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INVESTIGATIONS OF LIQUID FLASHING AND EVAPORATION DUE TO SUDDEN DEPRESSURIZATION

R. J. PETERSON,* S. S. GREWAL† and M. M. EL-WAKIL‡

* Nuclear Safeguards and Licensing Division, Sargent and Lundy Engineers, Chicago, IL 60603, U.S.A.;
† Advanced Reactor Systems Department, General Electric Co., Sunnyvale, CA 94086, U.S.A.;
‡ Departments of Mechanical and Nuclear Engineering, University of Wisconsin, Madison, WI 53706, U.S.A.

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Abstract—The thermal-hydraulic response of a quiescent liquid layer to sudden depressurization was examined. Freon-11 at room temperature was used as a test liquid. The degrees of depressurization were such that the liquid bulk became superheated and flashing occurred. Two sets of experiments were conducted. In the first, a 20.3 cm Mach–Zehnder interferometer, high-speed photography, and associated equipment were used to record a succession of interferograms of the flashing liquid. These showed a heterogeneous mixture of superheated, saturated, and subcooled liquid. The degree of subcooling corresponded to the saturation temperature at approximately twice the pressure drop. Initial conditions varied from 97.2 to 101.0 kPa pressure and 19.3 to 21.1°C temperature, and depressurizations varied from 11.4 to 27.0 kPa. Liquid superheats up to 5.7°C and subcooling as much as 9.2°C below saturation were noted. The second set of experiments were conducted to determine mass transfer under flashing conditions. These showed mass transfer rates during flashing to be 10–12 times those due to evaporation alone. This is due to the agitation of the liquid as well as to the presence of entrained drops of subcooled liquid in the departing vapor. An empirical 'flashing factor', F, defined as the ratio of the mass transfer found in flashing and in evaporation was determined and given for the conditions of the experiments by

$$F = 27.5 - 0.527T_0 - 0.129\Delta P,$$

where T_0 is the initial temperature (°C) and ΔP the pressure drop imposed (kPa).

NOMENCLATURE

F	flashing factor, dimensionless
M	molecular weight [g mol^{-1}]
m''_{EV}	evaporative mass transfer per unit area [g cm^{-2}]
m''_{EXP}	experimentally observed flashing mass transfer per unit area [g cm^{-2}]
m''_{FL}	flashing mass transfer per unit area from equation (3) [g cm^{-2}]
n	refractive index, dimensionless
N	molar refractivity [cm^3 mol^{-1}]
P	pressure [kPa]
ΔP	pressure drop imposed on liquid [kPa]
r	radius [cm]
S	fringe shift, dimensionless
T_{min}	minimum liquid temperature [°C]
T_0	initial liquid temperature [°C]
T_{sat}	saturation temperature [°C]
y	position variable [cm].

Greek symbols

λ	wavelength of light [cm]
ρ	density of liquid [g cm^{-3}].

Subscripts

∞	undisturbed state.

THE EVAPORATION AND FLASHING PHENOMENA

A THOROUGH understanding of the physics governing phase change is useful in the design of boilers, heat exchangers, steam generators, and refrigeration, distillation, and desalination equipment, and the containment of liquefied gases. The phenomenon has also received considerable attention in the nuclear power industry where containment structures, and emergency cooling and safety equipment must be designed to remedy reactor loss of coolant accidents (LOCA). A knowledge of the transient coolant heat and mass transfer rates could be used to facilitate design as well as verify the accuracy of various computational models currently used to predict the thermal and hydraulic response of a nuclear reactor to a LOCA.

Two types of phase change that are of interest in the above cases are surface evaporation and flashing. Both processes are caused by a reduction in pressure at the vapor–liquid interface and result in a cooling of the liquid as the change in internal energy is consumed as latent heat of vaporization.

During evaporation, a thin surface layer is cooled. Initially, conduction from the bulk of the liquid to this layer is the dominant mode of heat transfer. The cooling of the liquid results in low vapor pressure and mass transfer rates in this conduction period. After a time delay convective heat transfer develops, which brings warmer liquid to the surface, and consequently increases the surface temperature and mass transfer rates.

Flashing, on the other hand, is caused by large pressure drops, converting the initially subcooled liquid bulk into superheated liquid. The phenomenon is initially more violent at the surface and causes the liquid to acquire a very heterogeneous temperature profile composed of superheated, saturated, and subcooled liquid. The greater turbulence perpetuates the phenomenon, results in higher rates of mass transfer, and eventually causes cooling throughout the liquid. Flashing may occur in the absence or presence of bulk nucleation. Bulk nucleation may also originate from exceeding the spontaneous nucleation temperature which causes the bulk of the liquid to explode into the vapor state. The absence of nucleation sites and dissolved gases within the liquid causes flashing to occur only at the surface. After a period, the liquid bulk cools down and behaves in a similar manner to a liquid undergoing evaporation.

The two processes may be represented by different boundary conditions imposed at the liquid–vapor interface. Evaporation is caused by local surface instability corresponding to what is believed to be a linear temperature change at the boundary. In contrast, flashing, with a rapid change in total pressure, corresponds to a step change in surface temperature.

Experiments performed by various investigators have examined events such as surface evaporation, boiling, bubble nucleation and growth; slug formation and growth; and two-phase expulsion. However, most of these studies lacked detailed quantitative, instantaneous, and continuous data of the phenomena.

