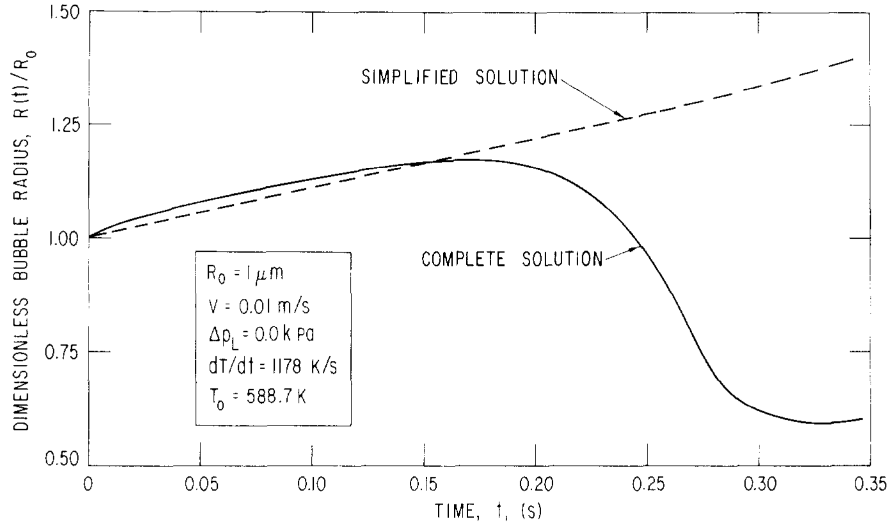

FIG. 1. Comparison of simple and complete models for the case of a core inlet blockage with small R_0.

the usefulness of the simplified model is also dependent on its range of applicability. Thus, comparisons between the predictions of the simplified and complete models were made for more severe transient conditions corresponding to abnormal LMFBR operation of the overpower and core blockage types. In the case of a mild overpower condition (exit liquid temperature of 686°C), similar excellent agreement was obtained between the two models for all values of initial bubble radius studied (1–1000 μm). The results of the core blockage transients, however, were found to be strongly dependent upon the initial bubble radius, R_0. In this case (liquid velocity of 0.01 m/s with continued full power heating) agreement was again excellent for $R_0 > 100\,\mu m$. The results of the two models began to diverge for values of initial radius less than 100 μm where differences of the order of 5% were observed in the predicted bubble radii for $R_0 = 10\,\mu m$, and at $R_0 = 1\,\mu m$ the differences were an order of magnitude larger. The results for bubble radii as predicted by the two models are shown in Fig. 1 for the last condition, $R_0 = 1\,\mu m$. The large differences between the two solutions are evident in Fig. 1 where the diffusion mechanism neglected in the simplified model is a contributing factor to the complete model solution. For initial bubble radii of 100 and 1000 μm, the maximum differences in computed bubble radii were 0.4 and 0.1%, respectively.

CONCLUSION

From these observations, an important conclusion was reached regarding application of the simplified analytical model to LMFBR situations. The dynamics of entrained inert gas bubbles can be described by a very simple model [equations (3)–(4)] with a high degree of accuracy for a wide variety of situations encompassing both normal and some abnormal LMFBR behavior. The applicability to abnormal LMFBR transient situations is limited, and the model must be used cautiously. However, the successful application of the simplified model to some relatively severe LMFBR transient conditions provides assurance of the accuracy of the model when applied to the range of LMFBR operational conditions generally considered to be near nominal.

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THE EFFECT OF TRANSVERSE OSCILLATIONS ON HEAT TRANSFER FROM A HORIZONTAL HOT-WIRE TO A LIQUID. HOLOGRAPHIC VISUALIZATION

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NOMENCLATURE

a,	amplitude of oscillation from center position to extreme position of oscillation;
ω,	pulsation of oscillation;
χ,	heat diffusivity coefficient;
β,	coefficient of thermal expansion;
g,	acceleration of gravity;
ΔT,	temperature difference between the wire and the liquid;
d,	wire diameter;
ν,	kinematic viscosity;

