cm is used, and we presume after reflection, absorption and scattering an approximate solar flux value F of 600 W m^{-2}. Substrate constants for concrete were taken to be $\lambda_s = 1.33$ W m^{-1} K^{-1} and $\alpha_s = 8.28 \times 10^{-7}$ m^2 s^{-1}, whereas for the water layer $\lambda_l = 0.557$ W m^{-1} K^{-1}, $\alpha_l = 0.131 \times 10^{-6}$ m^2 s^{-1} and $\rho_l L_l = 3.34 \times 10^8$ J m^{-3} for the volumetric latent heat were used. For the dimensionless critical thickness $\delta_m = 1.37 \times 10^{-3}$ it was possible to use the expansion (16) to obtain $\tau = 1.40 \times 10^{-3}$, the corresponding time of 57 s, an energy requirement of 3.4×10^4 J m^{-2} and a substrate loss of 2.3% of the incident energy. For this example $\beta = 0.95$ and substrate losses at very long times [equation (18)] can reach nearly 50%, the small substrate losses are due to the small dimensionless time value. In a second case, we assume that a radio frequency source will deliver 3.10×10^6 W m^{-2} to the outer skin of a 430 stainless steel rail. If 10^{-4} cm of ice at the rail interface must be melted for easy mechanical removal and with the substrate constants $\lambda_s = 26.2$ W m^{-1} K^{-1} and $\alpha_s = 7.32 \times 10^{-6}$ m^2 s^{-1} the dimensionless critical thickness is $\delta_m = 0.071$. From the numerical solutions of Fig. 2, the critical time $\tau = 0.13$ implies a melting time of 2.1×10^{-4} s, and an energy requirement of 6.5×10^2 J m^{-2} with a substrate energy loss of 44.4%. For this conducting rail $\beta = 6.29$ and asymptotic substrate losses (18) could reach 86% at very long times. Asymptotes form slowly enough that the latent heat sink can significantly reduce substrate heat losses during the melting process.

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THE INFLUENCE OF SOUND ON NATURAL CONVECTION FROM VERTICAL FLAT PLATES

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NOMENCLATURE

- A, width of plate;
- Gr_x^*, modified local Grashof number;
- H, height of plate;
- Nu_x, local Nusselt number without sound;
- Nu_{xf}, local Nusselt number with sound;
- X, co-ordinate of height along plate measured from bottom;
- f, frequency;
- q, heat flux;
- SPL, sound pressure level [dB].

INTRODUCTION

IN 1931 ANDRADE [1] carried out experiments on the isothermal streaming of tobacco smoke in a standing wave tube by photography. In the following year, Schlichting [2] published the mathematical solution of the problem of streaming around a circular cylinder. Since then, Fand and Kaye [3], and Richardson [4] have made general surveys of the literature in this field.

As for studies of the vertical flat plate, with which the present authors are concerned, June and Baker [5] reported their experiments using a siren. In their experiments, they combined temperature difference, sound intensity and frequency, and introduced the idea of the depth of penetration of sound. They compared their results with those for heat transfer occurring without sound. However, their experiments were limited to a single flat plate. Considering the fact that the geometry of the heat transfer surface is one of the important factors on the convective field itself, it seems probable that this limitation would mean that their results could not fully explain the influence of the sound field on the convective field.

The aim of this study is to investigate experimentally the influence of a sound field on the natural convective heat transfer from vertical flat plates by means of flat plates of various width.

APPARATUS

The apparatus used for these experiments was an echo chamber made of iron plates (dimensions: thickness 1 cm; height 80 cm; width 70 cm). It was fitted with two speakers separated by 130 cm. Several plates were placed vertically with both ends fixed at the centre of the inside of the echo chamber. The plates, of Ni–Cr foil, were 0.5 mm thick, 70 cm high, and 1, 2, 4 and 10 cm wide, respectively. Experiments were made at constant heat flux. The surface temperatures were measured by 17 pairs of iron–constantan thermocouples placed at a fixed separation along the centre lines of the plates. Sound was generated by two trumpet horn speakers (100 W each) facing each other. The sound around the plates was caught by a condenser microphone. The sound frequency and pressure level were measured by a frequency analyser.

