

## Control Of Flowing Liquid Films By Electrostatic Fields In Space

E. M. Griffing<sup>1</sup>, S. G. Bankoff<sup>1</sup>, <sup>1</sup>Chemical Engineering, Northwestern University, Evanston IL, 60208-3120, USA, e-griffing@nwu.edu, R. A. Schluter<sup>2</sup>, <sup>2</sup>Physics and Astronomy, Northwestern University, Evanston IL, 60208-3120, USA, M. J. Miksis<sup>3</sup>, <sup>3</sup>Engineering Science and Applied Mathematics, Northwestern University, Evanston IL, 60208-3120, USA

### INTRODUCTION

Future space missions will benefit greatly from light weight radiators capable of rejecting large amounts of heat. The generation of  $1\text{ MW}$  of electric power requires a compact source such as a nuclear reactor, which produces as much as  $1.5\text{ MW}$  of waste heat [11]. This heat must be radiated into space. Most current designs utilize high pressure heat pipes, which employ redundancy and possibly armor to protect against damage from micrometeorites. These radiators make up about a third of the system weight. New designs which safely incorporate thinner walls and lower the need for redundancy will dramatically reduce weight. Because of the expense of moving a given mass out of earth gravity, this weight savings translates directly into cost savings.

The Electrostatic Liquid Film Radiator (*ELFR*) was proposed by Kim, Bankoff, and Miksis [8] in 1991. This design utilizes thin film flow to carry heat over a large membrane. Low internal pressures allow for thin, lightweight, membrane walls. The heavy armor is dispensed with by allowing for holes due to micrometeorites. Coolant leakage is then prevented by the application of an internal electric field local to the 'leak' hole. The electric field creates a pressure drop across the fluid interface. If this pressure drop is greater than the internal pressure of the radiator and any normal gravitational force, *both free design parameters*, the pressure within the liquid at the radiator wall will be negative and leaks will be suppressed.

Redundancy in an *ELFR* is reduced, because the radiator can be operated with most micrometeorite holes. Current heat pipe designs, on the other hand, use 28% redundancy [11]. The radiator is partitioned, and a leak is stopped by turning off the damaged section. Several *ELFR* designs, such as a tubular radiator, and a spinning conical radiator are explored in Kim, Bankoff, and Miksis [9, 10]. Assuming the same operating temperature as used in the heat pipes, the conical radiator design, shown in figure 1 could in principle achieve a reduction in weight over present designs of the order of 90% [4]. This remains to be explored in detail, but clearly a vigorous effort is justified. These designs assume the radiator to be operating in zero  $g$ , but other designs may allow for operation on the moon or Mars.

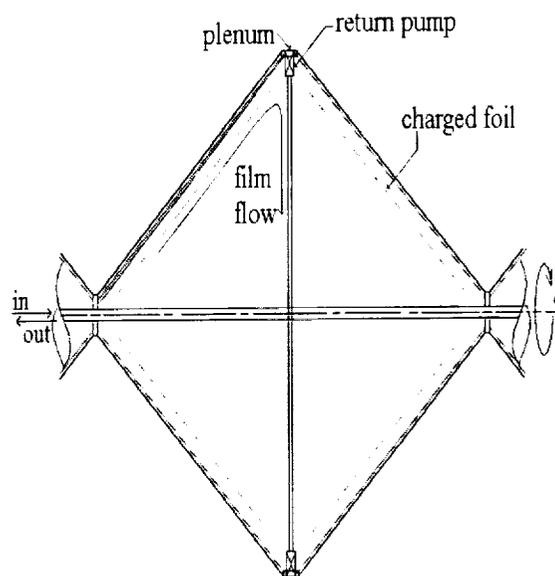


Figure 1: In this conical *ELFR* design, radiator fluid is distributed among multiple rotating cones. The cone angle,  $B$ , and rotation rate,  $\omega$  are used to set an artificial acceleration. Fluid flows radially along each cone, is collected by a plenum at the outer edge, and returned to the center by a small mechanical pump.