The work reported in this paper was undertaken to fill a gap caused by the lack of experimental data relating to the heat and mass transfer rates encountered during sudden depressurization. The goals were to obtain quantitative data to explain the flashing phenomenon and the differences between flashing and evaporation, as well as provide qualitative information about the behavior of the liquid layer under sudden depressurization.

The present investigation examines the thermal-hydraulic response of a quiescent layer of initially subcooled liquid to sudden depressurization. Mach–Zehnder interferometry, adjusted for liquid measurement, high-speed photography, and associated equipment were used to study the thermal behavior of a layer of Freon-11 refrigerant (trichlorofluoromethane) to a sudden depressurization. The depressurization corresponds to imposing an initial superheat on the liquid. Subsequent temperature gradients within the liquid resulted in changes in refractive index, and caused fringes to appear. The resulting interferograms were then analyzed and temperature profiles were constructed which revealed the heterogeneous nature of the layer.

A second set of experiments was designed to examine the mass transfer rates present during evaporation and flashing. A separate apparatus was designed to allow visual observation as well as measurements of the total mass transfer for various initial temperatures and depressurizations. The results revealed the large differences between mass transfer rates encountered in flashing and evaporation. These differences were examined and explained. Empirical equations were then developed to allow the calculation of mass transfer during flashing in these experiments.

LITERATURE REVIEW

Evaporation experiments, in general, have studied the behavior and the onset of convection, or have attempted to determine evaporation rates of liquids. Berg *et al.* [1] presents a fine review of evaporative convection. Other significant endeavors include observations of convective currents in water [2]; theoretical and experimental analysis of the stability of a homogeneous fluid cooled from above [3, 4]; studies of the transient nature of evaporation [5–7]; and calculation of evaporation and diffusion rates [5, 6, 8–11].

Several experiments have been reported on the depressurization and subsequent flashing of liquids in an attempt to model a LOCA. Fritz [12], Edwards and O'Brien [13], and Hoppner [14] have furnished qualitative observations about bubble growth and the ejection process by rapidly depressurizing a vessel, and recording the transient pressure and temperature history. Change of phase by flashing has also been studied [15–19].

Miyatake *et al.* [15] conducted experiments to describe the mechanism of flash evaporation for comparison to a flash evaporator by exposing a pool of water to a sudden pressure drop. Two exponential decaying processes were observed; an initial period when violent boiling occurs throughout the liquid, and a latter period when boiling takes place only at the surface.

Hooper and his colleagues [16, 17] conducted depressurization experiments in which a static pool of liquid was suddenly exposed to a pressure below the initial liquid saturation pressure. Hopper and Kerba [17] postulated a 'Law of Flashing' which states that during depressurization the initial static pressure within the liquid in the early part of transient flashing assumes a nearly constant value. This quasi-equilibrium pressure lies between the initial saturation and final blowdown pressure and is dependent only on initial liquid temperature and the physical properties of the fluid, and is unaffected by changes in initial or blowdown pressures.

Hooper and Luk [18] also conducted and photographed experiments in a glass U-tube using distilled and degassed water to eliminate nucleation. However, nucleation still occurred and upon depressurization, a lowering of the liquid level was noted in the superheated leg of the U-tube. They attributed this and other surface instabilities to the recoil force caused by the rapidly departing vapor.

Grolmes and Fauske [19] observed two-phase flashing and noted a definite threshold in the amount of superheat required for initiating and sustaining flashing. They found this initial superheat to be weakly inversely dependent on channel diameter. At low superheats, they observed evaporation only. At higher superheats, flashing caused rates of flow several orders of magnitude greater than rates found due to evaporation alone.

Theoretical studies are limited to work by Palmer [20], who investigated the stability of the stagnant layer beneath the liquid surface during depressurization. However, his analysis was limited to quasi-static processes, and therefore the results are not amenable to the sudden depressurization of a liquid which is best described by rapidly changing transients.

INTERFEROMETER EXPERIMENTS

The first set of experiments performed in this investigation used an interferometer to examine subcooled Freon-11 undergoing a sudden depressurization sufficient to transform it to a superheated liquid. The Mach–Zehnder interferometer, normally used to study heat transfer boundary layers in gases was adapted to study the temperature fields in the liquid. This technique has advantages over methods that employ thermocouples or other physical probes in that it produces a two-dimensional (2-D) field rather than point data, and its response is instantaneous, continuous, highly sensitive, and does not physically interfere with the measured phenomenon. Preliminary work was presented in ref. [21]. Hauf and Grigull [22] present a review of interferometry and its applications to the field of heat transfer.

The experiments were performed in a specially constructed cell which was placed in the test path of a 20.3 cm Mach–Zehnder interferometer (Fig. 1). Freon-11 was used because of its superior wetting capabilities and a low boiling point (23.8°C) which enables thermal studies to be conducted without subjecting the optically-flat glass plates in the test cell to high thermal stresses.

A schematic of the experimental apparatus is shown in Fig. 2. The test cell consists of a 8 cm machined aluminum spacer enclosed between two optically-flat glass plates (15.2 × 17.3 cm and 3.8 cm thick). The plates were flat to $\lambda/20$ and the spacer was hand polished to a fine finish to eliminate nucleation sites and inhibit bubble nucleation. A bead of molding and potting compound served as a seal between the spacer and plates.

