Int. J. Heat Mass Transfer. Vol. 29, No. 9, pp. 1333–1338, 1986
Printed in Great Britain

0017-9310/86 $3.00+0.00
Pergamon Journals Ltd.

Vapor condensation onto a turbulent liquid—II. Condensation burst instability at high turbulence intensities[†]

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(*Received* 20 *June* 1985 *and in final form* 30 *December* 1985)

Abstract—The process of vapor condensation onto a turbulent, subcooled liquid is shown to become unstable when the liquid-side turbulence intensity exceeds a threshold value which depends on liquid subcooling. Above the threshold, very short, high-intensity bursts of condensation occur intermittently. Data are presented on the nature of the bursts and the conditions for their onset.

1. OBSERVATIONS

In the preceding paper [1], the authors presented experimental data for the rate at which vapor condenses onto a subcooled, turbulent liquid interface. The steady-state condensation rate was found to be proportional to the root mean square turbulence velocity on the liquid side and the liquid subcooling. Studies in the same experimental apparatus also showed that at sufficiently high turbulence intensities, the steady, turbulent condensation process became unstable and very short, high-intensity bursts of condensation began to occur intermittently. These bursts appeared to result from a two-stage instability of the steady condensation process. The turbulence intensity being relatively high when the bursts occurred, the state before the bursts would be one where the surface was undulating with a wavelength of the order of the turbulence macroscale and an amplitude which was typically small, but not negligible, compared with the wavelength. An instability event would begin with the amplification of some part of the undulating motion. This first stage was relatively slow, the time scale being of the same order as that of the surface undulations (100 ms, say) and did not cause a significant increase in the instantaneous condensation rate. The second stage, or burst proper, occurred very abruptly. In about 1 ms (the interval between observations), the small-scale features of the interface changed, a condensation burst with an intensity of the order of a 100 times the pre-burst value would be initiated and the system pressure would drop abruptly. The burst would last of the order of 10 ms, and then turn itself off almost as abruptly as it began. Thereafter, the system would tend to return toward a steady state until it was interrupted by another similar event.

Figure 1 shows a film sequence, taken at 1000 frames per second, of the events that lead to a condensation burst, and Fig. 2 shows the system pressure history during a burst. The film and pressure data are not for the same burst, though both were taken in the smaller of the two test cells of ref. [1] and at the same turbulence intensity and subcooling. In Fig. 1, the initial state before the burst is illustrated in frame (a). The first stage, in which a finger-like depression moves into the water, occurs in frames (b)–(e) and takes about 100 ms (this happens to be a burst with a particularly pronounced first stage). The second stage is initiated in frame (f), which follows frame (e) by 1 ms. In a time of the order of 1 ms, the interface turns opaque, and a rapid steam condensation is signalled by both the falling system pressure (Fig. 2) and the collapsing depression in the water [Figs. 1(g)–(i)]. In 10 ms, the system pressure drops by about 0.25 bar. The condensation burst then appears to turn off, and the pressure rises back toward the initial 1 bar (actually overshooting it, apparently because air is sucked in via the exhaust valve during the depressurization, causing the condensation rate to fall below its initial steady-state value).

Some comments are in order based on the examination of a large number of film and pressure data. First, to forestall simplistic explanations that ascribe the condensation burst to the entrapment and collapse of a steam bubble, we stress that there was considerable statistical variability from event to event and the finger-like intrusion in Fig. 1 is a rather severe example of the first stage instability. Many condensation bursts occurred with no evidence of steam entrapment under the water. Second, although we examined a large number of films, and could identify the 'first stage' phenomena which indicated that a burst was likely (though not certain) to occur in the next 100 ms or so, we could find no reliable precursor to the actual burst (the 'second state') even a few milliseconds prior to its onset. Finally, it is worth

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[†] Work supported by the U.S. Nuclear Regulatory Commission under Grant NRC-G-04-83-004.