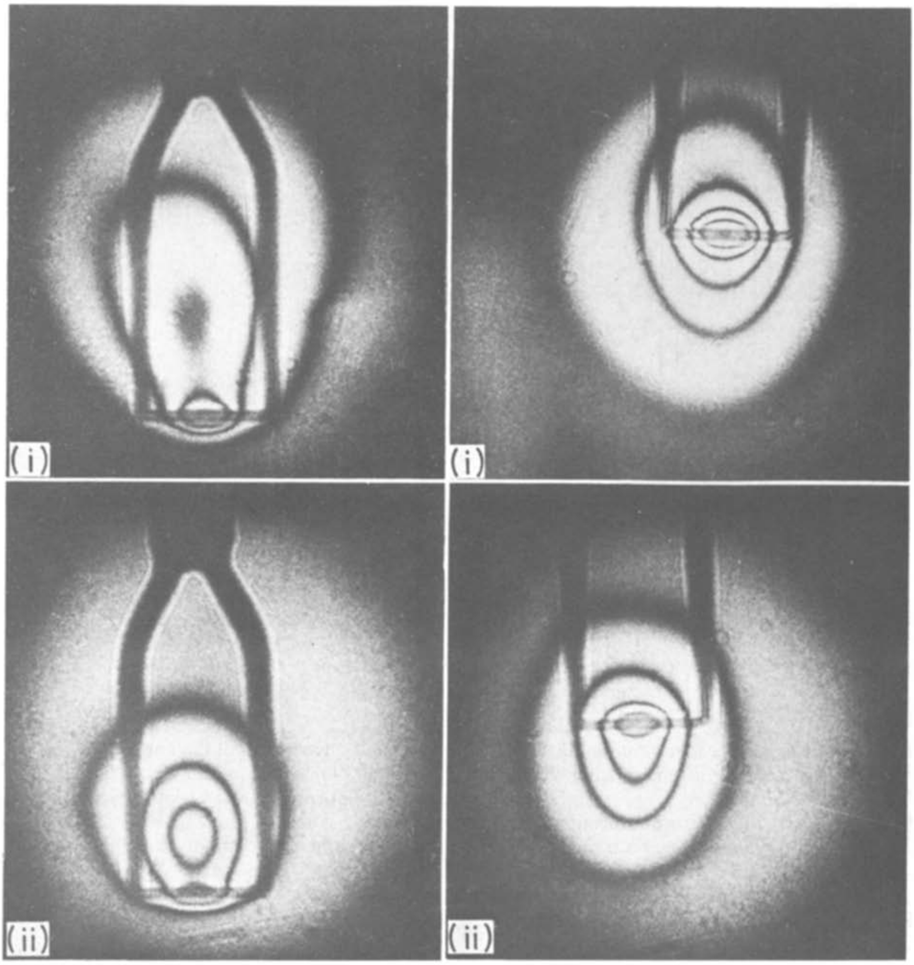

FIG. 1. Interferograms of temperature distributions around the hot-wire for end positions in the oscillation of the probe. (i) Amplitude, 2 mm; frequency, 0.1 Hz. (ii) Amplitude, 2 mm; frequency, 0.5 Hz.

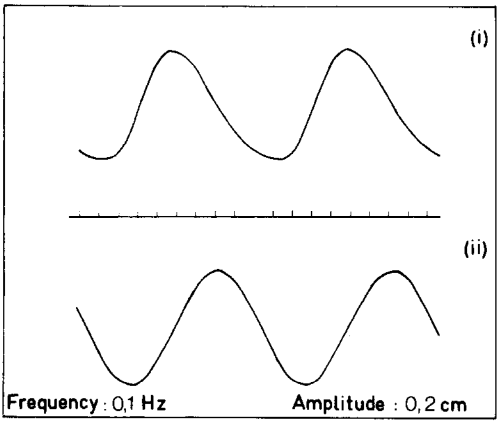

FIG. 2. Simultaneous recording for 0.1 Hz of: (i) output signal from the hot-wire; (ii) oscillation of the probe ($a = 2$ mm).

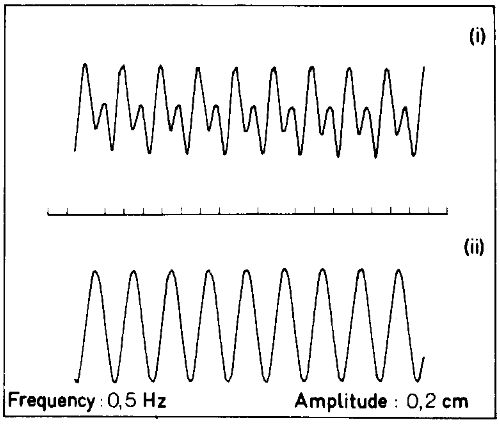

FIG. 3. Simultaneous recording for 0.5 Hz of: (i) output signal from the hot-wire; (ii) oscillation of the probe.

