

The Development of Novel, High-Flux, Heat Transfer Cells for Thermal Control in Microgravity

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Abstract

In order to meet the future needs of thermal management and control in space applications such as the Space Lab, new heat-transfer technology capable of much larger heat fluxes must be developed. To this end, we describe complementary numerical and experimental investigations into the fundamental fluid mechanics and heat-transfer processes involved in a radically new, self-contained, heat transfer cell for microgravity applications (patent pending). In contrast to conventional heat pipes, the heat transfer in this cell is based on a forced droplet evaporation process using a fine spray. The spray is produced by a novel fluidic technology recently developed at Georgia Tech (patent pending). This technology is based on a vibration induced droplet atomization process. In this technique, a liquid droplet is placed on a flexible membrane and is vibrated normal to itself. When the proper drop size is attained, the droplet resonates with the surface motion of the membrane and almost immediately bursts into a shower of very fine secondary droplets. The small droplets travel to the opposite end of the cell where they impact a heated surface and are evaporated. The vapor returns to the cold end of the cell and condenses to form the large droplets that are fragmented to form the spray. Preliminary estimates show that a heat transfer cell based on this technology would have a heat-flux capacity that is an order of magnitude higher than those of current heat pipes designs used in microgravity applications.

I. Introduction

Thermal management is a critical technology in the microgravity environment because it affects so many different areas in the operation of spacecraft. Power plants must be cooled properly for efficient operation and the living environment must be maintained within the proper temperature range. Sensitive scientific instruments used in space, such as low temperature CCD imagers, must be maintained at a constant uniform temperature in order to work effectively. In addition, there is an ever increasing demand for power in space missions, such as the Space Lab. Increasing the size of power plants aboard such spacecraft brings with it an even larger thermal management problem associated with the waste heat that is generated. Thus, more efficient methods to remove this heat are required.

One popular method for thermal control in a microgravity environment is the heat pipe. These devices can accommodate a wide range of operating temperatures, can transport large amount of heat, and can operate independently of gravity. The high heat transfer rates that can be achieved are typical of phase-change heat transfer devices. However, heat pipes have their own limitations, as described by Dunn and Reay (1994). One major limit is that the amount of heat transfer carried by these devices is governed by the liquid flow rate produced by capillary pumping in the wicking material of the heat pipe.

In this paper, we introduce a radically new, self-contained heat-pipe-like cell for microgravity applications (patent pending) that may overcome this traditional limitation of the heat pipe. The heat transfer in this cell is based on forced two-phase convection using a novel fluidic technology called VIDA (Vibration Induced Droplet Atomization) that has been recently developed at Georgia Tech (patent pending). Inside the cell, the VIDA technology creates a fine spray of droplets from the liquid condensate layer at the cold end of the cell. The fine droplets of the spray travel to the opposite hot end of the cell where they impact the hot surface and are evaporated. This evaporation

produces a large vapor pressure that forces the vapor back down the cell toward the cold end where it recondenses to form the liquid condensate layer used to supply the spray.

II. VIDA Technology

The VIDA technology that forms the basis of the design for this heat transfer cell is the result of a recent observation at Georgia Tech of a novel droplet instability. Consider a droplet of a condensed liquid attached to a metal diaphragm that is continuously vibrated normal to itself. As long as the diameter of the droplet is below a critical value, the liquid motion induced by the vibrations of the diaphragm are damped, ostensibly by viscosity and contact-line dissipation effects. As we increase the size of the droplet, the diameter soon reaches a critical value and an instability of the liquid-gas interface occurs due to disturbances at the vibrational frequency of the diaphragm. The instability manifests itself as a set of nonlinear surface waves that rapidly grow in amplitude. When the wave amplitude is of the order of the droplet height, the droplet breaks up and is *completely* drained into a spray of smaller (between one and two orders of magnitude) secondary droplets that is directed away from the diaphragm. The jet velocity near the surface appears to depend on the vibrational energy of the primary droplet prior to its breakup.

