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Explosive Boiling at Very Low Heat Fluxes: A Microgravity Phenomenon

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ABSTRACT

The paper presents experimental observations of explosive boiling from a large(relative to bubble sizes) flat heating surface at very low heat fluxes in microgravity. The explosive boiling is characterized as either a rapid growth of vapor mass over the entire heating surface due to the flashing of superheated liquid or a violent boiling spread following the appearance of single bubbles on the heating surface. Pool boiling data with saturated Freon 113 was obtained in the microgravity environment of the space shuttle. The unique features of the experimental results are the sustainability of high liquid superheat for long periods and the occurrence of explosive boiling at low heat fluxes (0.2 to 1.2 kW/m^2). For a heat flux of 1.0 kW/m^2 a wall superheat of 17.9 ^{o}C was attained in ten minutes of heating. This was followed by an explosive boiling accompanied with a pressure spike and a violent bulk liquid motion. However, at this heat flux the vapor blanketing the heating surface could not be sustained. Stable nucleate boiling continued following the explosive boiling.

NOMENCLATURE

p = pressure

q = heat flux

T = temperature

t = time

Subscripts

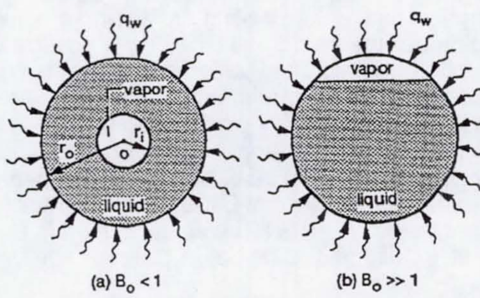
w = wall condition

s = saturated condition

INTRODUCTION

An important issue in microgravity fluid management is controlling pressure in on-orbit storage and resupply systems for cryogenic propellants and life support fluids; i.e., liquid hydrogen, oxygen and nitrogen. Pressurization occurs in closed cryogenic fluid storage tanks due to heat leaks through a tank's thermal protection system. In a microgravity environment, the liquid-vapor interface configuration is principally determined by the surface tension force. The interface configuration also depends on the fluid properties, tank geometry, and liquid fill level. Usually, the contact angle and Bond number (Bo) characterize the interface configuration. Figure 1(a) shows a representative liquid-vapor configuration for a wetting fluid in a spherical tank in a microgravity (Bo < 1) environment. The interface configuration on the ground where Bo > > 1 is shown in Fig. 1(b) for comparison.

The microgravity liquid-vapor configuration presents unique thermal problems for the storage of cryogenic



(a) Microgravity configuration, Bo < 1.

(b) Normal gravity configuration, Bo >> 1

Figure 1. Liquid-vapor configurations of a wetting fluid in a spherical tank

fluids in space environment. For a partially full tank there may not be direct contact between the tank wall and the vapor region. Heat transfer will occur from the tank wall to the liquid and then to the vapor. As a consequence, the entire liquid region may be superheated. The maximum liquid superheat will occur at the tank wall. A superheated liquid represents a metastable condition and may lead to pressure spikes of varying magnitudes in a closed system either due to boiling or flashing of superheated liquid. Lin and Hasan (1992) analytically investigated the problem of thermal stratification and self-pressurization of partially filled liquid hydrogen storage tanks subjected to a uniform wall heat flux in a microgravity condition. Their results show that in the absence of convective motion, a high liquid superheat can be attained even at very low heat fluxes. Of course, how high a liquid superheat can be sustained cannot be predicted theoretically. Such information has to come from experiments performed in the relevant acceleration environment.

The fact that even at very low heat fluxes, a high liquid superheat can be sustained for a long duration in microgravity was first demonstrated in a flight experiment titled "Tank Pressure Control Experiment" (TPCE). The TPCE was flown on the Space Transportation System, STS-43 in August 1991. The primary objective of the TPCE was to investigate the jet induced fluid mixing process in a long duration microgravity environment. A detailed description of the experiment and the experimental results are given by Bentz, et al. (1992) and Bentz, M. D. (1993).

