Shock-Tube Studies of Equilibrium Air Radiation

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The results of an experimental investigation of equilibrium air radiation in the wavelength region of 0.17 to 6.0 μ are presented. The data were obtained using a thin-film heat-transfer gage to measure the stagnation-point, equilibrium radiative heat-transfer rate on hemispherical models mounted in an arc-driven, shock-tube facility. Stagnation conditions corresponding to flight velocities between 26,000 and 52,000 fps and altitudes from 100,000 to 170,000 ft were simulated. The results are compared with existing theoretical calculations, and reasonable agreement is shown to exist. Recent measurements of radiative heat transfer at wavelengths down to 1200 Å are also discussed.

Nomenclature

E_t = total radiant energy emission per unit volume and unit time
F_1 = shock-layer shape correction factor
F_2 = thin-film gage geometric view factor
I = thin-film gage current
J = radiance
M = Mach number
P = pressure
$\dot{q}$ = heat-transfer rate
R_N = nose radius of hemispherical body
T = transmissivity; temperature
t = time
V = velocity
V_s = incident normal shock velocity
α_G = absorptivity of thin-film gage
δ = shock-detachment distance
λ = wavelength of radiation
ρ = gas density
ρ_0 = atmospheric density at standard conditions = 1.293×10^{-3} g/cm³

Subscripts

1 = initial shock-tube driven condition
2 = conditions behind incident normal shock
∞ = flight freestream conditions

1. Introduction

RE-ENTRY vehicles, moving at superorbital velocities, encounter sizeable heat transfer during atmospheric re-entry as a result of thermal radiation emitted from the high-temperature gas residing in the vehicle shock layer. This radiative heat transfer is caused by radiation from both 1) shock-heated gas in chemical nonequilibrium and 2) gas that has relaxed to the thermodynamic equilibrium state after passage through the bow shock. These two sources of radiative heating are respectively denoted as nonequilibrium and equilibrium radiation, and extensive investigations of these phenomena have been carried out.[1–15] These, in general, have been limited to consideration of the stagnation-region heating, since the magnitude of the radiative heat transfer falls off rapidly away from the stagnation point.[11]

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In Fig. 1, the relative contributions of the convective,[16] equilibrium radiative,[14] and nonequilibrium radiative[12] heating to the stagnation-point heat-transfer rate are shown as a function of flight velocity for a vehicle at an altitude of 200,000 ft and with a nose radius of 1 ft. It is assumed for Fig. 1 that there is no coupling between the different modes of energy transfer. As can be seen, the importance of shock-layer radiative emission in terms of the total heating associated with a superorbital velocity re-entry vehicle increases as the flight velocity increases. For planetary and solar probes re-entering the earth's atmosphere at velocities ranging up to 75,000 fps, the radiative heating actually may dominate the re-entry heat load. Even for an initial re-entry velocity equal to the escape velocity from earth, the radiative heating makes an important, although not dominant, contribution.

It should be noted from Fig. 1 that, at flight velocities where shock-layer radiation is important, the magnitude of the non-

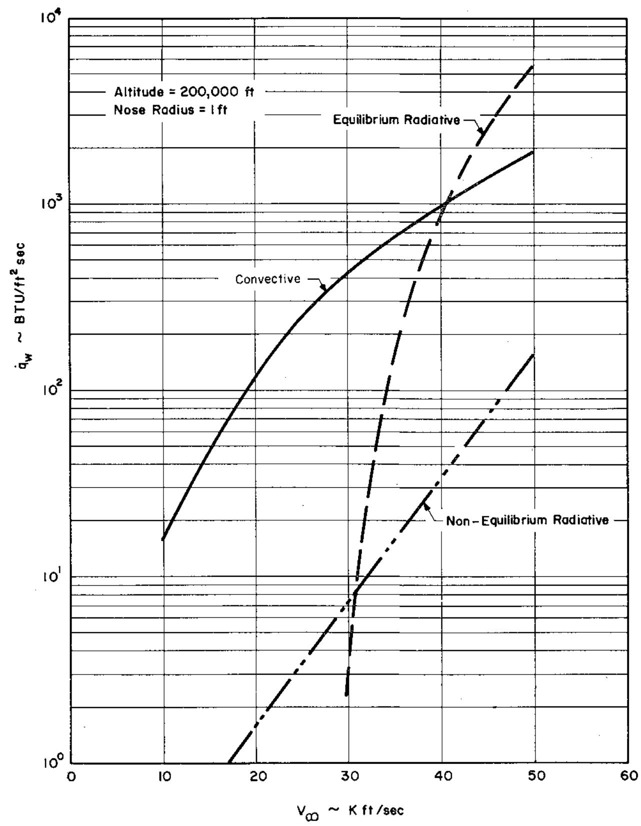

Fig. 1 Comparison of magnitude of stagnation-point convective and radiative heating for a re-entry vehicle at 200,000 ft.

