70\%$ with the measured pressure loss. It was felt that fog-flow theory, which postulates reentrainment of condensed droplets back into the vapor stream, best explained the data (visualization was not possible in the stainless steel test section).

‡Distributed flow assumes one phase to be continuous, the other phase need not be distributed over the same section of pipe; segregated flow occurs when the gas and liquid phases are continuous in the axial direction; intermittent flow results when the phases form alternating pockets across the tube.

A photographic experiment conducted by Namkoong et al.[25] with mercury vapor condensing in glass tubes failed to support the fog-flow hypothesis. In tubes with diameters ≥ 1 cm, the distribution of drops on the wall was concentrated on the tube bottom in 1-*g* conditions. Zero-*g* conditions led to a uniform distribution of droplets, both in the droplet stream and at the wall.

Mercury differs so enormously from the alkali metals (especially regarding wetting of the heat transfer surface), that it is not at all certain that the above studies have any relevance to alkali-metal two-phase flows. The main advantage in using mercury as an experimental fluid lies in its low melting temperature.

Rocket Tests

A 4-min rocket flight provided the microgravity environment for an experiment on bubble migration in molten glass ("fining") as reported by Wilcox et al.[7] A platinum heating strip melted a sample of sodium borate glass, which contained entrapped voids. During the 0-*g* portion of the flight, distinct migration of the bubbles toward the hotter portion of the sample was noted. This observation is in agreement with the Brown model[23] of thermocapillary bubble migration, which predicts motion against a thermal gradient.

Shuttle Tests

The shuttle program envisions a series of fluid mechanics experiments.[26] To this end, a Drop Dynamics Module and a Geophysical Fluid Flow Cell have been constructed for use in the payload bay. The former module was flown in 1985, and tests studying the dynamics of rotating and oscillating free drops have been done. No flow experiments have been performed on the shuttle to date.

Magnetic Field Tests

Several experiments have been performed with magnetic fields and a liquid metal (mercury). The objective was not to counteract gravity, but rather to note any perturbations engendered by the field on the boiling process. Faber and Hsu[13] applied a vertical magnetic field of 1 to 6 T to mercury undergoing nucleate pool boiling on a horizontal surface. Test results suggest that the magnetic induction encourages the incipience of boiling; i.e., boiling can be initiated at a lower heat flux in the presence of the field than without it, but a simultaneous reduction in heat transfer was observed. It was postulated that the retarding influence of the Lorentz force increases bubble population and inhibits bubble motion (i.e., buoyancy is reduced) and agitation. Analysis indicated that the growing bubbles become elongated spheroids, with the major axis aligned with the magnetic field. These mechanisms were thought to be the chief contributors to the observed effects.

An earlier experiment, reported by Hsu and Graham,[27] had the magnetic field oriented horizontally. Heat transfer was little perturbed thereby.

Petukhov and Zhilin[28] discuss a number of experiments performed with single-phase liquid metals in magnetic fields. Both transverse and longitudinal magnetic fields served to inhibit heat transfer. The effect was Reynolds-number-dependent, with the Nusselt number decreased up to 30% at intermediate values of the Reynolds number. It was suggested that the magnetic fields affect the turbulence, but its exact structure (e.g., vortices in transverse fields) was not elucidated. In any case, these mechanisms may be relatively unimportant in two-phase flows.

The applicability of the experiments noted to the situation of interest (reduced gravity accomplished by means of a magnetic field) is probably remote. First, the action of various mechanisms was postulated, not proven. Second, an electric current passing through an alkali metal, causing it to flow vertically within a horizontal magnetic field, represents a significantly different situation from the pool boiling studies. So the postulated mechanisms, even if valid, may be inoperable in a flow condition. All these issues need to be investigated more fully; analytical studies and small experiments ought to prove or disprove the merit of magnetic fields as a means for generating reduced-gravity.

Conclusions

A survey of past reduced-gravity two-phase convection experiments has disclosed a great need for more and better data. Past experiments are useful to the current effort more as guideposts than as sources of hard data. A brief summary of the chief 0-*g* experiments is provided in Table 2.