The initial conditions, such as the tank pressure and the liquid temperature stratification for each test of the TPCE were produced by flat heating surfaces immersed in nearly saturated Freon 113. The results of the heating phase of this experiment constitute the first set of pool boiling data obtained in the long duration microgravity environment of the space shuttle (Hasan, et al. 1993). The experimental data clearly demonstrated that stable nucleate pool boiling can be sustained in a long duration microgravity environment for very low heat fluxes. The data also showed that in microgravity, a high liquid superheat can be sustained for long periods (several minutes). The superheating was usually followed by pressure spikes of considerable magnitude which suggest that violent boiling or flashing of superheated liquid near the heater wall may have occurred. However, the photographic observation of the events could not be made during the experiment. This led to the reflight of the TPCE with the primary objective to obtain video observation of the thermal and fluid dynamic processes during the heating phase. The second experiment titled "Tank Pressure Control Experiment/Thermal Phenomena" (TPCE/TP) was performed in the Space Shuttle Columbia, STS-52, in October 1992.

From this experiment, a unique explosive boiling phenomenon from a large heating surface has been observed under a microgravity condition in a process of very slow heating of nearly saturated Freon 113. The phenomenon observed is distinctly different from explosive boiling of liquids under rapid heating conditions (Skripov and Pavlov, 1970 and Skripov, V. P., 1974). In this paper we present the photographic observations of the explosive boiling and the subsequent events following this particular type of boiling process in the long duration microgravity environment of the space shuttle.

THE EXPERIMENT

Figure 2 shows the schematic of the experimental system. It consists of a 0.254 m diameter cylindrical tank with hemispherical domes. The volume of the tank is 0.0137 m^3. The tank is filled with Freon 113 to about 83 percent by volume. A jet nozzle is positioned along the tank's major axis near one end of the tank to provide fluid mixing. Two pumps located outside the tank are supplied with vapor free liquid by a liquid acquisition device(LAD).

Two heaters, designated as heater A, and heater B, are immersed in the fluid. Heater A is located within 0.5 cm of the end of the tank wall opposite the jet nozzle. Heater B is off the tank major axis and approximately 2.5 cm away from the tank wall. Figure 3(a) shows the heater configuration and some details of its assembly. The two heaters are constructed of an etched-foil element encased in silicon rubber insulation, which is sandwiched between two 304L stainless steel plates. The outside dimensions of the heater assembly are 10.46 cm by 7.42 cm. The total surface area (both sides of the heater) is 155 cm^2. Both heaters are the same size, except that heater A is bent to a 12.1 cm radius to follow the curvature of the tank wall. The heater assembly is welded to a standoff tube which supports the assembly

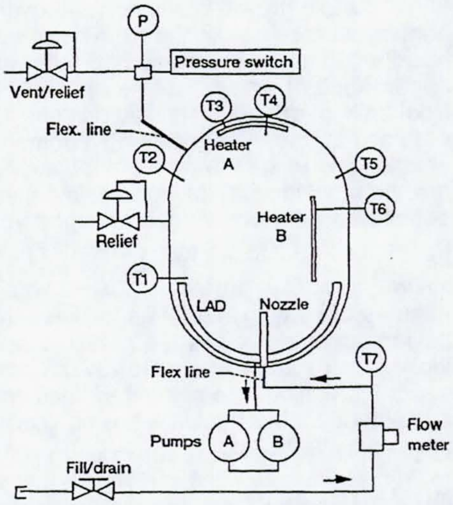


Figure 2. Schematic of experimental system

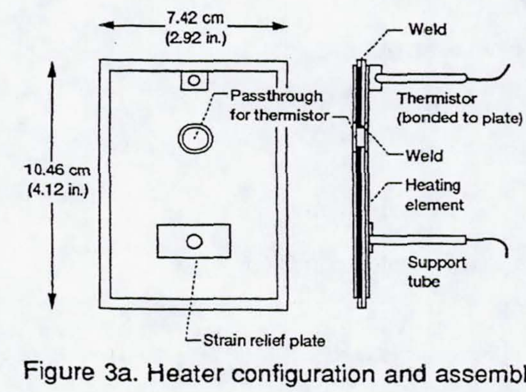


Figure 3a. Heater configuration and assembly

and contains the leads. The total mass of each heater, excluding the standoff tube and thermister, is 0.214 kg, and the thermal capacitance is estimated to be 0.10 kJ/C. Power is supplied to the heater by a battery pack consisting of 96 F-size alkaline cells. Figure 3(b) is a photograph of the two heaters.