The cell was connected to a large reservoir (0.3 m^3) by a bellows, and separated from the reservoir by an aluminum foil diaphragm. An X-shaped cutter was used to cut the diaphragm and begin each run.

The experiments began by closing a switch which sent a signal to the solenoid controlling the cutting mechanism and the trigger processor. The signal also activated the trigger delay and produced a signal capable of triggering the oscilloscopes and flash unit.

The test cell was instrumented with strain-gauge and piezo-electric pressure transducers both located in the vapor region and a thermocouple located in the liquid region. The output of the strain-gauge transducer was recorded on a digital oscilloscope with floppy-disc storage. The thermocouple was mounted inside an insulated hole that was drilled to within a few hundredths of a millimeter of the inner surface of the cell spacer. It was mounted in this manner to avoid bubble nucleation inside the cell.

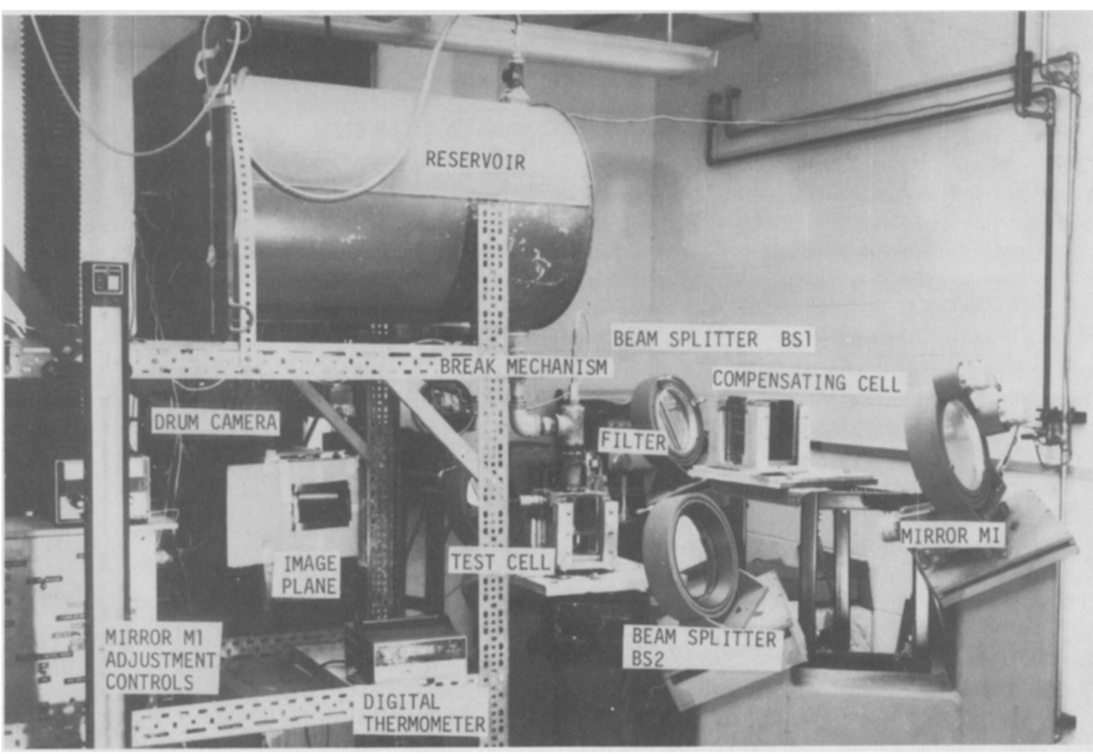

FIG. 1. Mach–Zehnder interferometer and supporting apparatus.

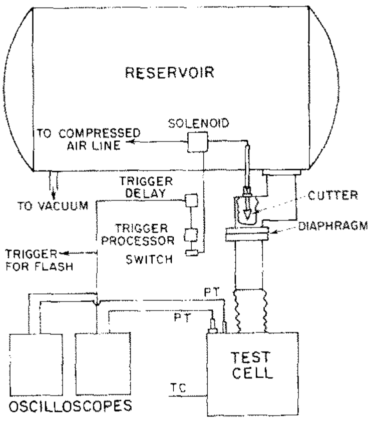

FIG. 2. Schematic of apparatus for interferometer experiments.

The photographic system to record the experiments used a large drum camera with a xenon flash tube as a light source. The speed of the camera could be continuously adjusted up to speeds of 122 rpm. The flash tube was controlled by a high power stroboscope and a programmable pulse generator. A 5330 Å filter with a 70 Å half width was used to monochromatize the light. Two meters of Kodak SP-940 TRI-X Pan film, cut and spliced in a loop, were used for each run. Typically, 23 interferograms (8.9 × 13.3 cm) were recorded at 100 ms intervals on each film.

The Freon-11 used in each experiment was distilled to remove impurities and added to the test cell. The foil diaphragm was then installed and the cell sealed. The cell temperature was monitored until equilibrium with ambient conditions was achieved. A continuous mercury arc light source was used in the interferometer to check fringe contrast and achieve an 'infinite fringe' condition. Next, the oscilloscope trigger levels, camera speed, programmable pulse generator, and time delay mechanism were checked and adjusted. The flash unit was then installed and a reference polaroid photograph exposed to ascertain the fringe condition. The test conditions were then recorded, the room darkened, the film cut and mounted, the reservoir vacuum pressure obtained, and the experiment initiated by firing the stroboscope and closing the switch to energize the break mechanism, oscilloscopes, and flash unit.