In order for a safe design and failure analysis to be made, more has to be learned about the fundamental behavior of a fluid film as it passes under an electrode. The film height and the electric field are coupled. This produces a mechanism whereby the fluid can touch the electrode and cause a breakdown of the field. Further complicating the situation, traveling waves are expected to form in the radiator. The interaction of these traveling waves with the field also needs to be studied. The dynamics of the fluid within a 'leak' hole present a complicated free surface problem which can affect leak rates, especially for lunar or Mars based applications.

The effect of an electric field on fluid interfaces is the subject of extensive study as it bears on ink jet printing, spray painting, emulsifying, etc. In 1964, Taylor and McEwan [13] derived a linear stability result for a stationary inviscid fluid of infinite depth under

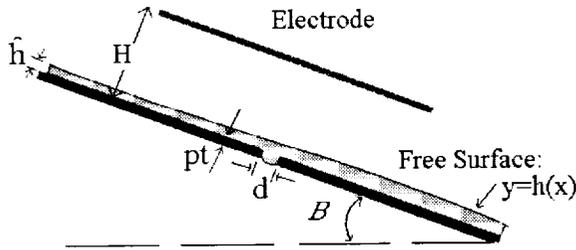


Figure 2: Coordinate scheme of flow under an electrode.

an infinite electrode. These results compare well with their experiments, which show the formation of ‘Taylor cones’ at a critical voltage. These cones form jets which touch the electrode and short the circuit when the fluid is a conductor. Other authors studying pattern formation and stability of horizontal interfaces in the presence of electric or magnetic fields include Silber and Knobloch [12], and Deyirmenjian et al. [1].

Work involving electric fields and thin moving films has been far less common. For this problem, Kim, et al. [7, 9] and Gonzalez and Castellanos [3, 2] have used long wave theory. Both authors calculate the stability of the Nusselt flow for an infinite electrode and show the field to be purely destabilizing. In the case of flow down an inclined plane with no field, the long wavelength instabilities are often not seen experimentally, as observable amplitudes are slow to develop. For an *ELFR*, the flow only has to be stable for the length of a radiator, so that only instabilities with a short enough characteristic development time are important. Kim, et al. use lubrication theory, Karman-Polhausen theory, the Korteweg-de Vries equation and Marker and Cell *SOLA* [5] algorithm to obtain 2D height and pressure profiles of a thin film in the presence of a fixed electric field for various geometries. The stability of these primary flows as they pass under an electrode and the coupling of the field and the fluid interface, in close proximity to the electrode, remain to be studied.

In the current work the flow under a finite electrode down a vertical plate is studied experimentally. Fluid height profiles and critical voltages for instability can be used to test theoretical predictions. Pressure profiles are obtained with a manometer, and leak rates are studied as a function of pressure driving force for various hole shapes and film Reynolds numbers.

## EXPERIMENT

We consider a thin liquid layer flowing down an inclined plate as shown in figure 2. The height and

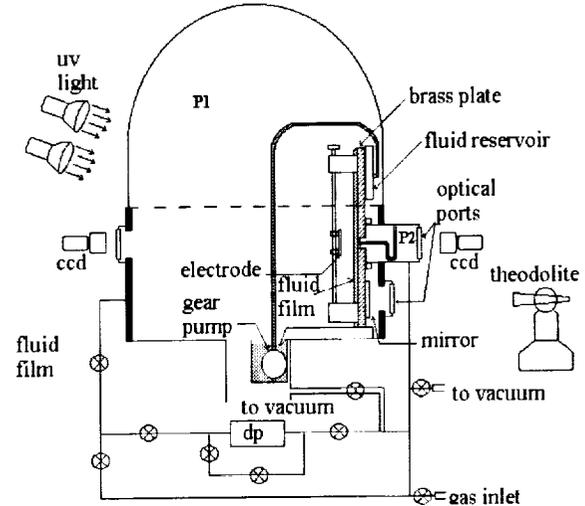


Figure 3: The experimental apparatus is used to measure fluid height and pressure profiles, instability voltages, and leak rates.

length of the electrode are given as  $H$  and  $l$ . The height of the fluid layer and the length of a typical disturbance are given as  $\hat{h}$  and  $L$ . The diameter of the ‘leak’ hole and the plate thickness are given as  $d$ , and  $pt$ . Typical experimental values of  $H$ ,  $l$ ,  $\hat{h}$ ,  $d$ , and  $pt$  are 1.5 cm, 5 cm, 0.05 cm, 0.1 cm, and 0.1 cm respectively. Because  $d \ll l$  and  $\hat{h} \ll H$ , the effect of the hole on the flow dynamics is negligible.

