CHARACTERISTICS OF SELF-EXCITED THERMOACOUSTIC OSCILLATIONS IN HEAT TRANSFER TO n-HEPTANE

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The speed of sound and wavelength are determined experimentally for thermoacoustic oscillations self-excited in connection with heat transfer to a flow of n-heptane under supercritical pressure conditions.

The results of numerous investigations of self-excited thermoacoustic pressure oscillations associated with the transmission of heat into various liquids have been published in recent years. A survey of work through 1974 is given in [1]. The investigations described therein present information about the conditions for the inception of self-excited thermoacoustic oscillations (SETAO), their frequency and amplitude characteristics, and various hypotheses submitted with regard to the physical nature of the phenomenon. Many studies have confirmed and elaborated the notion expressed by Kafengauz and Fedorov in 1966 [1], that the SETAO are standing pressure waves ([2, 3] and others). So far, however, it has been impossible to carry out any kind of quantitative calculations of SETAO for want of information about their propagation speed (speed of sound) in heat-transfer channels.

Whereas methods for the approximate calculation of the speed of sound exist for two-phase flows at subcritical pressures, there are no such methods for the case of supercritical pressures.

In the present study we have determined experimentally the wavelength and speed of sound for SETAO in heat transfer to a turbulent flow of n-heptane under supercritical pressure conditions. The experiments are carried out in a closed-loop heat-transfer test apparatus. The liquid is delivered by a gear-driven pump, and the fuel element is heated by passage of an electric current through it. The investigated liquid flows in the annular channel formed between the fuel element (d_{out} = 3 mm; d_{in} = 2 mm) and a glass tube with d_{in} = 4.4 mm. All the customary parameters are measured during the heat-transfer investigation: P, W_γ, q, t_w, t_{Lin}, and t_{Lout}. Also, a piezoelectric pressure probe and an SK4-3 spectrum analyzer are used to measure the SETAO frequency.

A Practika camera attachment loaded with high-sensitivity film is used to photograph the temperature nonuniformity of the outer surface of the fuel element.

Figure 1 gives a typical graph of t_w as a function of q for heat transfer to a turbulent flow of n-heptane at supercritical pressure (for n-heptane P_{cr} = 27 abs. atm and t_{cr} = 265°C). In the experiments P = 40 abs. atm, W_γ = 5000 kg/m²h, and t_{Lin} = 20°C. The curve $t_w = \varphi(q)$ represents in the initial interval ($q < 5.5 \cdot 10^6$ W/m²) ordinary convective heat transfer in a turbulent fluid flow, where q increases with t_w. For $q \geq 5.5 \cdot 10^6$ W/m² SETAO appear, intensifying the heat-transfer process and altering sharply the dependence $t_w = \varphi(q)$. SETAO occur in connection with strong isothermy, such that $t_w >> t_L$, i.e., with hot "gas" present in the wall layer and cold "liquid" in the flow core.

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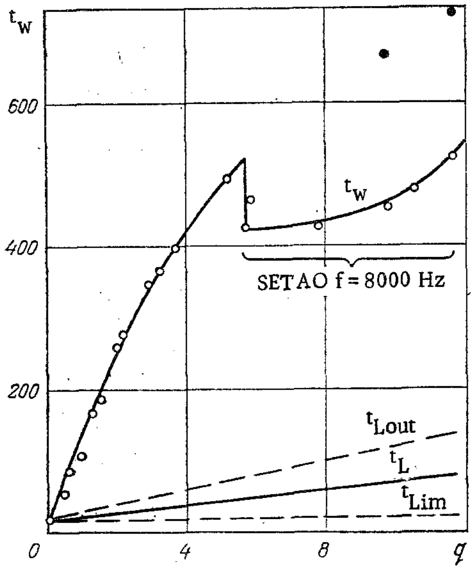

Fig. 1. Wall temperature t_w and liquid temperature t_L (°C) versus heat flux q (10^6 w/m^2) into n-heptane at supercritical pressure.

The SETAO frequency in the experiment described here is 8000 Hz.

Some researchers have remarked that with the inception of SETAO, particularly for $P > P_{cr}$, the wall temperature of the fuel element is lengthwise-nonuniform [1]. We have verified in the present study that this nonuniformity becomes more pronounced with increasing heat flux and for certain sets of conditions can be observed visually and photographed. One such photograph is given in Fig. 2, clearly evincing the wavelike variation of the temperature along the surface of the fuel element; the wavelength of the effect diminishes from the liquid entry toward the outlet. Also shown in this figure is an approximate graph of the temperatures of the outer and inner surfaces of the fuel element (the values of t_w at maximum-temperature sites are indicated in Fig. 1 by heavy dots). The observed behavior of t_w is not fortuitous and could not be elicited, for example, by nonuniformity of the wall thickness of the fuel element. We have definitely established that the wavelength varies in strict accordance with the SETAO frequency; the higher the frequency the shorter is the wavelength, and in the absence of SETAO the temperature t_w remains constant along the fuel element.

The observed wavelike pattern of the fuel element wall temperature along its length can clearly be attributed to the influence of SETAO on the heat-transfer process.