The resulting interferograms were analyzed on an optical comparator at 62.5× magnification. The chaotic fringe patterns encountered within most of the liquid could not be quantitatively analyzed, and only fringe patterns within symmetric drops were measured. The process consisted of measuring the width of every half fringe across a symmetric drop. A fringe consists of a pair of thin black and white bands, which represent lines of constant optical path difference corresponding to lines of constant temperature.

A computer program was developed to calculate the temperature profile within symmetric drops using a numerical integration of the Abel integral equation [22] which is

$$S(y)\cdot\lambda = 2\int_y^{\infty} \frac{n(r)-n_{\infty}}{\sqrt{(r^2-y^2)}}\, r\,\mathrm{d}r, \tag{1}$$

where S is the fringe shift, λ is the wavelength of light (5330 Å), n is the refractive index, ∞ represents the undisturbed state, y is the position at which the fringe shift is S, and $n(r)$ is the refractive index profile of the drop. The density profile is obtained from the Lorentz–Lorenz equation

$$\frac{n^2-1}{n^2+2} = \frac{\rho N}{M}, \tag{2}$$

where ρ is the density, M the molecular weight and N the molar refractive index. The temperature profile is found by a relationship between temperature and density for Freon-11 [23].

RESULTS AND ANALYSIS OF THE INTERFEROMETER EXPERIMENTS

A total of 68 different runs comprised the set of interferometer experiments. However, due to the rare appearance of nonoverlapping symmetric drops, only seven runs provided interferograms which could be quantitatively analyzed. Figures 3 and 4 show sample

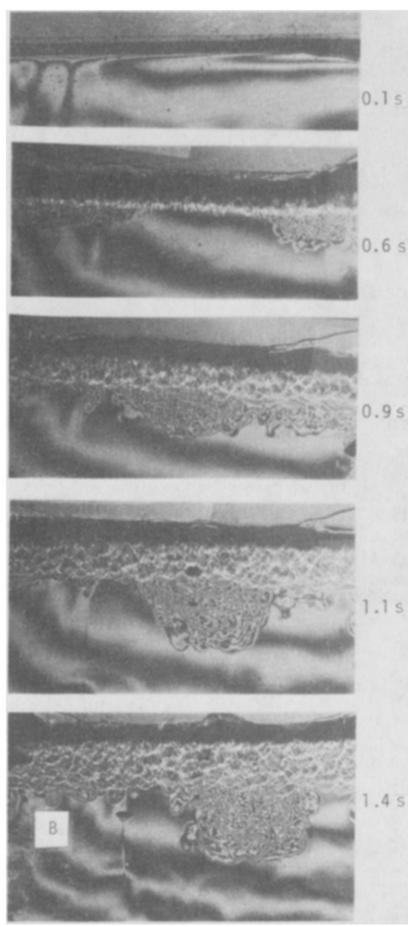

FIG. 3. Interferogram sequence for initial conditions 19.7°C, 97.4 kPa, depressurization 75.9 kPa: 0.1–1.4 s.

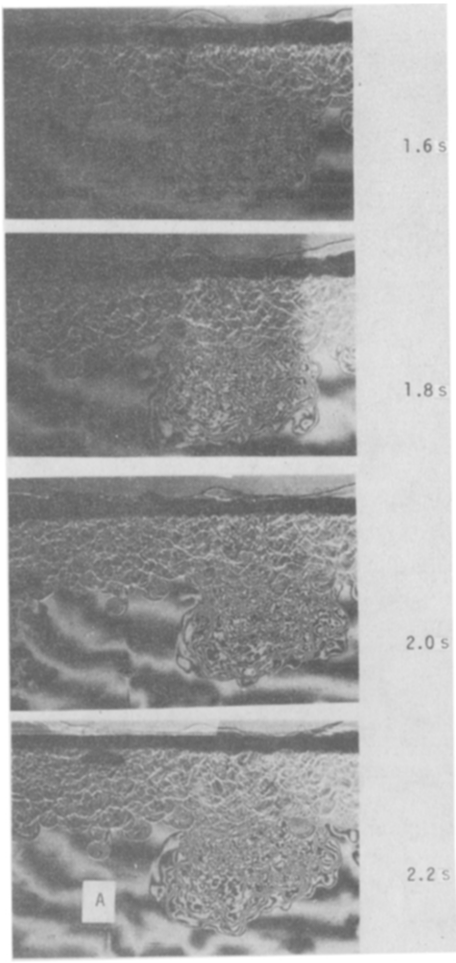

FIG. 4. Same interferogram sequence as Fig. 3: 1.6–2.2 s.

interferograms from a typical run. The conditions for this run were an initial temperature of 19.7°C and an initial pressure of 97.4 kPa depressurized to 75.9 kPa, corresponding to a saturation temperature of 15.9°C and therefore a superheat of 3.8°C.