III. Current and Planned Reduced-Gravity Experiments

Although a large number of reduced-gravity experiments are being planned or proposed, only a few are actually in progress. The costs and complexities associated with such experiments are effective deterrents to wide participation. While some interest has been stirred in the private sector by NASA urgings, nothing substantive has been accomplished with private funds. It appears that, until industry sees a clear benefit from reduced-gravity experiments, only meager attention will be given this area. One of the difficulties with assessing reduced-gravity experiments is lack of information; there is no central repository or clearinghouse on active programs.

NASA Plans

A variety of fluids and fluids-related experiments are proposed in NASA documents (e.g., Refs. 29–32). Only a few two-phase flow experiments are actually in progress, and descriptions follow. These involve mainly universities, although several study contracts have been arranged with industry.

Regarding future fluids experiments, most activities for the shuttle and the space station deal with cryogen storage.[33] Very little from those studies will be applicable to two-phase turbulent alkali-metal flow and heat transfer.

University Activities

Several universities (e.g., the University of Michigan) have small drop towers that have seen use for thesis work.[18] NASA has contracts with three universities to perform a series of tests, spanning facilities from drop towers to Spacelab. The University of Houston is responsible for adiabatic pressure drop/flow regime delineation in reduced gravity.[2] The NASA mandate for the University of Michigan is to examine the onset of nucleate-pool boiling, initially in the LeRC 5.2-s facility, and ultimately onboard the shuttle.[2] Meanwhile, at Texas A&M University forced-flow condensation and heat transfer are being examined on the JSC KC-135 aircraft.[34]

Less formal arrangements also exist between NASA and some other universities. Thus, the universities are able to use facilities such as the LeRC 2.2-s drop tower and Learjet for thesis work.

It appears that much of this work could prove to be of major import to the space reactor program. All three university groups are interested in defining the basic physical phenomena associated with reduced-gravity two-phase flow and heat transfer. As such, no specific application has influenced the nature of the proposed activities. Perhaps inputs from MMW programs and organizations (including funds) could sway the experiments to represent in-core boiling mechanisms.

Industry Activities

Industry has been reluctant, in spite of its expressed interest, to initiate reduced-gravity experiments on its own. To stimulate industry participation in the shuttle and space station experimental programs, NASA has set up several technology centers and offered seed money to begin experimental programs. The response has been gratifying, and there are high hopes that industry will become an active partner in future endeavors.

The extent, timing, and specificity of industrial experiments remain to be determined. Until more information becomes available, one will have to reserve judgment on the relevance of

Table 2 Reduced gravity two-phase convection experiments

Type	Investigated	Fluids	Flow	Heat Transfer	Liquid State	Conclusions	Comment	Reference
Drop test	Single bubble growth	Water, toluene, hexane	No	Not examined	Saturated	Simple correlations found for growth and shape with g as parameter	Not directly useful for present needs	Cooper, Judd, and Pike[14]
Drop test	Vapor generation at liquid surface and in bulk fluid	Refrigerant 11 (R-11)	No	Not examined	Saturated	No vapor generated (i.e., bubbles) in bulk liquid upon venting at 0 g	Not relevant	Labus, Aydelott, and Lacovic[15]
Drop test	Forced convection boiling at low heat flux and velocity	Distilled water	Yes	Not examined	Slightly subcooled	Simple correlation found for bubble diameter vs evaporation layer	Not relevant	Cochran[16]
Drop test	Pool boiling. Effects of surface tension, viscosity, and subcooling	Water, ethanol-water, sucrose-water	No	Varied in some tests	Various subcoolings	Water boiling (i.e., bubble size) independent of g, at high subcooling	Trends of interest	Cochran, Aydelott, and Spuckler[17]
Drop test	Pool boiling (nucleate plus film)	Various	Yes	Yes	Various	Critical flux proportional to $g^{1/4}$	Preliminary results; g fields high (approx. 0.01)	Siegel[19]
Drop test	Pool boiling	N_2, R113	No	Yes	Saturated	Surface superheat less in 0 g	Transient results; g fields high (approx. 0.004)	Oker and Merte[18]
Aircraft	Flow regimes and pressure drop	Air and water	Yes	None	N/A	g-level influences flow regime, which influences ΔP	Good basis for future work	Heppner, King, and Littles[20]
Aircraft	Flow regimes in condensation	R-12	Yes	Qualitative	Super-heated/ saturated	Baker chart valid; no reduction in heat transfer with 0 g	Not directly useful	Williams[21] Keshock et al.[22] Williams, Keshock and Wiggins[6]
Aircraft	Pressure drop and phase velocities in condensation	Mercury	Yes	Yes	Superheated/ dropwise condensation	Little difference between 0-g and 1-g data	Not directly useful	Albers and Macosko[24] Namkoong et al[25]
Rocket	Void (i.e., bubble) migration in molten glass	Sodium borate glass	No	Not examined	N/A	Bubbles migrate against thermal gradient at 0 g	Not directly useful	Wilcox et al.[7]