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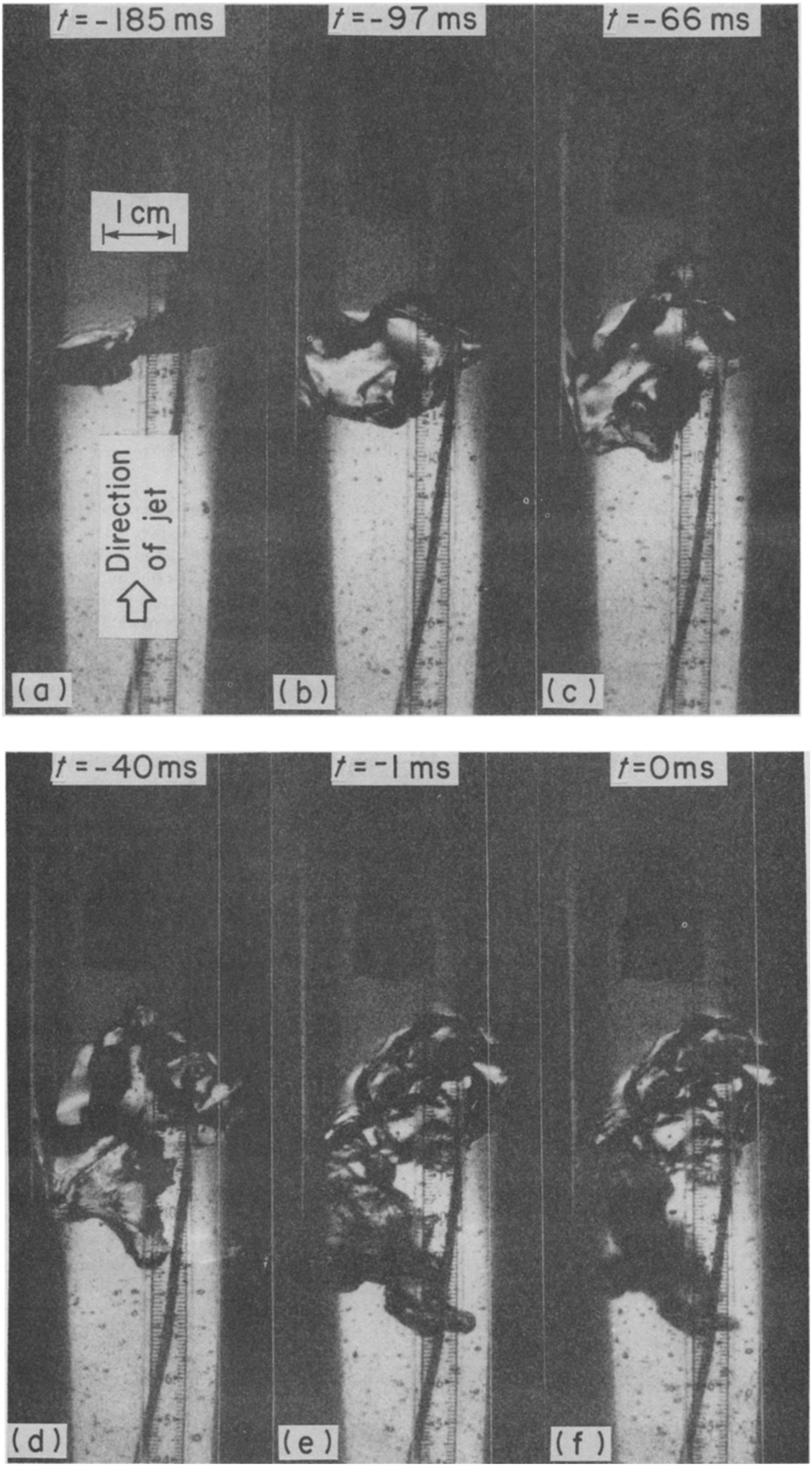
t = -185 ms
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1 cm
Direction of jet
(a)
(b)
(c)
t = -40 ms
t = -1 ms
t = 0 ms
(d)
(e)
(f)

FIG. 1.

