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Heat balance for flight vehicles

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THE PREPARATION OF THIS DATA ITEM

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HEAT BALANCE FOR FLIGHT VEHICLES

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HEAT BALANCE FOR FLIGHT VEHICLES

1. NOTATION AND UNITS

Any set of consistent units may be used. Two sets are indicated below.

		SI	British
a	local Reynolds analogy factor, St/C_f		
a_m	mean Reynolds analogy factor, St_m/C_{fm}		
B	Stefan-Boltzmann radiation constant	$W/m^2 K^4$	$Chu/ft^2 s K^4$
C_f	local skin friction coefficient		
C_{fm}	mean skin friction coefficient		
c_p	specific heat capacity of air at constant pressure	$J/kg K$	$Chu/slug K$
c_w	specific heat capacity of wall material	$J/kg K$	$Chu/slug K$
h	local forced convection heat transfer coefficient, $q/(T_{wr} - T_w)$	$W/m^2 K$	$Chu/ft^2 s K$
h_m	mean forced convection heat transfer coefficient, $q_m/(T_{wr} - T_w)$	$W/m^2 K$	$Chu/ft^2 s K$
i	enthalpy	J/kg	$Chu/slug$
J	mechanical equivalent of heat	$N m/J$	$ft lbf/Chu$
k	thermal conductivity	$W/m K$	$Chu/ft s K$
M	Mach number		
Nu	local Nusselt number, hx/k		
Pr	Prandtl number, $\mu c_p/k$		
q	local forced convection heat flux intensity	W/m^2	$Chu/ft^2 s$
q_m	mean forced convection heat flux intensity	W/m^2	$Chu/ft^2 s$
q_s	solar radiation heat flux intensity	W/m^2	$Chu/ft^2 s$
R_x	Reynolds number based on distance from appropriate boundary layer origin, $\rho_1 u_1 x / \mu_1$		
r	temperature recovery factor		

St	local Stanton number, $q/\rho_1 u_1 (i_{wr} - i_{*w}) = h/\rho_1 u_1 c_p$ when c_p is invariant with temperature		
St_m	mean Stanton number, $q_m/\rho_1 u_1 (i_{wr} - i_{*w}) = h_m/\rho_1 u_1 c_p$ when c_p is invariant with temperature		
T	temperature	K	K
t	time	s	s
u	velocity	m/s	ft/s
x	distance measured from appropriate boundary layer origin	m	ft
α	normal total surface absorptivity		
α_s	normal total solar absorptivity		
γ	ratio of specific heat capacities		
δ_w	wall (or skin) thickness	m	ft
ε	normal total surface emissivity		
ε_G	gas emissivity		
μ	viscosity	kg/m s	slug/ft s
ρ	density	kg/m ³	slug/ft ³
ρ_w	density of wall material	kg/m ³	slug/ft ³
Suffixes			
e	relating to equilibrium (steady state) conditions		
H	relating to stagnation conditions		
i	relating to incompressible flow ($M_1 = 0$, $T_w = T_{wr} = T_1$)		
r	relating to recovery (zero convective heat transfer) conditions ($T_w = T_{wr}$)		
w	relating to conditions at wall		
1	relating to conditions at edge of boundary layer		
∞	relating to conditions in uniform flow upstream		

* In cases where the variation of c_p with temperature is significant the use of a Stanton number based on enthalpy rather than temperature is preferable.

2. INTRODUCTION

The rise in temperature of the air adjacent to the external surface of a vehicle travelling at high speed can cause the transfer of heat into the vehicle. The amount of heat generated either by direct compression, as at a stagnation point, or by friction, as in the boundary layer, depends directly on the speed of the vehicle and increases with increase in speed. At low speeds these heating effects are unimportant from the structural designer's point of view although from the systems designer's viewpoint they may well be very significant when allowable temperatures within the vehicle are dictated by the presence of flight crew and passengers. At high speeds however the temperature attained by the external surface of the vehicle can dictate the design of the vehicle to a very large extent by introducing problems such as reduced structural strengths as well as difficulties with regard to the insulation of certain components such as fuel tanks.

From the foregoing it can be seen that for most flight speeds and certainly for high speed flight it is essential for the designer to be able to determine the skin temperature of a vehicle with reasonable accuracy, and it is in this régime that the ensuing discussion will be concentrated.

The factors affecting the temperature attained by the skin are as follows:-

- (1) Aerodynamic heat transfer by forced convection to the skin.
- (2) External radiation from the skin.
- (3) Solar radiation to the skin.
- (4) Atmospheric radiation to the skin.
- (5) Near-field radiation from the hot gas cap around the nose of the vehicle.
- (6) Internal radiation to and from the skin.
- (7) Internal free convection from the skin.
- (8) Conduction along and through the skin.
- (9) Forced convection heat transfer from the skin due to some cooling process.

These factors are not all equally important in determining the skin temperature of a high speed vehicle. In the absence of forced convection due to some cooling process (9), components (1) to (4) are important at supersonic speeds although the importance of (3) and (4) relative to (1) varies from one problem to another. For example, if the sun is at a small angle of incidence relative to the surface under consideration then the solar heating term (3) will be small, possibly negligible. Also, if the surface temperature is significantly greater (more than twice, say) than ambient then the atmospheric radiation term (4) will be small. At hypersonic speeds components (1) and (2) predominate but component (5) can be important if the Mach number is high enough (see References 10 and 15). This is complicated by dissociation, surface reactions and ionisation. Internal radiation (6) and free convection (7) are small, being typically less than one per cent of aerodynamic heat transfer. Likewise skin conduction effects (8) are negligible (typically one or two per cent of aerodynamic heat transfer) provided that the skin is thin and the surface is almost at a constant temperature. The effects of heat transfer due to some other cooling process (9) (e.g. by circulation of a cooling liquid) will obviously vary with the process and should be taken into account where significant.