The experimental apparatus, shown in figure 3, consists of a vertical brass plate, fluid reservoir, pump, and electrode inside a vacuum chamber. The vacuum is used to reach high fields without electrical breakdown. Fluid flows continuously down the plate passing under the electrode. The whole apparatus can be tilted to a desired angle  $85^\circ < B < 95^\circ$ , which is measured with a theodolite. This allows for a normal component of gravity of  $-100 \text{ cm/s}^2 < g_n < 100 \text{ cm/s}^2$ . A manometer is used to measure pressure profiles, and a fluorescence imaging method [6] is used to measure height profiles. The electrode is held on threaded rods so that it can be moved in the direction of flow to vary the relative position of the ‘leak’ hole, and normal to flow to vary  $H$ .

The primary flow velocity profile without the field is parabolic. Several primary flow height profiles for an uncoupled electrostatic field, as calculated by Kim, et al., are shown in figure 4. The amplitude of the steady standing wave decreases as the Reynolds number increases. This is due to a momentum flux balance

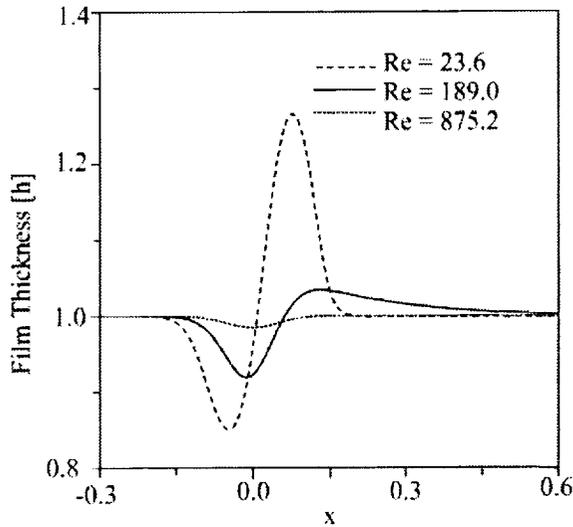


Figure 4: Reprinted from Kim, et al.[7]. The steady state wave amplitude is shown to decrease as  $Re$  is increased.

between the pressure exerted by the field and convection away from the electrode due to the flow. As the electric field is increased past some critical voltage, a new type of electrohydrodynamic instability, *EHI*, is observed experimentally. This instability is similar to Taylor cones, but is more complex. The fluid changes from a 2D shape to a distorted moving 3D cone which emits a liquid jet in less than a tenth of a second. In the case of a dielectric fluid, the liquid jet passes under the electrode harmlessly. In the case of a conductor, the jet induces breakdown and causes the system to fail.

In the horizontal static film case, the formation of the cones is governed by a balance of the destabilizing electric force with the stabilizing gravitational and surface tension forces. The surface tension and the gravitational forces then form a selection mechanism making most dangerous wavelengths of approximately 1.6 cm for water and 1.1 cm for organic oils [13]. In the experiment with a vertical plate, there is no normal gravitational force, the fluid is of finite depth with velocity, and the electrode is finite. Linear stability theory for an infinite electrode shows the longest waves to be the most unstable, but also the slowest growing [14]. In this case, the observed lengths of the *EHI* are less than 2 cm.

Because the *EHI* can cause the failure of the system, the critical voltage of the onset of the instability represents the limit of the force which can be exerted by the field. The coupling of the field and the fluid

interface in the horizontal case was shown significantly to reduce the critical field for electrode heights  $H < 1$  cm. For  $H = 1.5$  cm and  $5 < Re < 40$ , the *EHI* is observed at  $V \approx 15$  Kv. This corresponds to a pressure of  $\approx 50$  dynes/cm<sup>2</sup>. The vapor pressure of lithium, a suggested radiator fluid, is 9 dynes/cm<sup>2</sup> at 700K. Using these figures, an artificial acceleration as large as  $\approx 0.5$  g could be overcome with the electric field.