Figure 1 shows a sequence of snapshots of this droplet breakup. A water droplet having a planform diameter of 5 mm is placed on a horizontal circular metal diaphragm with a diameter of 25 mm and a thickness of 0.2 mm. As the diaphragm vibrates in its fundamental axisymmetric mode, droplet resonance and breakup is achieved as the amplitude of the vibration reaches a critical limit. The evolution of the droplet instability and breakup were recorded using a video camera. Figure 1a shows the unforced droplet for reference. As the excitation level is increased, waves first appear around the perimeter of the droplet near its contact line with the surface (Figure 1b). The waves then increase in amplitude and progress towards the crest of the droplet (Figure 1c). In this figure we also see that a few secondary droplets have already been ejected from the large droplet. Finally, in Figure 1d, the breakup is complete and the ejected secondary droplets have landed on the surface of the diaphragm under gravity. Figure 2 is a side view of a similar event. The unforced droplet is shown in Figure 2a and the droplet in the middle of the spray process is shown in Figure 2b. The black disk at the bottom of Figure 2b is the holder of the diaphragm and it is approximately 25 mm in diameter. This scale shows that most of the secondary droplets are within 5 cm of the surface.

Once the droplets are formed, they are propelled upwards at speeds that can exceed 50 cm/s near the surface. If the primary liquid droplet is continually replenished, then the small secondary droplets form a continuous spray. The mass flow rate of this spray can be significantly larger than the flow rate possible in the wick of a heat pipe and so a phase-change heat-transfer device based on this principle will have significantly better performance than conventional heat pipes.

III. The VIDA Heat Transfer Cell

A prototypical cell based on the VIDA technology described above is shown in Figure 3 (patent pending). It is a completely sealed rectangular container with one end attached to a surface being cooled while the other is attached to a hot surface. The lateral surface of this cell would be insulated or slightly heated to prevent condensation. The cold end of the cell is vibrated at a specific frequency and amplitude. As the vapor in the cell condenses on the cold surface at specifically constructed condensation sites, the condensation droplets will begin to grow. When these droplets reach a critical size, the free-surface instability produced by the vibration will cause the droplets to disintegrate into a spray of smaller secondary droplets that will be propelled across the cell. When these droplets impact the opposite heated surface, they spread out and are vaporized. The vapor produced by this process travels back across the cylinder and condenses on the cold end to complete the heat transfer cycle in the cell.

