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CALCULATION OF THE TEMPERATURE WHICH A PARACHUTE CANOPY ATTAINS AT HIGH ALTITUDE

Dr. E. R. G. Eckert

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by

Dr. E. P. G. Eckert

BIOGRAPHICAL NOTE

Prof. Dr. E. P. G. Eckert is an expert on thermodynamics, especially concerning heat transfer and gas turbines. From 1938 to 1943 he was head of the department for thermodynamics at the Institute for Aircraft Engines at the LFA in Brunswick. In 1943 Dr. Eckert became professor and director of the Institute for Thermodynamics at the University of Prague.

He finished his studies at the University of Prague in 1927 and later became lecturer at the same University. From 1934 to 1938 Dr. Eckert was senior engineer of the engine laboratory at the University of Danzig. In 1942 he was lecturer at the University of Brunswick. At the LFA he was in charge of research on gas turbines and jet propulsion. Dr. Eckert holds two degrees of Doctor of Engineering.

His work comprises heat radiation; heat transfer, especially at high velocities; research on jet propulsion and gas turbines, especially that concerning high temperatures; combustion problems; flow investigations on turbine blades employing the optical interferometer; and heat exchangers for gas turbines.

He is now employed in Propulsion Section, Analysis Division, Intelligence T-2, AMC, Wright Field, Dayton, Ohio.

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CALCULATION OF THE TEMPERATURE WHICH A PARACHUTE CANOPY ATTAINS AT HIGH ALTITUDE

1. Introduction

Since at high altitudes the air density is very low, a parachute descends with a very high speed. Therefore, relative to the parachute, the air moves with great velocity. In the boundary layer, which builds up along the surfaces of the parachute, and in the wake behind it, the air is decelerated and its kinetic energy is converted into heat. Thus the parachute is heated up, but, on the other hand, it radiates heat into the universe and to the earth. During the day it also absorbs solar heat radiation. The temperature which the canopy attains under all these influences is calculated in the following paragraphs.

2. Inherent Temperature and Heat Transfer by Convection

In a high-velocity gas stream a body which loses no heat by radiation attains an equilibrium temperature higher than the temperature T_A which is indicated by a thermometer moving along with the stream. This temperature of the body is called its "inherent" temperature. It can be calculated by the following formula:

$$T_E = T_A + \sigma \frac{V^2}{2gC_pJ} \quad (1)$$

T_E	inherent temperature of the body	°R
T_A	static temperature in the gas stream (atmospheric temperature)	°R
V	velocity of the gas stream relative to the body	ft/sec
g	gravitational constant	ft/sec ²
C_p	specific heat of gas at constant pressure	BTU/lb °R
J	mechanical equivalent of heat	ft lb/BTU
σ	nondimensional factor	

For air the denominator $2gC_pJ$ has the value 12,000 ft²/sec² °R. The factor σ depends on the shape of the body. For a streamlined body in an air stream it is $\sigma = 0.85 - 0.90$, for a cylinder in a flow normal to its axis $\sigma = 0.5 - 0.7$. (Ref. 1). In an air stream σ never can be greater than 1. No measurements are known for a hemisphere with its opening against the stream, which shape should correspond to the parachute canopy. Since we are interested in the highest temperature of the canopy, we may, therefore, calculate with the

value $\sigma = 1$, which gives an upper limit.

If the temperature of the body is lower than the inherent temperature (e.g., by radiation), a continuous flow of heat streams from the boundary layer to the body, given by the formula:

$$Q_c = h_c A (T_i - T_s) \quad (2)$$

Q_c	flow of heat by convection	BTU/hr
h_c	heat transfer coefficient	BTU/hr ft ² °R
A	surface of the body	ft ²
T_i	inherent temperature of the body	°R
T_s	surface temperature of the body	°R

By calculation and experimentation it was proved that, for streamlined bodies, the heat transfer coefficient does not depend materially on the Mach number, so that formulas derived by experimentation with low velocities can also be applied to supersonic flow. (Ref. 1). In supersonic flow the velocities along the surface are decreased by shock waves arising in front of a blunt body. Again, no experiments on shapes similar to a parachute canopy are known, so we must use formulas of other bodies. We shall use the results from tests on spheres. They can be expressed by the formula (Ref. 2).