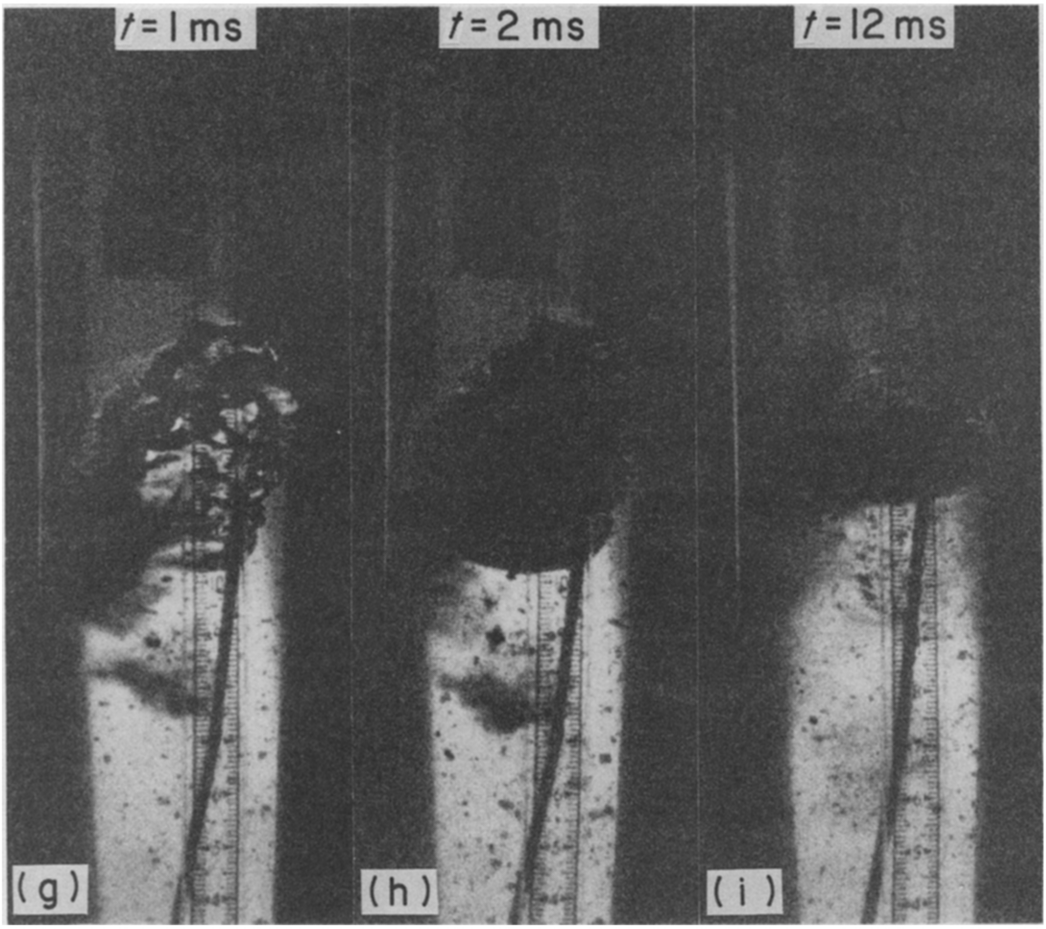

FIG. 1. Interface motion prior to and during a condensation burst: small system [1], steam on water, $\Delta T = 60$ K, $z_s = 0.130$ m, $Q/Dd = 0.39$ m s^{-1}, $p \simeq 1$ bar. The burst occurs at $t \simeq 0$ ms.

noting that once the burst occurred, its tell-tale effects on the interface (the opaqueness it caused in the films) appeared over virtually the entire interface in about 1 ms. Whatever the actual form of the interfacial disturbance, its scale (1 mm or less) appeared to be very small compared with the interfacial wavelength and its onset over the entire surface region abrupt.

