Absorption of Infrared Radiation by High-Density Oxygen

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THE oxygen storage tanks on the Apollo 13 mission had electrical fans and heaters to assure the homogeniety of the oxygen temperature and density under a zero-*g* gravity field and to expel oxygen from the tank at sufficient pressure to operate the fuel cells. As noted in the public press, failure of the fan circuits produced by operational mistakes started the fire (and explosion) in the Apollo 13 service module. To prevent a recurrence of a similar accident, the stirring fans, the heater temperature-limiting switches, and their wiring have been eliminated. These changes might, at first glance, be expected to lead to overheating of the heater elements and to increased heat transfer to the oxygen through absorption of infrared radiation from the heater. In this Note, the role of infrared radiation in limiting the maximum heater temperature and in transferring heat to the high-density oxygen are examined. Upper limits to both the heater temperature and the radiant heat-transfer rate are derived.

The heater is contained in two spiral stainless-steel tubes that are brazed to a 5-cm-diam support tube which has a surface area of approximately 760 cm². This assembly is located near the center of the spherical oxygen storage tank which has an inner radius of 31.8 cm. In this Note, the heater will be approximated as a tube of uniform temperature and constant emissivity ϵ equal to that of slightly oxidized stainless steel (i.e., $\epsilon = 0.32$)[1] that dissipates an input power of 100 w. This dissipation is jointly due to conduction, convection, and radiation. The power P radiated by the heater is given by

$$P = \epsilon A \sigma (T_h^4 - T_w^4) \tag{1}$$

where A = area of the heater = 760 cm²; ϵ = infrared emissivity of the heater = 0.32; σ = Stephen-Boltzmann constant = 5.67×10^{-12} w/cm² − (°K)⁴; T_h = temperature (°K) of the heater; and T_w = temperature (°K) of the inner sphere wall (which is assumed equal to the oxygen temperature). This equation may be written to give the maximum temperature that the heater may reach in the absence of cooling by conduction or convection:

$$T_h(\max) = (P/\epsilon A \sigma + T_w^4)^{1/4}$$

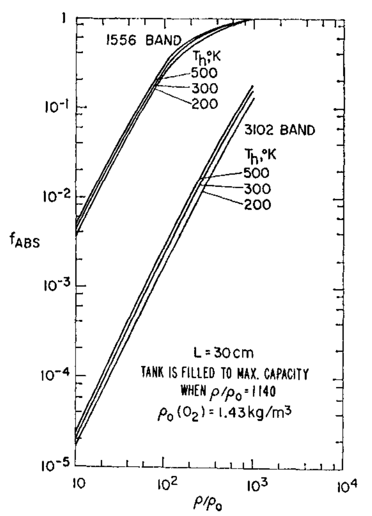

Fig. 1 Fractional absorption as a function of heater temperature and gas density.

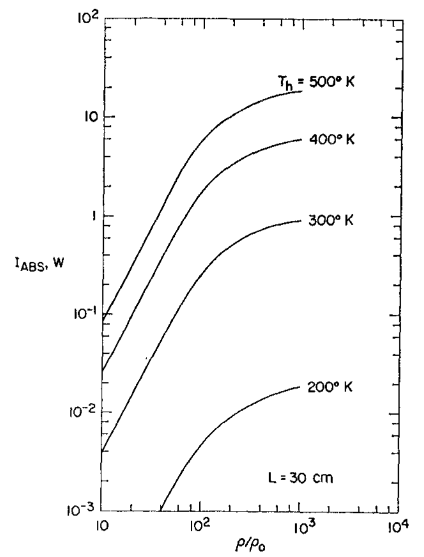

Fig. 2 Radiant power absorbed by the oxygen from the heater as a function of heater temperature and gas density.