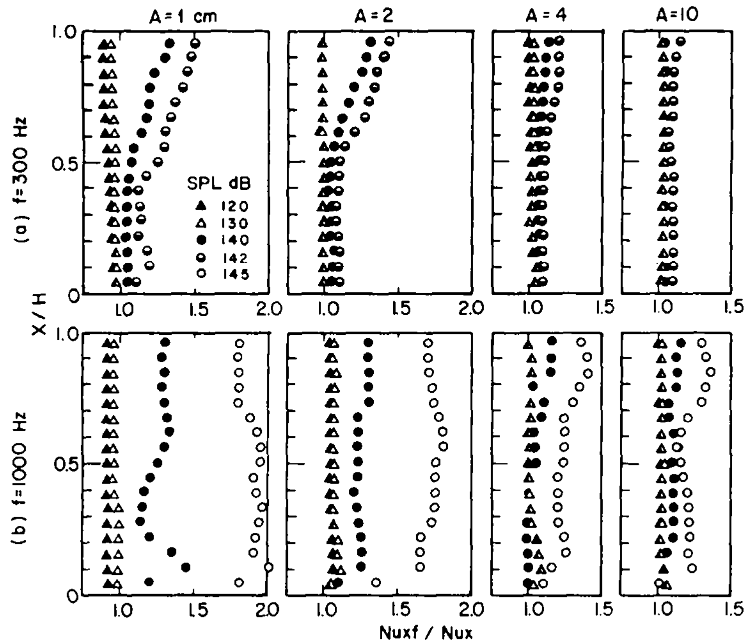

FIG. 1. The influence of SPL on the local heat transfer rate.

RESULTS

Various SPL sound waves of 300 Hz and 1000 Hz frequency were emitted to heated plates. The details of the heat transfer changes are shown in Fig. 1. When SPL = 120 and 130 dB, the influence of the sound field was relatively small, irrespective of the plate width and the frequency. However, when SPL was over 130 dB, heat transfer increased as the plate width was reduced and SPL increased [Fig. 1(b)]. This shows that one of the factors governing the increase or decrease of the heat transfer of the plates is the intensity of the sound waves. On the other hand, as seen in Fig. 1(a), the distribution of the local heat transfer rate with wide plates remained almost the same with or without sound. Therefore the influence of sound on the convective field was considered small. As the width of the plate was reduced, heat transfer rapidly increased around x = H/2, and, the smaller the plate width, the more the position was shifted to the upper stream. When we compare this with the case of Fig. 1(b), we can conclude that the frequency of sound is also an important factor on heat transfer.

Figure 2 shows the relation of the above stated results and Gr_x^*. Figure 2(a) shows that when the plate width was large, heat transfer remained almost unchanged within the range $5 \times 10^5 < Gr_x^* < 5 \times 10^{10}$, irrespective of the existence of sound; but heat transfer increased when Gr_x^* was around and over 5×10^{10}. As the plate width was reduced, the value of Gr_x^* at which heat transfer began to increase became smaller, the tendency being more noticeable when there was little temperature difference between the heat transfer surface and the air flow around. The reason for this can be explained as follows: when the temperature difference is small, the slow flow is disturbed by the disturbance of sound waves, and, with the reduction of the plate width, interference occurs in the flow on the heat transfer surface by the side flow that crosses the

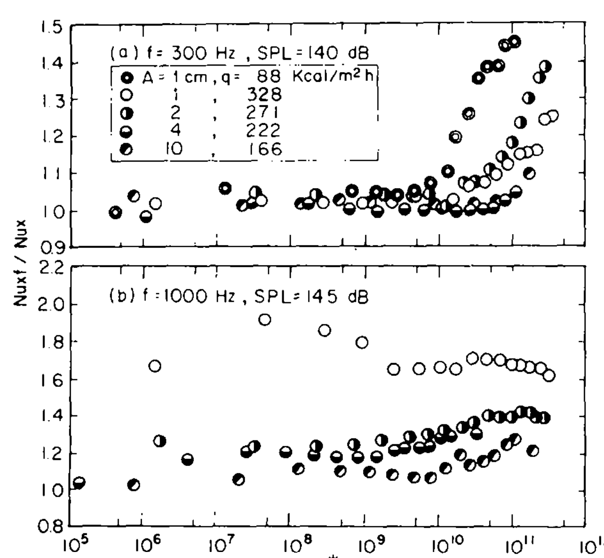

FIG. 2. The influence of the plate width on the heat transfer rate.