Figure 3 summarizes the data for the threshold turbulence intensity at which the condensation bursts would just begin to occur at a steam pressure of 1 atm. For the purposes of the figure, the threshold is defined as the lowest value of v_s' at which one condensation burst was observed during a randomly selected 6-min period after the system had reached steady state. Here v_s' is the r.m.s. value of the local horizontal velocity component extrapolated from the bulk of the liquid to the surface, as defined in ref. [1] (note that the turbulence in the bulk liquid, below the damped layer, was essentially isotropic in the test cells where these data were taken). At values of v_s' about 50% higher than the threshold 6–12 bursts would typically occur in a 6-min period. Although there is some data scatter, the threshold v_s' appears to be approximately a function of the subcooling only, the bursts occurring at lower turbulence intensity if the subcooling is high.

It should be noted that subcooling affected not only the threshold v_s' but also the nature of the condensation bursts thermselves. At high subcooling a single, intense burst would usually occur with each instability event, while at low subcooling there would often be a sequence of small bursts. This made it difficult to establish a distinct threshold for subcoolings below 30–40 K, and none are shown in that range in Fig. 3.

The condensation bursts were very similar to the ones observed in our laboratory by Anderson [2] in connection with the transient injection of steam into cold water from the bottom of a 10-cm-diameter, vertical pipe. In Anderson's tests, the pipe was initially filled with cold water. Steam was then injected from the top of the pipe until the water was heated up. The hot steam–water interface was then displaced out of the pipe by the steam at a speed of 1.3 m s^{-1}, giving rise to turbulence intensities in the water of the same order as in our present experiments. Anderson found that a condensation burst would occur somewhat after the steam–water interface had emerged from the pipe