industry efforts to the task described here. But most of the papers presented at a recent space research workshop[33] are of only marginal interest because they dealt with cryogen storage and boil off problems. Also, these papers generally dealt with reduced-gravity issues in a rudimentary manner, so it appears that considerable time will elapse before realistically designed industrial experiments will be able to take place.

One fluid experiment will have a decided bearing on future two-phase activities. The NASA JSC has recently (1985) awarded a contract to a firm to engineer a shuttle mid-deck experiment.[35] The objective is to obtain basic two-phase flow data; initial experiments will be adiabatic, using an air/water mixture. This experiment may be performed in cooperation with one of the aforementioned universities. It is anticipated that the experiment, which will take about 1.5 h, will be flown aboard the shuttle with several years' delay past the originally planned date.[35]

The reason for optimism on this particular experiment is that the firm receiving the contract has extensive expertise in such research, having in the past completed a detailed design of a similar experiment.[36] That design, and the accompanying test plan, had features that could readily be incorporated into any future experiments.

IV. Proposed Two-Phase Reduced-Gravity Experiments

The broad objective of this MMW experimental program is to obtain sufficient data to characterize two-phase alkali-metal flow and heat transfer in a reduced-gravity environment. While this goal on the MMW program is clear enough, its attainment is anything but simple.

Approach

The twin issues posed by experimental facility limitations and the difficulties inherent in working with alkali metals must be squarely faced by any realistic test program. Thus, the only viable approach is to perform, to the maximum possible extent, experiments with innocuous fluids such as air, water, and Freon in place of the alkali metals. Only if the desired data were to be seriously flawed by replacement fluids will alkali metals themselves become the working fluids. At this time the

Table 3 Candidate fluid properties

Property		Fluid: Potassium	Water + Air[a]	Water	Freon-11	Methanol	Ammonia
Temperature °K[b]		1450	295	483	330	395	293
Pressure, Pa[b]		1.65×10^6	9.21×10^5	1.90×10^6	2.89×10^5	6.66×10^5	8.53×10^5
ρ, kg/m^3	ℓ	562	995	850	1396	686	609
	v	6.25	11.07	9.53	15.60	7.61	6.72
Expansion ratio, ρ_ℓ/ρ_v[c]		89.9	89.9	89.2	89.5	90.1	90.5
ν, m^2/s	ℓ	1.68×10^{-7}	9.64×10^{-7}	1.49×10^{-7}	2.28×10^{-7}	2.45×10^{-7}	2.39×10^{-7}
	v	3.69×10^{-6}	1.64×10^{-6}	1.70×10^{-6}	7.79×10^{-7}	1.68×10^{-6}	1.68×10^{-6}
ν_v/ν_ℓ		22.0	1.70	11.4	3.42	6.87	7.01
σ, N/m		3.56×10^{-2}	7.25×10^{-2}	3.55×10^{-2}	1.41×10^{-2}	1.35×10^{-2}	2.14×10^{-2}
k_ℓ, W/mK		20.39	0.604	0.655	0.079	0.175	0.494
$h_{\ell v}$, J/kg		1.70×10^6	—	1.89×10^6	1.69×10^6	9.63×10^5	1.18×10^6
U, m/s[e]	ℓ[d]	1.78	1.01	1.18	0.716	1.46	1.64
	v[f]	160	90.3	105	64.1	131	149

