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AXIAL PROPAGATION OF FREE SURFACE BOILING INTO SUPERHEATED LIQUIDS IN VERTICAL TUBES

BY

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AXIAL PROPAGATION OF FREE SURFACE BOILING INTO SUPERHEATED LIQUIDS IN VERTICAL TUBES

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Abstract

A unique free surface boiling phenomenon has been observed as a result of rapid depressurization of an initially saturated or slightly subcooled stagnant liquid column in the absence of wall and bulk nucleation sites. Closeup high-speed photographs of water, refrigerant-11, and methyl alcohol in tubes from 0.2 to 15 in. diameter reveal that the initiation of violent free surface flashing (vapor plus entrained liquid) follows from the development of Marangoni-type surface waves. The rate of propagation of the flashing surface shows evidence of choked flow limitations and proceeds at a rate which is several orders of magnitude greater than surface evaporation (vapor only) alone. The onset of free surface flashing was found to be dependent upon both the degree of initial liquid superheat and the tube diameter.

NOMENCLATURE

P : Pressure
P_f : Pressure during flashing
ρ_ℓ : Liquid density
h_{fg} : Latent heat of vaporization
ρ_v : Vapor density
T_o : Initial temperature
ΔT_{si} : Initial liquid superheat defined in text
T_s : Saturation temperature at reference pressure
G : Mass flow rate per unit cross section area
S : Entropy
x : Vapor mass fraction

Subscripts
o : Stagnation conditions
f : Saturated liquid
eq : Equilibrium condition
exp : Experimental
R : Reservoir
B : Base of test section

INTRODUCTION

A rather unique two-phase flow phenomenon has been observed in a process of investigating rapid expulsion of a superheated liquid from a vertical tube.[1] In these experiments, the extent of initial liquid superheat was achieved by rapid depressurization of a previously saturated or slightly subcooled stagnant liquid column. In the absence of nucleation sites at the tube walls and dissolved or entrained gas in the bulk liquid, flashing occurred only at the free surface, i.e., no bulk flashing occurred. After initiation, this interface from which the two-phase flow proceeded continued to propagate into the stagnant superheated liquid column to the end of the same.

A number of experimental studies have been reported on the rapid depressurization of nearly saturated liquids. However, as noted below, these studies generally involved bulk nucleation and therefore differs markedly from the present study. Terner[2] reports of the rapid depressurization of water heated to initial temperatures of up to 238°C. However, only qualitative discussion of some resulting pressure-time traces were presented. No special preparation of the water or test channel was noted and no direct visual observation of the events were reported. It is therefore difficult to assess the exact nature of the events following depressurization. However, the more detailed observations and measurements of Edwards and O'Brien[3] at similar high temperatures (242°C and 284°C) with depressurization to one atmosphere may likely be pertinent to the previous study. The test channel was filled under vacuum with degassed water, pressurized and heated to the desired temperature. Following depressurization, simultaneous pressure, temperature, and X-ray void fraction measurements were recorded at various axial locations. Temperature and pressure measurements at the same location indicated thermodynamic equilibrium in the bulk of the fluid was attained almost instantly as the initial rarefaction wave passed through the liquid. This was supported by X-ray void fraction evidence of void formation within the bulk of the fluid within the same short time after rupture of the diagram.

These X-ray observations of void formation are in agreement with the visual observations of Friz.[4] Friz studied the expulsion resulting from the rapid depressurization of water at lower pressures (1-3.5 atm). A glass test section was employed and the depressurization event was recorded photographically with a high speed camera. Both degassed and unprepared water were employed. However, following depressurization, in both cases many bubbles were immediately observed in the bulk of the fluid below the initial liquid level. The expulsion of the two-phase fluid was characterized by an "acceleration front" whose depth was reported to be several centimeters. On the visual evidence of the formation of many bubbles, thermodynamic equilibrium was assumed of this acceleration front. It was also suggested that the overall expulsion process was a two-phase critical flow.

Similar studies with water at low pressures (1 to 4 atm) were briefly reported by Le Gonidec et al.[5] Little detailed discussion of the phenomena was reported. However, it was indicated that pressure measurements indicated near saturation conditions in the fluid following depressurization and results similar to those of Ref. 4 were obtained.

More recently, Hooper et al.[6] reported on an experimental study of flashing of numerous liquids and proposed a new "Law of Flashing." The internal static pressure within the liquid during the early part of the transient flashing period while vapor bubbles are growing was found to assume a nearly constant value. This quasi-equilibrium pressure, which lies between the saturation and blowdown pressures, is given by the empirical relationship

$$(P_f/\rho_\ell h_{fg} J)_{T_o} = 0.318\ (\rho_v/\rho_\ell)^{4/3}_{T_o} \qquad (1)$$

It is seen that P_f depends only on the initial liquid temperature T_o and the physical properties of the fluid, and is independent of the initial and blowdown pressures and of the shape of the column. Equation 1 is only valid when inertia effects dominate and when bulk nucleation occurs.