The primary measurements during the heating phase of a test include the tank pressure, heater power, heater surface temperature and the liquid temperature as functions of time. The temperature probes shown in Fig. 2 are thermistors encapsulated in stainless steel sheaths. Thermistors T3 and T6 measure the surface temperature of heaters A and B, respectively. Other thermistors measure liquid temperature at various locations in the tank. Three accelerometers are installed on the tank support to measure acceleration in three axes. Video observations are recorded by two modified 8-mm camcorders. The apparatus and the range and accuracy of measuring devices are described in detail by Bentz (1993). Figure 4 is a photograph of the plexiglass test tank showing heaters and other accessories installed.

Twenty one tests, consisting of various combinations of jet flowrates and heaters were performed. Each test is designated as "Run Number". The initial condition of each test was established by heating the fluid with either heater A, or heater B, or both heaters on. The heating phase for each test lasted either 10 minutes or 18 minutes. Video observation of the entire heating period was recorded. The heating rate for each test was constant, but varied between 7.2 to 18.0 W during the test matrix. The heat flux corresponding to the above heating rates ranged from 0.2 to 1.2 kW/m^2. In this paper, we present only the experimental observations of the boiling process from heater A.

RESULTS AND DISCUSSION

Experimental results of all twenty one test runs and complete video record are presented elsewhere (Hasan, et al. 1993). This paper includes the results of the heating phase of test runs 6, 7, 8, 12 and 13. Only heater A, was turned on during these tests. The unique features of the experimental results are the sustainability of high liquid superheat for long periods and the occurrence of explosive boiling at low heat flux of about 1.0 kW/m^2. Based on the photographic observation of the boiling process, we characterize the explosive boiling as either a rapid growth of vapor mass over the entire heating surface due to flashing of superheated liquid or a violent boiling spread following the appearance of single bubbles on the heating surface.

Figure 5, a still photograph taken from the flight video tape, shows an actual liquid-vapor configuration during a flight experiment. The tank wall is entirely wetted by the liquid. The nearly spherical vapor bubble (also referred to as ullage bubble) surrounded by liquid represents 17 percent vapor volume. The location of the ullage bubble could not be controlled during a test. However, for most of the test runs during "Tail First" orbiter attitude (Bentz, M. D. 1993), the ullage bubble remained approximately in a symmetric position with respect to heater A.

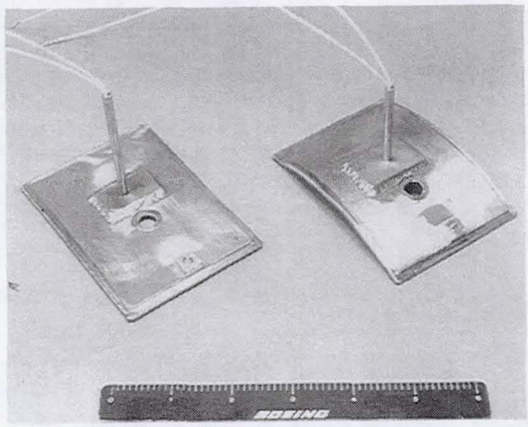


Figure 3b. Heaters

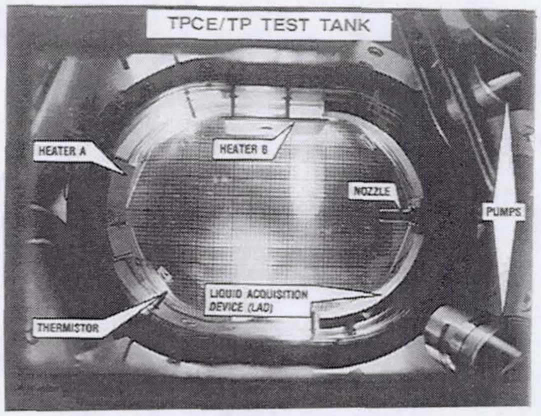


Figure 4. Plexiglass test tank showing heaters and other accessories

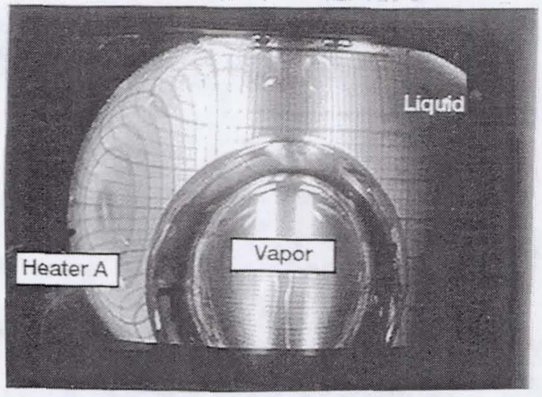


Figure 5. Actual liquid-vapor configuration during a flight experiment

The experiment was performed under steady state thermal conditions. At the start of the heating period, the maximum temperature stratification in the liquid was less than 1^{o} C. Thermistor T1 measures the liquid temperature farthest from either heater A or heater B. Therefore, the temperature measured by thermistor T1, is taken as the bulk liquid temperature. At the start of the heating phase, the bulk liquid temperature was within

