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AN ESTIMATION OF THE INTERNAL-COOLING REQUIREMENTS OF AN AIRCRAFT-ENGINE CYLINDER WHEN USING OXYGEN BOOST

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INTRODUCTION

The use of increased oxygen concentrations in the intake air as a means of supplementing the supercharger capacity of an aircraft engine at altitude is discussed in reference 1. Experiments on a Wright R-1820 G200 cylinder (reference 1) indicated the amount of internal cooling that was required to maintain engine temperatures when gaseous oxygen boosting was applied. The use of liquid oxygen boosting in conjunction with internal coolants is also feasible.

Because only a small amount of experimental data is available, a method has been developed to estimate the quantities of internal coolants required to prevent overheating of the aircraft cylinder when oxygen boost is applied. Inasmuch as many factors have been neglected, the results reported herein are intended to serve only as qualitative indications of the internal-coolant requirements.

COMPUTATIONS

Method. - For the purposes of the calculation, suppose that oxygen is injected into the engine of an airplane whose normal critical altitude is 30,000 feet for an inlet-manifold pressure of 44 inches of mercury absolute. Consider that critical-altitude horsepower is desired at 40,000 feet, at which altitude the manifold pressure would be reduced to 27.4 inches of mercury absolute. The reduction in air consumption at 40,000 feet requires the injection of enough additional oxygen to give the airplane engine the same total oxygen consumption that it normally had at 30,000 feet. The determination of the necessary additional oxygen therefore requires a knowledge of the mass air flow to the engine. In the following computations, any effects that the injected internal coolants or oxygen may have upon the normal air consumption of the engine have been entirely neglected.

Assume that the intake-valve arrangement of the engine offers no resistance to the incoming charge and that the exhaust residuals are isothermally compressed by the incoming charge. The air consumption of the engine per cycle will then be represented by the following equation:

$$m = \rho v_d + \rho v_c \left(1 - \frac{p_e}{p}\right) \tag{1}$$

where

m mass of charge air per engine cycle

ρ inlet-charge density

v_d engine displacement volume

v_c engine clearance volume

p_e exhaust back pressure

p intake-manifold pressure

In terms of compression ratio and inlet-air pressure, equation (1) can be written:

$$\frac{m}{v_d} = \frac{\rho_c\ r}{p_c\ (r - 1)} \left(p - \frac{p_e}{r}\right) \tag{2}$$

where

ρ_c inlet-charge density at critical altitude

p_c intake-manifold pressure at critical altitude

r engine compression ratio

In order to estimate the engine cooling effectiveness of the various internal-coolant combinations, assume that the engine and its heating effects are replaced by an adiabatic mixing chamber. The internal coolants will then be injected at some initial temperature (depending upon the internal coolant) and mixed with the combustion gases until a final temperature T_g is reached. The temperature T_g is herein assumed to be the mean effective gas temperature, which represents the average cycle gas temperature effective in the transfer of heat from the gases within the cylinder chamber to the cylinder walls, discussed in reference 2. The heat absorbed by each internal coolant will then be the difference between its total heat content at T_g and its total heat content at the assumed inlet temperature.

Application of method. - When the exhaust back pressure is 12 inches of mercury absolute, the compression ratio is 7.0, the inlet-air temperature is 225° F, and the engine speed is 2500 rpm, the air consumption at the critical altitude (from equation (2)) is 4.16 pounds per hour per cubic inch of engine displacement; the air consumption at 40,000 feet is 2.53 pounds per hour per cubic inch of engine displacement. Thus, the maintenance of critical-altitude total oxygen consumption requires 0.38 pound of added oxygen per hour per cubic inch of engine displacement. The injection of this amount of oxygen will give the inlet air a final oxygen concentration of approximately 33 percent by weight.