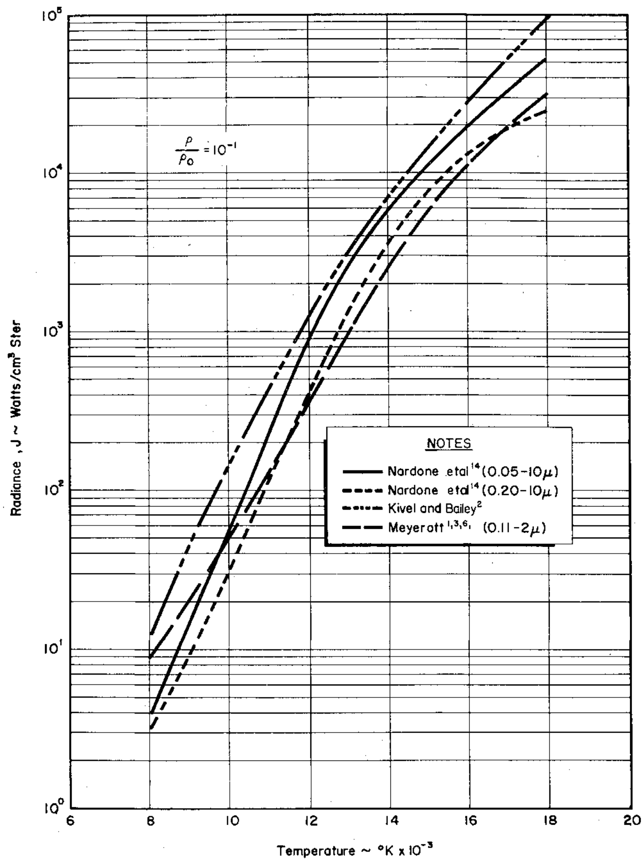

Fig. 2 Comparison of existing theoretical calculations of radiance of high-temperature equilibrium air.

equilibrium radiative heating is small compared with that of the equilibrium radiative heating. In general, it can be shown that this nonequilibrium mode of heating makes a relatively minor contribution to the total heat load of a typical re-entry vehicle and that it is the convective and equilibrium radiative heating that will control the design of the thermal protection system for superorbital velocity re-entry.[18] Thus, although more information is needed on nonequilibrium radiation and the associated chemical reactions before the re-entry environment can be completely defined, the present investigation has been limited to the study of equilibrium radiation.

High-temperature equilibrium air radiative emission has been considered to be dominated by the molecular bands of nitrogen, oxygen, nitric oxide, and ionized molecular nitrogen, the continuum radiation associated with the deionization of N^+ and O^+, the Bremsstrahlung emission of N and O, and the line radiative emission from nitrogen and oxygen atoms.[13] In addition, continuum radiation due to photo attachment to form the N^- ion has recently been identified as a possible important radiation source.[17] A comparison of the existing theoretical estimates for the radiance of high-temperature equilibrium air[1–3,6,14] is shown in Fig. 2, where none of the theoretical calculations includes the N^- photo attachment process or atomic line radiation. Note from Fig. 2 the extent of the disagreement existing among these theories. Present estimates of radiative heating during re-entry are thus characterized by considerable uncertainty. This is particularly true at high temperatures where continuum radiation dominates.

Because of this uncertainty in our knowledge of shock-layer radiative phenomena, experimental studies of equilibrium radiative heating during re-entry were undertaken and are continuing at The Ohio State University. Using an arc-driven shock-tube facility, experimental measurements of the total stagnation-point equilibrium radiative heat flux in the wavelength region of 0.17 to 6.0 μ have been carried out over a range of simulated flight velocities from 26,000 to 52,000 fps and at simulated altitudes from 100,000 to 170,000 ft. It has been the purpose of these studies to assess the accuracy of presently available theoretical estimates of the radiance of high-temperature equilibrium air so as to provide more accurate information on re-entry radiative heating for use in engineering design calculations. The experimental techniques applied, and the results obtained are reported in this presentation.

2. Experimental Technique

The present investigation of radiation from high-temperature equilibrium air was performed in The Ohio State University arc-driven shock-tube facility.[19,20] This facility is capable of generating shock velocities in excess of 40,000 fps and of simulating flight velocities approaching 60,000 fps.

The shock tube has a driven section that is 4 in. in i.d., about 28 ft long, and fabricated from steel. The driver section is also 4 in. in diameter and contains a coaxial electrode assembly that is recessed in a *T* arrangement. A capacitor bank of 11,100 μfarads with a maximum of 6000 v (200,000 joules at full capacity) furnishes the energy for heating the driver gas, which is normally helium. The operation of such an arc-driven shock tube resembles that of a conventional pressure-driven shock tube with the exception of the energy addition process; a complete description of The Ohio State University facility and its operating characteristics may be found in Refs. 19 and 20.

The present measurements were performed using the shock-generated flow and in the free-jet region formed where the driven tube terminates in a dump tank. Hemisphere-cylinder models, 0.5 in. and 1.0 in. in diameter, were mounted in this high enthalpy, supersonic flow; and stagnation-point radiative heat-transfer measurements were carried out at initial-driven tube pressures of 1.00, 0.200, and 0.060 mm Hg. The thermodynamic state of the high-temperature air residing in the model stagnation-region shock layer was determined from normal shock-wave calculations, as carried out by Laird and Heron[21] for shock-tube conditions, together with measurements of the shock velocity and of the driven tube initial pressure. The shock velocity was determined using ionization probes, and although precursor ionization affects the performance of such probes, the use of proper probe voltages allows accurate measurements to be carried out. The driven tube pressure was measured using a sloped silicon fluid U-tube manometer board for pressures on the order of 1 mm Hg and a thermocouple gage for pressures of less than 500 μ. The re-entry flight conditions simulated were based on the establishment of the same stagnation-region shock-layer density and total enthalpy as produced in flight.[22]

It should be noted that, in a previous paper,[23] the authors discussed the interpretation of the present experimental data based on the use of shock-tube properties as calculated by Ziemer.[24] Subsequently, more accurate calculations[21,25] have become available, and these have necessitated the revised interpretation of the experimental results to be presented here.