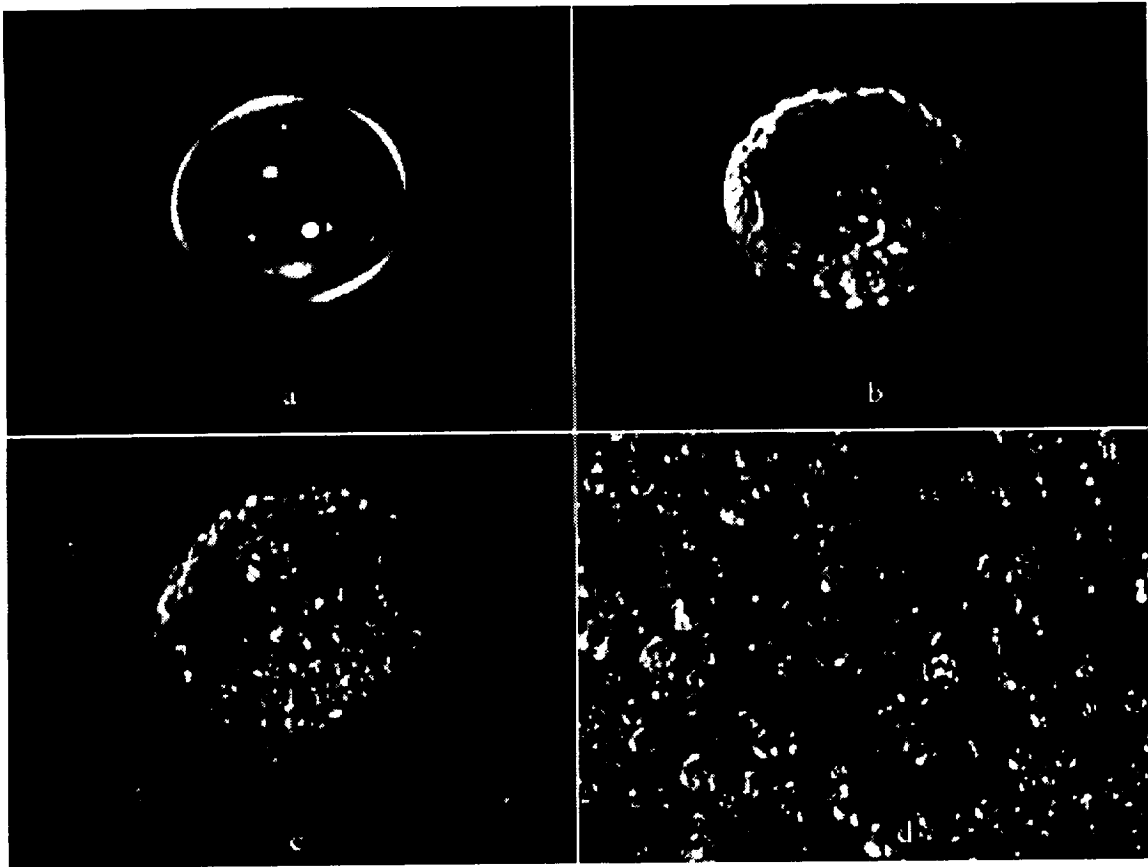


Figure 1: Four views of a liquid droplet on a vibrating diaphragm. a) The undisturbed droplet, b) the appearance of waves around the periphery, c) small waves over the entire droplet surface and the shedding of a few secondary droplets, and d) the total disappearance of the initial droplet.

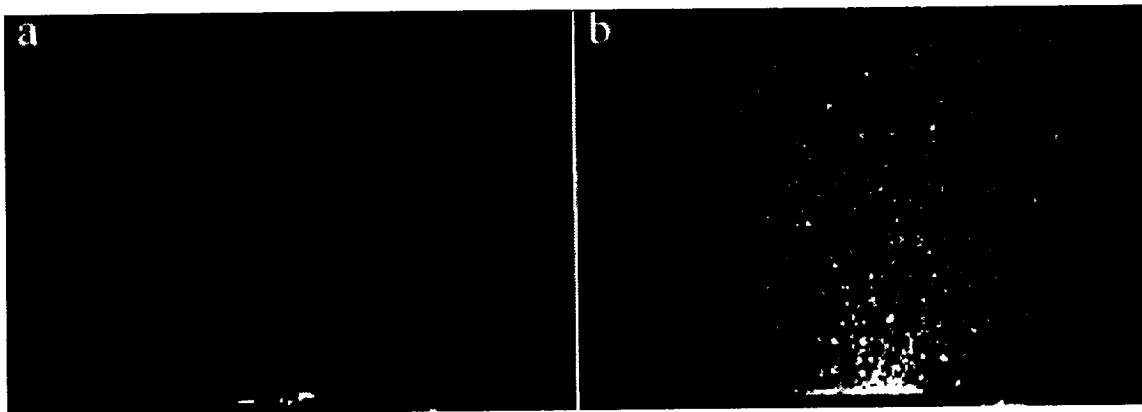


Figure 2: A side view of the droplet on a vibrating diaphragm. a) The undisturbed droplet, and b) the spray produced by the droplet resonance. Figure 2b is for a time somewhere between that of Figures 1c and 1d.