It may be shown that whenever the oxygen storage tank contains at least $\frac{1}{8}$ of its maximum capacity and the heater has run continuously for as long as 30 min, the greatest difference between T_w and the oxygen temperature will be less than 22°K. Therefore, under most operating conditions, T_w and the oxygen temperature will be nearly the same. Insertion of the appropriate numerical value into this equation shows the heater temperature T_h cannot exceed 520°K if $\epsilon = 0.32$. If the heater has been blackened to give it an ϵ of 1.00, its temperature will not exceed 390°K.

Molecular oxygen has no permanent electric dipole moment and hence might not be expected to absorb the infrared radiation of the heater. However, at high gas pressures, it is found experimentally that oxygen does absorb infrared radiation because of quadrupole effects, collision-induced transitions, and possibly the formation of an O_2 dimer.[2] Because of the low T_h, only the fundamental and first overtone bands of the vibration-rotation spectrum at 1556 cm⁻¹ and 3102 cm⁻¹ absorb significant amounts of infrared radiation. The absorption coefficients for these two bands were derived from the data of Shapiro and Gush.[3] These molecular bands show

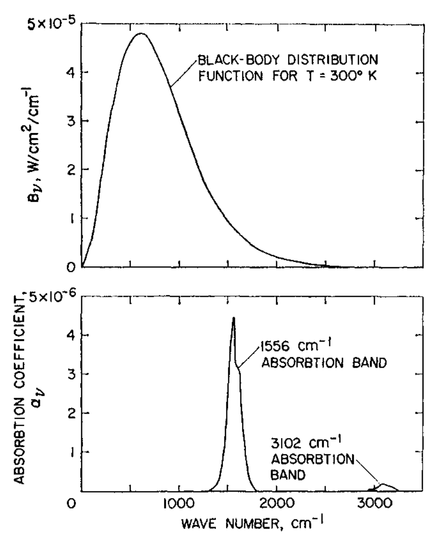

Fig. 3 Comparison of the position and extent of the oxygen infrared absorption bands with that of a 300° K blackbody source.

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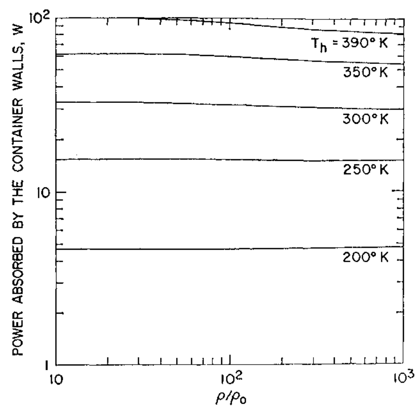

Fig. 4 Power absorbed by the container walls vs heater temperature and gas density.

no rotational structure because of the high densities involved. Hence their absorption coefficients are smoothly varying functions of wave number. This allows the absorption along any ray in the fluid to be evaluated from Eq. (2):

$$I_{\text{abs}} = \epsilon \int_{\nu_1}^{\nu_2} B_\nu (1 - e^{-\tau_\nu}) d\nu \qquad (2)$$

where B_ν = blackbody function; ν = wave number, cm^{-1}; and τ_ν = optical depth: $\tau_\nu = \alpha_\nu(\rho/\rho_0)^2 L$, where α_ν = spectral absorption coefficient, $\text{amagat}^{-2}\text{-cm}^{-1}$, ρ/ρ_0 = gas density, amagat, and L = path length, cm.

The integration limits ν_1 and ν_2 correspond to wave numbers at which the spectral absorption coefficients are taken as zero. To calculate the absorption from the band tails (i.e., that portion of each molecular band that had absorption coefficients too small to be experimentally measured) exponential tails were added to the strongest absorption band. Calculations show that these tail bands never contributed more than 20% to the total absorbed power and hence could safely be neglected.