Initially, instabilities develop at random locations on the surface. Rapid vaporization occurs as the result of the decrease in pressure and a cooled layer of liquid is formed at the surface. This is evident by the appearance of closely spaced fringes at 0.1 s into the experiment which result from the high rate of heat transfer at the surface. At the site of the initial disturbances, small hemispheric fringe patterns develop. These represent liquid cooled by rapid evaporation. They grow in size and, being denser than the warmer liquid around them, descend into that warmer liquid. Hence they are named 'drops' in this investigation. The increased instability causes surface waves which results in the formation of more drops. As the drops descend, they become warmer due to heat transfer from the liquid bulk and increase in size as they approach the bulk liquid temperature. Two such drops are shown as B in Fig. 3 and A in Fig. 4. Figure 5 shows an enlargement of drop A at 2.0 s. For this drop, adjacent fringes represent a temperature

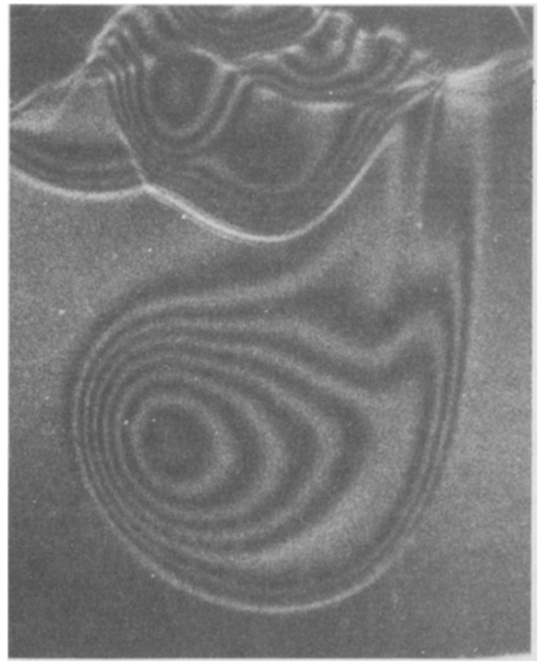

FIG. 5. Enlargement of drop A from Fig. 4 at 2.0 s.

difference of 0.46°C (a much lower value than encountered in interferometric measurements in air).

A temperature profile obtained from a typical interferogram is shown in Fig. 6. This clearly shows the changing size and the heterogeneous mixture of superheat, saturated, and subcooled states for that drop. From such profiles, the minimum temperature for each drop could be found.

Table 1 shows the initial and depressurized conditions and results for the seven analyzed runs. It should be noted that the minimum temperature could have been lower at earlier times when the interferograms could not be analyzed. However, the minimum temperature is well below the saturation value at the depressurization pressure. It is hypothesized that this is due to the inversion of a depressurization wave upon impact with the liquid surface. Ideally, this reduces the pressure by twice the actual depressurization.

Hoppner [14] performed depressurization experiments on both subcooled and saturated water, and measured the pressure above and below the liquid surface. The pressure above the liquid decreased to the new level and remained constant. For subcooled liquids, the pressure within the liquid oscillated around the depressurized value, but with saturated liquids, the oscillations were not as severe. This shows the presence of the rarefaction wave within the liquid. In the current study, the pressure transducers were located in the vapor region and therefore it is assumed that rapid vaporization at the liquid surface dissipated the rarefaction wave reversal and prevented it from propagating back to the pressure transducers.

The pressure oscillations do offer a plausible

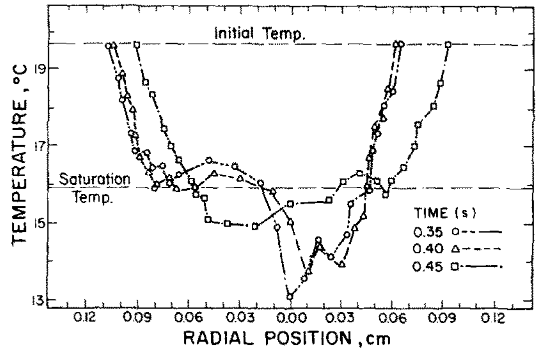

FIG. 6. Typical temperature profile $T_0 = 19.8°C$; $\Delta P = 21.5$ kPa.

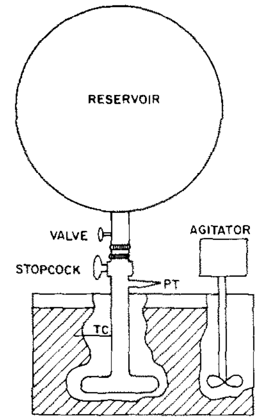

FIG. 7. Schematic of experimental apparatus for mass transfer experiments.

explanation for the low temperature of the descending drops. During depressurization, the vapor is continuously removed, and therefore the temperature of the liquid surface should ideally correspond to the saturation temperature of the minimum pressure attained. It was noted in the experiments that minimum liquid temperatures compared favorably with saturation temperatures at twice the depressurization.

As a final comment on the depressurization experiments: it should be noted that while numerous cool liquid drops always form, they often interfere or overlap with each other, and therefore those that are distinguishable and could be analyzed were rather rare.