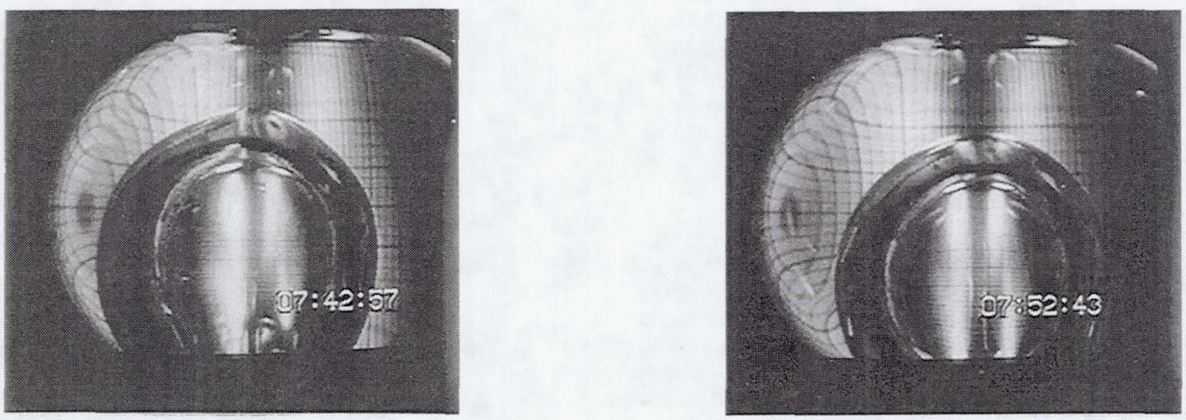
1° C of the saturation temperature at the tank pressure. The initial tank pressure during the test runs reported in this paper ranged from 44 to 51 kPa. The heater power was constant during each test. The heating period for each of test runs 6, 7 and 8 lasted for 10 minutes, and for runs 12 and 13, the heating continued for 18 minutes. Experimental data shows that a relatively high liquid superheat can be sustained for long periods (several minutes) in microgravity. The boiling delay time and the incipient boiling wall superheat were found to be affected by location of the ullage bubble. The boiling delay time and the incipient boiling wall superheat for test runs 6, 7, 8, 12 and 13 are listed in Table 1.

Figures 6(a) to 6(f) are still photographs taken from the flight videotape for run 13. The sequence of the

Table 1. Boiling delay time and incipient boiling wall superheat

RUN NO.		T1	T_s	T_w	T_w-T_s	P	q_w
6	t_o=0	23.7	24.4	22.7		43.5	
	t_1=2.73	23.8	24.8	30.1	5.3	44.1	.107
	t_2=2.82	23.9	26.3	30.0		46.9	
7	t_0=0	24.2	24.9	23.6		44.3	
	t_1=6.21	24.4	26.2	37.3	11.1	46.7	.104
	t_2=6.25	24.5	31.9	36.8		58.2	
8	t_0=0	24.5	25.2	24.0		43.0	
	t_1=6.47	24.8	27.7	38.3	10.6	49.6	.103
	t_2=6.51	24.9	33.3	38.2		61.4	
12	t_0=0	26.9	27.8	25.8		49.6	
	t_1=8.76	27.2	30.3	41.2	10.9	54.8	.098
	t_2=8.79	27.3	35.8	41.2		67.4	
13	t_0=0	27.7	28.2	26.7		50.3	
	t_1=9.77	27.7	28.3	46.2	17.9	50.7	.097
	t_2=9.79	27.7	36.9	46.0		70.0	

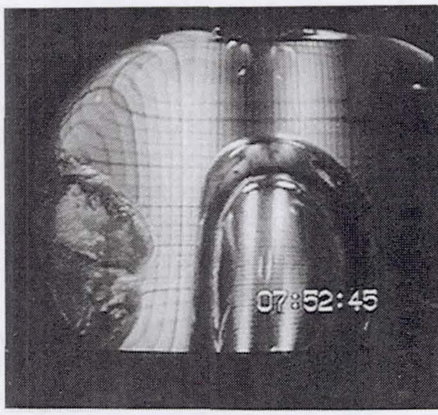
t_0 (min): Heater is turned on
t_1 (min): Boiling inception time
t_2 (min): Tank pressure reaches peak value



6(a) Initial liquid-vapor configuration:
Elapsed heating time = 0 second.

