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Progress Report

HEAT TRANSFER TO LIQUID OXYGEN CONTAINERS

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ABSTRACT

A theoretical analysis of the heat transfer to a 5-liter liquid-oxygen container indicates the importance of the mechanism of radiation. Future work is to include an experimental study of heat transfer through layers of powders such as silica gel. The effects of gas pressure and container surface are to be investigated first for standard Aro containers with the insulating space filled with silica gel. A survey of the literature indicates promise for the successful use of powders in combination with a moderate vacuum.

OBJECTIVE

The objective of this program is the determination of the engineering fundamentals involved in the design of liquid-oxygen containers. The utility of this information will be in permitting the prediction of optimal design characteristics.

INTRODUCTION

A theoretical analysis of heat transfer to a 5-liter oxygen container (presented in a following section of this report) indicated that roughly 70 percent of the total heat transfer takes place by radiation from the outer to the inner shell of the container and that the remainder is mainly due to conduction through the metal rods supporting the inner container. Hence, it seems desirable to focus attention on methods of reducing radiative heat transfer or on securing acceptable values at lower manufacturing costs.

Sufficient data have been found in the published literature to warrant the conclusion that a finely powdered solid, if used in the space between the inner and outer shells, may give the same insulating effect as the present construction but may not require as high a vacuum. Dewar[1] conducted high-vacuum tests at low temperature, using double-walled glass tubes having an annular space of 4-5 mm. For such tubes, having nonsilvered walls, the insulating effect is increased 4 to 6 times by filling the annular space with finely divided powders such as silica, charcoal, bismuth oxide, etc., having a voids fraction of about 0.50. With tubes having silvered surfaces the effect was much less. However, this may be due to the narrow annular space used.

Kistler and Caldwell[2] conducted overall heat-transfer measurements on finely ground silica gel at atmospheric temperature and under vacuum. For 100-200-mesh gel, the heat transfer decreases with increasing vacuum until an absolute pressure of 0.5 mm Hg is reached. Below this pressure increasing vacuum has little further effect.

White[3] found that silica gel (Santocel) is somewhat transparent to infrared radiation and tried the addition of several materials as opacifiers. His tests ranged from room temperature to 400°F. He was especially successful with silicon, the optimum addition being about 15 percent by weight.

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1. Dewar, Sir James, Proc. Roy. Inst., XV, 815-829 (1898), as quoted in Collected Papers, Cambridge Univ. Press, 1927.

2. Kistler, S. S., and Caldwell, A. G., Ind. Eng. Chem., 26, 658 (1934).

3. White, J. F., Ind. Eng. Chem., 31, 827 (1939).

FUTURE WORK

It is planned to determine rates of heat transfer to the Aro 5-liter oxygen container when using 100-200-mesh silica aerogel (Santocel) in the space between the inner and outer shells of the container as a function of the absolute pressure in the space. These tests will probably be conducted on two Aro containers, one of which will have the normally used inner reflecting surfaces and the other to be one in which the inner surfaces are not specially prepared to obtain a low emissivity. For reference purposes, it is planned that a standard Aro container also be used so that comparative results may be obtained.

The tests will be performed with liquid nitrogen rather than with liquid oxygen to reduce safety hazards. The rate of heat transfer will be determined from weight-loss determinations, using essentially the same procedure as is used by Aro for acceptance tests on the containers.

The objectives of these preliminary tests will be to answer the following questions:

1. How effective is 100-200-mesh silica gel as a radiation shield at low temperatures?

2. If silica gel is effective, what is the optimum absolute pressure to be used?

3. Are shiny metal surfaces necessary when using powders such as silica gel?

If the results of these preliminary experiments are encouraging, the experimental program will be expanded. The variables to be investigated would then include the following:

1. Particle size, composition, and shape.
2. Container geometry and surface.
3. Gas composition and pressure.
4. Preparative techniques.

AN ANALYSIS OF THE MECHANISM OF HEAT TRANSFER IN A 5-LITER LIQUID-OXYGEN CONTAINER

The following is a summary of calculations made to determine the principal mechanism by which heat is transferred to a liquid-oxygen container as manufactured by the Aro Equipment Corporation. In this investigation the 5-liter container operating at 300 psig was considered and all calculations and recommendations apply quantitatively to this system. However, they may be extended qualitatively to any system of this general type. The results indicated that improvements in efficiency could be obtained in several ways. The factors indicated in these improvements are the coating used on the outside of the container and the degree of vacuum which is maintained between the two shells of the container.