The self-excited thermoacoustic pressure oscillations form a standing wave, the parameters of which are customarily determined from the expression

$$A/A_0 = \sin 2\pi f\tau \cos \frac{2\pi y}{\lambda}.$$

At each instant the SETAO amplitude varies along the length of the channel according to the cosine law

$$A/A_0 = \cos \frac{2\pi y}{\lambda}$$

with maximum value at the antinodes and minimum value at the nodes (quarter-wave spacing between nodes and antinodes).

The intensity of the influence of SETAO on the heat-transfer process corresponds to the amplitude of the pressure oscillations; at the wave antinodes the heat-transfer coefficient undergoes the greatest increase, and as a result the temperature of the cooled surface drops the most, while at the pressure nodes the heat-transfer coefficient does not change, and the wall temperature is not lowered. Thus, the variation of the fuel element wall temperature

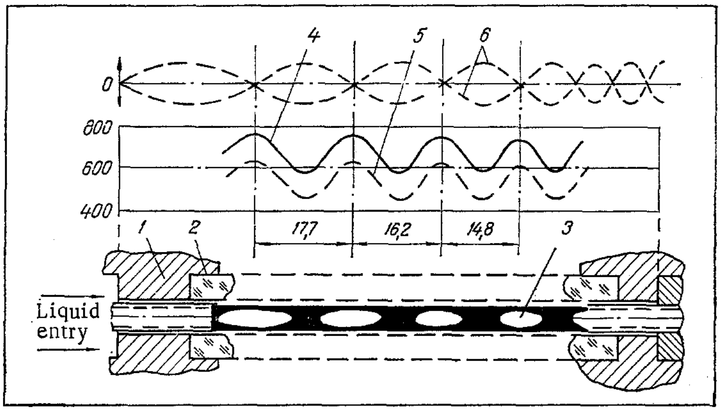

Fig. 2. Diagram of the test section; photograph of the outer surface of the fuel element during an experiment with $q = 9.8 \cdot 10^6$ W/m^2; distributions of wall temperature and SETAO amplitude along the length of the fuel element. 1) Outer casing of test section; 2) outer glass tube; 3) fuel element; 4) temperature of inner surface of fuel element; 5) temperature of outer surface; 6) SETAO pressure amplitude.

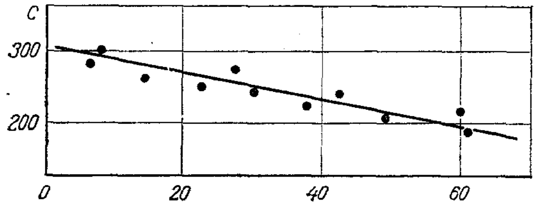

Fig. 3. Speed of sound c (m/sec) in n-heptane versus distance (mm) measured lengthwise along the flow channel from the test section inlet, $q = 9.8 \cdot 10^6$ W/m^2 (experimental).

emulates the variation of the pressure amplitude in the standing wave. The SETAO pressure amplitude is plotted in Fig. 2 in accordance with the plotted wall temperature of the fuel element. Inasmuch as the test section of the heat-transfer apparatus has acoustically dissimilar ends ("open" at the inlet and "closed" at the outlet), the standing pressure wave is asymmetrical, with a node at the inlet and an antinode at the outlet.

The photographs obtained of the wall-temperature distribution along the length of the fuel element enables us to measure (with maximum 5% error) the half-wavelength of the pressure oscillations and to determine the speed of sound from the expression

$$c = f\lambda,$$

in which $f = \text{const} = 8000\ \text{sec}^{-1}$.

The values thus measured for the speed of sound according to the data of two experiments are given in Fig. 3.

The results indicate that under the conditions of heat transfer to a liquid flow at supercritical pressure and with strong nonisothermy (with a wall layer of hot "gas" and a flow core of cold "liquid") the speed of sound decreases considerably in the flow direction. In the given experiments on heat transfer to n-heptane the speed of sound is 300 m/sec at the channel inlet and 200 m/sec at the outlet; the average speed of sound is approximately one fourth the value in liquid n-heptane.*

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*The speed of sound in liquid n-heptane at 40°C is equal to 1140 m/sec [4].

The striking decrease in the speed of sound along the heat-transfer channel suggests that the relation used in SETAO investigations to determine the standing-wave parameters, namely $f = (c/2l)n$, which pressuposes $\lambda = 2l/n = \text{const}$, is not really correct; accordingly, neither are the standing-wave equations given above correct (precise), as is evident from the plotted variations of the wall temperature and pressure amplitude along the length of the channel (Fig. 2).

The SETAO frequency as well as the wavelength and profile of the standing wave must be determined in correspondence with the lengthwise variation of the speed of sound along the heat-transfer channel.

The foregoing conclusions are probably also true of the SETAO occurring in heat transfer to a liquid flow with surface boiling under subcritical pressure conditions.

NOTATION

A, amplitude of pressure oscillations; A_0, maximum amplitude; c, speed of sound; f, SETAO frequency; l, length of test section; n, order of SETAO harmonic; q, heat flux; P, pressure; t_W, wall temperature; t_{Lin}, t_{Lout}, inlet and outlet temperatures of liquid; t_L, liquid temperature in the middle of the test section; W_γ, mass flow rate; y, distance from pressure-wave reflecting boundary; λ, wavelength; τ, time.

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