[a]For room temperature adiabatic experiment. [b]Saturated conditions. [c]Probably most important parameter for similitude. Set equal to potassium value. [d]Assumes $x = 0.0$. [e]At $G = 1000$ kg/m^2 s (maximum) in a 0.02-m ID tube. [f]Assumes $x = 1.00$.

Table 4 Comparison of candidate fluids at $G = 1000$

Nondimensional number[a]	Phase	Fluid: Potassium	Water + Air	Water	Freon-11	Methanol	Ammonia
Re	ℓ	2.12×10^5	1.35×10^5	1.58×10^5	6.29×10^4	1.19×10^5	1.37×10^5
	v	8.67×10^5	1.06×10^6	1.23×10^6	1.65×10^6	1.56×10^6	1.77×10^6
Fr[b]	ℓ	1.58×10^5	5.05×10^4	6.91×10^4	2.56×10^4	1.06×10^5	1.35×10^5
	v	1.28×10^9	4.08×10^8	5.50×10^8	2.05×10^8	8.62×10^8	1.11×10^9
We	ℓ	1.00×10^3	2.77×10^2	6.62×10^2	1.02×10^3	2.16×10^3	1.54×10^3
Bo	ℓ	6.33×10^{-3}	5.49×10^{-3}	9.58×10^{-3}	3.98×10^{-2}	2.04×10^{-2}	1.14×10^{-2}
Pr[c]	ℓ	2×10^{-3}	6	0.8	3.5	2.1	2.0
	v	1	1	1	1	1	1

[a]Based on data in Table 3. [b]Assumes $g \sim 10^{-3}$. [c]Approximate.

feeling is that perhaps alkali metals might be acceptable for use in drop towers and the KC-135 aircraft,[5] but would present an unacceptable hazard in any other reduced-gravity test facilities.[2]

Doing the experiments in a piecemeal manner ensures safety, timeliness, and reduced cost, but there is a negative side to such a scheme: the reliability of the data so obtained is in question. That is, there is no assurance that the data obtained with various fluids can ever be assembled to represent an alkali metal. Yet this approach appears to have been validated in rudimentary fashion[37-39] and was recently employed successfully in designing the Fast Flux Test Facility (FFTF) at Hanford.[40] Note that the alkali metal coolant in the FFTF does not undergo a phase change. Plus, the complication of zero gravity further strains possible analogies among different fluids. Still, the approach has merit, and there is the hope that, by exercising care and judgment, one can achieve results valid for alkali metals. Arguments substantiating this claim are provided below.

Boiling phenomena associated with low-Prandtl-number fluids (e.g., alkali metals) differ substantially from those of higher-Prandtl fluids (e.g., water, ammonia, Freons). Heat transport is by different mechanisms, bubble formation and fluid agitation evince different characteristics, and interaction with the container surface (i.e., wettability) is a potential problem. However, there is some overlap in the properties of high- and low-Prandtl-number fluids. For example, the physical properties of water at 0.2 MPa and in the 300 to 400°K range are quite similar to the properties of potassium in the 825 to 1150°K range.

The data in Table 3 provide a comparison of the relevant properties of potassium with various fluids being considered for testing in its place. Potassium properties are given at a temperature and pressure that might be representative for a boiling alkali metal nuclear reactor; the properties of the other fluids were selected for expansion ratios (i.e., ρ_ℓ/ρ_v) equal to that of the potassium. It is felt that this matching best ensures similarity in boiling mechanisms, although other measures of similitude (such as the viscosity ratio, ν_v/ν_ℓ), may be equally important in certain flow regimes at high-Reynolds number.[20]

From Table 3, it is clearly evident that several fluids closely resemble the potassium, with water and ammonia yielding the best match. Freon-11 is somewhat less akin to potassium but offers the advantage of a low-temperature and low-pressure boiling point. Methanol fits between the extremes of the other fluids.