Gr,	Grashof number, $= \dfrac{g\beta\Delta T d^3}{\nu^2}$;
Pr,	Prandtl number;
Re,	average Reynolds number;
Pe,	Peclet number;
φ,	phase lag of the second order term in Fourier spectrum with respect to the sinusoidal motion velocity.

1. INTRODUCTION

THIS note deals with the heat transfer occurring from a vertically oscillating hot-wire to a stationary surrounding fluid. This study consists first in a visualization of the instantaneous temperature distribution around the wire during its movement, using a holographic interferometer. A discussion of the heat-transfer processes resulting from free

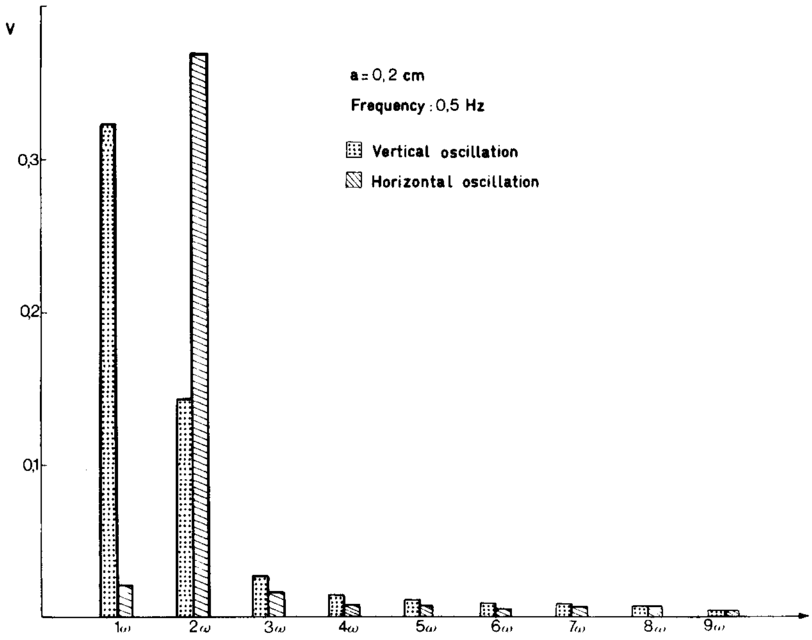

FIG. 4(a). Amplitude spectra of the output signal for vertical and horizontal oscillations at a frequency of 0.1 Hz ($a = 2$ mm).

and forced convection is then carried out using measurements of the hot-wire electric current passing through it during the oscillation.

Many investigations of the effects of vibration on heat-transfer from wires and cylinders have been made over last years [1–4] to provide a better understanding of the processes that affect heat transfer in oscillatory flow. More recently Carr and Black [5–6] using interferometric measurements have shown the strong dependence of the vibration parameters on the instantaneous heat-transfer rate. In the present study the sensing element of the hot-wire is a cylinder having a diameter of 70 μ, the frequency of oscillations ranging from 0.1 to 1 Hz with amplitude of vibration between 0.1 and 1 cm. With the average Grashof number of the experiment ($Gr \sim 0.4 \times 10^{-3}$) and Prandtl number for our specific fluid ($Pr \sim 70$), the characteristic velocity for natural convection is in the range of the oscillatory flow velocities.

Observation of the temperature field surrounding the wire for different experimental situations indicates that this field can demonstrate a "frozen-in" effect in the fluid, depending upon both amplitude and frequency of the oscillatory motion of the probe. In other words, the temperature field may be subjected to an oscillatory self-movement having in general a phase-lag with respect to the driving motion. Consequences of this kind of process on heat transfer have been investigated by studying the variations of the electric current required to keep the hot-wire at a constant temperature. A Fourier analysis of the probe response has made possible a separation, in the overall heat transfer, of the specific component corresponding to the oscillatory movement. The main characteristics of this component are then obtained as functions of the parameters of the problem at hand.

