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Spontaneous cavitation in liquid n-butane at negative and positive pressures

V.G. Baidakov *, V.E. Vinogradov, P.A. Pavlov

Institute of Thermophysics, Ural Branch of the Russian Academy of Sciences, Amundsen Street 107a, Ekaterinburg 620016, Russia

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ABSTRACT

The method of pulsed liquid superheating on a wire heater in a tension wave has been used to investigate the kinetics of spontaneous boiling-up of liquid n-butane. Experiments were conducted in the pressure range from −6.8 to 2.55 MPa. Stretchings in a liquid were created by the inversion of a compression pulse at the liquid–vapor interface. The values of limiting superheatings for n-butane have been determined, as well as the effective nucleation rates $J = 10^{20} - 10^{22}\ \mathrm{s}^{-1}\ \mathrm{m}^{-3}$ and the value of the derivative of the nucleation rate with respect to the temperature $G_T = d\ln J/dT$. A satisfactory agreement between classical nucleation theory and experiment in the derivative G_T has been established, which is a weighty argument in favor of realization of the homogeneous nucleation mechanism in experiment, with a systematic understatement of superheatings (stretchings) achieved by experiment with respect to their theoretical values. It has been noted that this may be connected with the fact that classical nucleation theory does not take into account the size dependence of the surface tension of critical bubbles.

1. Introduction

Cavitation, i.e. a fracture of liquid continuity under the action of a local decrease in pressure with the formation of vapor–gas voids in it, is observed in hydraulic systems of energetics, chemical industry, aircraft and rocket engineering, etc. [1–3]. The arising vapor–gas voids collapse abruptly after their transition into a zone of elevated pressure or the onset of a compression half-period in an acoustic wave. This is accompanied by an enormous concentration of energy, which leads to a local heating and hydrodynamic perturbation in the form of microshock waves, microcumulative jets and liquid microflows. Cavitation phenomena find use in cleaning parts, deburring, dispersion, emulsification, etc. At the same time cavitation causes the erosion of solids, chemical reactions, leads to the destruction of materials and energy losses. It is evident that at times it is necessary to develop cavitation to perform useful work, and at other times it is necessary to prevent its origination in order to avoid undesirable consequences. In this connection, the determination of the maximum possible tensile stresses and the lifetime of a stretched liquid becomes a topical problem.

In technical devices cavitation begins, as a rule, on heterogeneous vaporization centers (heterogeneous nucleation), which in liquid are a dissolved gas, gas–saturated solid particles or sections of the vessel walls, poorly wettable inclusions, etc. There are no means of guaranteed removal of such centers, therefore rupture tensile stresses are usually small [4–7].

In the absence of heterogeneous centers new-phase nuclei arise at the expense of fluctuations. Such a process is known as homogeneous nucleation. Homogeneous nucleation has no physical prohibitions. Its feasibility in conditions of real experiment with “the background” of heterogeneous nucleation requires evidence. In planning an experiment it is possible to stake not on the removal from the liquid of heterogeneous and readily activated vaporization centers, but on the excess of the density of fluctuation centers over completed ones at considerable stretches. This signifies the dominant contribution of fluctuation bubbles to bulk vaporization. With a rapid introduction of heat into a liquid or an ambient pressure release, owing to the finite growth rate of the vapor phase, one can indicate such a rate of temperature growth $\dot{T}$ or of pressure decrease $\dot{p}$ at which the liquid superheating (stretching) will continue despite the action of heterogeneous vaporization centers. In this case the accumulation of homogeneous nuclei will proceed faster than of heterogeneous. Such a regime of phase transition is known as the shock one [8,9]. Owing to the lack of information on the kinetics of bubble nucleation on heterogeneous centers and the quantity of such centers, the rates required for realization of a shock regime may be determined only by experiment.

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* Corresponding author.
E-mail address: baidakov@itp.uran.ru (V.G. Baidakov).

