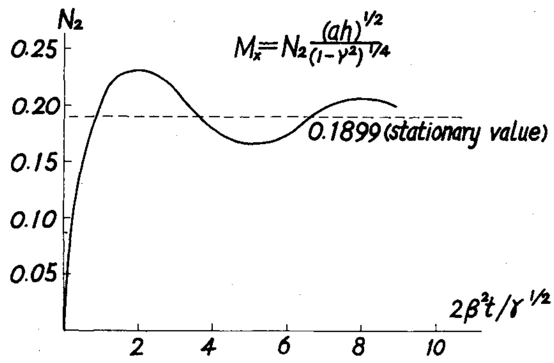

Fig. 3 Variation of $M_x(0,t)$.

which coincides with the corresponding static solution of Eq. (10). Hence, compared to $w(x,t)$, $M_x(x,t)$ approaches its stationary value more rapidly.

Numerical Results and Conclusions

The dynamic responses of w and M_x have been worked out from Eqs. (7) and (8) and presented in Figs. 2 and 3. From the results, the following conclusions can be drawn:

1) For $\infty > t > 0$, w and M_x oscillate with decreasing amplitudes around their stationary values. These regular patterns prove the correctness of the solutions in Eqs. (7) and (8).

2) Compared with w, M_x approaches its stationary value much faster, a conclusion in line with that drawn from the asymptotic solution of Eq. (12).

3) The ratio of maximum to static M_x in the present problem is 1.23 and is of the same order as the dynamic effect coefficients found in some design specifications.[5] However, owing to some idealizing factors involved in the present analysis [such as the idealizing external load $H(t)\,\delta(0)$], the ratio we gain must be somewhat higher than that occurring in the real process.

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Thermoacoustic Convection Heat-Transfer Phenomenon

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Introduction

IT is known that rapid heating of a fluid at a boundary (or in a mixing process where chemical reaction takes place) can cause sudden expansion of the fluid near the boundary, giving rise, in turn, to the appearance of pressure waves. These pressure waves, which are of thermal origin, are called thermoacoustics. The appearance of these waves and the ensuing compression and rarefication of the fluid produces a fluid velocity that can result in enhancement of heat-transfer processes by addition of a convective mode. The presence of thermoacoustics has been known for a long time in such configurations as Sondhauss and Rijke tubes, where they can attain frequencies within audible range.[1,2]

One of the main motivations in the investigation of thermoacoustic convection (TAC) heat tansfer is in space application. Manufacturing processes, cryogenic storage, and fluid handling processes in space may all include large TAC heat-transfer rates. Thus in zero-gravity space environment, where it is assumed that conduction is the only heat-transfer mode, TAC heat transfer can play a significant role in the enhancement of heat transfer by introducing a convective mode.

The study of the contribution of the thermally generated pressure waves and the ensuing fluid velocity to heat-transfer processes has been limited primarily to analytical investigations. These studies show that large temperature gradients can produce significant thermoacoustics, giving rise to large heat-transfer rates and short transient times, leading to rapid establishment of steady-state temperature profiles. There has, however, been no experimental investigation of TAC heat transfer in both zero-gravity or gravity environments.

Figure 1 shows the geometrical configuration that was studied in two numerical investigations of a one-dimensional TAC heat transfer.[3,4] Two infinite parallel plates, a distance L apart, that contain an ideal gas are all assumed at an initial temperature T_0. At time $t=0$, the top plate temperature is suddenly increased to $2T_0$. It was found that gas temperature rapidly approaches that of steady state in a very short time. Figure 2 shows the results of the nondimensional temperature profile of helium gas at $x=\frac{1}{2}L$ after 0.2 s. The temperature profile for pure conduction, as well as the linear steady-state results, are also presented in Fig. 2. These results show a very rapid rise of temperature due to the presence of TAC relative to the slow conduction mode. A study of time scales in this one-dimensional TAC heat-transfer problem confirmed that a significant difference between conduction and TAC heating time scales exists.[5]

In order to generate significant thermoacoustic convection heat transfer in a gas, the rate of increase of temperature imposed on the boundary should be large. For the configuration shown, numerical analysis of the governing equations by the authors[6] indicates that thermoacoustic flow velocity is present when the rate of increase of boundary temperature is 22°C/s or larger. For an example of "slow" rise of boundary temperature (approximately a constant rate of 0.7°C/s), which corresponds to Appollo 14 experiments, the numerical solution of the governing equations for a one-dimensional radial model shows no significant contribution of TAC heat transfer[4]; that is, for this slow rate of increase of boundary temperature, the convective heat-transfer mode remains small and conduction effects dominate energy transport to the gas.