2. APPARATUS

The hot-wire, used in this investigation, was a DISA 55 R 11 probe. The movement of this probe was produced by an oscillation generator type PRODERA. The fluid used in those experiments was a mixing between water (35%) and glycerol (65%) thermalized at the ambient temperature (20°C), whereas the probe was maintained at the constant temperature of 40°C. This probe was operated as the varying resistance of a Wheatstone voltage bridge, the electrical current through the probe being regulated instantaneously as a function of the thermal extraction.

Direct observation of the temperature field was achieved using a holographic interferometric bench [7] giving fringe shifts proportional to the local temperature gradients. This technique possesses the capability for visualizing the temperature field under rapidly changing transient conditions, the reference state being any given state during the oscillation.

3. RESULTS AND DISCUSSION

Pictures of interferograms corresponding to the temperature distribution were made while the wire executed vertical sinusoidal motion (Fig. 1). The interferograms show that isotherms themselves execute an oscillating movement having generally a phase-lag with respect to the motion of the wire. At low speed motions, the temperature profile can follow the wire during its oscillations whereas it tends to execute a separated motion with increasing velocities. For greater speed values, the temperature distribution seems to be "frozen" in the liquid, or, in other words can no longer follow the wire oscillation.

Moreover, one can denote the strong difference between two temperature profiles for end positions in the oscillation of the probe (though for the same zero velocity). This asymmetry is mainly a result of the effect of free convection on the profile.

In addition, one can also denote that for the range of the studied values of amplitudes and frequencies, and taking into account the characteristic diffusion time in the fluid used, one part of the backward movement of the wire occurs into its own thermal wake. The wire and the surrounding temperature pattern having a relative movement, one can say that the wire is oscillating in a non-uniform temperature medium. This may produce a time dependent modification of the Grashof number leading to a time dependence of the natural convection from the wire during its oscillation.

Thus, the temperature distribution and/or heat transfer around the wire is related in a complex manner to the oscillating movement of the probe and to the resulting modifications in free convection. The heat transfer being produced by dissipation of the electrical current through the wire, we have studied the time variation of this current in correlation to the hot-wire sinusoidal motion.

At low velocities (Fig. 2) the output signal is nearly sinusoidal with the same frequency as the forced motion. In this case, the effects caused by free convection are

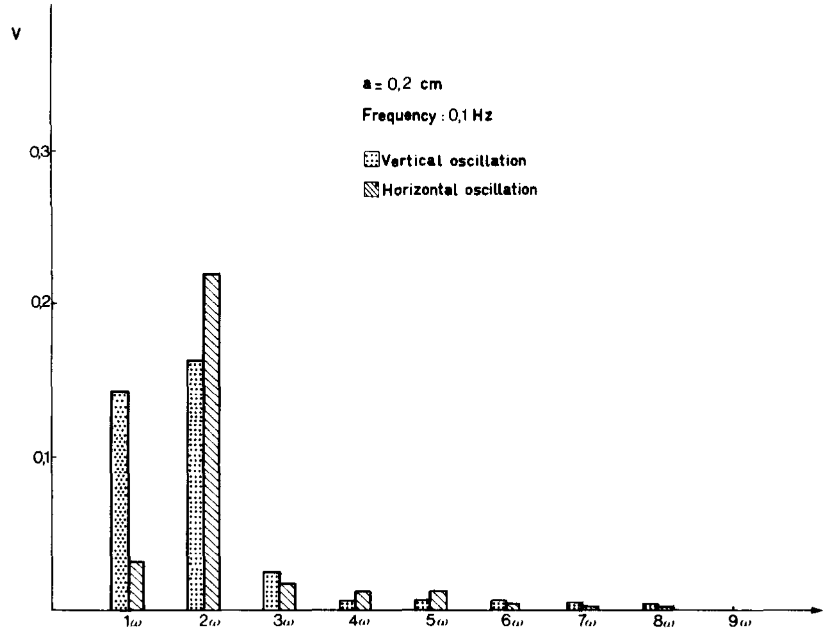

FIG. 4(b). Amplitude spectra of the output signal for vertical and horizontal oscillations at a frequency of 0.5 Hz ($a = 2$ mm).