METHOD USED AND ASSUMPTIONS MADE IN OBTAINING HEAT BALANCES

The general nature of the problem considered in this investigation is as follows. The liquid-oxygen container is considered to be filled with liquid oxygen and it is assumed that it has remained in this condition for a sufficient length of time so as to be in equilibrium with its surroundings. The problem is therefore a steady-state one and any heat transferred to a portion of the system must exactly equal the heat leaving that portion. The portion of the system chosen as a basis for a heat balance was the outer shell of the container.

To set up the problem in equation form, the net heat transfer by radiation, convection, and conduction, with respect to the outer shell, was set equal to zero. The solution of this problem in general would be difficult due to the possibility of the existence of circumferential temperature gradients in the shell. A solution of the problem was obtained by making several simplifying assumptions, the validity of which was established later. The assumptions are:

1. The inside-shell temperature is the liquid-oxygen temperature, and there are no radial or circumferential temperature gradients.

2. The outside shell is at a uniform temperature.

3. Radiation and convection transfer to the tubing and suspension rods between shells is neglected.

NOMENCLATURE

T = temperature, °R
q_r = heat transferred by radiation, Btu/hr
q_c = heat transferred by conduction and convection, Btu/hr
A = area in ft^2
G = Stefan-Boltzmann constant
ϵ = emissivity of surface
F = "F" factor for gray-body radiation

h_2 = heat-transfer coefficient for natural convection, from surrounding air to outer shell, Btu/hr ft^2 °R

h_3 = heat-transfer coefficient for conduction and convection by the gas between the shells, Btu/hr ft^2 °R

k = thermal conductivity, Btu/hr ft °R

L = length in ft

Subscript 1 refers to surroundings.
Subscript 2 refers to outer shell.
Subscript 3 refers to inner shell.
Subscript s refers to suspension rods.
Subscript st refers to stainless steel.
Subscript e refers to equivalent.

Making a heat balance over the outer shell gives

$$q_{r_{1-2}} + q_{c_{1-2}} = q_{r_{2-3}} + q_{c_{2-3}} \quad , \tag{1}$$

where

$$q_{r_{1-2}} = A_2F_{2-1}\ (T_1^4 - T_2^4) \quad , \tag{2}$$

$$q_{r_{2-3}} = A_2F_{2-3}\ (T_2^4 - T_3^4) \quad , \tag{3}$$

$$q_{c_{1-2}} = A_2h_2\ (T_1 - T_2), \text{ and} \tag{4}$$

$$q_{c_{2-3}} = A_2h_3\ (T_2 - T_3) + \frac{keAe}{Le}\ (T_2 - T_3) \quad . \tag{5}$$

The first term in the last equation accounts for the heat transferred from the outer shell to the inner shell by conduction and convection through the gas and the second term accounts for that transferred by conduction along the tubing and rods.

Now by assumption (1) T_3 is the temperature of saturated oxygen at 300 psi, which is 242°R. Therefore, for any value of T_1 equation (1) may be solved for T_2, provided the coefficients can be determined. With T_2 the heat transferred by the various mechanisms may be calculated using equations (2 - 5), and these values may be compared with the total transfer to determine the relative importance of each.

To compute the various coefficients the following procedure was followed. The area and length terms were computed from the dimensions given on the drawings for the 5-liter container. The value of F_{2-1} was taken equal to the emissivity of the outside surface of the outer shell. This is valid since the container is small compared to the dimensions of the surroundings. The value used for F_{2-1} was 0.60, which is the highest reported value for the emissivity of an aluminum paint. F_{2-3} was determined assuming gray-body radiation and using the method described by McAdams.[1] The value of F_{2-3} was found to be 0.0325, using an emissivity for the Cu surface of 0.07. The coefficient

$$\frac{keAe}{Le}$$

was calculated from the known dimensions of the tubing, suspension rods, and reported values of the thermal conductivity of Inconel and stainless steel. The coefficient h_2 was calculated using experimentally determined correlations for natural convection to spheres, as reported by Jacob.[2] The value of h_2 depends on T_2, T_1, and the dimensions of the outer shell. The method used to calculate h_3 depended on the assumed value of the pressure between the shells. For extremely low pressures (10^{-5} mm Hg) the method outlined by Kennard[3] was used. For higher pressures, where the thermal conductivity is independent of pressure, and where natural convection is important, the method given by Jacob[4] was used. In either case the value of h_3 depends not only on the pressure but also on T_3 and T_2. At the higher pressures h_3 also depends on the distance between the two shells.