In order to verify the importance of TAC heat transfer in zero-gravity and gravity environments relative to pure conduction in fluids, an experimental investigation of a one-dimensional heat-transfer model was initiated under the sponsorship of NASA Lewis Research Center. The preliminary results of this study will be presented following a brief description of the experimental apparatus used in the investigation.

Experimental Study and Results

The experimental apparatus consisted of a cylinder containing air. The cylindrical diameter and height are 0.31 m (1 ft) each. The side walls of the cylinder were insulated to

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ensure a one-dimensional heat flow. The top boundary of the cylinder was chosen as the surface subject to sudden temperature change to eliminate any contribution to heat transfer by buoyancy effects in gravity environment. The change in temperature was achieved by resistance heating using copper wire and a large battery pack. Figure 3 shows the temperature rise of the resistance element on the top surface as a function of time for the two different power settings used in the experiments. For reasons of limitation on the size and weight of the battery pack in the experimental package used in NASA Lewis Drop Tower Facilities, the heating element used in this preliminary study did not cover the entire area of the top boundary. Therefore, even though rapid heating could be achieved by means of resistance heating, only a fraction of the top surface area (12%) was subject to a high rate of temperature change. Due to this limitation and for purposes of presentation of experimental results, it was found convenient to define a time- and space-averaged top boundary temperature $\bar{T}_s$, calculated by averaging surface temperature on the top disk over both surface area and experimental time period (approximately 2 s).

A series of thermocouples were placed along the axis ($r=0$) of the cylinder. With x defined in Fig. 1, the locations of these thermocouples were at $x=7.6$, 15.2, 22.9 cm (3,6, and 9 in., respectively). The output of the thermocouples were displayed on digital thermometers. These displays were recorded on film during the experiment using a high-speed camera. Control circuits were used to initiate and terminate the current through the heating element as well as the operation of the camera.

Some of the results obtained are presented in Fig. 4. In this figure, the nondimensional rise in temperature in the air is presented as a function of time for two resistance heating rates of 1315 and 3368 W. The rise in temperature of the air ($\Delta T = T_{gas} - T_0$) is nondimensionalized using ($\bar{T}_s - T_0$). Temperature rise measured at the location of other thermocouples [$x=15.2$ and 22.9 cm (6 and 9 in.)] were very small and within experimental uncertainty and therefore, are not presented herein. The uncertainties in the experimental measurements were 15 and 20% for 1315 and 3368 W power settings, respectively. For comparison purposes, the temperature rise for pure heat conduction for similar resistance heating rates were also calculated and are presented in this figure.

These preliminary results cannot directly be used to verify the numerical solution of the equations[4] due to differences in initial and boundary conditions. These results, however, illustrate qualitatively the importance of TAC. For the purpose of a more quantitative verification of TAC significance, a more comprehensive numerical and experimental investigation of the one-dimensional TAC phenomenon is under way, which will address this issue specifically.

It can be shown that length scale for pure conduction heating in a semi-infinite medium with a constant boundary temperature is of the order of $\sqrt{\alpha t}$, where α and t are diffusivity of air and time, respectively. The temperature rise in air for pure conduction was calculated from the known analytical solution of conduction in a semi-infinite medium. An average temperature for the top surface corresponding to average temperature of the heating element was used in this constant-temperature model. The result shows almost zero temperature rise within 2 s heating time and is indistinguishable from the horizontal axis as shown in Fig. 4.

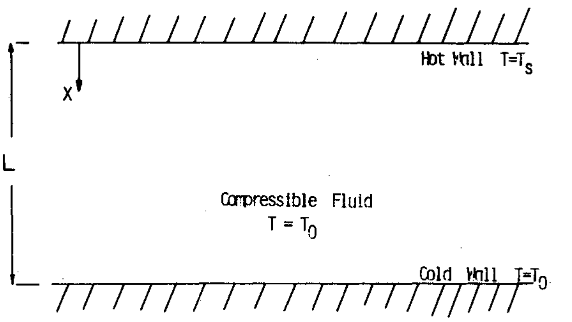

Fig. 1 Geometrical configuration of the problem.