Thus, the available studies of the consequences of rapid depressurization of various liquids would suggest the immediate appearance of many bubbles within the bulk of the fluid. The purpose of the present paper is to discuss an experimental study involving rapid depressurization of a number of nearly saturated liquids in the absence of wall and bulk nucleation.

EXPERIMENT

The experimental facility is illustrated in Fig. 1.

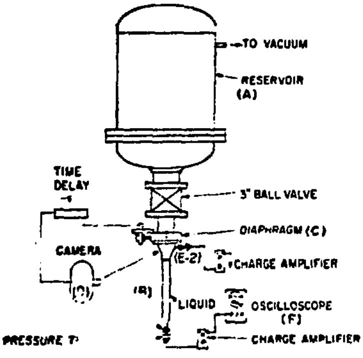

Fig. 1. Experimental Test Apparatus

The large reservoir (A) can be evacuated to serve as a low pressure sink. The volume of the reservoir ($\approx$ 10 ft^3) is large compared to the volume of the test sections (B). Glass test sections of diameters 2 through 50 mm and lengths 10 to 80 cm were used. One test section 20 mm x 30 cm length was provided with an outer jacket for the circulation of heating water to establish uniform test fluid temperature at any level above ambient up to $\approx$ 80°C. After filling with the test fluid, the test section was attached to the reservoir at the diaphragm burst assembly (C). An aluminum diaphragm separated the test fluid from the low pressure reservoir. The fluid was depressurized by rupturing the diaphragm with a solenoid actuated knife blade and depressurization was accomplished in less than 2×10^{-3} sec. A short time before the diaphragm break the high-speed camera (D) was started so that the desired running speed could be established at the instant of depressurization. The resulting phenomena was recorded on the motion picture film. During the expulsion, in some tests, pressures at the base of the test section (E1) and at the expansion section (E2) were measured with quartz piezoelectric pressure transducers and displayed on a dual-beam memory oscilloscope (F). The initial fluid temperature was taken to be either ambient temperature or the heating water temperature in the jacketed test section. Prior testing with actual measurements of the fluid temperature and comparison with either ambient or heating fluid temperature showed this to be a sufficiently good estimate of the test fluid temperature. Upon depressurization, the initial liquid superheat ΔT_{si} was taken to be the initial liquid temperature T_o less the saturation temperature corresponding to the reservoir pressure $T_s(p_r)$. The test fluids were water, methyl alcohol, and the freon refrigerant 11 and 113. In many instances, with water and in some instances with methyl alcohol depressurization produced many bubbles appearing in the fluid below the initial liquid level (similar to previous studies summarized above). These bubbles appeared to come off the wall. However, with careful cleansing and rinsing of the test section and degassing of the water by vigorous prior boiling, this appearance of bubbles in the fluid below the initial liquid level after depressurization could be completely prevented.

Less care was required in the case of the refrigerants. These fluids appear to wet the glass surface well and do not appear to degass readily upon depressurization. In fact, covering the free surface of F-11 with glycerol permitted slow depressurization to the extent that the fluid readily sustained liquid superheat in excess of 95°C before release through nucleation at some wall cavity site. None the less for all fluids mentioned above sufficient care in test procedure would insure the initiation of free surface boiling with no bubbles in the bulk of the liquid. A more detailed description of this phenomena follows.

DESCRIPTION OF FREE SURFACE BOILING

Closeup high-speed motion pictures of the free surface before, during, and after depressurization revealed an interesting concentric ring surface wave pattern at the free surface being established within 1 ms of the arrival of the depressurization front. This surface wave activity was also observed in a separate apparatus of 6 in. diameter. In this case, the wave pattern took on a more irregular configuration, sometimes cell-like, but not sustained in any simple geometric pattern. These waves are likely a result of surface tension variation induced at the free surface more commonly referred to as the Marangoni effect. The onset of such phenomena have been discussed in terms of stability analysis by Pearson,[6] Sternling and Scriven,[7] Vidal and Acrivos,[8] and others. Vidal and Acrivos point out the difficulty in assessing a

Table 1. Expulsion data for F-11, Water, and CH_3OH

RUN	A	B	C	D	E	F
Fluid	F-11	F-11	H_2O	H_2O	CH_3OH	CH_3OH
Initial liquid temperature, °C	23.9	40.0	71.7	81.1	50.6	66.1
Reservoir pressure, atm	.0167	.010	.010	.004	.007	.008
Initial liquid superheat referred to reservoir pressure, °C	80.5	102.2	65.0	98.9	73.9	82.8
Measured pressure at bottom of test section, atm	.3±.1	.45±.1	.22±.06	.27±.06	.19±.03	.32±.03
Liquid superheat during expulsion, °C	30.0	36.7	9.4	13.9	22.2	20.0
Measured mass flux, $\frac{K_g}{m^2sec}$	478±48	634±97	278±20	336±20	297±29	380±49
Calculated mass flux, $\frac{K_g}{m^2sec}$	449	683	244	346	293	425