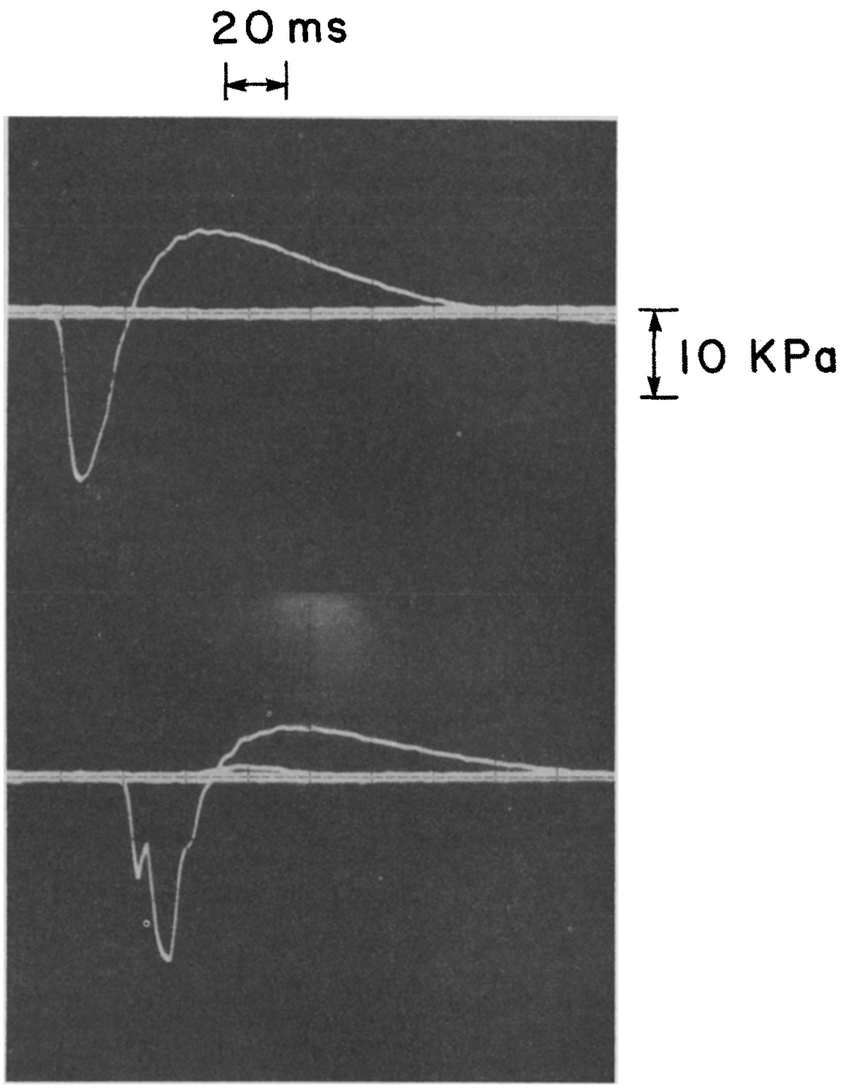

FIG. 2. Typical system pressure histories during condensation bursts. Same conditions as Fig. 1.

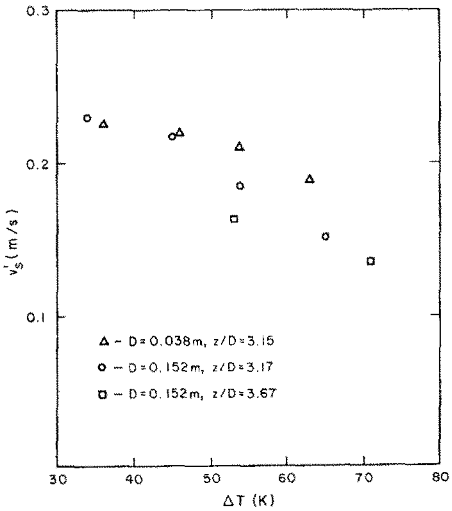

FIG. 3. Threshold turbulence level for condensation bursts as function of subcooling. Atmospheric pressure, steam on water.

exit into the cold water outside. At a subcooling of about 75 K his measurements indicated bursts with an average duration of 6 ms, roughly consistent with the bursts in our present data, and an average condensation heat transfer rate during a burst of some 600 kW m^{-2} K^{-1}.

Although no attempt was made in our present study to determine accurately the condensation rate during the bursts, some rough estimates were made based on the transient increase of bulk water temperature following a burst and on the burst duration implied by the system pressure histories [3]. These estimates gave values of the same order as Anderson's, i.e. about a factor of 100 higher than the average condensation heat transfer rate in our present tests prior to the onset of the bursts.

2. DISCUSSION

Table 1 compares the steady-state conditions near the burst threshold, as determined in the present

Table 1. Conditions prior to and during condensation bursts at $\Delta T \simeq 70°\mathrm{C}$

Steady state at burst threshold ($v_s' = 0.15\,\mathrm{m\,s^{-1}}$)	
Condensation mass flux	$\dot{m}_c = 0.18\,\mathrm{kg\,m^{-2}\,s^{-1}}$
Vapor momentum flux	$\dot{m}_c^2/\rho_{\mathrm{steam}} = 0.006\,\mathrm{mmH_2O}$
Condensation heat flux into water	$q_c = 0.42\,\mathrm{MW\,m^{-2}}$
Thermal layer thickness	$\delta = 0.1\,\mathrm{mm}$
Burst characteristics [2]	
Average condensation mass flux	$\dot{m}_c \simeq 20\,\mathrm{kg\,m^{-2}\,s^{-1}}$
Average vapor momentum flux	$\dot{m}_c^2/\rho_{\mathrm{steam}} \simeq 68\,\mathrm{mmH_2O}$
Average condensation heat flux into water	$q_c \simeq 45\,\mathrm{MW\,m^{-2}}$
Duration	$\Delta t \simeq 6\,\mathrm{ms}$
Final thickness of layer heated by burst	$\delta_B \simeq 2\,\mathrm{mm}$