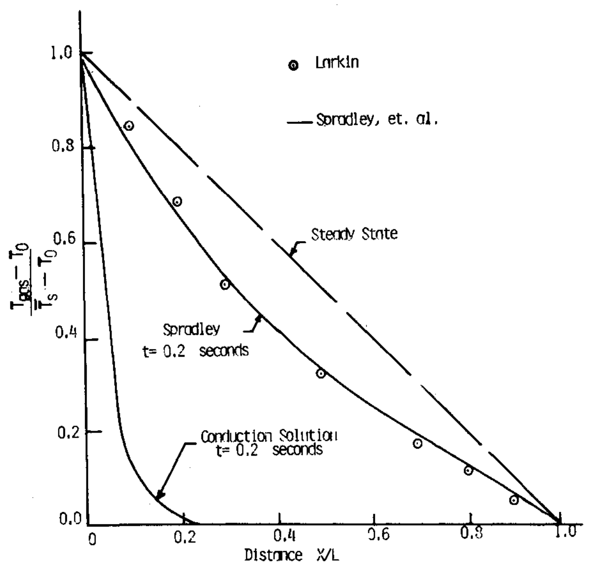

Fig. 2 Dimensionless temperature vs distance at time $t=0.2$ s.[4]

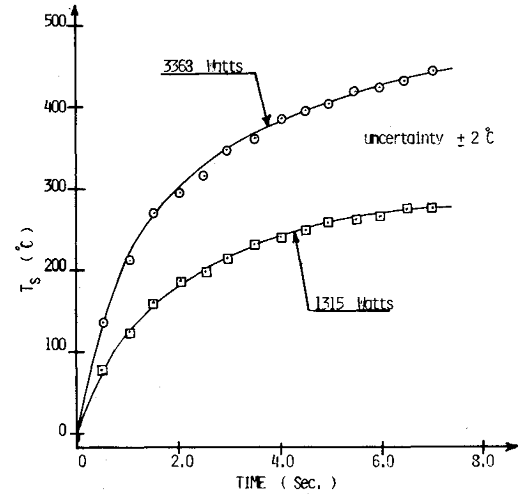

Fig. 3 Top surface heating element temperature vs time at two power settings.

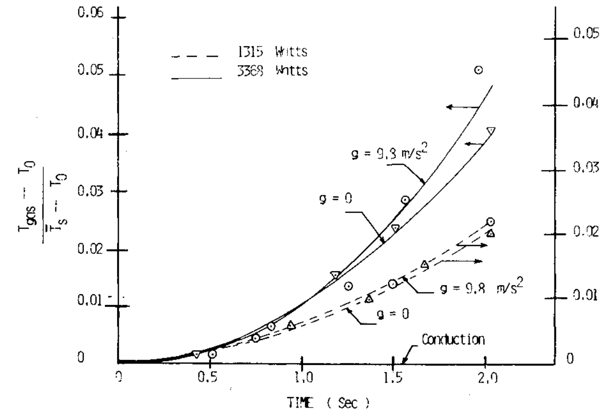

Fig. 4 Dimensionless air temperature vs time for gravity and zero-gravity conditions at different power settings.

The characteristic penetration depth for pure conduction, as mentioned earlier, is $\sqrt{\alpha t}$. Using the experimental results, a characteristic length for TAC heat penetration $\bar{x}$ can be obtained. It is observed that for both power settings (1315 and 3368 W), the ratio $\bar{x}/\sqrt{\alpha t}$ is approximately 10; that is, penetration depth of TAC heat transfer in this one-dimensional model is one order of magnitude larger than the corresponding conduction heat-transfer penetration depth.

Conclusions

The inspection of the results shown in Fig. 4 suggests the following conclusions. First, that within the experimental uncertainty the results show negligible difference between gravity and zero-gravity TAC heat transfer in the air; that is, for the resistance heating rates and experimental time period used in this investigation, the change observed between the temperature rise in air in zero gravity and temperature rise in air in gravity environment is within experimental error. Second, the results indicate a significant rise (one order of magnitude) in air temperature in TAC heat transfer (both in zero-gravity and gravity environment) relative to pure conduction case. This suggests that higher heating rates could produce an even more significant temperature rise and, therefore, shorter transient time for processes involving TAC as compared with conduction. Therefore, it is expected that during transition, TAC could indeed be the dominant mode of heat transfer and only with dissipation of convective mode and establishment of steady-state conditions does the pure conduction heat-transfer mode become dominant.

Acknowledgment

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