MASS TRANSFER EXPERIMENTS

The second set of experiments were designed to examine mass transfer rates during flashing and evaporation. It was deemed impractical to conduct the experiments within the interferometer setup, and a separate apparatus was designed and constructed. It consisted of a reservoir, an agitator, and an instrumented glass test column as shown schematically in Fig. 7. The column was composed of a stopcock with a 2.5 cm bore fused to the top of a 33 cm glass cylinder. The inside diameter of the cylinder was 3.7 cm. A thermocouple was mounted on the outside of the column 13.0 cm from the bottom, and a tube was located 26.7 cm from the bottom to monitor the cell pressure. The cell was immersed in an insulated 0.05 m^3 constant temperature bath which was controlled by a circulator. The agitator increased the mixing rate and aided in maintaining temperature uniformity. The column was connected to the vacuum reservoir previously used in the interferometer experiments by a 28 cm segment of steel pipe.

Prior to each experiment, Freon-11 was distilled to remove impurities, placed in the constant temperature bath, and allowed to reach the pre-determined initial experimental temperature. The reservoir was then evacuated to the desired vacuum pressure, and the test column filled to a height of 16.5 cm with Freon-11, closed by turning the stopcock, and weighed. The test column was then put in the insulated bath, and the thermocouple and pressure transducer mounted in place. The initial conditions were recorded and the stopcock opened to begin the experiment. The new conditions were recorded and the experiment allowed to run to a predetermined time limit before being resealed and reweighed. This procedure was repeated at the same initial conditions by increasing the time limit to arrive at a continuous curve.

A large number of experiments were conducted. More detail on apparatus and procedure may be found in ref. [23]. The results of one series of experiments performed at 20.8°C are shown in Fig. 8. The pressure

Table 1. Experimental conditions and results from the interferometer experiments

	Initial conditions			Depressurized conditions		
Run	T_0 (°C)	P (kPa)	T_{sat} (°C)	P (kPa)	T_{sat} (°C)	T_{min} (°C)
51*	19.3	98.5	23.0	85.6	19.1	16.2
52*	20.2	98.0	22.9	86.0	19.2	17.5
58*	19.7	97.4	22.7	79.5	17.1	16.1
67*	19.8	97.4	22.7	75.9	15.9	13.3
7†	21.0	101.0	23.7	74.0	15.3	9.4
117†	21.1	97.2	22.6	85.8	19.2	15.2
120†	20.8	98.4	23.0	79.0	17.0	7.8

* From ref. [8].
† From ref. [23].

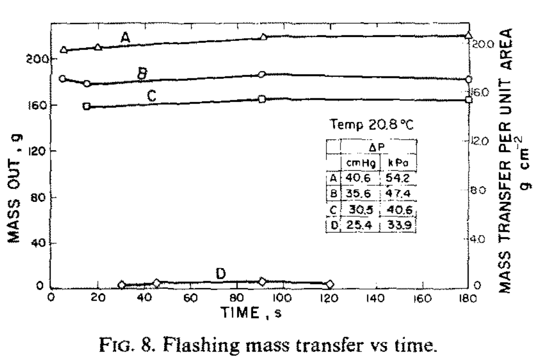

FIG. 8. Flashing mass transfer vs time.

drop was varied to allow initial liquid superheats of up to 17.7°C. The plot reveals a large initial increase in mass transfer due to flashing, followed by a period of low mass transfer due to evaporation alone. This can be explained by the fact that the liquid bulk cooled rapidly after the initial flashing period. Miyatake *et al.* [15] noted similar behavior during their experiments on suddenly depressurizing water.

Figure 9 shows the dependence of the mass leaving the system on the initial temperature and depressurization. Higher initial temperatures and higher depressurizations result in higher losses, as expected.

In some runs the onset of flashing was delayed by 30 s or less. These delays showed a random dependence on initial conditions.

Occasionally at lower pressure drops no flashing was observed. Instead, only evaporation occurred at the surface. The results of these runs are shown in Fig. 10 and can be accurately described by a linear relationship. Note the larger time scale in that figure.

Photographs of the departing mass were taken. They showed mass leaving the system as a mixture of vapor and entrained liquid. In one run at 20.8°C and 47.4 kPa, some departing liquid was at 18.1°C, again showing the cooling which occurs during flashing.

ANALYSIS OF MASS TRANSFER EXPERIMENTS

It is now desired to relate the experimental flashing mass transfer to theoretical mass transfer rates due to evaporation alone. For this, an analytical study of the evaporation phenomenon was performed to develop a computer program to calculate the evaporation rate for various initial temperatures and pressure drops. The evaporation model consisted of a semi-infinite column of liquid suddenly exposed to a lower pressure. The Hertz–Knudsen equation was used to calculate the evaporation rate and a method described in ref. [23] was used to calculate the surface temperature profiles

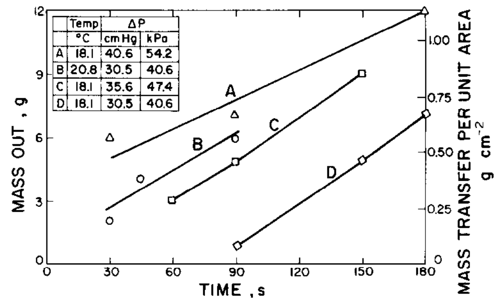

FIG. 10. Evaporative mass transfer vs time at various initial temperatures and depressurizations.

by incorporating corrections to account for the motion of the vapor molecules and the interface between the liquid and vapor regions. The analytical results for a series of runs performed at conditions similar to those of the experiments are presented in Fig. 11.

