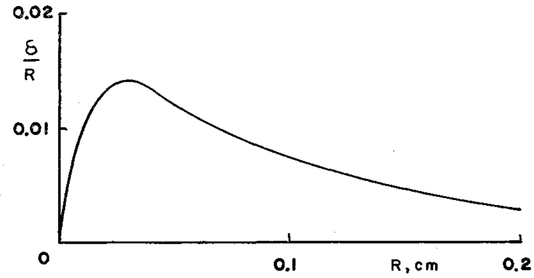

Fig. 4 Equilibrium-layer thickness for edge located where $(dT_1/dX)\ (R/T_\infty) = -100$.

dissociation fields, a thickness for the layer can be defined as the distance from the body surface at which the slope becomes greater than an arbitrarily set value. When this is done, the thickness δ shows a consistent pattern as shown on Fig. 4. The thickness is zero in the frozen limit ($R = 0$), exhibits a maximum somewhere in the nonequilibrium regime, and approaches zero asymptotically in the equilibrium limit ($R \to \infty$). This implies that the surface equilibrium layer is present throughout the entire nonequilibrium regime, with large slopes and large over-all changes near the frozen limit, and still large slopes but vanishing over-all changes as the equilibrium limit is approached (see Fig. 2).

Conclusions and Suggestions for Future Research

Large temperature, density, and degree of dissociation gradients are present near the stagnation region in blunt-body, nondiffusive, nonequilibrium flows in what may be called an equilibrium layer. The dominant features in this layer are small velocity and velocity variations and even smaller (higher-order) pressure variations. This essentially uncouples the dynamics and chemistry of the flow. The equilibrium layer appears, then, as a thin region of constant-pressure chemical relaxation where the degree of dissociation varies almost linearly with temperature. The layer appears to persist throughout the nonequilibrium regime, with vanishing over-all changes in the flow properties as the equilibrium limit is approached, and large over-all changes as the frozen limit is approached. In the frozen limit, the layer has zero thickness and the behavior at the wall could perhaps be analyzed locally by means of the powerful modern techniques for dealing with singular perturbation problems.

It is suggested that the method of truncations may provide a good tool for studying the interaction between viscous effects and the equilibrium layer throughout the nonequilibrium flow regime. A situation to some extent similar to the equilibrium layer occurs in the flow of transparent radiating gases,[3] where the long local residence time near the stagnation point is responsible for the gas radiating all of its energy away. The effect of radiation on the equilibrium layer may be another area of interest for future research.

In the present investigation the equilibrium layer was computed near the stagnation point. Its development and behavior along the body are open to further research.

In near-frozen flows changes in entropy along streamlines are small. However, the stagnation streamline and neighboring streamlines undergo drastic chemical reactions in the equilibrium layer. The subsequent entropy gain is expected to persist along the body in a layer similar to the entropy layer due to bluntness. The study of such a layer may also prove to be of interest for future research.

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Experimental Convective Heat-Transfer Measurements

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An extensive series of stagnation-point heat-transfer experiments has recently been completed at the Jet Propulsion Laboratory (JPL). The purpose of these investigations was to determine the range of uncertainties in convective heat transfer due to the limited knowledge of the atmospheres of the near planets. Three atmospheric models were investigated: 9% CO_2, 90% N_2, 1% A; 100% CO_2; and 65% CO_2, 35% A. The Model Atmosphere I is thought to be the most likely composition of the Venus atmosphere. Model Atmosphere II is one of the extremes of the Mars atmosphere. A comparison of these two atmospheres allows general conclusions to be reached regarding carbon dioxide and nitrogen atmospheres. Model Atmosphere III investigated the effect of argon in the Mars atmosphere as indicated by Kaplan.[1] All measurements were made in the JPL hypervelocity shock tube.[2] Calorimeter heat-transfer gages[3] were used on 1- and 2-in. hemispherical cylinders.

The experimental results for Model Atmosphere I are given in Figs. 1 and 2. Since there is only 9% CO_2 present in the mixture, it was thought fruitful to make a comparison with Avco air data.[4] For this particular model atmosphere the convective heat transfer does not differ greatly from that of air. A further comparison is given with General Electric data[5] in Fig. 2 for essentially the same atmosphere (9% CO_2, 91% N_2). Excellent agreement is indicated by the data.

The experimental results for Model Atmosphere II, 100% CO_2, are given in Fig. 3. A comparison is given with the JPL Model I data. The general trend of the 100% CO_2 data is of the order of 10% higher than the 9% CO_2 data. Data from both 2- and 1-in. hemispherical cylinders are shown. It is clear that the data scale as expected. A further comparison with data recently presented by Nerem[6] et al. is given.‡

In Fig. 4 is presented the data for the Model Atmosphere III. It is believed that this is the first experimental data

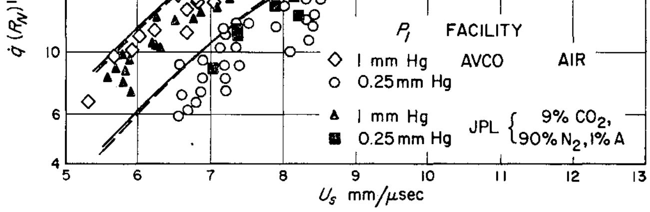

Fig. 1 Comparison of 9% CO_2 data with Avco air data.