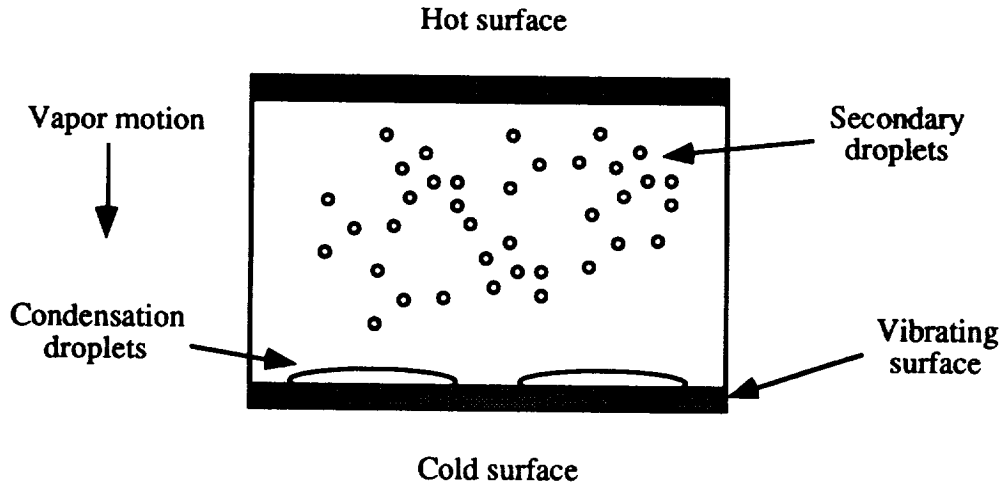


Figure 3: A schematic of the VIDA heat transfer cell.

IV. Physical Mechanisms

The physics associated with this droplet breakup instability must be understood in order to optimize the design of a heat transfer device based on this effect. The mechanism that causes the droplet instability is not well-known at this time, but there are a number of possibilities. The first is that the waves seen on the large droplet are a form of Faraday wave, similar to those seen when a container of liquid is vibrated vertically. (Faraday waves have recently been reviewed by Miles and Henderson, 1990.) At some specific frequency, the system goes into resonance and the Faraday waves on the droplet grow in amplitude and eventually pinch off to form the droplets. These waves are essentially a capillary wave and so their wavelength is related to the capillary length scale and the resonant frequency of the system. Thus, it is reasonable to assume that the size of the secondary droplets shed in the spray is also related to this wave length.

Despite the similarity with Faraday waves, there are several differences. The first is that classical Faraday waves are produced when a whole container of liquid is vibrated (an effective oscillation of the gravitational field). For the droplet, only the lower surface is oscillated and the liquid is not even contained at all. The second difference is that the resonant frequency of the droplet is larger than the frequencies typically used to explore Faraday waves.

A second possibility is that the waves on the large droplet are cross waves. Such waves were studied by Miles (1988). They are formed when a rigid plate is inserted part way into a liquid and then vibrated across the free surface. This causes an oscillatory motion of the contact line along the plate that in turn produces short stubby waves normal to the rigid plate. For the droplet, the contact-line motion is produced by the action of the surface vibration as it tends to periodically flatten and extend the droplet. In Figure 1b, we see that the first indications of wave motion seems to occur around the periphery of the droplet.

A third speculation on the cause of the droplet instability is that it is the result of high frequency pressure fluctuations that occur inside the droplet due to the vibrating diaphragm. When these pressure fluctuations resonate with the capillary waves on the surface of the droplet, they produce a large amplitude surface wave that pinches off at the crest to eject a small secondary droplet from the surface. This may be somewhat related to the mechanism for the atomization process of liquid jets as studied by Kang and Lin (1990) and Dressler and Kraemer (1990). However, for these jets the oscillation is along the axis of the jet parallel to the free surface, not normal to the free surface as in our droplets.