Now, as part of this experimental investigation, the test duration was monitored during virtually all of the tests using a photomultiplier looking across the shock-generated flow and through a collimated slit system. These test duration measurements are shown in Fig. 3 and are in good agreement with the results of a previous study at The Ohio State University.[26] Only heat-transfer data obtained at conditions where there was a minimum of 10 μsec of test time were considered as valid.

In order to minimize the presence of CN, a common shock-tube contaminant, and also other possible contaminants, the following operating procedure was used. After each test, the shock-tube walls were cleaned in order to remove, as nearly as possible, any contaminating deposits. The driven tube was then evacuated to a pressure on the order of 5 μ or less, and the test gas was let in through a dry ice-acetone cold trap in order to remove the water vapor. The driven tube was then purged using this same cold-trap system and at a pressure approximately equal to the initial pressure to be set for the subsequent test. Less than a minute before firing, the final driven tube conditions were established, and the vacuum pump and intake valves were closed. Since the apparent "leak rate" of the tube was approximately 3 μ/min, any outgassing effects should be minimal. Thus, it is felt that the test gas in the present experimental program was a good representation of the media encountered by re-entry vehicles.

In analyzing the results of this investigation, it was imperative that both the properties of the stagnation-region shock layer and the shock-detachment distance be known; and although the equilibrium air stagnation-region properties[21] and the shock-detachment distance[27] could be determined readily, the question of whether equilibrium actually existed in most of the shock layer was not so easily answered. It is evident that relaxation phenomena in this case will not be the same as in the free-flight case because of the different condition of the gas immediately ahead of bow shock. In fact, the maximum overshoot temperature at the bow shock will be much less in the shock-tube case than in the flight case, where the same equilibrium conditions exist behind these shock waves. This is because of the lower freestream Mach number associated with the shock-tube flow and is shown in Fig. 4a. The calculations presented in Fig. 4a are based on the assumption of frozen composition and vibrational energy excitation during passage through the shock for both the flight and shock-tube cases. Because of the strong temperature dependence of hot gas radiation, the nonequilibrium radiation thus will be much less significant in the shock-tube case than in the flight case, and in fact for the conditions of the present investigation, it will be negligible.

Measurements on relaxation phenomena behind reflected shock waves have recently been performed at The Ohio State University. The results of this investigation indicate that the relaxation times will be as much as a factor of 4 faster than the conservative upper limit estimated by Rose and Stankevics.[28] This is shown in Fig. 4b, in the form of the relaxation distance behind the model bow shock as calculated by Rose and Stankevics and also as estimated using the reflected shock

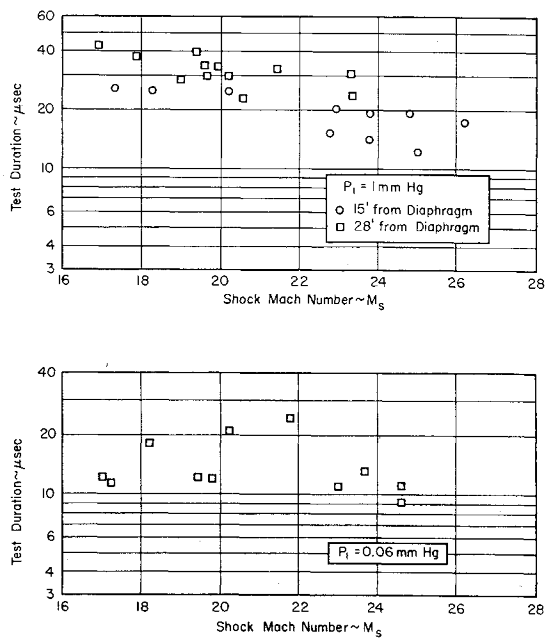

Fig. 3 Arc-driven shock-tube test duration measurements.

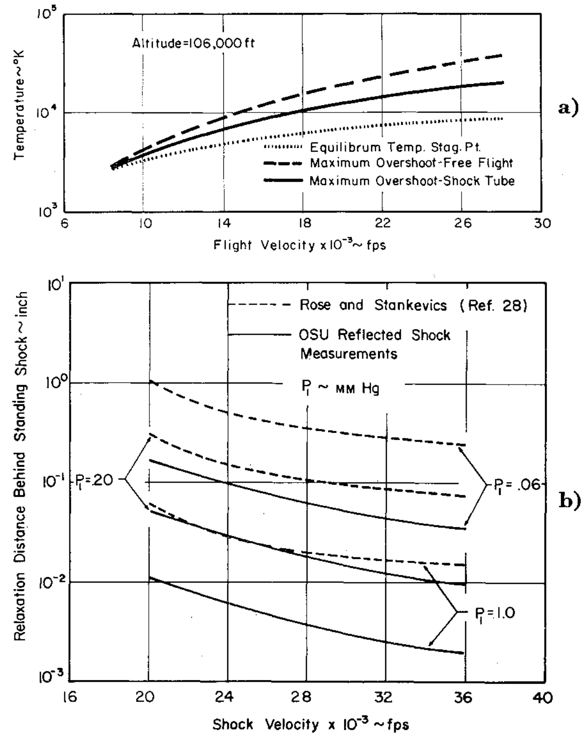

Fig. 4 a) Nonequilibrium overshoot temperature behind normal shock; b) relaxation distance behind standing normal shock in shock-tube flow.

measurements. In both cases, the relaxation distance is based on an average shock-layer velocity equal to one-half of the velocity immediately behind the model bow shock.