Several nondimensional numbers, thought to be important in 0-g work, have been calculated from the data in Table 3 and are given in Tables 4 and 5. The values in Table 4 are based on a constant $G = 1000$ kg/m^2 s, while dynamic similitude, with constant Reynolds numbers, results in the values in Table 5. From these data, it is concluded that a partial similtude can always be achieved, but never a total one. Bomelburg[41] provides an excellent discussion of this topic and identifies some of the pitfalls in using analogies. He has reservations regarding the use of water in place of alkali metals, especially for heat-transfer experiments. Recent European experiments with adiabatic two-phase alkali-metal flow support the validity of using water for pressure-drop correlations.[42] A different

Table 5 Comparison of candidate fluids at constant Re

Nondimensional number[a]	Phase	Fluid: Potassium	Water + Air	Water	Freon-11	Methanol	Ammonia
Re	ℓ	2.12×10^5	2.12×10^5	2.12×10^5	2.12×10^5	2.12×10^5	2.12×10^5
	v	8.67×10^5	8.67×10^5	8.67×10^5	8.67×10^5	8.67×10^5	8.67×10^5
Fr[b]	ℓ	1.58×10^5	5.24×10^6	1.26×10^5	2.92×10^5	3.38×10^5	3.23×10^5
	v	1.28×10^9	2.53×10^8	2.72×10^8	5.71×10^7	2.86×10^8	2.64×10^8
We	ℓ	1.00×10^3	2.88×10^4	1.20×10^3	1.16×10^4	6.87×10^3	3.67×10^3
Bo	ℓ	6.33×10^{-3}	5.50×10^{-3}	9.54×10^{-3}	3.98×10^{-2}	2.03×10^{-2}	1.14×10^{-2}
Pe[c]	ℓ	4.24×10^2	1.27×10^6	1.70×10^5	7.42×10^5	4.45×10^5	4.24×10^5
	v	1.02×10^6	6.16×10^5	1.04×10^6	6.85×10^5	3.29×10^5	7.46×10^5
U, m/s	ℓ[d]	1.78	10.2	1.59	2.42	2.60	2.54
	v[e]	160	71.1	73.8	33.8	73.0	72.7

[a]Based on data in Table 3; U differs, however. [b]Assumes $g \sim 10^{-3}$. [c]Approximate. [d]Assumes $x = 0.0$. [e]Assumes $x = 1.00$.

Table 6 Test approach options and ratings

Issue	Options: Global approach	Rating ($-5 \rightarrow +5$)	Partitioned approach	Rating ($-5 \rightarrow +5$)
Fluid	Reliable data	+5	Care must be exercised to assemble data to fairly represent alkali metals	−2
	Instrumentation difficulties; prohibitive safety requirements and costs	−4	Test program goals can be achieved at reasonable cost, in a reasonable time frame	+4
Facility	Space-based laboratory facility would provide the most reliable data	+3	Require more tests, several test packages; less reliable data are obtained	−2
	No such facility will exist until the construction of the space station in the mid-1990's	−5	Efficient use of existing facilities	+3
Experiment	Most direct approach; straightforward	+1	Complex	−1
	Difficult to measure all parameters simultaneously	−4	Parameter-specific; provides valid correlations	+4
Totals		−4		+6

conclusion is reached from a Russian experiment,[43] indicating the two-phase alkali-metal pressure drop is greater for adiabatic than nonadiabatic conditions. Like so many alkali-metal experiments, it also was performed in a very small-diameter (5-mm I.D.) tube, so extension to large-diameter flows remains questionable.