The experimental results presented in Fig. 8 and similar plots in ref. [23] were correlated by a least squares fit to yield the following relationship

$$m''_{FL} = 0.02T_0\,\Delta P - 1.9, \tag{3}$$

where m''_{FL} (g cm^{-2}) refers to the mass transfer per unit area during flashing, T_0 is the initial temperature (°C), and ΔP is the pressure drop (kPa), imposed on the liquid. The correlation is based on data in a range of initial temperatures from 12.8 to 20.8°C and a range of pressure drops from 40.6 to 54.2 kPa.

It is convenient to define a flashing factor, F, as

$$F = \frac{m''_{FL}}{m''_{EV}}, \tag{4}$$

where m''_{EV} is the mass transfer per unit area due to evaporation alone.

Table 2 presents the experimental mass transfer m''_{EXP}, m''_{FL} determined from equation (3), m''_{EV}

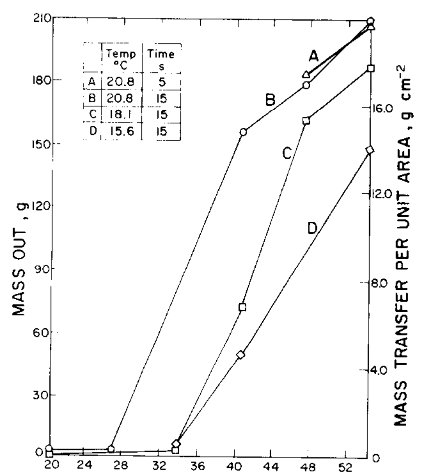

FIG. 9. Mass transfer at constant initial temperature vs depressurization.

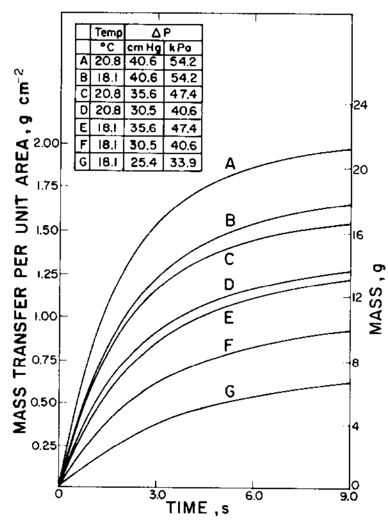

FIG. 11. Analytical evaporative mass transfer vs time at various initial temperatures and depressurizations.

Table 2. Mass transfer data and results

T_0 (°C)	ΔP (kPa)	m''_{EXP} (g cm^{-2})	m''_{FL} (g cm^{-2})	m''_{EV} (g cm^{-2})	F
20.8	54.2	20.5	20.4	2.0	10.0
20.8	47.4	17.4	17.4	1.6	10.9
20.8	40.6	15.3	14.4	1.3	11.1
18.1	54.2	17.8	18.7	1.7	10.1
18.1	47.4	15.9	14.0	1.3	11.6
18.1	40.6	11.8	10.9	1.0	12.5
12.8	47.4	10.5	7.3	0.7	15.0

determined from evaporation theory, and the flashing factor for several sets of conditions.

The value of F for the present experimental apparatus is closely correlated by

$$F = 27.5 - 0.527T_0 - 0.129\,\Delta P, \tag{5}$$

with an average value of 11.6 for the range of experiments.

This equation is, of course, based on data obtained from the experimental apparatus described above. It, however, predicts trends and reveals the large differences between mass transfer during flashing and evaporation.

The higher rates of mass transfer encountered in flashing are caused by the high rates of evaporation due to severe agitation and, perhaps more importantly, due to the entrainment of drops of subcooled liquid with the departing vapor as noted previously.

CONCLUSIONS

The sudden depressurization of an initially subcooled layer of liquid is often sufficient to impose an amount of superheat on the liquid. At low pressure drops normal evaporation takes place. If the change in pressure is large enough, flashing occurs. Both phenomena cause a cooling of the liquid as its internal energy is converted to latent heat of vaporization. Flashing results in a heterogeneous mixture of superheated, saturated, and subcooled liquid with a minimum temperature well below the saturation temperature at the depressurized conditions.

Mass transfer rates in flashing were found to be 10–12 times the rates due to evaporation alone. These higher rates in flashing are believed to be caused by severe agitation and the entrainment of drops of subcooled liquid with the departing vapor. Empirical relationships are suggested to allow the calculation of the mass transfer during flashing.

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RECHERCHE SUR LA DEPRESSURISATION ET LA VAPORISATION INSTANTANEE D'UN LIQUIDE

Résumé—On examine la réponse thermo-hydraulique d'une couche liquide au repos à une soudaine dépressurisation. On utilise comme liquide d'essai le Fréon 11 à la température ambiante. Les degrés de dépressurisation sont tels que le coeur du liquide devient surchauffé et la vaporisation instantanée apparait. Deux séries d'expériences sont conduites. Dans la première, un interféromètre Mach-Zehnder 20,3 cm, une photographie à grande vitesse et un équipement associé sont utilisés pour enregistrer une suite d'interférogrammes du liquide en évaporation. Elle montre un mélange hétérogène de liquide surchauffé, saturé et sous-refroidi. Le degré de surchauffe correspond à la température de saturation à environ deux fois la chute de pression. Les conditions initiales ont varié de 97,2 à 101,0 kPa, de 19,3 à 21,1°C et la dépressurisation de 11,4 à 27,0 kPa. On note des surchauffes jusqu'à 5,7°C et des sous-refroidissements allant jusqu'à 9,2°C au-dessous de la saturation. La seconde série d'expériences est faite pour déterminer le transfert massique associé. Elle montre que les flux transférés sont 10 à 12 fois ceux dûs à l'évaporation seule. Ceci est lié à l'agitation du liquide et à la présence de gouttes entrainées de liquide sous-refroidi dans la vapeur. Un 'flashing factor' F défini comme le rapport du transfert massique à celui dans l'évaporation est déterminé et, pour les conditions expérimentales, il est donné par:

$$F = 27{,}5 - 0{,}527T_0 - 0{,}129\Delta P,$$

où T_0 est la température initiale (°C) et ΔP la chute de pression imposée (kPa).

EINE UNTERSUCHUNG DER ENTSPANNUNGSVERDAMPFUNG UND VERDAMPFUNG AUFGRUND PLÖTZLICHER DRUCKENTLASTUNGEN

Zusammenfassung—Die thermo-hydraulische Empfindlichkeit einer ruhenden Flüssigkeitsschicht auf plötzliche Druckentlastung wurde untersucht. Als Versuchsflüssigkeit diente R11 bei Raumtemperatur. Die Druckentlastungsverhältnisse wurden so gewählt, daß die Flüssigkeitsmasse überhitzte und Entspannungsverdampfung einsetzte. In der ersten von zwei Versuchsreihen wurde ein 20,3 cm Mach-Zehnder-Interferometer, Hochgeschwindigkeitsphotographie und zugehörige Geräte verwendet, um eine Reihe von Interferogrammen der plötzlich verdampfenden Flüssigkeit aufzunehmen. Die Interferogramme zeigten ein heterogenes Gemisch aus überhitzter, gesättigter und unterkühlter Flüssigkeit. Die Unterkühlung entspricht der Sättigungstemperatur bei doppelter Druckerniedrigung. Die Ausgangsbedingungen variierten beim Druck zwischen 97,2 und 101,0 kPa, bei der Temperatur zwischen 19,3 und 21,1°C; die Druckentlastung variierte zwischen 11,4 und 27,0 kPa. Flüssigkeitsüberhitzungen bis zu 5,7 K und Unterkühlungen von mehr als 9,2 K unter der Sättigungstemperatur wurden festgestellt. Die zweite Versuchsreihe wurde durchgeführt, um den Massentransport unter den Bedingungen der Entspannungsverdampfung zu untersuchen. Bei den Versuchen ergaben sich Stoffübergangsraten, die 10–12 mal höher lagen als die bei alleiniger Verdampfung. Dies läßt sich sowohl auf die Rührwirkung der Flüssigkeit als auch auf das Vorhandensein von im abströmenden Dampf mitgerissenen unterkühlten Flüssigkeitstropfen zurückführen. Ein empirischer 'Entspannungsverdampfungsfaktor' F, der als Verhältnis des Stoffübergangs bei Entspannungsverdampfung zu dem bei alleiniger Verdampfung definiert ist, wurde ermittelt, der sich für die gegebenen Versuchbedingungen durch

$$F = 27{,}5 - 0{,}527T_0 - 0{,}129\Delta P$$

berechnen läßt. Hierbei ist T_0 die Ausgangstemperatur und ΔP die Druckerniedrigung.

ИССЛЕДОВАНИЯ МГНОВЕННОГО ВСКИПАНИЯ ЖИДКОСТИ, ОБУСЛОВЛЕННОГО ВНЕЗАПНЫМ СБРОСОМ ДАВЛЕНИЯ

Аннотация—Изучена тепло-гидравлическая реакция неподвижного слоя жидкости на внезапный сброс давления. В качестве тестовой жидкости применялся фреон-11 при комнатной температуре. Уровни сброса давления были таковы, что объем жидкости перегревался и происходило мгновенное вскипание. Были проведены две серии экспериментов. В первой серии для записи последовательности интерферограмм мгновенно испаряющейся жидкости были использованы интерферометр Маха-Цандера (20,3 см), скоростная фотосъемка и соответствующие приборы. Интерферограммы указали на наличие гетерогенной смеси перегретой, насыщенной и переохлажденной жидкости. Степень переохлаждения соответствовала температуре насыщения в случае приблизительно удвоенного падения давления. Начальные условия для давления изменялись от 97,2 до 101,0 кПа, для температуры – от 19,3 до 21,1 С, а для сброса давления от 11,4 до 27,0 кПа. Были отмечены перегрев жидкости до 5,7 и переохлаждение порядка 9,2 С ниже насыщения. Вторая серия экспериментов была проведена с целью определения массопереноса в условиях мгновенного вскипания. Они показали, что скорости массопереноса при мгновенном вскипании в 10–12 раз больше скоростей испарения. Это обусловлено перемешиванием жидкости, а также присутствием в выходящем паре увлеченных капель переохлажденной жидкости. Был найден эмпирический «коэффициент мгновенного испарения», F, равный отношению массопереноса при мгновенном вскипании и при испарении. Для условий эксперимента он равен

$$F = 27{,}5 - 0{,}527T_0 - 0{,}129\Delta P,$$

где T_0 начальная температура (С), а ΔP падение давления (кПа).