Since the model shock-detachment distance is approximately 0.14 in. on the 1.0-in. nose radius model and 0.07 in. on the 0.5-in. nose radius model, then it can be seen from Fig. 4b that the model shock layer virtually will be in complete equilibrium for initial driven tube pressures of 1.00 and 0.200 mm Hg and in partial nonequilibrium at 0.060 mm Hg. Based on existing knowledge of nonequilibrium phenomena behind hypervelocity shock waves,[12,13] it would appear that any nonequilibrium effect should evidence itself as an increase in radiative heating due to the overshoot in radiative intensity. As was indicated previously, this overshoot radiation is not important in the shock-tube case at the present conditions. Thus, the radiative heating measured during this investigation has been interpreted as being caused by equilibrium radiative emission. However, because the shock layer is in partial nonequilibrium for an initial-driven tube pressure of 0.060 mm Hg, these data are considered to be possibly questionable. The analysis of the results of this investigation is thus based largely on the data at pressures of 1.00 and 0.200 mm Hg. At these two higher pressures, two models with different nose radii were tested, and no nonequilibrium effect, as evidenced by nonlinear scaling of the radiative heat-transfer rate with model nose radius, was detected.

It should be noted that calculations of the radiative heat transfer measured due to emission from high-temperature air residing outside the bow shock layer indicate that this effect is negligible. In addition, photomultiplier measurements of driver-gas radiation, which is due to the presence of impurities, indicate that this effect is also negligible.

The experimental radiative heat-transfer measurements were performed using a thin-film radiative heat-transfer gage, which is described in Refs. 31 and 32. This heat-transfer gage uses a thin-film sensing element that actually consists of two layers. The top layer, which is exposed to the incident radiation, is a nonelectrically conducting material called Luster Black No. 4771, which provides the proper surface

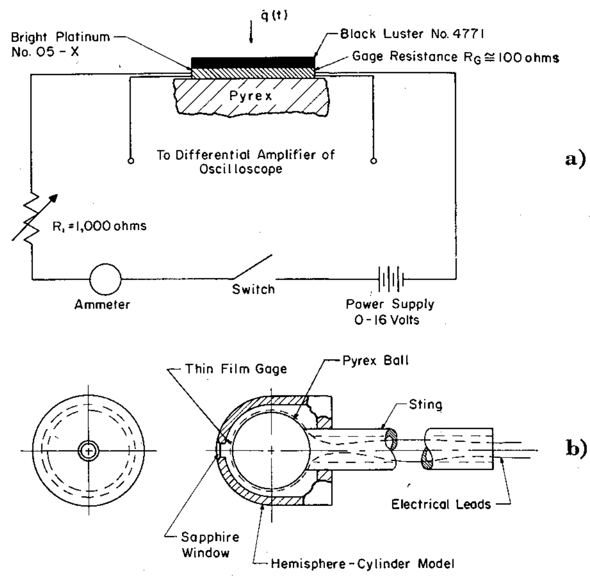

Fig. 5 a) Schematic of thin-film gage and electrical circuit; b) diagram of radiation heat-transfer models.

spectral absorptivity. The bottom layer is an electrically conducting material called Bright Platinum No. 05-X. Both of these materials are liquid metal suspensions manufactured by the Hanovia Liquid Gold Division, Engelhard Industries. Specific details with regard to the application of these materials may be found in Ref. 33, and the use of these materials in heat-transfer gages is discussed in Refs. 29–32.

Schematics of the stagnation-point radiative heat-transfer models and the thin-film radiative heat-transfer gage circuit are presented in Fig. 5. The hemisphere-cylinder models were built with a sapphire window, 0.25 in. in diameter and 0.020 in. thick, mounted at the stagnation point, and with the thin-film gage recessed in the model and positioned behind the window. The sensing element of the gage is mounted on a pyrex ball, which acts as a semi-infinite slab and is part of a constant current electrical circuit, which is designed to measure the time-history of the voltage drop across the gage.