The fluid height is measured by the fluorescence imaging method, the details of which are given in Johnson et al.[6]. A fluorescent dye is introduced into the working fluid, and incident ultraviolet light induces fluorescence in the visible range. A digital camera held normal to the fluid is then used to record the fluorescence intensity produced by a patch of fluid. The intensity is then correlated with fluid height through a model equation. Preliminary experiments show that the steady state profiles in the parameter ranges of the experiment are smaller than the accuracy of the imaging system, which is roughly 2% of the film depth. A more accurate 16 bit camera will be used in future work to obtain the height profiles.

The pressure profiles are obtained with a manometer, which taps the vertical plate and uses the working fluid, so that only one fluid interface affects the measurement. A traveling microscope is then used to measure the displacement of the interface. The pressure is obtained as a function of position in the direction of flow by moving the electrode with respect to the manometer. Because  $g_n$  is zero, lubrication theory shows that for low  $Re$ ,  $dP/dy$  is zero to first order. The pressure exerted by the electrode at the interface is then transmitted across the fluid film. Figure 5 shows the experimental pressure profiles for various  $Re$  and  $A$ , the aspect ratio of the hole,  $pt/d$ , as compared with the pressure profiles predicted by an uncoupled calculation of the electrostatic field. These data confirm that the pressure drop across the film is within the error of the measurement, 3 dynes/cm<sup>2</sup>. For the case of a dielectric fluid, the thickness of the brass plate, or  $A$ , will affect the field within the 'leak' hole and possibly the measured pressure.

To measure leak rates, the fluorescent imaging system is again used. In this case, a macroscopic lens is used to focus on the back of the leak hole. Depending on flow conditions, either a single or a double rivulet forms as the leaking fluid drains down the plate. By getting the height profile of these rivulets in the transverse direction and assuming a parabolic profile, we can instantaneously estimate the relative flow rate of the leak. Figure 6 shows an example image of a double rivulet leak and the transverse flow rate profile. Figure

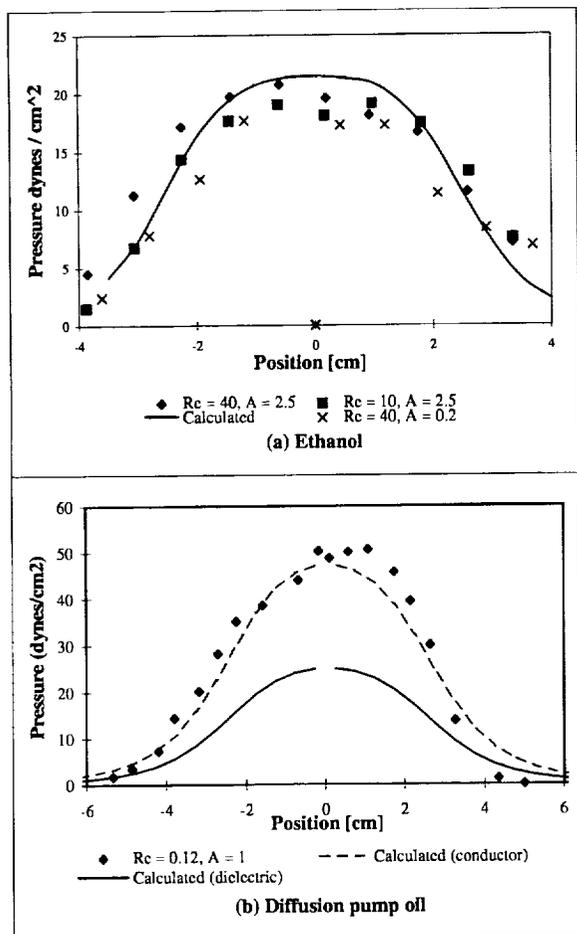


Figure 5: Measured pressure profiles confirm that the pressure exerted by the field at the fluid / vapor interface is transmitted across the film with unmeasurable hydrodynamic effects.