study, with the conditions during the actual burst. The latter were obtained from Anderson [2]; the values in the table represent ensemble averages over many bursts. The steady-state thermal layer thickness, δ, was computed from equations (32) and (31) of ref. [1]. The final thickness δ_B of the burst-heated water layer is defined as the thickness of water which would be heated by $\Delta T/2$ by the heat $q_c \Delta t$ transported into the water during the burst, ΔT being the liquid subcooling and Δt the burst duration.

The vapor momentum flux is the likely driving force for the instability which leads to a burst. Below the burst threshold, the mean momentum flux corresponds to a pressure, or stress, of less than 10^{-2} mm of water. Turbulent momentum flux fluctuation of this order will not give rise to significant vertical surface perturbation. They can, however, give rise to significant horizontal perturbations of the turbulence in the water. Local instantaneous variations in the condensation mass flux $\dot{m}_c$ will give the vapor flux a horizontal component, and cause an effective shear stress $\tau_{\mathrm{sur}} = \varepsilon \dot{m}_c^2/\rho_{\mathrm{steam}}$ on the interface, where ρ_{steam} is the steam density and ε is a constant which would be expected to be small compared with unity if the steam's angle of incidence is near the vertical. This shear stress will fluctuate with a time scale of the order of the contact time, which according to the discussion in Section 5 of ref. [1] is given by $\tau \sim 7\times10^{-4}/v_s'^2$ or 31 ms at the typical threshold value $v_s' = 0.15\ \mathrm{m\ s^{-1}}$. Now, an instantaneously applied surface stress will give rise to a laminar acceleration of the water near the interface, and the surface velocity will increase according to $u \sim (\tau_{\mathrm{sur}}/\rho)(t/\nu)^{1/2}$. From these relations, and the data of Table 1, it follows that the turbulent fluctuation in the vapor flux (i.e. in the condensation rate) can accelerate the surface horizontally to a speed of the same order as the imposed turbulence velocity $v_s' \simeq 0.15\ \mathrm{m\ s^{-1}}$, provided that ε is greater than about 10^{-2}. Since the latter is a quite reasonable figure, it follows that turbulent vapor flux fluctuation can cause significant perturbations of the imposed turbulence near the surface at threshold conditions and can in principle amplify the condensation rate. These phenomena occur on the relatively slow time scale of the turbulent motion in the liquid, however. The precise nature of the very abrupt second stage of the instability (the burst) is at this point unknown. Several analyses have been published on the stability of laminar interfaces across which heat and mass transport takes place [4–7]. None of these can be applied directly to our present problem, where the interface is at a constant temperature (the saturation value) and the liquid side is turbulent.

Once the burst occurs, the momentum flux of the condensing vapor increases by a factor of 10^4. An effective thermal diffusivity α_B during the burst itself can be computed from $\alpha_B \sim \delta_B^2/\Delta t$. Based on the figures in Table 1, one obtains $\alpha_B \sim 5\times10^{-4}\ \mathrm{m^2\ s^{-1}}$, which is over three orders of magnitude higher than the molecular thermal conductivity in water. If the effective thermal diffusivity is associated with eddies then one can make the association $\alpha_B \sim vl$, where v and l are the velocity and length scales associated with the turbulent or eddying motion triggered by the instability, and obtain an estimate of the Reynolds number as $vl/\nu \sim 500$. The motion associated with the burst is thus a reasonably high Reynolds number one, as would be expected in an instability phenomenon where momentum is a destabilizing factor.