The heat flux to the gage can be related to the variation in the voltage drop across the gage ΔE by the relation[29]

$$\dot{q}_{\text{gage}} = \tfrac{1}{2}(\pi\beta_m)^{1/2}(1/I\alpha R)_0\Delta E/(t)^{1/2} \qquad (1)$$

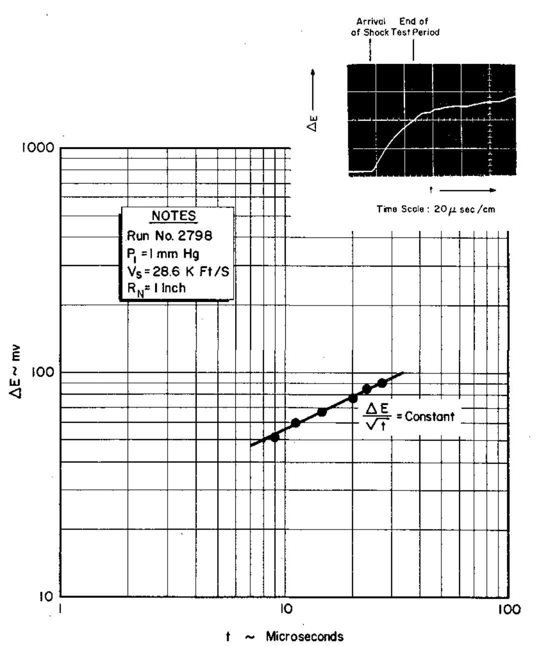

Fig. 6 Typical thin-film gage output.

for the case of a constant heat-transfer rate. Here t is the time length of exposure to the heat flux, I is the current through the gage, $\alpha R_0 = \Delta R/\Delta T$ gives the temperature dependence of the thin-film resistance, which is assumed to be linear, and β_m is a property of the backing material. The value of β_m was obtained from Ref. 34, and αR_0 was evaluated from static calibrations, which were carried out for each gage. A correction for variable backing material thermal properties was applied using the results of Ref. 35.

For an optically thin gas, which corresponds to the model shock-layer conditions in this investigation, the radiance of the high-temperature air residing in the shock layer may be related to the radiative flux as measured by the recessed gage through the equation[32]

$$J = \dot{q}_{\text{gage}}/2\pi\delta F_1F_2(T)\alpha_G \qquad (2)$$

Equation (2) takes into consideration the transmissivity T of the sapphire window, which was evaluated from Refs. 36–39; the absorptivity of the gage surface α_G, which was determined from the manufacturer's data[33]; the geometric view factor F_2, which relates the actual stagnation-point radiative flux to that of the gage and can be evaluated from purely geometric considerations[32]; and the shock shape and the variation of properties in the shock layer, which may be accounted for through the use of a bow shock correction factor F_1 (taken here as equal to 0.90).[11, 40] The shock detachment distance δ was determined from Ref. 27.

It should be noted that, based on the manufacturer's data on reflectivity and transmissivity,[33] the spectral absorptivity of the gage is approximately independent of wavelength, having a value of 0.80. The spectral characteristics of thin films, such as used in this investigation, do depend on the thickness and uniformity of the film, and thus the spectral absorptivity of a particular thin-film radiation gage may differ from that calculated using the manufacturer's data. However, such differences should be small and may be neglected. As an example, an obviously extreme deviation of 50% in the reflectivity of the gage surface from that quoted by the manufacturer produces only a 10% change in the absorptivity. This negligible difference between the surface characteristics of different gages was borne out in this investi-

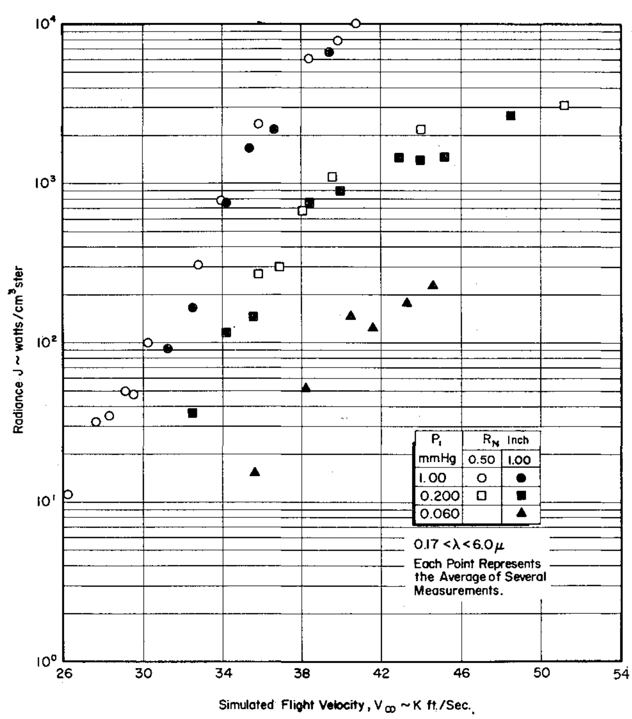

Fig. 7 Experimental shock-tube data on radiance of high-temperature equilibrium air.

gation by comparing the results of the three thin-film radiative heat-transfer gages used.

It should also be noted that the sapphire windows used transmit in the wavelength region of 0.17 to 6.0 μ. Thus, the measurements obtained during this investigation correspond to the total integrated radiance of high-temperature equilibrium air in this wavelength region. These measurements were performed using two hemisphere-cylinder models with over 100 data points being obtained. A typical gage output and data reduction is shown in Fig. 6.

