MECHANISM OF THERMOACOUSTIC SELF-OSCILLATIONS

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UDC 66.096.5:536.24:532.517.4

Using the example of heat transfer to n-heptane under supercritical pressure conditions, it is shown that the frequency of the oscillations of the volumes of pseudobubbles is the same as the frequency of the pressure oscillations but is out of phase by a quarter of a period.

In recent years a number of papers have been published on the thermoacoustic oscillations that occur during heat transfer to a turbulent flow of liquid in tubes [1]. It has been established that both for surface boiling under subcritical pressure conditions and for "pseudoboiling" under supercritical pressure conditions the thermoacoustic self-oscillations are a standing pressure wave whose frequency is determined by the velocity of propagation of sound in the flow and the channel geometry, while the amplitude depends on the heat flow and the vapor content.

Many hypotheses have been put forward to explain the mechanism of thermoacoustic self-oscillations, but none of them is sufficiently satisfactory. One of the main characteristics of thermoacoustic self-oscillations, largely determining their mechanism, is the relation between the phases of the pressure oscillations and the volumes of the vapor phase (when $P < P_{cr}$) or of the "pseudovapor" phase (when $P > P_{cr}$). Three different relations between the phases of P and V are possible: They are in phase, the phase of the P oscillation leads the phase of the V oscillation, and the phase of P lags behind the phase of V. In the first case the oscillations of the volume of vapor bubbles (or pseudobubbles) perform no work; in the second case the bubbles perform positive work — they give oscillatory energy to the flow of liquid; and in the third case the opposite occurs, namely, the change in the volumes of the bubbles is due to pressure oscillations; i.e., there is an external source of oscillatory energy.

The majority of investigators (Nayama, Kafengauz, and Federov, Gerliga, and others [1]) assume that changes in the volume of the vapor bubbles ($P < P_{cr}$) or pseudobubbles ($P > P_{cr}$) give oscillatory energy to the flow of liquid.

Nesis and Dorofeev [2] hold to the opposite point of view; i.e., they assume that the oscillations of the bubbles result from pressure oscillations of the liquid, which in turn are excited by the action of parametric resonance due to a pronounced dependence of the change in the vapor content on the velocity of sound. They verify this hypothesis with appropriate experiments (under subcritical pressure conditions). No experiments have yet been made to determine the relation between the phases of the P and V oscillations under supercritical conditions.

In this paper we describe the results of an investigation of thermoacoustic self-oscillations which occur during heat transfer to a turbulent flow of n-heptane when $P > P_{cr}$. Experiments were made on a heat-transfer apparatus with a working part in the form of a ring channel with a transparent external wall. The apparatus and the working part are described in [3]. The ring channel was a glass tube (internal diameter 4.1 mm) inside of which there was a heat-dissipating element with an external diameter of 3.0 mm. The length of the element was 60 mm.

To carry out our investigation the heat-transfer apparatus was fitted with equipment for recording the frequency of the pressure oscillations and of the volumes of the pseudobubbles. The frequency of the pressure oscillations was measured with an SKCh-3 frequency analyzer. The frequency of the pseudobubble-volume oscillations was measured using a photomultiplier by the method described in [4]. The signal from the photomultiplier was applied

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G. M. Krzhizhanovskii Power Institute, Moscow. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 34, No. 5, pp. 773-775, May, 1978. Original article submitted May 11, 1977.

0022-0841/78/3405-0525$07.50 © 1978 Plenum Publishing Corporation

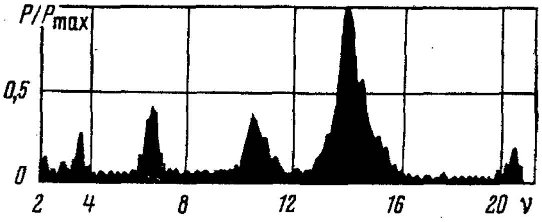

Fig. 1. Thermoacoustic self-oscillations characteristic for heat transfer to n-heptane; ν is the frequency of the thermoacoustic oscillations, kHz; p/p_{max} is the amplitude of the thermoacoustic oscillations.

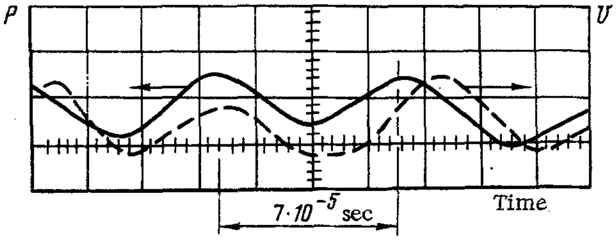

Fig. 2. Relation between the phases of the pressure oscillations (P) and the pseudobubble-volume oscillations (V).

to the first input of a double-beam oscilloscope matched to the photomultiplier with a cathode follower. The signal from the pressure probe was applied to the second input. Since the intensity of the light reflected from the working part was greater, the greater the dimensions of the pseudobubbles, this equipment enabled us to record changes in their volume. The double-beam oscilloscope enabled us to see and photograph the P and V oscillations simultaneously on the oscilloscope screen.