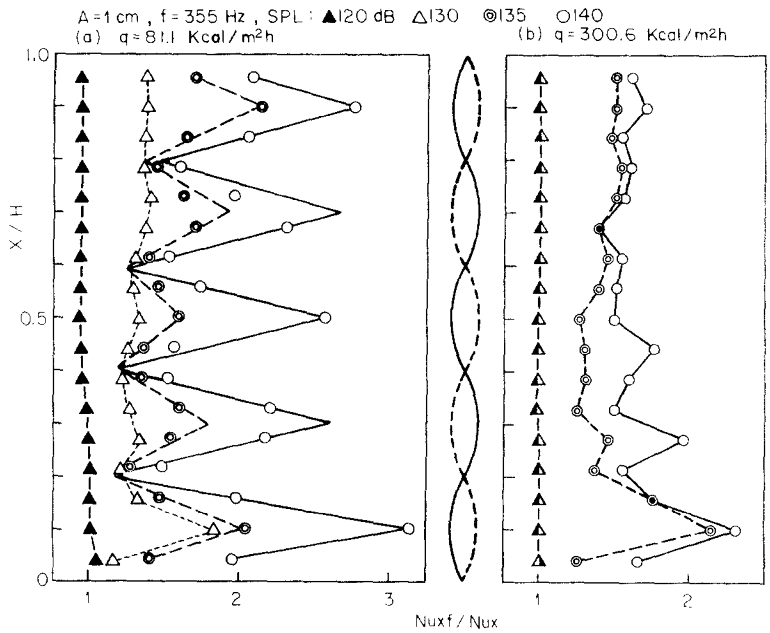

FIG. 3. The local heat transfer rate distribution for the resonant state.

surface at right angles. Consequently, by the mixed influence of these, the flow around the plates becomes unstable, quickens the transition to turbulent flow. On the contrary, the results in the case of $A = 1$ cm, $q = 328$ kcal m^{-2}h^{-1} with a large temperature difference were almost the same as the results of the case without sound, within the range of $5 \times 10^6 < Gr_x^* < 3 \times 10^{10}$. An explanation of this is that when the temperature difference is large, the inertia of the flow around the plate is also large, and so it can overcome the disturbance of sound waves, and the basic character of natural convection boundary layer is not changed by it.

As for the case of Fig. 2(b) (1000 Hz), the violent vibration of the air hindered the rising flow from the convective field as SPL increased, and the flow was drawn in the vibrational direction, and thus the flow became more unstable. Consequently, the disturbance spread generally over the convective field, and, by the eddy conductivity effect, the convective field was disturbed so much that it could not retain the original character. A similar phenomenon can be observed in the shadowgraphs of Holman [6]. (When the sound waves of 1660 Hz were emitted to a horizontal heated circular cylinder, rising flow almost disappeared at $SPL = 142$ dB.)

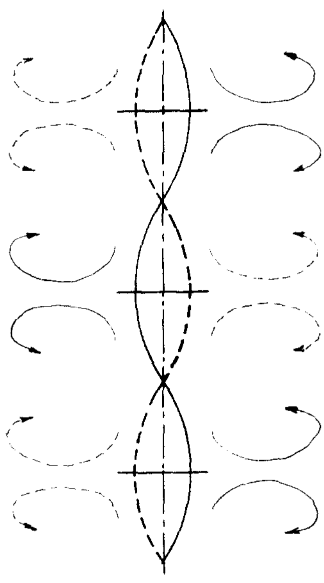

FIG. 4. The streaming for the resonant state.

When the frequency was 355 Hz, the sound field became very intense and the vibration reached the concrete wall (10 cm thick) which covered the echo chamber. This is considered to be a state of reasonance caused by the accordance of the natural frequency of the chamber and the phase of the sound source of the speakers. Figure 3 shows the distribution of heat transfer rate when $A = 1$ cm, $f = 355$ Hz, for various values of SPL.

An interesting phenomenon observed was that distinct variations occurred in the thermal field when the magnitude of heat flux was changed. Especially, when the heat flux was small [Fig. 3(a)], pulsation could be observed in the thermal field at $SPL > 130$ dB, and at $SPL = 140$ dB, the local heat transfer rate increased tremendously. The rate reached 300% at its highest, compared to the case without sound. By observation through the measuring window, it was revealed that the plates vibrated in distinct standing waves with five anti-nodes. By examining them with magnifying glasses, it was measured that the amplitude was about 1.4 mm, which was three times as large as the plate thickness. In Fig 3(a), the maximum value of the local heat transfer rate is just at the position of the anti-node of wave motion. The reason for this is considered to be that a violent vortex shedding motion at the anti-node in Fig. 4 markedly enhanced the heat transfer rate.

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