In order to analyze the experimental results, the data were treated statistically. If it is assumed that the scatter in the data corresponding to a particular shock velocity and initial-driven tube pressure is caused by inherent random inaccuracies and not by a consistent error in experimental technique, then the average of the experimental data points at that test condition should be representative of the true value, which would have been measured experimentally had there not been random inaccuracies. On this basis, the data at each driven tube pressure and for each model were grouped, such that all data points in a group had a velocity within a 1000-fps range. The points in each group were then linearily averaged. For example, the measured intensity of all of the points for the 0.5-in. nose radius model at 1 mm Hg, and with shock velocities between 22,500 and 23,500 fps, were averaged. It is these average data points that were considered in analyzing the results of this investigation. In this manner the data scatter was greatly reduced, and a more meaningful analysis of the data was made possible. These average data points are presented in Fig. 7 in terms of the radiance of high-temperature air vs the simulated flight velocity. It should be noted that the mean deviation of the data from the average values was 21%.

3. Discussion of Results

The present experimental measurements of the radiance of high-temperature equilibrium air are compared with the existing theoretical calculations of Kivel and Bailey,[2] Meyerott,[1,3,6] and Nardone et al.[14] in Figs. 8–10. It can be seen from Fig. 8 that the data obtained at an initial driven tube pressure of 1 mm Hg are in reasonable agreement with calculations based on the results of Nardone and Breene[14] over virtually the entire temperature range of the measurements. Only at the lower temperatures do the data appear to support the calculations of Kivel and Bailey.[2] It can also be seen that the curve based on the absorption coefficients of Meyerott and his co-workers[1,3,6] lies slightly lower than the present results.

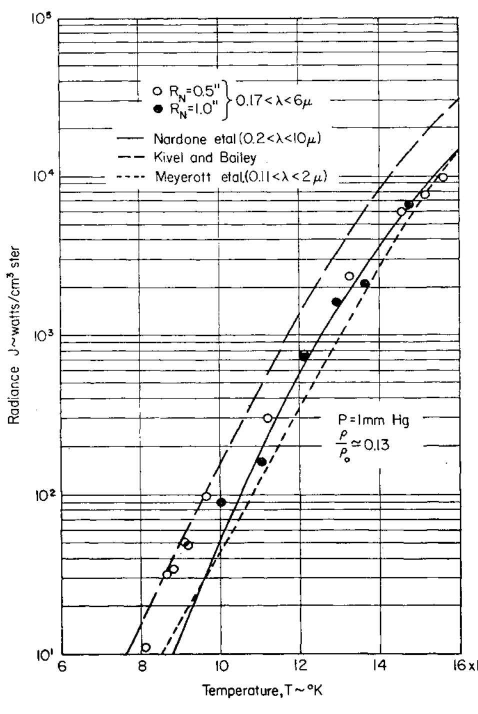

Fig. 8 Comparison of experimental data with existing theoretical calculations, P_1 = 1 mm Hg.

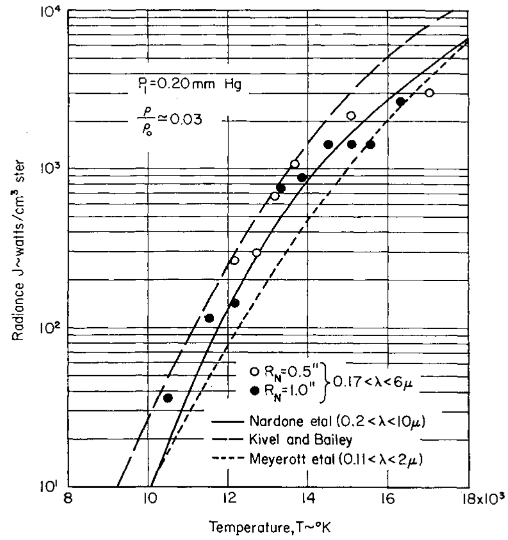

Fig. 9 Comparison of experimental data with existing theoretical calculations, P_1 = 0.200 mm Hg.

At an initial driven tube pressure of 0.200 mm Hg (Fig. 9), the data obtained are also in reasonable agreement with the calculations of Nardone and Breene,[14] being slightly higher at temperatures below 14,000°K and tending toward a slightly lower value as the temperature approaches the order of 17,000° K. Here also there appears to be a possible preference of the data for the results of Kivel and Bailey[2] at the lower temperatures. The curve based on the calculations of Meyerott is seen at these conditions to be consistently low.

Finally, at the lowest initial driven tube pressure of 0.060 mm Hg, Fig. 10, the data obtained are in good agreement with the calculations of Nardone and Breene[14] over the limited temperature range covered at this density level. The curve based on the calculations of Kivel and Bailey[2] is consistently high in this case, whereas that based on the absorption coefficients of Meyerott[1,3,6] is again somewhat low.

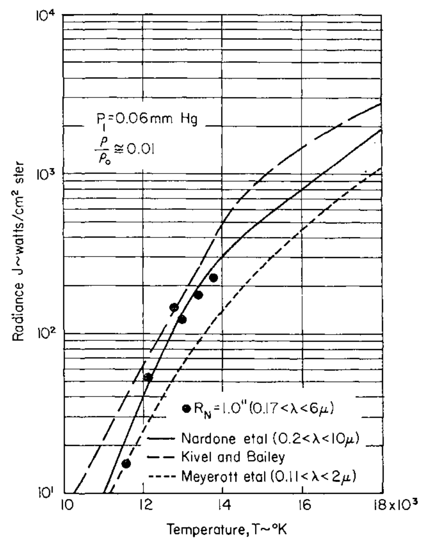

Fig. 10 Comparison of experimental data with existing theoretical calculations, P_1 = 0.060 mm Hg.