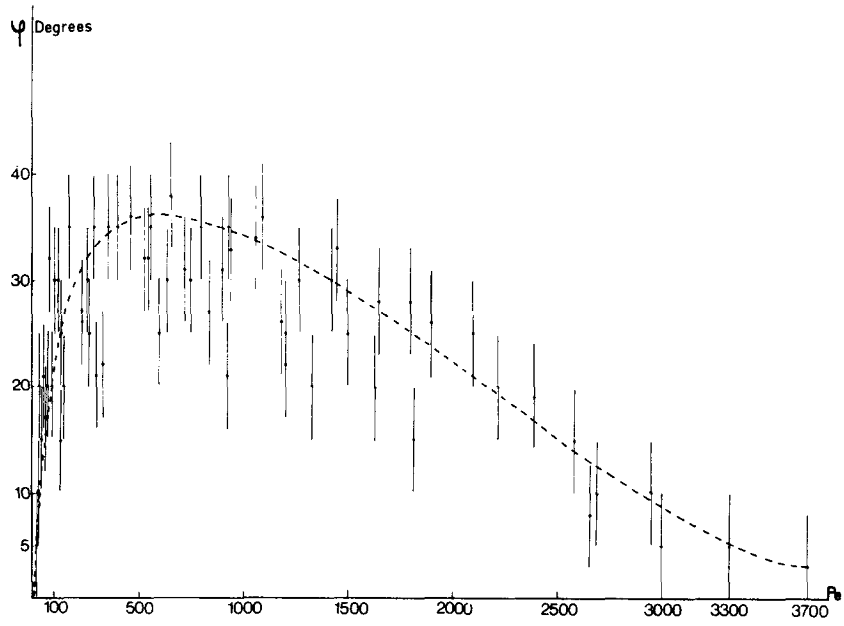

FIG. 5. Phase-lag φ vs Peclet number Pe.

dominant on the overall heat-transfer time dependence. The fact that the free convective flow acts alternatively in the same direction as the imposed motion and counter to it creates a periodicity in the probe response equal to that of the movement.

For greater speed (Fig. 3) the heat transfer resulting from forced convection is more important and the response of the probe is strongly distorted as compared to the previous one. It is then of interest to make a more detailed study of this signal deformation using a Fourier analysis.

Two examples of amplitudes spectra for 0.1 and 0.5 Hz resulting from this analysis are plotted in Fig. 4. One can observe that the first order terms in those spectra are important in the vertical oscillation, as a result of the asymmetrical effects occurring during the movement due to free convection. Corresponding spectra for horizontal oscillations are also plotted in Fig. 4. It is seen from the figure that the first order terms in this case are becoming smaller than the second order harmonic.

In this case the free convection has a symmetrical effect during the oscillation because the free convective flow is perpendicular to the direction of the motion. Thus, for a horizontal oscillation, the second order term in the Fourier amplitude spectra results from both forced and free convection, whereas for a vertical movement it depends on forced flow only, the first order term being significant of free convection in this case. The forced flow induces a transfer which is achieved by the action of heat convection and conduction, the relative magnitude of those two processes being expressed by the Peclet number $Pe = RePr = a\omega^2/\chi$.

Thus, for a given Peclet number the heat transfer resulting from forced convection is delayed from the imposed movement. This delay time is significant of the relative magnitude of the dragging action caused by the forced flow on the temperature distribution to the "frozen-in" effect in the medium. The phase lag φ of the second order term with respect to the sinusoidal motion velocity is plotted in Fig. 5 as a function of the corresponding Peclet numbers.

The phase lag φ decreases to zero for both small and high values of Peclet number ($Pe > 3000$). The phase lag φ reaches the maximum value of $\varphi \sim 35°$ for a Peclet number about 600.

4. CONCLUSIONS

The Fourier analysis of the probe current can be used to separate the effect of a vertical forced oscillatory motion from the free convection. The corresponding mode in the response is shown to have a phase lag with respect to the periodic motion of the hot wire, this phase lag being related to the Peclet number of the system. This phase shift can be due to the relative motion between the temperature profile and the oscillating wire, as observed on interferograms. Thus, the heat transfer is no longer significant of the instantaneous velocity of the hot wire movement. The phase lag increases with increasing values of Pe for small Pe (< 600), as a consequence of the enhancement of the frozen-in effect for the temperature distribution in the medium. For larger increasing values of Pe, the phase lag decreases due to the fact that heat transfer is then certainly occurring by forced-diffusion in the immediate vicinity of the probe as a result of the observed enhancement of the thermal gradients in this situation.

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