7 shows the flow rate decrease to zero as a voltage of  $\approx 11$   $Kv$  is approached. The Reynolds number,  $Re$ , was varied over  $5 < Re < 40$ , and no significant change in the critical voltage required to stop a leak was observed.

Several important aspects of this experiment should be noted. The effect of gravity is to make a pressure drop from the top to the bottom of the leak hole of  $77$   $dynes/cm^2$ , significantly affecting leak stopping experiments on earth. Also, the fluid in this case is ethanol, which wets the brass plate. Capillary forces therefore induce leaking, and cause a complicated moving contact line problem at the back of the hole. Future experiments will determine the effect of wetting and possibly gravity on leak rates. Finally, the interface at the back of the

hole in a non-leaking situation is observed to vibrate at a frequency which is greater than  $24$   $Hz$ . The  $g$  force associated with this vibration has not been measured. In all future experiments of this nature, the whole apparatus is to be suspended by a  $2m$  chain to suppress these high-frequency oscillations.

The major result here is that it has been shown experimentally that leaks from a low-volatility fluid (lithium at  $700$   $K$  and gallium or diffusion pump oil at  $525$   $K$ ) pumped-loop *ELFR* can be stopped by application of an electric field well below the critical value for the *EHI* under space conditions. Weight comparisons for equivalent power with a conventional heat-pipe radiator are difficult to make, since the two radiator systems are quite different. However, purely on a basis of estimated weight per kilowatt at a radiator temperature of  $525$   $K$ , for a  $1675$   $Kw$  radiator, the *ELFR* has been roughly estimated to be well below one by Mason et al. in 1989 [11, 4].

A major source of difficulty in conducting a leakage experiment in earth gravity is the tendency for the fluid to drain down the back side of the plate. In a space experiment, gravity will be nearly zero, or else radially outwards, so that the meniscus at a round hole will remain symmetric with no preferred direction for leakage.

## ACKNOWLEDGMENTS

This work is supported by NASA. The contribution of Mr. R. Gwinner under a grant from the German government for the design phase of the work is acknowledged with thanks.

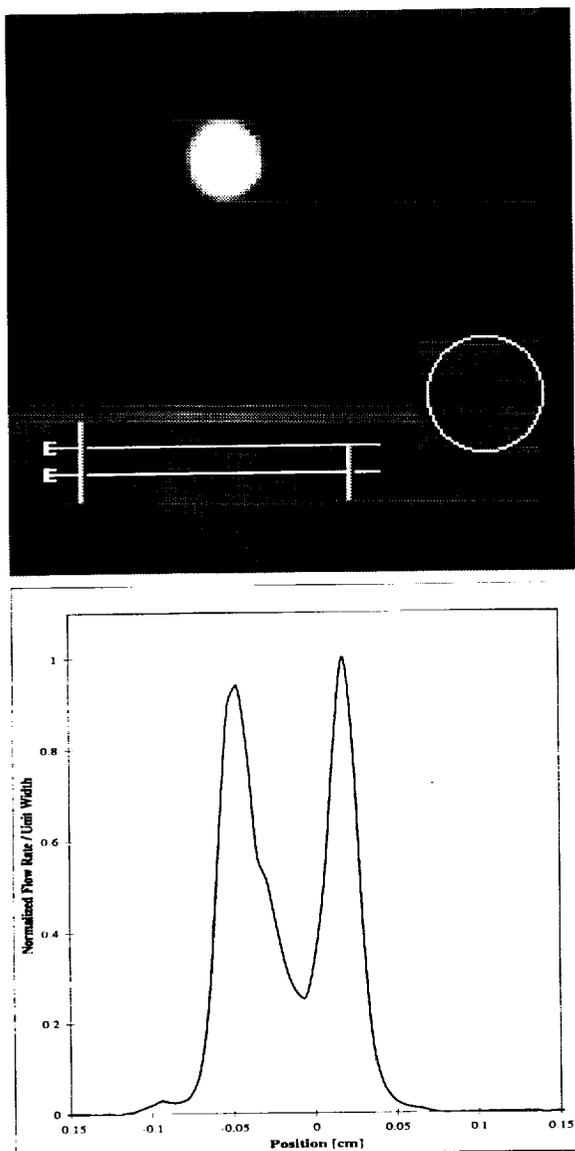


Figure 6: Leak rates are measured with the fluorescence imaging method. The bright circle is the 1 mm leak hole. The flow rate is calculated as the integral of the flow rate profile across the rivulet at the horizontal lines. The area within the circle is used to normalize the incident light intensity.