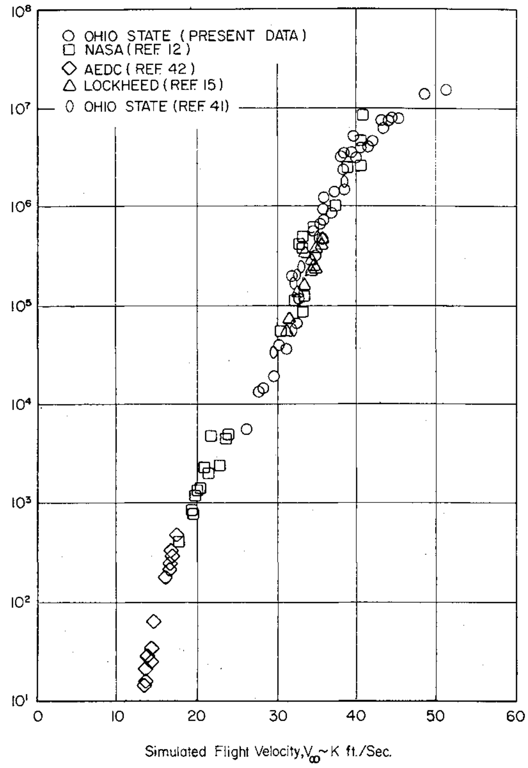

Fig. 11 Comparison of existing experimental results on radiative emission from equilibrium air.

It thus appears that the present data, although not in complete agreement with any one of the theoretical calculations over the entire range of the experiment, do support the calculations of Nardone and Breene[14] at the higher temperatures corresponding to stagnation conditions at velocities in excess of the earth's escape velocity. At lower temperatures, corresponding to orbital velocities, the present data appear to favor the calculations of Kivel and Bailey.[2] It should be noted, however, that the calculations of Kivel and Bailey actually include radiation at wavelengths below 1700 Å and thus might be expected at the higher temperatures to predict emission rates in excess of those indicated by the present data.

It should also be noted that none of the existing theoretical calculations of the radiative properties of high-temperature equilibrium air include atomic line radiation or N^- photo-attachment radiation. Unfortunately, the present experimental results are of such a nature so as to prohibit any conclusion regarding the importance of these processes.

Finally, as noted before, the previous interpretation of the present experimental measurements represents a revision from that earlier presented in Ref. 23. This revised interpretation is based on the more accurate calculations of shock-tube thermodynamic properties carried out in Ref. 21. As an example of the differences that exist between these calculations and the earlier calculations of Ziemer,[24] discrepancies in stagnation temperature approach the order of 1000°K at some of the conditions covered by the present study. Similarly, the stagnation-point density as calculated by Ziemer is as much as 20% in error at some conditions. It is thus obvious that any interpretation of shock-tube data depends not only on the accuracy of the measurements but also on the accuracy of the calculated shock-tube generated flow properties.

Now, there have been other investigations of the radiance of high-temperature equilibrium air. At the NASA Ames Research Center, experimental measurements have been carried out using a series of photomultipliers to determine the spectral distribution of the shock-layer emission for a blunt body.[10,12] Flight velocities up to 40,000 fps have been simulated using gun-launched models in a counterflow facility.[10] These measurements have shown a marked preference for the theoretical calculations of Kivel and Bailey[2] at low flight velocities corresponding to low stagnation temperatures. At higher simulated flight velocities, Page[12] has indicated that, though the scatter in the NASA data is large, these results also tend to support the higher predictions of Kivel and Bailey.[2] Actually, if one omits from consideration the data obtained at NASA using polycarbonate models, because of the possible influence of ablation product radiation on the measurements, then the remaining data appear to scatter between the predictions of Kivel and Bailey[2] and those of Nardone and Breene.[14]

Hoshizaki[15] has also carried out stagnation-point radiative heat-transfer measurements using a combustion-driven shock-tube generated flow. These measurements were performed at an initial-driven tube pressure of 1.16 mm Hg and are shown in Fig. 11, together with the results of the present investigation. Here, the radiative emission per unit volume and unit time has been normalized by the stagnation-region density ratio to the 1.7 power.[12] Also shown are the results of Page of NASA[12] (where the data obtained using polycarbonate models have been omitted), unpublished results obtained in a ballistic range at Arnold Engineering Development Center,[41] and earlier results obtained at The Ohio State University.[42] As can be seen, there is good agreement among these existing experimental data on equilibrium air radiation in the wavelength region from approximately 0.17 to 6.0 μ.

