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# Comparison of Methodologies for Describing Relaxation in Nonequilibrium Gaseous Systems

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abstract

*The heat transfer process in hypervelocity vehicles is dominated by nonequilibrium gas dynamics. One model used in CFD codes to predict hypervelocity heat transfer is the "two-temperature" model. An analysis has been made to test the validity of the two-temperature model for predicting another nonequilibrium phenomenon, sound absorption and deviation of signal speed in a high temperature gas. It is found that the two temperature model's prediction capabilities degenerate with increasing temperature. These results are felt to have significance concerning the two-temperature's ability to predict heat transfer in hypervelocity flows.*

The goals for future research in space flight include the design of vehicles which can travel through the atmosphere at extremely high velocities. The application for such a requirement include the Mars mission return, the Aeroassisted Orbital Transfer Vehicle, and the National Aerospace Plane. The heat transfer associated with hypervelocity is extreme and must be well understood if adequate designs are to be developed for these applications.

Molecular nonequilibrium dominates physical processes in the transfer of frictional heat developed at hypervelocities. At hypervelocities, the characteristic time scale of the flow is shorter than the time required for energy to equilibrate among the various molecular energy modes. At the shock wave interface, the density gradient of the gas is so great that the gas's kinetic energy is converted almost instantaneously to heat. With the sudden injection of heat energy, the various molecular modes; translation, rotation, vibration, and electronic excitation; are activated at different rates. Heat transfer, therefore, will be due mainly to radiation from a non-equilibrium gas.

Compared to the physics of a gas which is in atomic equilibrium, nonequilibrium gas dynamics historically have not received a great deal of attention. The mechanisms of energy transfer between atomic states is extremely complicated, and few scientific or engineering applications to date have required a knowledge of nonequilibrium gas dynamics; consequently, laws governing nonequilibrium gas dynamics are virtually unknown.

In spite of the fundamental lack of understanding, several models have been proposed for predicting the heat transfer related to nonequilibrium gas dynamics associated with hypervelocity.

One such model, the multi-temperature model, would predict the heat transfer using a modified version of the Navier-Stokes equations in which different temperatures are assigned to different atomic modes. The modal temperatures are coupled to each other through the Landau-Teller terms which include the relaxation time for each mode to reach equilibrium. The concept of modal temperature restricts the population of energy states within those modes to a Boltzmann distribution. We have posed the question as to whether the two temperature model permits the degree of freedom necessary to model the effect of non-equilibrium accurately.

In order to analytically test the validity of the two-temperature model, we considered a sound propagation problem. Sound absorption as well as sound signal speed deviation is controlled by the modal relaxation of translation and vibration. The sound transmission problem has received a great deal of attention from the acoustics community and, therefore, the theory is well understood. Signal frequency in the sound propagation problem is directly analogous to fluid speed in the hypervelocity problem. The problem can be posed in such a way as to be manageable analytically. For frequencies less than 0.1 MHz, the transport terms in the Navier-Stokes equations can be neglected; furthermore, if small signal sound waves are assumed, the equations are linear. The distribution of energy level population among a ground state and two excited states within the vibration mode can be described using rate equations. In the rate equation model, no restriction is made concerning the dynamics of energy level population. The set of equations are solved through the use of successive differentiation and substitution until a wave equation containing the dependant variable of parcel displacement is obtained. A solution in the form of a wave is substituted for this dependant variable. The resulting algebraic equations are solved to obtain an expression for sound absorption and propagation speed.

The figures below illustrate the results for sound absorption. At low temperatures, the lowest excited state is activated relatively infrequently so that sound adsorption is small and the mode's energy is proportional directly to the population of that excited state. Figure 1 shows that, at a low translational mode temperature, 300K, the two temperature model's prediction of sound absorption is identical to the analytical. Figure 2 indicates, however, that, as the temperature is increased, 2000K, the two-temperature model becomes increasingly inaccurate. For the larger temperatures, the second as well as the first excited energy level is populated in a manner not described by a Boltzmann distribution. A given "temperature"; consequently, cannot accurately model vibration mode distribution. Further investigation revealed that when the characteristic time of the sound propagation is low relative to the relaxation time (ie. vibration frequency is large relative to relaxation frequency), the two temperature model predicts sound propagation speed inaccurately regardless of temperature.

Figure 1.
T=300K

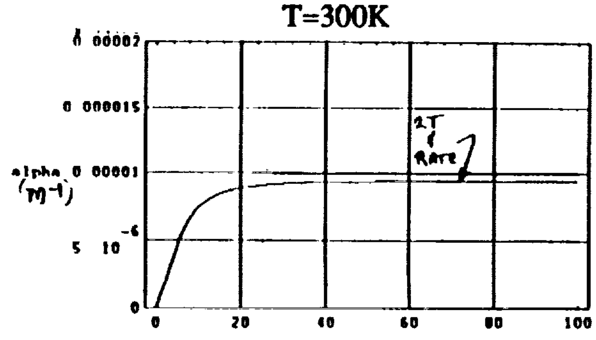


Figure 2.
T=2000K