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

Dr. E. R. G. Eckert

Restricted classification cancelled 18 months from date by authority of Commanding General, AMC
By January 9, December 1946

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RESTRICTED

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BIOGRAPHICAL NOTE

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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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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:

$$T_e = T_a + \sigma \frac{V^2}{2gC_p\rho}$$

Where:
- $T_e$ = inherent temperature of the body
- $T_a$ = static temperature in the gas stream (atmospheric temperature)
- $V$ = velocity of the gas stream relative to the body
- $g$ = gravitational constant
- $C_p$ = specific heat of gas at constant pressure
- $\rho$ = mechanical equivalent of heat
- $\sigma$ = nondimensional factor

For air the denominator $2gC_p\rho$ has the value 12,000 ft$^2$/sec$^2$ °R. The factor $\sigma$ 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 $\sigma$ 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 \( c' = 1 \), 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:

\[
Q_c = \dot{R}_c A (T_e - T_0)
\]

(2)

- \( Q_c \) flow of heat by convection [BTU/hr]
- \( \dot{R}_c \) heat transfer coefficient [BTU/hr ft\(^2\) \(^\circ\)R]
- \( A \) surface of the body [ft\(^2\)]
- \( T_e \) inherent temperature of the body [\(^\circ\)R]
- \( T_0 \) surface temperature of the body [\(^\circ\)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):

\[
\frac{\dot{R}_c D}{\kappa} = 0.33 \left( \frac{D \gamma}{\nu} \right)^{0.6}
\]

(3)

- \( D \) diameter of the sphere [ft]
- \( \kappa \) heat conductivity [BTU/ft hr \(^\circ\)R]
- \( \nu \) 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 \( \Delta p \) on both sides of the cloth. On the other hand, dimensional analysis requires
that a relationship

$$\Delta p = \gamma \frac{v^2}{2g} \int (Re)$$  \hspace{1cm} (4)

exist (\(\gamma\) 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 \(\mu\) of the air (\(Re = \frac{vD}{\mu}\)), we get a linear dependency between the pressure difference \(\Delta p\) and the porosity \(v\) in eq 4 only if

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

This results in

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

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

$$Q_c = \frac{1}{2} \alpha v (T_i - T_s)$$  \hspace{1cm} (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 ft²/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:

$$Q_{ni} = \varepsilon \alpha A \rho c \alpha (T_e - T_i)$$  \hspace{1cm} (6)

\(Q_{ni}\) heat exchange by radiation between parachute and earth \(BTU/hr\)
\(\alpha\) area of projection of parachute on a horizontal \(ft^2\)
The solar radiation at high altitudes on 1 ft² area normal to the sun rays is $Q_0 = 425 \text{ BTU/ft}^2\text{hr}$. If $A_{PH}$ is the projection of the parachute in this direction, the solar radiation absorbed by the parachute is

$$Q_s = \alpha A_{P H} Q_0$$

(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 $A_{P H}$ as in Eq. 6, namely the projection on a horizontal plane has to be used.

The absorptivity $\alpha$ 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.

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:

$$\frac{A}{2} \gamma c \frac{dT_a}{dt} = \frac{A}{2} \gamma c \frac{dT_a}{dH} V$$

(9)
thickness of the parachute cloth \( \lambda \) ft

specific weight parachute cloth \( \gamma \) lb/ft\(^2\)

specific heat parachute cloth \( C \) BTU/lb \( ^\circ\)F

time \( t \) sec

altitude \( H \) ft

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

\[
\frac{1}{2} \alpha \gamma C (t_e - t_a) = \frac{1}{4} \left( \frac{E}{\mu_a} + \frac{\lambda}{2} \right) C_a T_a^4 - \frac{1}{4} \left( \frac{E}{\mu_a} + \frac{\lambda}{2} \right) C_a T_e^4 + \frac{1}{2} \alpha E C_a (t_e - t_a)^2 - \frac{1}{2} \alpha E C_a T_e^2 \tag{10}
\]

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

\[
\frac{1}{2} \alpha \gamma C (t_e + T_a) = \frac{1}{4} \left( \frac{E}{\mu_a} + \frac{\lambda}{2} \right) C_a T_a^4 + \frac{1}{4} \left( \frac{E}{\mu_a} + \frac{\lambda}{2} \right) C_a T_e^4 + \frac{1}{2} \alpha E C_a (t_e - T_a)^2 \tag{11}
\]

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:

\( \gamma = 1 \); \( \epsilon = 0.8 \); \( \mu_a = 0.2 \) (white cloth); \( \frac{E}{\mu_a} = 0.13 \); \( \gamma = 0.7 \)

\( \lambda = 0.3 \) BTU/lb \( ^\circ\)F; \( h = 0.01 \) in. The temperature of the atmosphere are recorded in Fig. 1; the temperature of the earth was assumed to be \( T_e = 490^\circ\)F.

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

<table>
<thead>
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<th>Air temperature (^\circ)F</th>
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<th>122</th>
<th>212</th>
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<tr>
<td>Thermal conductivity BTU/hr ft ( ^\circ)F</td>
<td>0.0134</td>
<td>0.0150</td>
<td>0.0182</td>
<td>0.0204</td>
<td>0.0241</td>
</tr>
<tr>
<td>Kinematic viscosity (10^4 ) ft(^2)/sec</td>
<td>1.02</td>
<td>1.47</td>
<td>1.99</td>
<td>2.56</td>
<td>3.87</td>
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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 \( P \).

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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 \( t_a \) gives the surface temperature of the canopy, if the heat storage is neglected (according to formula 10); curve \( t_b \) represents the surface temperature taking into account the heat storage. The second curve was calculated from equation 10 by isoclinal method. It can be seen that the differences between the two temperatures \( t_a \) and \( t_b \) 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 (\( \alpha = 0.6 \)). A value of 340°F was found.

6. References


Fig. 1 - Surface Temperatures of a Parachute-Canopy
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Note:
There are no drawings on page 8.