Unfortunately, there are virtually no experimental results available on the magnitude of the radiative flux at wavelengths below 0.17 μ. Nardone et al.[14] have predicted theoretically the presence of an intense continuum radiation in the wavelength region of 0.05 to 0.13 μ due to the deionization radiation of N^+ and O^+. A recent experiment performed at The Ohio State University has obtained measurements of the stagnation-point equilibrium radiative heat-transfer rate at wavelengths down to 0.12 μ using lithium fluoride windows mounted at the stagnation point of the previously described hemisphere-cylinder models. The interpretation of the thin-film gage output, in terms of heat transfer for these measurements, was somewhat difficult because of an apparent photoelectric effect of the vacuum ultraviolet radiation on the gage material which produced an erratic gage output during the test period. However, it was possible to determine the increase in gage temperature for the entire test duration, and from this to calculate the average heat-

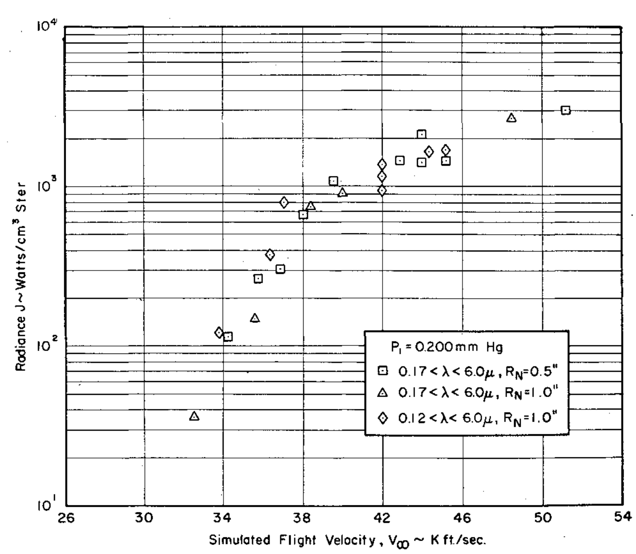

Fig. 12 Recent measurements showing importance of radiation in wavelength region of 0.12–0.17 μ.

transfer rate over the test period. These results are shown in Fig. 12, together with previous results obtained using the synthetic sapphire windows. The close agreement of the two sets of data in Fig. 12 indicates that no major source of radiation is present in the wavelength region of approximately 0.12 to 0.17 μ.

Allen, at the Avco-Everett Research Laboratory, has recently carried out measurements of equilibrium air radiation at wavelengths below 1200 Å.[43] These measurements were performed using a tungsten photoelectric gage at conditions corresponding to temperatures from 6000° to 9500°K and a density on the order of 0.004 of that at standard conditions. These results indicate that the gas is partially black over the wavelength region of gage response and for the experimental conditions noted previously. However, more experimental measurements will be necessary before any conclusion can be reached on the intensity of equilibrium air radiation at vacuum ultraviolet wavelengths.

4. Application to Re-Entry

The results of this investigation have application in the prediction of equilibrium radiative heating at superorbital velocities and in the determination of the effect of shock-layer radiation on the convective heating. As an example, for an optically thin shock layer in which the energy loss due to radiation is small as compared to the total enthalpy of the flow, the stagnation-point equilibrium radiative heat-transfer rate is directly proportional to the radiance of the shock-layer gas. Based on the present experimental results, it appears that at superorbital velocities a reasonable estimate of the radiance J over the wavelength region of 0.2–10 μ may be obtained using the calculations of Nardone and Breene.[14] Alternatively, the equilibrium air radiation may be estimated using the available experimental results as summarized in Fig. 11.

At vacuum ultraviolet wavelengths, calculations of the spectral radiance by Nardone and Breene[14] are also available. As has been noted, the results of Allen[43] indicate that in this region the gas will be at least partially black for most re-entry conditions where radiation is important. Although the calculations of Nardone and Breene[14] do include self-absorption, they are based on a shock-layer thickness of 1 cm. Thus, in making engineering estimates of re-entry heating due to vacuum ultraviolet radiation, it may be more realistic in many cases to assume the gas to be black over the wavelength region of 0 to 1100 Å. However, more information is certainly needed before this contribution to the re-entry heat load can be defined.

For flow fields more complex than the stagnation-point shock layer, and for conditions where effects due to radiative energy loss and self-absorption may be important, any determination of the equilibrium radiative heating distribution is obviously also dependent on knowledge of the radiative properties of high-temperature equilibrium air. Solutions have been recently carried out, i.e., Refs. 44 and 45, using mean absorption coefficients for high-temperature equilibrium air from the existing theoretical calculations.[1–3,6,14] The results of this investigation suggest that the use of either the calculations by Nardone and Breene,[14] or those by Kivel and Bailey,[2] should result in a reasonable estimate of the influence of shock-layer radiation on flow field properties and on the convective heating.

5. Concluding Remarks

The stagnation-point equilibrium radiative heat-transfer measurements presented in this paper were carried out in the wavelength region of 0.17–6.0 μ using an arc-driven shock-tube facility. The data obtained have been compared with existing theoretical calculations, and at the higher temperatures corresponding to stagnation conditions at velocities in excess of the earth's escape velocity they support the calculations of Nardone and Breene.[14] At lower temperatures, the data appear to support the calculations of Kivel and Bailey.[2] The present data have also been compared with experimental measurements performed at other laboratories, and it has been shown that there is reasonable agreement among these existing experimental results for equilibrium air radiation in the wavelength region ranging from approximately 0.2 to 6 μ.

Recent measurements obtained at wavelengths down to 1200 Å are also reported; based on these data, there appear to be no major sources of radiation in the wavelength region of 1200 to 1700 Å. Below 1200 Å, Allen's data[43] indicate that the gas may be partially black; however, more data are needed to define the contribution of vacuum ultraviolet radiation to heating at superorbital velocities.

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