Figure 1 is a plot of the fractional absorption (f_{abs}) for a distance equal to R, the inside radius of the tank. This fraction is defined as I_{abs} normalized by the emission intensity of the heater in the pertinent spectral regin for both the 1556 and 3102 cm^{-1} absorption bands and is plotted vs ρ/ρ_0 for various T_h's. It may be seen that for ρ/ρ_0 between 10^2 and 10^3 amagat (i.e., for most operational conditions), the 1556 absorption band is strongly absorbed while the 3102 absorption band is only weakly absorbed.

Because of the moderate coefficient of absorption of the tank wall, much of the radiation in the 3102 cm^{-1} spectral range may be reflected or scattered back into the oxygen. This means that appreciably more of the radiated heater power in this spectral range may be ultimately absorbed by the oxygen. It can be shown that an upper limit to the power absorbed by the oxygen is given by

$$I_{\text{abs}}\ (3102\ \text{cm}^{-1}\ \text{band}) \leq \frac{\bar{\alpha}(\rho/\rho_0)^2 R(2-\epsilon)}{1-(1-\epsilon)[1-2\bar{\alpha}(\rho/\rho_0)^2 R]} \cdot \pi\epsilon A \int_{\nu_1}^{\nu_2} B_\nu d\nu \qquad (3)$$

where $\bar{\alpha}$ is defined by

$$(1 - e^{-\bar{\alpha}(\rho/\rho_0)^2 R}) \int_{\nu_1}^{\nu_2} B_\nu d\nu = \int_{\nu_1}^{\nu_2} B_\nu (1 - e^{-\bar{\alpha}_\nu(\rho/\rho_0)R}) d\nu$$

where $\epsilon = 0.32$. When Eq. (3) was evaluated for $200°\text{K} \leq T_h \leq 500°\text{K}$, and $10 \leq \rho/\rho_0 \leq 1000$, it was found that I_{abs} (3102 cm^{-1} band) was always less than 1% of I_{abs} (1556 cm^{-1} band). Hence, it too may be neglected.

Figure 2 shows the total infrared power absorbed from the heater. Even under the circumstances most favorable to absorption (i.e., at the very highest densities and heater temperatures) the upper limit to I_{abs} will be less than 20 w. The reasons that I_{abs} is so small are that both oxygen absorption bands are narrow and that the absorption coefficients of the 3102 cm^{-1} band are very low. This is shown in Fig. 3 where the spectral distribution of the blackbody function and the spectral extent of the absorption bands are plotted against wave number.

Since the oxygen absorbs only a small fraction of the heater radiation, most of the power radiated by the heater is absorbed by the container wall, which heats the oxygen by conduction. (The heat-transfer rate from the wall to the outside is very small and may be neglected.) As Kamat[4] has pointed out, supplying heat to the oxygen by conduction from the container wall is a very good way of minimizing temperature gradients and preventing pressure collapse in super critical oxygen storage systems. Hence, to maximize this method of heat transfer, the heater should be operated in such a way as to deliver the largest possible fraction of its dissipated power as radiation. Figure 4 shows the power absorbed by the walls as a function of ρ/ρ_0 and T_h for the heater after it has been blackened to produce an ϵ of 1.00. It can be seen that at $T_h \geq 350°\text{K}$, more than half the heat dissipated by the heater will be transferred to the oxygen by conduction from the container wall. Under such circumstances, the temperature gradients throughout the fluid will be minimized and the possibility of pressure collapse will be diminished.

In conclusion, it has been shown that in cryogenic oxygen storage systems employing a central heater, infrared radiation acts to prevent overheating of the heater and to reduce temperature gradients in the oxygen by supplying heat to the container wall.

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An Improved Method for Accelerometer Precision Centrifuge Test Data Reduction

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Introduction

THE determination of accelerometer nonlinearity coefficients from precision centrifuge tests is a difficult exercise in both test design and data reduction method. The problem is compounded when the unit under test exhibits a substantial odd second-order coefficient (i.e., a term proportional to the algebraic acceleration times the absolute value of acceleration). Twice recently TRW has tested units having this characteristic, one of them a major missile guidance accel-

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