$$\frac{h_c D}{k} = 0.33 \left(\frac{D V}{\nu} \right)^{0.6} \quad (3)$$

D	diameter of the sphere	ft
k	heat conductivity	BTU/ft hr °R
ν	kinematic viscosity	ft ² /sec

It is expected that the heat transfer from the wake to the rear of a hemisphere representing the parachute canopy is approximately the same as the heat transfer on the rear of the sphere. The heat transfer on the inner surface of the hemisphere is certainly smaller than the heat transfer on the front half of the sphere. If we calculate with formula 3 for the parachute canopy, we get values too high for the heat flow from the air to the parachute canopy, and therefore an upper limit for the surface temperature.

The permeability of the parachute material may influence the heat transfer. So we check our results by calculating the heat flow in a different way. It was proved by experiments that the volume of air v in cu ft, leaking through one sq ft of the parachute cloth per sec increases linearly with the pressure difference Δp on both sides of the cloth. On the other hand, dimensional analysis requires

that a relationship

$$\Delta p = \gamma \frac{v^2}{2g} f(Re) \quad (4)$$

exist (γ specific weight of air). If we build up the Reynolds No. Re with the porosity v , (which has the dimension of a velocity), the diameter D of the parachute canopy, and the dynamic viscosity μ of the air ($Re = \frac{\gamma v D}{\mu}$), we get a linear dependency between the pressure difference Δp and the porosity v in eq 4 only if

$$f(Re) = \frac{1}{Re}$$

This results in

$$\Delta p = \frac{\mu}{2gD} v$$

The formula shows that the porosity does not depend on the air density. Therefore we can use the results of experiments at normal pressure for the descent at high altitude also.

Now we may assume that this air leaking through the canopy is cooled down from the inherent temperature T_i (for $\sigma = 1$) to the surface temperature T_s of the canopy. This gives a heat flow Q_c to the canopy.

$$Q_c = \frac{A}{2} c_p v (T_i - T_s) \quad (5)$$

The factor 1/2 arises because in A both sides of the canopy surface are included.

It is proposed to calculate, with formula 2 or 5, which of the two gives higher values for the heat flow Q_c . The porosity of normal parachute cloth is 1.3 ft³/ft²sec. In the example calculated in paragraph 5, the heat flow calculated with eq 2 becomes approximately twice as great as that calculated with eq 5. Therefore eq 2 was used for the final computations.

3. Heat Exchange by Radiation

The parachute canopy radiates heat to the universe and to the earth and on the other hand absorbs heat radiated from the earth and from the sun. As long as the altitude is small compared with the diameter of the earth, the inner part of the surface A of the parachute canopy exchanges heat by radiation practically only with the earth. This gives the formula:

$$Q_{R1} = \epsilon A_{pr} C_r (T_a^4 - T_e^4) \quad (6)$$

Q_{R1} heat exchange by radiation between parachute and earth BTU/hr
 A_{pr} area of projection of parachute on a horizontal plane ft²

ϵ emissivity of parachute surface

C_r Stefan-Boltzmann constant 0.174×10^{-8} BTU/ft²hr °R⁴

T_c temperature of earth °R

Since a part of the radiation emitted by the inner surface strikes other areas of this same surface and is absorbed by it, only the projection area A_{proj} on a horizontal plane is inserted in Eq 6. The essential part of the radiation at the temperatures the canopy attains, lies in the wave-length range between 2 and 10 μ . For these wave lengths the emissivity of all electrical nonconductors is $\epsilon = 0.80$ to 1.0. The color of the surface does not influence this value.

The upper half of the canopy surface exchanges heat by radiation with the universe. Since the temperature of the universe is 0 °R, the second term in Equation 6 vanishes and the heat flow is given by

$$Q_{rad} = \epsilon \frac{A}{2} C_r T_c^4 \quad (7)$$

The solar radiation at high altitudes on 1 ft² area normal to the sun rays is $q_s = 425$ BTU/ft²hr. If A_{proj} is the projection of the parachute in this direction, the solar radiation absorbed by the parachute is

$$Q_s = \alpha A_{proj} q_s \quad (8)$$

The projection area is maximum when the sun is vertically above the parachute. To get an upper limit for the surface temperature, the same value of A_{proj} as in Eq 6, namely the projection on a horizontal plane has to be used.