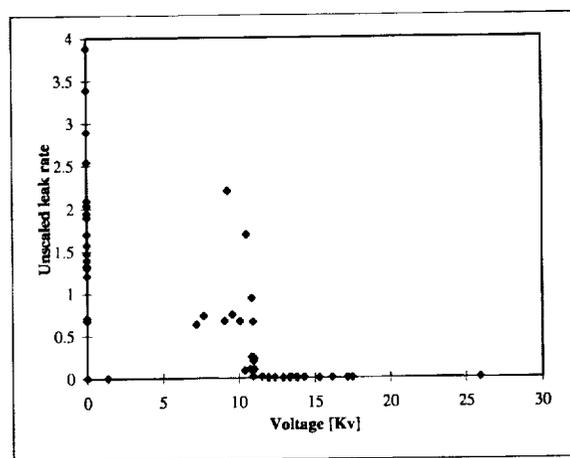


Figure 7: The leak rates measured as in Figure 6 decrease to zero as a critical voltage is reached.

## REFERENCES

## References

- [1] V.B. Deyirmenjian, A.D. Zahir, and S. W. Morris. Weakly nonlinear analysis of electroconvection in a suspended fluid film. *Physical Review E*, 56(2), 1997.
- [2] A. Gonzalez and A. Castellanos. Korteweg-de Vries-Burgers equation for surface waves in non-ideal conducting liquids. *Physical Review E*, 49(4), 1993.
- [3] A. Gonzalez and A. Castellanos. Nonlinear electrohydrodynamic waves on films falling down an inclined plane. *Physical Review E*, 53(4), 1995.
- [4] R.R. Gwinner and S.G. Bankoff. Design study of an electrostatic liquid film space radiator. Unpublished technical report, chemical engineering, Northwestern university, 1992. Contact gbankoff@nwu.edu.
- [5] C.W. Hirt, B.D. Nichols, and N.C. Romero. SOLA - A Numerical solution algorithm for transient fluid flows. Technical report, Los Alamos Scientific Laboratory of the Univ. of California, Los Alamos, 1975.
- [6] M.F.G Johnson, R.A. Schluter, and S.G. Bankoff. Fluorescent imaging system for global measurement of liquid film thickness and dynamic contact angle in free surface flows. *Rev. Sci. Instrum.*, 68(11), 1997.
- [7] H. Kim, S.G. Bankoff, and M.J Miksis. The effect of an electrostatic field on film flow down an inclined plane. *Phys. Fluids*, 1991.
- [8] H. Kim, S.G. Bankoff, and M.J Miksis. Lightweight space radiator with leakage control by internal electrostatic fields. In *Proc. Eighth Symp. On Space Nuclear Power Systems*, CONF.-910116, 1991.
- [9] H. Kim, S.G. Bankoff, and M.J Miksis. Interaction of an electrostatic field with a thin film flow within a rotating conical radiator. *AIAA Journal*, 1992.
- [10] H. Kim, S.G. Bankoff, and M.J Miksis. Cylindrical electrostatic liquid film radiator for heat rejection in space. *J. of Heat Trans.*, 1994.
- [11] Lee S. Mason, Harvey S. Bloomfield, and Donald C. Hainley. SP-100 power system conceptual design for lunar base applications. Technical Report TM 102090, NASA Lewis Research Center, Cleveland, OH 44135, 1989.
- [12] M. Silber and E. Knobloch. Pattern Selection in Ferrofluids. *Physical Review D*, 30, 1988.
- [13] G.I. Taylor and A.D. McEwan. The stability of a horizontal fluid interface in a vertical electric field. *J. Fluid Mech.*, 22(1), 1965.
- [14] C.S. Yih. *Fluid mechanics: a concise introduction to the theory*. West River Press, Ann Arbor, Mich, 1988.