We will give the results obtained in experiments on heat transfer to n-heptane for the following parameters: P = 40 atm (for n-heptane P_{cr} = 27.01 atm and t_{cr} = 267°C), W_γ = 5000 kg/m²•sec, Re = 16,500, t_{in} = 20°C, t_{out} = 70°C, q = $9 \cdot 10^6$ kcal/m²•h, and t_s = 500°C. These parameters correspond to the so-called "improved" heat-transfer mode due to the presence of pronounced thermoacoustic oscillations [3].

It has been established previously that the heat transfer to a flow of liquid under supercritical pressure conditions and very high temperature gradients over the transverse cross section of the tube is accompanied by the formation and disappearance of pseudobubbles (which are a distinctive form of the usual large-scale turbulence). When thermoacoustic oscillations occur, the formation and disappearance of pseudobubbles are intensified considerably and occur simultaneously over the whole heat-transfer surface [3].

In the experiment described the frequency of the pressure oscillations was represented by a spectrum of frequencies which were multiples of 3.5 kHz (3.5, 7.0, 10.5, 14.0, 17.5, and 21 kHz), in which the pressure oscillations at a frequency of 14 kHz had the maximum amplitude (Fig. 1).

The oscillations of the pseudobubble volumes occurred with strict periodicity, the frequency of which was equal to 14 kHz, i.e., was exactly the same as the frequency of the pressure oscillations which had maximum amplitude.

The oscillograms of the P and V oscillations show that the P oscillations lead the V oscillations by approximately a quarter of a period (Fig. 2). The relation obtained between the phases of the P and V oscillations confirms the suggestion put forward in [3] that the pseudobubbles perform positive work; i.e., they give oscillatory energy to the liquid flow (this can be shown by constructing a P—V diagram in which the area bounded by the closed curve will represent the work done by the pseudobubbles during a single oscillation period).

This result agrees with experimental and theoretical data [5] obtained in an investigation of self-oscillations occurring during heat transfer to water under subcritical pressure conditions and indicates that the mechanism of thermoacoustic oscillations for surface boiling ($P < P_{cr}$) and that for pseudoboiling ($P > P_{cr}$) are the same.

NOTATION

V, volume of the pseudobubbles; P, pressure; P_{cr}, critical pressure; t_{cr}, critical temperature; t_{in}, t_{out}, temperatures of the n-heptane at the input to the working section and at the output from it; t_s, temperature of the cooled surface of the heat-dissipating element; q, heat flow; W_γ, mass velocity.

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THEORY OF THE TEMPERATURE STABILIZATION PROCESS IN GAS-CONTROLLED HEAT PIPES

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UDC 536.248.2

This paper presents results of an analytical investigation of the temperature-stabilization process in gas-controlled heat pipes. Expressions are obtained for the temperature-sensitivity coefficients.

Heat-pipe technology includes the use of heterogeneous heat-transmitting systems with constant-volume change of state, i.e., gas-controlled heat pipes, which possess the temperature-stabilization property.

The investigators in [1] encountered phenomena associated with blockage of the condenser by a noncondensible gas. Cotter [3] noted that the length of the blocked zone depends on the heat flux. Katzoff [2] suggested using the condenser blockage effect for temperature stabilization. Bienert [4] was the first to describe analytically the temperature-stabilization process using a gas-controlled heat pipe, which was later accomplished by Marcus [5]. More complete information on gas-controlled heat pipes can be found in [6].

The present paper deals with an analytical investigation of the gas-controlled heat pipe and pays particular attention to the temperature-sensitivity coefficient.

In examining the temperature-stabilization process employing a gas-controlled heat pipe, we use the model shown in Fig. 1. In analyzing this one-dimensional model we make the following assumptions: 1) The heat pipe is a closed thermodynamic system; 2) the vapor—gas mixture in the blocked zone obeys all the ideal gas laws; 3) the vapor and the gas are incompressible; 4) the vapor motion is laminar; 5) the heat pipe is horizontal; 6) the heat-pipe regime is evaporative.

Equation of State for the Vapor—Gas in a Gas-Controlled Heat Pipe

In the equilibrium state of a gas-controlled heat pipe, in the absence of energy exchange with the surrounding medium, and with assumption 1, the heat-transfer agent and the

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