The absorptivity α for sun radiation depends very much on the color of the parachute. For white cloth it is approximately $\alpha = 0.2$, for dark cloth it may increase to almost 1.

4. Calculation of Surface Temperature

Now the surface temperature may be calculated by a heat balance. During the descent, the temperature of the parachute changes continuously. The heat stored in the material of the parachute per unit time is:

$$\frac{A}{2} \gamma c \frac{dT_s}{dt} = \frac{A}{2} \gamma c \frac{dT_s}{dH} V \quad (9)$$

Δ	thickness of the parachute cloth	ft
γ	specific weight parachute cloth	lb/ft ²
c	specific heat parachute cloth	BTU/lb °R
T	time	sec
H	altitude	ft

In the above formula the small temperature differences within the parachute cloth are neglected. Now the heat balance gives:

$$\frac{1}{2} \gamma c V \frac{dT_s}{dt} = h_c (T_i - T_s) + \alpha \frac{E_{\text{sun}}}{A} q_{\text{net}} - \epsilon \frac{E_{\text{sky}}}{A} C_s (T_s^4 - T_e^4) - \epsilon \frac{1}{2} C_s T_s^4 \quad (10)$$

If the heat storage in the parachute material can be neglected, the left-hand term becomes zero and the surface temperature T_s may be determined from

$$h_c T_s + \epsilon \left(\frac{E_{\text{sun}}}{A} + \frac{1}{2} \right) C_s T_s^4 = h_c T_i + \alpha \frac{E_{\text{sun}}}{A} q_{\text{net}} + \epsilon \frac{E_{\text{sky}}}{A} C_s T_e^4 \quad (11)$$

Since the heat storage in the canopy decreases the temperature variations during the descent, Eq. 11 gives the highest temperature possible.

5. Numerical Calculations

For a parachute descending from 100 miles altitude with the velocities (Ref. 3) given in Fig. 1, the surface temperatures are calculated with Eq. 10 and 11. The following values were used:

$$c = 0.3; \quad \epsilon = 0.8; \quad \alpha = 0.2 \text{ (white cloth).} \quad \frac{E_{\text{sun}}}{A} = 1/3; \quad \gamma = 8.7$$

lb/ft³; $c = 0.3$ BTU/lb °R; $\Delta = 0.01$ in. The temperature of the atmosphere are recorded in Fig. 1; the temperature of the earth was assumed to be $T_e = 492^\circ\text{R}$.

The property values for air are given in the following table:

Air temperature °F	-58°	32°	122°	212°	392°
Thermal conductivity BTU/hr ft °F	0.0134	0.0159	0.0182	0.0204	0.0241
Kinematic viscosity 10 ⁴ ft ² /sec	1.02	1.47	1.99	2.56	3.87

The kinematic viscosity is given for normal pressure p_n . It must be multiplied with the ratio of the normal pressure p_n to the pressure p to get the value for pressure p .

The results of the calculation are presented in Fig. 1.

At altitudes above 60 miles the convective heat-transfer coefficient h_c from the boundary layer becomes so small because of low air density that the surface temperature is determined only by the exchange of radiated heat.

The curve t_1 gives the surface temperature of the canopy, if the heat storage is neglected (according to formula 10); curve t_2 represents the surface temperature taking into account the heat storage. The second curve was calculated from equation 10 by isoclinical method. It can be seen that the difference between the two temperatures t_1 and t_2 are small. The highest temperature (312°F) occurs at 37 miles altitude, where the convective heat transfer is already great and the velocity still high.

This maximum temperature was also calculated for a canopy of dark cloth ($\alpha = 0.8$). A value of 340°F was found.

6. References.

1. E.R.G. Eckert: "Heat Transmission of Bodies in Rapidly Flowing Gases," Progress Report No. 46 IRE 46 (1946).
2. W. H. McAdams: "Heat Transmission," 2nd Ed. McGraw-Hill, New York, 1942 p. 237.
3. "Considerations on the Descent of a Parachute from High Altitude," by P. L. Chambre and P. T. Nalina - California Institute of Technology - 30 April 1946.