The decrease in the quantity of inducted nitrogen in passing from the critical-altitude condition to that at 40,000 feet amounts to 1.25 pounds per hour per cubic inch of engine displacement. The cooling properties of this quantity of nitrogen must be compensated by injection of an internal coolant to prevent overheating of the engine.

When an initial inlet-air temperature of 225° F and a final mean effective gas temperature T_g of 1150° F (approximated from the experimental values in reference 3) are assumed, the heat absorbed by nitrogen, as estimated from figure 1, is 238 Btu per pound. When water is injected as an internal coolant at 60° F, it will absorb 1490 Btu per pound. Thus, water is 6.3 times more effective than nitrogen as an internal coolant and, hence, the amount of water required to replace the cooling capacity of the nitrogen is 1.25/6.3, or 0.20 pound per hour per cubic inch of engine displacement. At a fuel-air ratio of 0.09, this value corresponds to a water-fuel ratio of 0.53. Although water was not tested as an internal coolant during the tests reported in reference 1, the ammonium-hydroxide data presented in figure 1 of that report indicates that about 0.5 pound of water per pound of fuel at a fuel-air ratio of 0.09 would provide sufficient cooling when a 33-percent concentration of oxygen is used. The calculated value is thus of the correct order of magnitude.

If liquid oxygen is used rather than gaseous oxygen, the required water will be reduced by an amount corresponding to the quantity of heat absorbed by the oxygen in passing from the liquid state at its boiling point (-298° F) to the gaseous state of 225° F. This heat amounts to 206 Btu per pound. Hence, the amount of water required to cool the engine will be 0.15 pound per hour per cubic inch of engine displacement, corresponding to a water-fuel ratio of 0.39 at a fuel-air ratio of 0.09.

If enough liquid nitrogen is added to the liquid oxygen to make water internal cooling unnecessary, the required amount of liquid nitrogen is 0.48 pound per hour per cubic inch of engine displacement. Liquid air containing 44 percent oxygen should therefore give adequate internal cooling for this type of oxygen boost. A comparison of the amount of liquid nitrogen required with the amount of liquid water required shows that, on a weight basis, water is 0.48/0.15, or 3.2 times more effective than liquid nitrogen as an internal coolant.

The use of liquid air containing 23.2 percent oxygen would overcool the engine by an amount equivalent to the cooling effect of 0.24 pound water per hour per cubic inch of engine displacement. The curves of reference 3 indicate that this amount of cooling would lower T_g approximately 290° F at a fuel-air ratio of 0.09.

Summary of calculations. - Inasmuch as many factors have been neglected, the results reported herein are intended to serve only as qualitative indications of the cooling requirements when using several combinations of oxygen boost and internal coolants. A brief summary of the results calculated on the basis of an engine speed of 2500 rpm, a critical altitude of 30,000 feet, and a total oxygen consumption at 40,000 feet (by oxygen boost) equal to that at 30,000 feet is presented in the following table:

Type of boost and internal coolant	Altitude (ft)	Inlet-air pressure[a] (in. Hg absolute)	Added oxygen (lb/hr) (b)	Added water (lb/hr) (b)	Added nitrogen (lb/hr) (b)	Total fluid weight (lb/hr) (b)
Normal operation	30,000 (critical)	44.0	0	0	0	0
Gaseous oxygen and liquid water	40,000	27.4	.38	.20	0	.58
Liquid oxygen and liquid water	40,000	27.4	.38	.15	0	.53
Liquid oxygen and liquid nitrogen	40,000	27.4	.38	0	.48	.86
Liquid air	40,000	27.4	.38	[c]-.24	1.25	1.63

[a]Pressure does not include pressure due to added material.
[b]These quantities are given per cubic inch of engine displacement.
[c]The negative value represents overcooling by an amount equivalent to this quantity of water used as an internal coolant. The value of T_g would be decreased approximately 290° F.