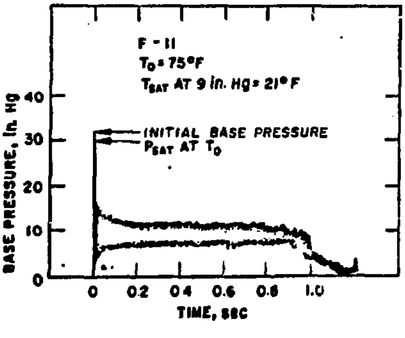

Fig. 3. Pressure Trace at Base of Test Section during Two-phase Flashing Run A

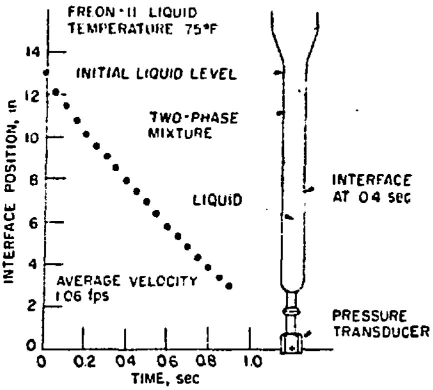

Fig. 4. Two-phase Flashing Interface Position vs Time

based on energy, momentum and continuity balance written about either side of the interface with the assumptions of saturated liquid conditions on one side and critical flow rate on the other. While the assumption of a saturated liquid is not verified by the data listed in Table 1, it is, however, interesting to note that an equilibrium critical flow rate evaluated at the measured base pressure P_B (which is different from the exit pressure) and

$$G = \left(\frac{\partial p}{\partial v}\right)_S^{-1/2} \tag{2}$$

an equilibrium quality $x_{eq} = S_o - S_f/S_{fg}$ shows good agreement with all three fluids. However, as indicated in Figs. 5a and b, the flow may not be truly choked depending upon the reservoir pressure conditions (the extent of depressurization). Note the full expansion of the plume in Fig. 5a at the lowest reservoir pressure (characteristic of critical flow) and the rather uniform ejection of the products at the higher reservoir pressure. A slightly lower interface velocity is noted in the latter case.

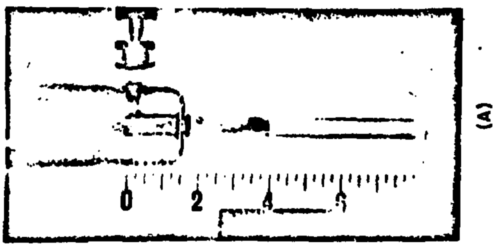

Fig. 5a. Illustration of Exit Region of Flashing Flow Illustrating Markedly Different Flow Expansion.
T_o = 26.5°C, P_R = 0.01 atm,
G^o = 400 K_g/m^2sec

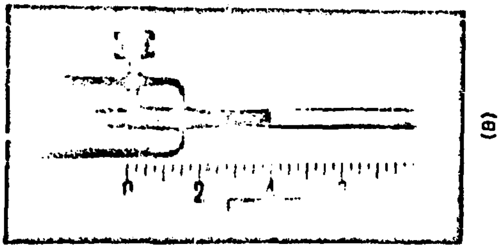

Fig. 5b. Illustration of Exit Region of Flashing Flow Illustrating Markedly Different Flow Expansion. $T_o = 26.5°C$, $P_R = 0.22$ atm, $G^o = 350\ K_g/m^2 sec$

An additional and perhaps equally important observation is a definite threshold in the liquid superheat required for initiating and sustaining free surface boiling. This initial threshold superheat is diameter-dependent for a given fluid, as shown in Fig. 6 for Freon-11 and Methyl Alcohol. For the data in Fig. 6, the initial temperature T_0 was approximately 30°C (86°F) and T_s was the saturation temperature at the reservoir pressure after rapid depressurization. The data should be interpreted in the following manner: for initial liquid superheat less than indicated in Fig. 6 for a given tube diameter, only evaporation takes place at the free surface and there is no two-phase flashing. For initial liquid superheat greater than indicated for a given tube diameter, two-phase flashing occurs; vapor plus entrained liquid are observed to proceed from the free surface (Fig. 5). Within the indicated uncertainty of the initial liquid superheat, the free surface boiling is intermittent and unsustained. These data along with the previous observations indicate that while two-phase critical flow rates may be present in this phenomenon, mass and energy transport at the interface itself must be better understood and is equally important in determining the actual two-phase flow regime.

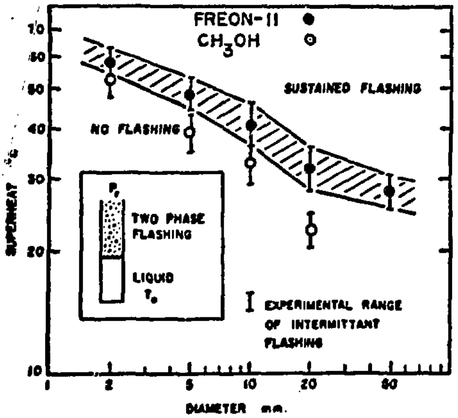

Fig. 6. Test Section Diameter Effect Upon Initial Liquid Superheat Required to Initiate and Sustain Two-phase Flashing from Free Surface

ACKNOWLEDGMENT

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