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Nomenclature

Latin letters

a	thermal diffusivity, m^2/s
c	velocity of sound, m/s
c_0	specific heat capacity, J/(kg K)
d	diameter of a platinum wire, m
G_T	derivative of the nucleation rate with respect to the temperature, K^{-1}
j	vapor flow density, kg/(m^2 s)
J	nucleation rate, s^{-1} m^{-3}
k_B	Boltzmann constant, J/K
m	mass of a molecule, kg
p	pressure, MPa
q	the density of a heat flow, W/m^2
r	heat of evaporation, J/kg
R	bubble radius, m
s	area of the dry spot under a single bubble, m^2
t	time, s
T	temperature, K
$\dot{T}$	rate of temperature growth, K/s
υ_t	average thermal velocity of molecular motion, m/s
W_*	the work of formation of a critical nucleus, J

Greek letters

ρ	the number of particles in a unit volume
σ	surface tension, N/m
λ	thermal conductivity, W/(m K)
η	dynamic viscosity, (N s)/m
Ω	angle of contact

Subscripts

s	belonging to the saturation line

Primes

no primes	liquid properties
single primes	vapor properties

Enormous powers are required for providing a shock regime when a considerable liquid mass is transferred to a metastable state. For instance, a power of $\sim 10^9$ W is necessary for superheating 1 m^3 of n-butane to the boundary of fluctuation boiling-up at atmospheric pressure and a density of heterogeneous boiling centers of 10^8 m^{-3}. Such an intense heat release will lead to an increase in pressure of tens of atmospheres close to a bubble. A shock boiling-up regime without changes in pressure can be realized only in cases where small quantities of liquid are superheated or in superheating separate parts of a cold liquid. The temperature of intense fluctuation nucleation is achieved with relative ease near a wire heated in a liquid by a short electric-current pulse [8,9]. In this case, owing to the fact that a superheated wall layer is thin, the effective growth rate of bubbles on heterogeneous vaporization centers is small, and at a moderate density of such centers the shock-regime conditions will be met.

A transition from the region of positive into the region of negative pressures toughens the realization of the shock regime of phase transition. First, a decrease in the liquid temperature and an increase in the tensile stresses lead to an increase in the density of readily activated boiling centers. The latter is connected with decreasing sizes of critical bubbles. Second, an increase in tensile stresses is accompanied by an increase in the growth rate of bubbles, which complicates the attainment of a shock regime. Thus, at high negative pressures the question of attainability of the mechanism of homogeneous nucleation in a system with completed and readily activated boiling centers remains debatable. One of the signs of realization of such a nucleation mechanism may be the close similarity of the slope of the temperature dependence of the nucleation rate registered in experiment to that calculated from homogeneous nucleation theory, at a simultaneous agreement of the achieved and calculated values of liquid superheating (stretching).

The present paper has assumed the following strategy of realization of fluctuation nucleation at negative pressures created by the inversion of a plane compression wave at a liquid–gas interface. A plane tension wave captures a sufficiently large amount of liquid and, consequently, initiates the action of a great number of completed and readily activated vaporization centers. The bubble formation in the direction of the wave propagation leads to its rapid attenuation and prevents the achievement of high nucleation rates. To overcome this, a miniature transducer-heater is located in the liquid. Cavitation is initiated at the instant a tension wave passes through the liquid region being heated, which is adjacent to the transducer-heater. Localization of the cavitation zone makes it possible to increase considerably the nucleation rate observed, and measurement of a thermal perturbation of the transducer-heater caused by cavitation bubbles, to obtain information on the kinetics of bubble nucleation.

The subject of the investigation is liquid n-butane. Previously, the cavitation strength of this liquid was not investigated. Later on, we are planning to supplement the study of spontaneous cavitation with measurements of the density of liquid n-butane in compression and tension waves. This will make it possible to obtain information on the boundary of thermodynamic stability, i.e. the spinodal.

The paper consists of an introduction, three sections and a conclusion. The second section examines classical nucleation theory as applied to the description of cavitation in a stretched liquid. The experimental procedure and the results of measurements are presented in the third section. The fourth section is devoted to the comparison of the data obtained with classical nucleation theory and the substantiation of the attainability of the homogeneous nucleation mechanism by experiment. Inferences about the work performed are presented in the conclusion.

2. Classical nucleation theory

Classical nucleation theory treats the fluctuation growth of subcritical bubbles as the process of their diffusion along the bubble-size axis (bubble radius R or volume V) in a field of thermodynamic forces [8,10]. In a stationary case a flow of nuclei is independent of the bubble size and equals the number of supercritical nuclei that form in a unit time in a unit liquid volume (nucleation rate)

$$J = \rho B \exp(-W_*/k_B T). \tag{1}$$

Here ρ is the number of particles in a unit volume of a metastable liquid, B is the kinetic factor which takes into account the dynamics of the bubble growth, W_* is the work of formation of a critical nucleus, k_B is the Boltzmann constant, and T is the temperature.

The kinetics of a transition of nuclei over the critical size is determined by the thermal and hydrodynamic situation near the nucleus, and also by the rate of liquid evaporation into the bubble. To evaluate the kinetic factor B, it is necessary to set off the determining pro-