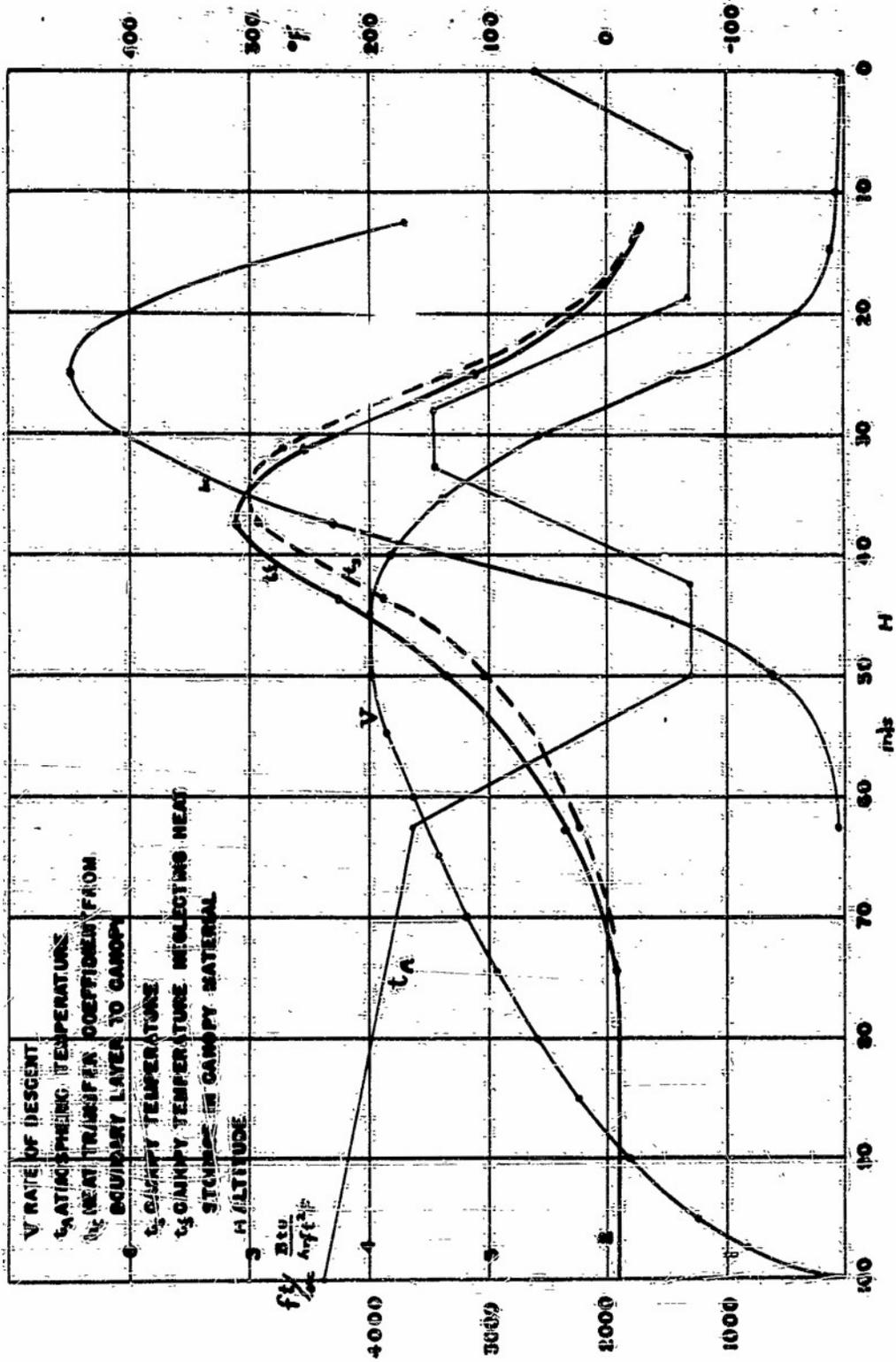


Fig. 1 - Surface Temperatures of a Parachute-Canopy

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