3. CONCLUSIONS

When the turbulence intensity on the liquid side is increased beyond a threshold value, the process of vapor condensation onto the liquid becomes unstable and very short, high-intensity bursts of condensation begin to occur intermittently. The threshold turbulence, which depends on liquid subcooling, has been established for atmospheric steam condensing on water. The condensation rate during each burst is of the order of 100 times the steady-state value. The ratio of the burst duration to the interval between bursts is typically less than 10^{-2}, so that the average condensation rate is only moderately increased in the burst condensation mode. However, depending on the vapor volume relative to the liquid interface area, the bursts can give rise to dramatic transient system depressurizations.

REFERENCES

1. A. A. Sonin, M. A. Shimko and J.-H. Chun, Vapor condensation onto a turbulent liquid—I. The steady condensation rate as a function of liquid-side turbulence, *Int. J. Heat Mass Transfer* **29**, 1319–1332 (1986).
2. W. G. Anderson, Transient condensation in a vertical pipe discharging steam onto a subcooled water pool. Ph.D. thesis, Department of Mechanical Engineering, MIT (1982).
3. M. A. Shimko, Scalar transport at a turbulent liquid free surface, M.S. thesis, Department of Mechanical Engineering, MIT (1985).
4. C. A. Miller, Stability of moving surfaces in fluid systems with heat and mass transfer, *A.I.Ch.E. Jl* **19**, 909–915 (1973).
5. H. J. Palmer, The hydrodynamic stability of rapidly evaporating liquids at reduced pressure, *J. Fluid Mech.* **75**, 487–511 (1976).
6. H. J. Palmer and J. C. Maheshri, Enhanced interfacial heat transfer by differential vapor recoil instabilities, *Int. J. Heat Mass Transfer* **4**, 117–123 (1981).
7. A. Prosperetti and M. S. Plesset, The stability of an evaporating liquid surface, *Phys. Fluids* **27**, 1590–1602 (1984).

CONDENSATION DE VAPEUR SUR UN LIQUIDE TURBULENT—II. INSTABILITE DE BOUFFEE DE CONDENSATION AUX FORTES INTENSITES DE TURBULENCE

Résumé—Le mécanisme de la condensation de vapeur sur un liquide turbulent et sous-refroidi devient instable quand l'intensité de turbulence du coté du liquide dépasse une valeur critique qui dépend du sous-refroidissement du liquide. Au dessus de cette limite, de très courtes bouffées de condensation à grande intensité apparaissent de façon intermittente. On présente des données sur la nature des bouffées et les conditions de leur apparition.

KONDENSATION AN EINER TURBULENTEN FLÜSSIGKEIT— II. INSTABILITÄT DER KONDENSATION BEI HOHEN TURBULENZINTENSITÄTEN

Zusammenfassung—Es zeigt sich, daß der Prozeß der Kondensation von Dampf an einer turbulenten, unterkühlten Flüssigkeit instabil wird, wenn die Turbulenzintensität der Flüssigkeit einen Grenzwert überschreitet. Dieser hängt von der Unterkühlung der Flüssigkeit ab. Oberhalb des Grenzwertes treten intermittierend sehr kurze Kondensations-Stöße von hoher Intensität auf. Über die Natur dieser Stöße und die Bedingungen ihres Auftretens werden Ergebnisse mitgeteilt.

КОНДЕНСАЦИЯ ПАРА НА ТУРБУЛЕНТНОМ ПОТОКЕ ЖИДКОСТИ—II. ПИКОВАЯ НЕУСТОЙЧИВОСТЬ КОНДЕНСАЦИИ ПРИ ВЫСОКОЙ ИНТЕНСИВНОСТИ ТУРБУЛЕНТНОСТИ

Аннотация—Показано, что процесс конденсации пара на турбулентном потоке недогретой жидкости становится неустойчивым, когда интенсивность турбулентности приграничной жидкости повышает пороговое значение, зависящее от недогрева жидкости. Выше порогового значения периодически возникают очень короткие высокоинтенсивные пики конденсации. Представлены результаты по природе пиков и условиям их возникновения.