One further issue remains to be discussed. Liquid-metal flow development is much more gradual than is the case with a high-Prandtl fluid such as water.[44] Now both the test section and actual space hardware (such as the reactor, heat exchangers and piping) will necessarily have low length/diameter ratios. Thus, flow development will exert a significant influence on the performance (ΔP and heat transfer) of this equipment. Yet the developing flow and velocity profiles in the experimental device will tend to mask, or modify, the measured parameters and effects. Extrapolating what is observed with water under 0-g conditions to a liquid metal with a very different flow development length requirement may prove difficult.

In spite of all the caveats noted, it is felt that use of alternate fluids in place of alkali metals is justified. Every attempt will be made to verify that the experiments with these fluids will truly represent alkali-metal behavior.

Another aspect of the proposed test series is one of partitioning. This entails doing the experiments at various times and facilities and examining phenomena such as pressure drop and heat transfer in separate experiments. Given the large variation in facility features (see Table 1), several test packages will have to be constructed because no single package will be satisfactory for all. In fact, each facility employed will probably require a unique test package, which imposes an additional burden in terms of time and effort expended to accomplish the task. As before, the reason for having a multiplicity of tests, fluids, test packages, and other factors is one of practicality. The goal is to obtain the data as expeditiously and cost-effectively as possible.

As was mentioned, one partitioning envisioned is the separation of adiabatic and heat transfer tests. In this manner, the adiabatic experiments will yield data on pressure drop and flow regimes—data that are much easier to secure without trying for simultaneous heat-transfer measurements. Similarly, the heat-transfer experiments will concentrate on the heat-transfer mechanisms with only perfunctory pressure-drop measurements. The overall benefits anticipated are more accurate data obtained in the most efficient way.

In conclusion, the approach taken here is fairly typical of experiments that delve into complex phenomena. Fluid-flow and heat-transfer effects in reduced gravity can be elucidated via narrowly scoped experiments that assess only a few parameters. The methodology is succinctly portrayed in Table

6, which, while it has an element of subjectivity, still quantifies the issues and arguments raised. In sum, the "partitioned" approach is more realistic than an all-encompassing "global" approach and achieves its objective in a sort of evolutionary manner. Great flexibility is a side benefit.

Objectives

Each experiment (e.g., pressure drop/flow regime, heat transfer, maximum heat flux) under the MMW thermalhydraulics task will consist of a series of tests whose objective is to "map" the parameters of interest over a broad range of conditions. The variables to be measured will consist of temperatures, pressures, mass flow rates, velocities, and void fractions; flow regimes will be determined from film.

Because all Earth-based reduced-gravity test facilities are able to provide a reduced-gravity of only short duration, rapid instrument response and high data-transfer rates are important. Accurate and reliable data must be ensured, so the measurements must be copious over the short test time and must provide evidence that steady-state conditions prevailed during some portion of the test. Data scatter must be $\leq 20\%$ to be acceptable. These objectives can be met with state-of-the-art instrumentation and data acquisition systems.

The literature is replete with two-phase, pressure-drop, heat-transfer, and critical heat flux correlations.[27,36,45] As the test data become available, existing correlations will be examined and, if feasible, adapted to represent reduced-gravity conditions. Alternatively, new correlations will be developed as needed. It is impossible to predict what form these may take, as the experiments are the only valid source for the correlations. If one were able to derive such correlations from first principles, the need for experiments would be obviated. But two-phase flows are not fully understood even in normal gravity, so reduced-gravity mechanisms and trends can be postulated but not proven theoretically.

General Plans

Although all the details and ramifications of a reduced-gravity two-phase experimental program have not been determined, still the main tasks can be broadly scoped. MMW activities must be coordinated with NASA and researchers (e.g., University of Michigan, University of Houston, Texas A&M University) regarding ongoing and planned reduced-gravity experiments. The intent here is to avoid duplication and perhaps to exert some influence on the nature of the experiments performed for non-MMW projects.

A parallel task in securing information should examine the reactor concepts being proposed that employ two-phase alkali metals. This will permit selection of the alkali metals and parameter ranges for study.