An actual solution of equation (1) was obtained by first assuming T_2. With this assumed value h_2 and h_3 were calculated and these values used in equation (1) to calculate a value for T_2. This process was repeated until the assumed and calculated values of T_2 agreed.

RESULTS

The above procedure was used first to determine the relative amounts of heat transferred by each of the mechanisms for a container of the type now manufactured by Aro. On the basis of these calculations the factors which had the greatest effect on the heat-transfer rates were noted, and calculations were then made in which these factors were varied so that improvements on overall efficiency would be obtained. It should be pointed out that recommendations are made with primary regard to the heat-transfer characteristics and that there may be some mechanical reasons which would not make them feasible.

The results for the 5-liter container as manufactured are given in Table I. As has been mentioned before, the oxygen pressure was taken at 300

1. McAdams, W. H., Heat Transmission, 2nd ed., McGraw-Hill, 1942, p. 59.
2. Jacob, M., Heat Transfer, J. Wiley and Sons, 1949, p. 525.
3. Kennard, E. H., Kinetic Theory of Gases, McGraw-Hill, 1938, p. 319.
4. Jacob, M., op. cit., p. 541.

TABLE I

PREDICTED HEAT TRANSFER FOR 5-LITER BOTTLE AS-IS

Mechanism	Btu/hr	Percent of Total
Radiation to outside shell from surroundings	10.8	98.4
Convection and conduction to outside shell through surrounding air	0.2	1.6
Radiation from outside shell to inside shell	7.7	70
Convection and conduction from outside shell through gas to inside shell	approx. 0	approx. 0
Conduction from outside shell through tubing and rods to inside shell	3.3	30

psig. At this pressure the inner-shell temperature, T_3, is 242°R. For convenience 520°R or 60°F was used as the surrounding temperature, T_1. Using a pressure of 10^{-5} mm Hg between the shells, the outer-shell temperature was calculated to be 52°F. In Table I are given the amounts of heat transferred by each of the mechanisms as well as the percent relative to the total, the total heat-transfer rate in this case being 11 Btu/hr.

From Table I it is apparent that radiation is the important mechanism inside and outside the outer shell. Considering the radiant heat transfer to the outside shell, the rate of which is given by equation (2), it can be seen that the factor which can be changed most easily so as to give a lower rate is F_{1-2}, which is equal to the emissivity of the outside surface. For example, a highly reflective surface such as chrome plate would afford a substantial reduction in radiant transfer since its emissivity is as much as 10 times less than that of the present finish. No actual calculations were made with regard to this factor because of the uncertainty as to the value of the emissivity, which depends not only on the surface material but also on the surface roughness and age. However, it is felt that this factor is important enough to warrant considering the use of a highly reflective surface.

The calculations to this point have always assumed that the pressure between the shells was 10^{-5} mm of Hg, and as can be seen from Table I the heat leak through the gas between shells is negligible. However, since this high vacuum is difficult to obtain in practice, it was decided to determine if the same insulating power could be obtained at a lower vacuum. One method of accomplishing this is to fill the jacket with a fine powder and evacuate to a pressure of perhaps 0.1 mm Hg. This method is capable of reducing the thermal conductivity of air by a factor of about 10. The values given in Table II were estimated on this basis, and it was found that the heat leak increased by 50% (to 16.2 Btu/hr). The surface temperature, T_2, in this case was 48°F.

TABLE II

ESTIMATED HEAT LOSS FOR POWDER-FILLED JACKET

Mechanism	Btu/hr	Percent of Total
Radiation to outside shell from surroundings	15.6	96
Convection and conduction to outside shell through surrounding air	0.6	4
Radiation from outside shell to inside shell	0	0
Convection and conduction from outside shell through gas to inside shell	4.0	25
Conduction from outside shell through tubing and rods to inside shell	12.2	75

While the method of prediction is not good enough to give an accurate result, these figures are of the right order of magnitude and indicate a possibility of success for the use of powders.

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