Received July 1, 1964.

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‡ There appears to be a discrepancy between the two graphs presented by Nerem for his CO_2. The graph presenting the final results has been used in this comparison.

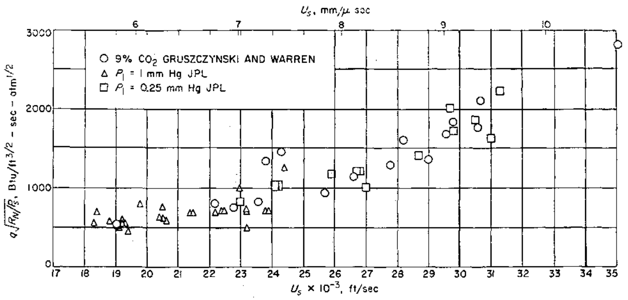

Fig. 2 Stagnation-point heat transfer 9% CO_2, 90% N_2, and 1% A.

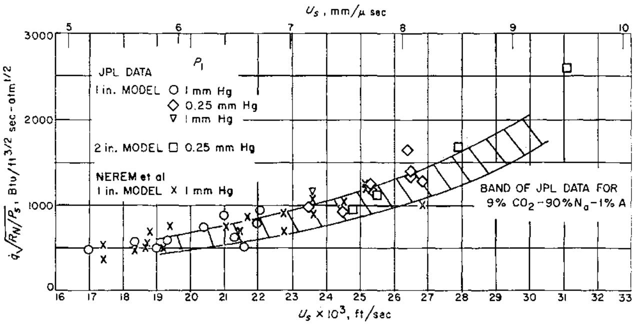

Fig. 3 Convective heat transfer in 100% carbon dioxide.

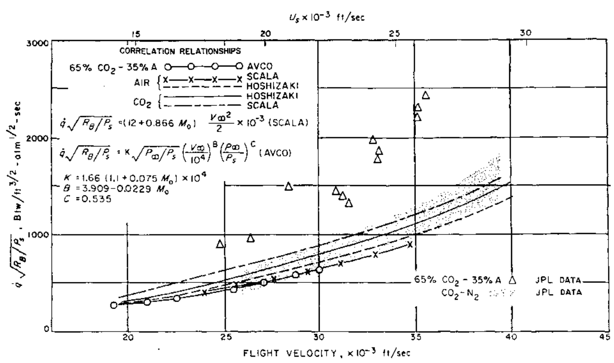

Fig. 4 Convective heat transfer in 65% CO_2 and 35% A.

available on the effect of argon on convective heat transfer in the given velocity range. A large increase in convective heat transfer over that of air-CO_2 mixtures is shown. Thus at 25,000 fps, which is approximately the entry velocity for Mars, there is approximately a twofold increase in the confective heat transfer. Comparison is made also with semiempirical predictions by Scala[7] and Avco[8] for convection with varying molecular weight. A further comparison is given with the theoretical predictions of Hoshizaki.[9] Good agreement is obtained for air CO_2-N_2 mixtures, but there is a large difference between theory and experiment in the case of argon.

No correction has been made to the data for additional heat transfer due to radiation. This correction is less than 10% for the high velocity data points.

In summary, the carbon dioxide and nitrogen atmospheres have convective heat-transfer rates similar to that of air. The presence of argon in the atmosphere increases the convective heat transfer by about a factor of 2 for the model atmosphere investigated.

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Some Dimensional Considerations of Studies in Space-Flight Simulation

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It is the attainment of the low-density, high-Mach-number and high-temperature flow conditions, and not merely the attainment of very low density, that poses the real problem in the simulation studies of the flight of objects in the earth's upper atmosphere and outer space. This may be regarded as some advantage in the sense that, under certain conditions as those discussed in this note, it is not necessary to exactly duplicate in the laboratory model studies the low densities encountered in space flight. For example, if the characteristic length of the model l_{mo} bears a ratio α to the corresponding length l of the prototype, the corresponding ratio of the gas densities would be $1/\alpha$ provided that the chemical composition, degree of ionization, and temperature are maintained identically equal in the two situations. In this note, the principle of dimensional similitude is applied to the laboratory model studies of the motion of bodies in an ionized atmosphere pervaded by a magnetic field, and the correspondence relationships for the various characteristic parameters in the actual and model cases are obtained. It is then shown that the scaling relationships satisfy the conditions for aerodynamic, magnetohydrodynamic, and electrodynamic similitude. Such studies are important for the design of instrumentation for diagnostics and the understanding of the dynamics of bodies in space, the interpretation of data on space environment, and the nature of the object-space interactions.

Let us designate the physical parameters in the model experiment by the subscript mo and introduce the scaling factor

$$\alpha = l_{mo}/l \tag{1}$$

and assume that the fractional chemical composition, degree of ionization (n_e/n_0), kinetic temperature T, and flow speed V are identically equal in the two situations. Then,

$$\frac{n_e}{n_0} = \left(\frac{n_e}{n_0}\right)_{mo} \qquad T = T_{mo} \qquad V = V_{mo} \tag{2}$$

where n_e and n_0 are the number densities of charged and

Received July 7, 1964.

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