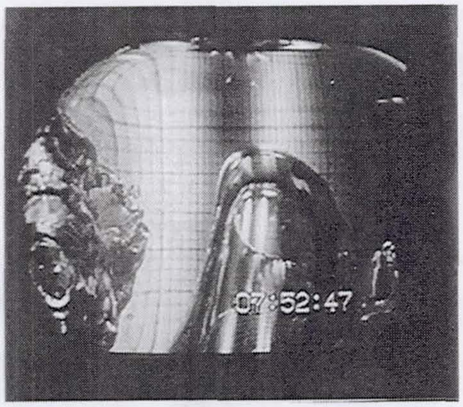
6(b) Liquid-vapor configuration:
Elapsed heating time = 9 minutes 46 seconds.

Figure 6. Explosive boiling from heater A and subsequent events; Run no. 13.

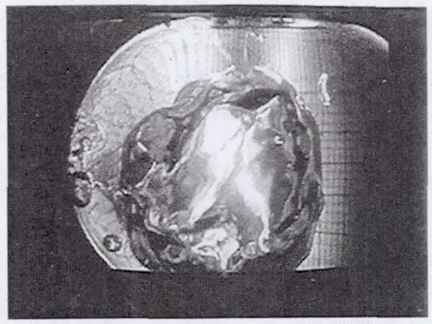


6(c) Initiation of explosive boiling: Elapsed heating time = 9 minutes 48 seconds: Wall superheat 17.9^{o} C.

6(d) Growth of vapor mass and violent bulk liquid motion: Elapsed heating time = 9 minutes 49 seconds.



6(e) Same as (d): Elapsed heating time = 9 minutes 50 seconds.



6(f) Stable nucleate boiling: Elapsed heating time > 12 minutes.

Figure 6. Concluded.

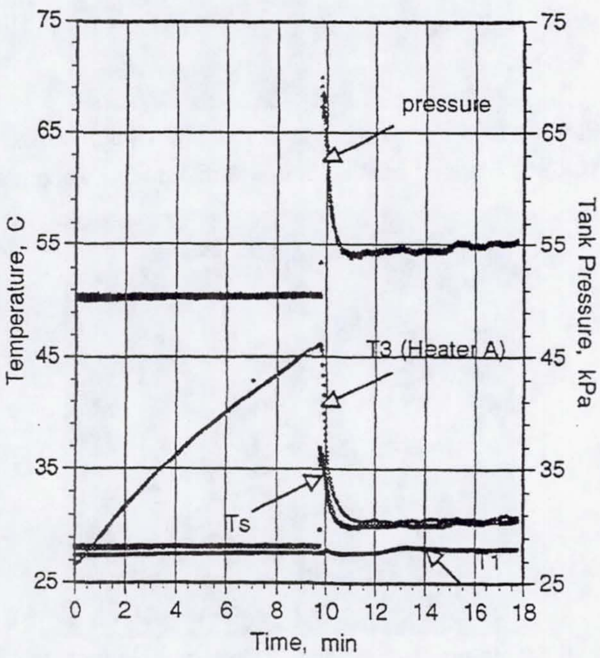


Figure 7. Heater and liquid temperatures (T3 and T1) and tank pressure as functions of time: Run no. 13.