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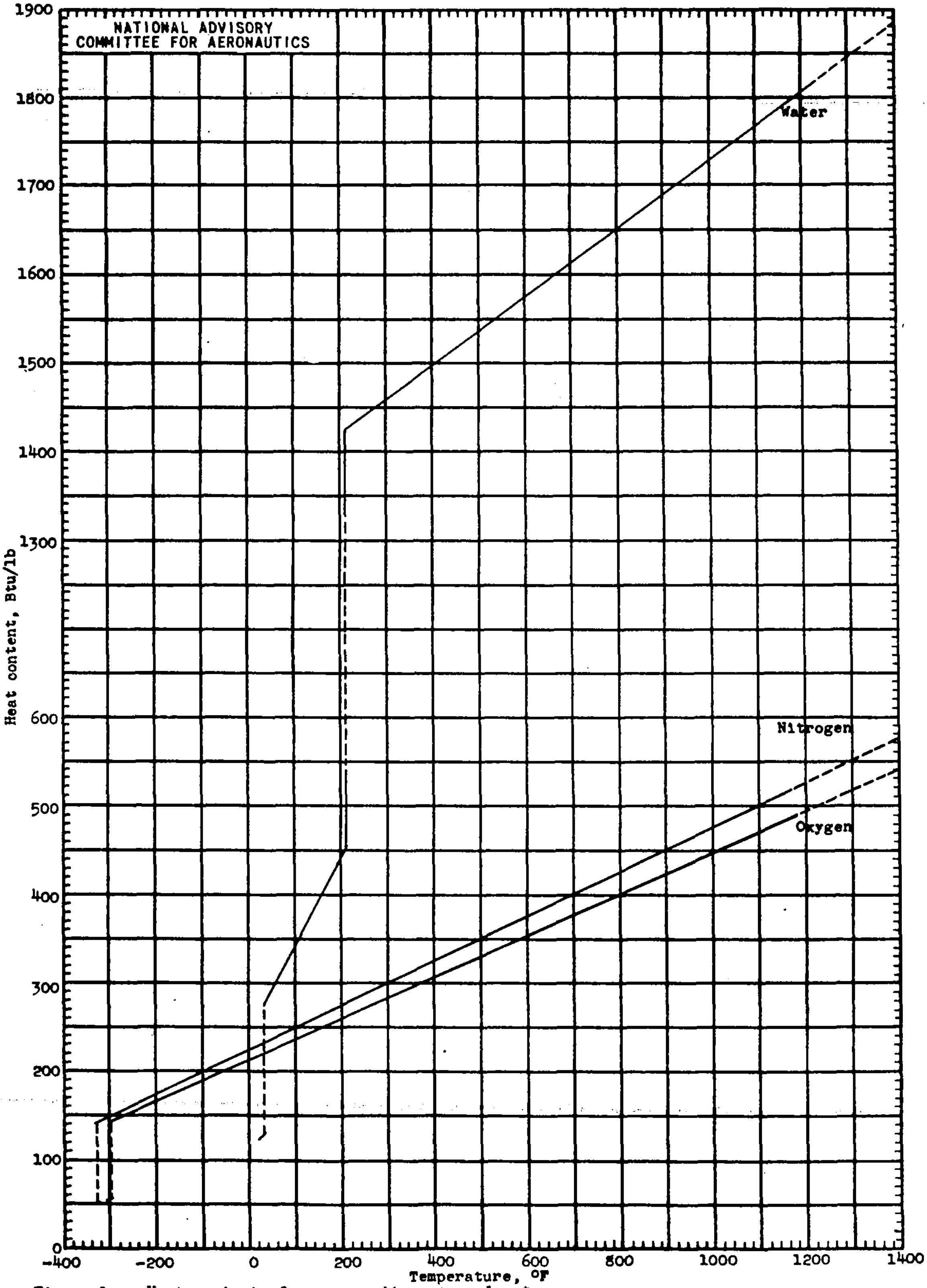

Figure 1. - Heat content of oxygen, nitrogen, and water.