In order to fully examine the capability of this heat transfer cell, our current work is directed towards an understanding of the spray formation process. We are examining a small droplet on a

solid surface in which the surface vibrates vertically at a fixed frequency. From the frame of reference of a coordinate system moving with the plate, the system looks like a droplet subjected to an oscillatory gravitational body force. The flow is governed by the Navier-Stokes equations with the relevant free-surface boundary conditions. In addition, we pose a dynamic contact-line boundary condition and slip at the contact line. Although there is a great deal of similarity between this problem and the classical Faraday wave problem, one crucial difference is that a flat surface is not an equilibrium solution for the droplet problem. Thus, we can not treat this as a normal instability problem and use the standard weakly nonlinear techniques in the way discussed by Miles and Henderson (1990). The obvious inertial effects and nonlinearities exhibited by the droplet in Figure 1 indicate that we will most likely have to solve the full Navier-Stokes equations. We shall solve these equations numerically. We anticipate some difficulty in this calculation when the resonant frequency is approached and the wave amplitudes become very large. This difficulty is associated with the extremely fine scale at which the primary droplet breaks down into the spray. Another difficulty will be the precise model and computation for the motion of the contact line on the flat solid surface. One approximation that may be effective is to assume very small viscosity in the liquid. This seems reasonable in the light that we are examining a resonance phenomena in which damping may not play very much of a role. A perturbation analysis applied to this problem for small damping will produce the inviscid model to leading order. Solving this should be considerably easier than the fully-viscous problem, and it should simplify the difficulties associated with slip at the contact line. First-order effects of viscosity can be found using the usual regular perturbation methods.

The experimental work on this problem will investigate the effect of the liquid and surface properties on the evolution of the droplet instability, and, in particular, on the breakup of the primary droplet and the formation of the spray. Important parameters include the surface tension, density, and viscosity of the liquid, the wetting characteristics of the solid surface, and the amplitude of the surface vibration. The effect of liquid properties and droplet size on the amplitude threshold of the surface motion that is necessary for the onset of the breakup will be investigated. The time constants associated with the amplification of the instability and on the onset of primary droplet breakup and ejection of secondary droplets will be measured. The breakup and ejection process will be studied using high-speed and time exposure photography. The effect of liquid properties and primary droplet size on the size and density of the ejected secondary droplets will be investigated. Laser sheet illumination will be used to study the distribution, concentration and size of the secondary (ejected) droplets in planes that are vertical to and normal to the surface. Of particular interest is the nominally axisymmetric angular distribution in a plane that is normal to the surface and passing through the axis of the primary droplet. We will obtain estimates of velocity distributions (and thus of linear momentum) of the secondary droplets by using fast double shuttering of the laser sheet similar to what is done in PIV (particles image velocimetry) techniques. This can be accomplished using either video imaging or photographic film.

V. Conclusions

Our work on the VIDA technology has indicated that our proposed heat transfer cell design will lead to an order of magnitude increase in heat-flux performance over conventional heat pipes used in current microgravity applications. The primary reason for this performance is that the proposed heat transfer cell uses a forced phase-change convection process that breaks through the capillary wicking limit of conventional heat pipes. Our current program of ground-based research is directed towards support of the conceptual design and the construction of a prototype of the heat transfer cell discussed above. Once constructed and tested, we believe that the heat transfer cell will be ready for direct use in a space experiment designed to demonstrate its performance in a microgravity environment.

References

Dressler, J. L. & Kremer, G. O. (1990) "A multiple drop-size drop generator for calibration of a phase-doppler particle analyzer," *Liquid Particle Size Measurement Techniques: 2nd Volume*.

ASTM STP 1083, E. Dan Hirlman, W. D. Bachalo, and Philip G. Felton, Eds., American Society for Testing and Materials, Philadelphia, pp. 30-44.

Dunn, P. D. & Reay, D. A. (1994) "Heat Pipes," Elsevier Science Ltd.

Kang, D. J. & Lin, S. P. (1990) "Navier-Stokes flow for the initial stage of atomization," J. Colloid Interface Sci. 134, pp. 74-81.

Miles, J. (1988) "Parametrically excited, standing cross-waves," J. Fluid Mech. 186, pp. 119-27.

Miles, J. & Henderson, D. (1990) "Parametrically Forced Surface Waves," Ann. Rev. Fluid Mech. 22, pp. 143-65.