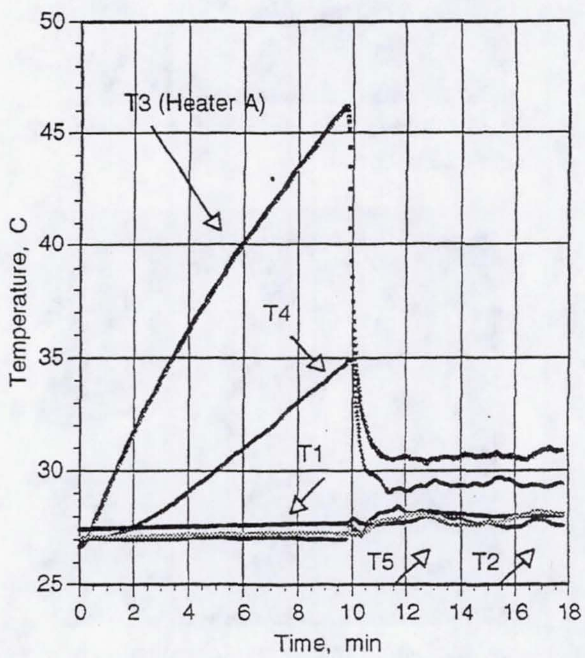
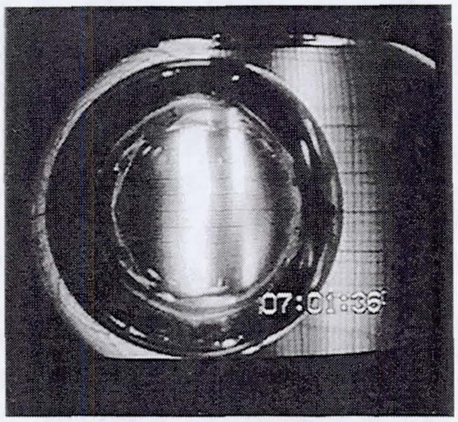


Figure 8. Liquid temperatures as functions of time: Run no: 13

photographs clearly shows the occurrence of explosive boiling from heater A and the subsequent liquid motion. Figure 6(a), taken just when heater A was turned on shows the initial liquid-vapor configuration.The ullage bubble was approximately 4 cm away from heater A.. Figure 6(b), taken after 9 minutes and 46 seconds of heating time shows that the ullage bubble location remained practically unchanged. Figure 7 shows the heater wall temperature and the tank pressure as functions of time for run 13. During 9 minutes and 46 seconds of heating period the heater wall temperature, T_W (measured by thermistor T3) , increased from 26.7^o C to 46.2^o C. The tank pressure during this time changed only slightly from 50.3 to 50.7 kPa. The bulk liquid temperature, T1, remained constant at 27.7 ^{o} C. The wall superheat at this point reached a value of 17.9^o C. Figure 8 shows that the liquid temperature, T4, approximately 1 cm away from heater A, is 35^o C. This represents a superheat of 6.7^o C. Figure 6(c) shows the inception of explosive boiling accompanied by a pressure spike as indicated in Fig.7. The explosive growth of vapor mass as indicated in Figs. 6(d) and 6(e) is due to rapid evaporation. This imparts momentum to the liquid bulk which then induces violent liquid motion and eventually sweeps away the vapor mass from the heating surface.The heater temperature dropped from 46.2^o C to about 30.8^o C and remained steady during rest of the heating period. The vapor blanketing the heating surface could not be sustained at this low heat flux, 1 kW/m^2. The heater surface temperature profile, shown in Fig. 8, and the video observation beyond 12 minutes of heating clearly show that stable nucleate boiling continued following the explosive boiling.

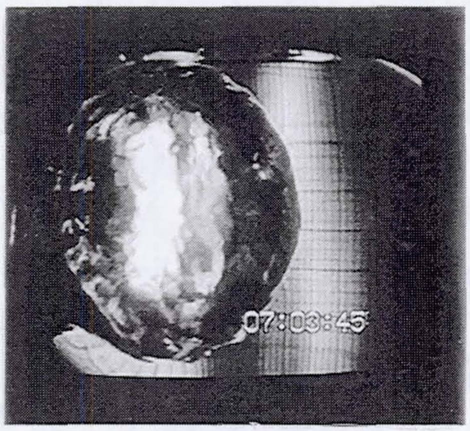
For test runs 7, 8, and 12 the ullage bubble location during the heating period was nearly identical. The ullage bubble was symmetric with respect to heater A, and was located within 2 cm away from the heater. Experimental results from test runs 7, 8, and 12 show remarkable similarity. The incipient boiling superheat for each test was nearly the same. Table 1 shows that incipient boiling wall superheat varied between 10.6^o to 11.1^o C. Boiling inception was accompanied with rapid growth of vapor mass and momentary pressure spikes.