Subsequently, a number of choices must be made. These include determination of the parameters to be measured in the experiments; fluids to be tested, selection of instruments and data acquisition systems; and finally, design of a control scheme that will require a minimum of human intervention. The options available are strongly circumscribed by the availability and features of the reduced-gravity facilities. More than likely, the selection process will be an iterative one as facility constraints set the experiment bounds, while data needs favor certain facilities over others.

Once the above task is complete, an experimental package to house the experiment and ancillary equipment can be designed and constructed. This sets the stage for the writing of a detailed test plan, and its execution. As the test series progresses, the data obtained will be evaluated in terms of validity and applicability to MMW needs. If any deficiencies are observed, suitable corrective action will be taken. Given the exploratory nature of the experiments and the broad scope of this project, flexibility in execution of the tests is an absolute must. These same tasks are illustrated in flow chart format in Fig. 1. Some indication of the scheduling and timing of individual tasks is also provided. Proper scheduling is critical, for two reasons: 1) to ensure availability of test facilities; and 2) to ensure timely availability of data and correlations to the code development effort.

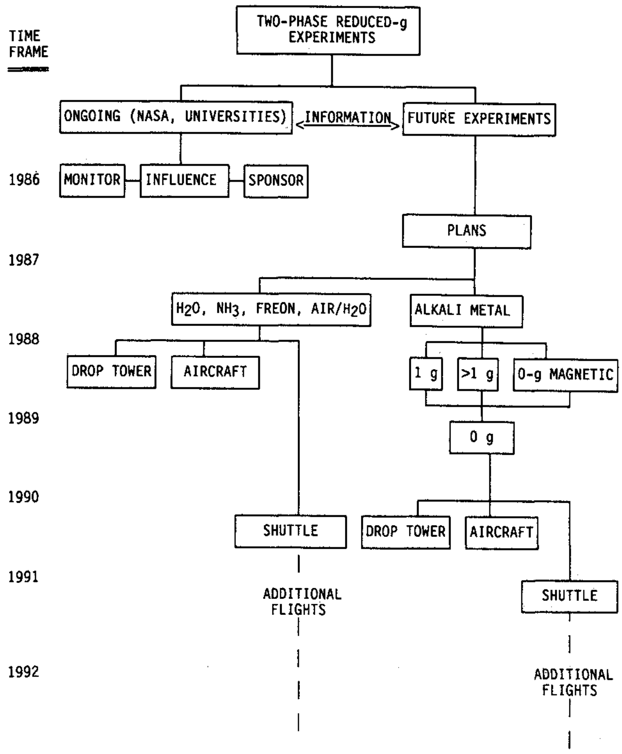

Fig. 1 Task flow for two-phase reduced-gravity alkali-metal experiments and related efforts.

As noted earlier, it is hoped that all, or most, reduced-gravity experiments can be done with nonhazardous fluids and still provide data and correlations applicable to alkali metals. Hazardous materials are to be avoided in shuttle flights. As data become available and evaluation indicates the need for reduced-gravity alkali-metal experiments, serious consideration will have to be given to what constitutes an acceptable experimental package. Perhaps a free-flying module, to be launched from the shuttle, could be designed with suitable safety equipment to permit alkali-metal use. No doubt this will prove an expensive option, but it may be necessary so as not to compromise an even more expensive MMW design and mission.

V. Conclusions and Recommendations

The MMW thermal-hydraulics experimental effort about to be embarked upon will be a demanding one. Great care will have to be exercised in both planning and execution of the requisite two-phase experiments. The time constraints are fairly severe, and much needs to be done in a relatively short time frame. This holds especially for any two-phase alkali-metal experiments that may have to be done in a reduced-gravity environment.

The recommended approach to this experimental task is to use substitute fluids in place of the alkali metals and to use ground-based facilities to the maximum extent. A separate document for each experiment should be generated, incorporating a detailed account of the specific procedure, equipment, test plan, and other features. Such a document has already been written for the pressure-drop/flow-regime experiment, which is to be performed in drop towers with an air/water mixture. Other documents will be forthcoming as needed.

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