Figures 9(a) to 9(d) show the events occurring during heating phase of run 12. The ullage bubble location

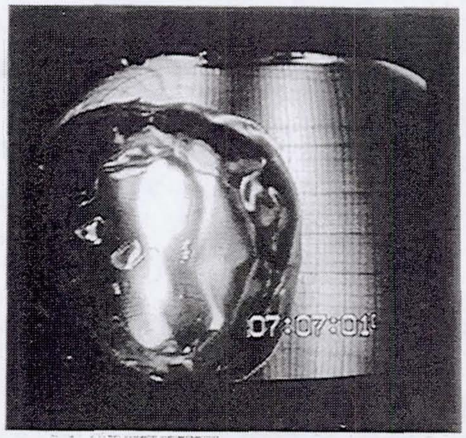


9(a) Ullage bubble location: Elapsed heating time= 6 minutes 39 seconds

9(b) Explosive growth of vapor mass: Wall superheat 10.6^{o}C: Elapsed heating time = 8 minutes 47 seconds



9(c) Growth of vapor mass, surface agitation and bulk liquid motion.



9(d) Stable nucleate boiling : Ullage bubble acts as a sink to smaller bubbles

Figure 9. Boiling process on heater A: Run no. 12

shown in Fig. 9(a) corresponds to elapsed heating time of 6 minutes 39 seconds. The bubble location at the start of the heating phase was almost the same as shown in Fig. 9(a). After 8 minutes and 47 seconds boiling with explosive growth of vapor mass occurred, (see Fig. 9(b)). Boiling inception was accompanied with a momentary pressure spike of about 18 kPa, as indicated in Fig.10. The rapid growth of vapor mass induced significant surface agitation and liquid motion is shown in Fig. 9(c). Figure 9(d) shows the large vapor bubble nearly touching the heater surface and a vapor sink to smaller bubbles. The bubbles form on the heater surface and merge with the large vapor bubble, thus helping to sustain the nucleate boiling in microgravity. A similar phenomenon in a short duration reduced gravity experiment was observed by Siegel and Keshock (1964).

The type of explosive boiling described in this paper was also observed by Ervin, et al. (1992) in a short duration (5 seconds) microgravity pool boiling experiment with nearly saturated Freon 113. Based on the drop tower result, they suggested a lower limit of heat flux of 40 kW/m^2 that might produce explosive boiling. The results obtained in the long duration microgravity environment show that conditions leading to explosive boiling from a large heating suface can be produced with heat flux as low as 1 kW/m^2.

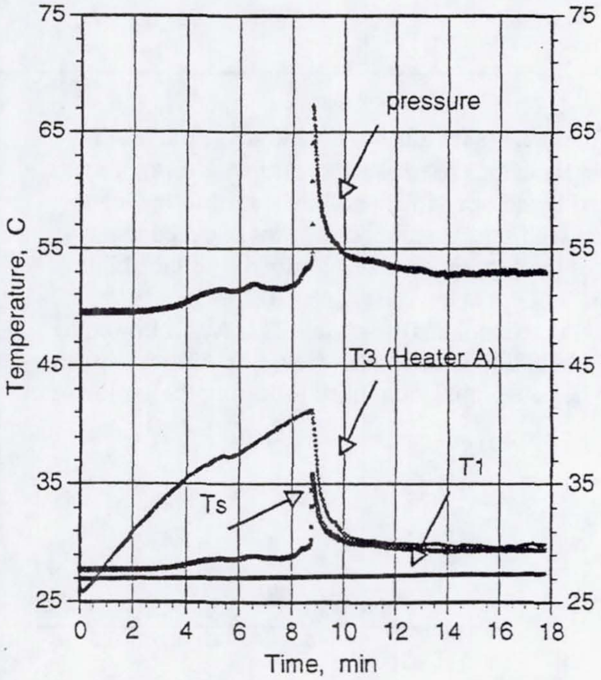


Figure 10. Heater and liquid temperatures and tank pressure as functions of time : Run no. 12.

CONCLUSIONS

Experimental observations of pool boiling in the microgravity environment of the space shuttle clearly demonstrated the sustainability of high liquid superheat for long periods and the occurrence of explosive boiling at heat fluxes as low as 1 kW/m^2. High liquid superheat and explosive boiling at such a low heat flux are uniquely microgravity phenomena.

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13. ABSTRACT ***(Maximum 200 words)***

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