Aerodynamic heating

Sunday, December 31, 2017 17:42

For the glory of God

§. Introduction

· Aerodynamic heating is defined as the heating of a solid body produced by its high speed through air where its kinetic energy is converted to heat by skin friction on the surface of the object.

· It is most frequently a concern regarding re-entry vehicle and the design of high speed aircraft.

· Aerodynamic heating can become so severe at hypersonic speeds that it is the dominant design consideration for hypersonic vehicle.

· In the history of flight on February 1, 2003


Boston Sunday Globe

Space shuttle Columbia lost on reentry; 7 astronauts dead

⇒ Several of the thermal protection tiles near the leading edge of the left wing had been damaged by debris during the launch. This allowed hot gases to penetrate the surface and destroy the internal wing structure.

§. Drag vs. Aerodynamic heating in hypersonic vehicle design

· In conclusion, at very high velocity, Aerodynamic heating becomes a dominant aspect of hypersonic vehicle design.

· This is why ;

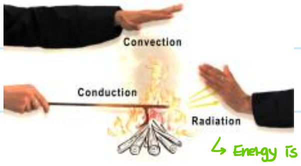
- In terms of Aerodynamic drag, it is proportional to the square of the velocity. i.e. $D = \frac{1}{2}\rho_\infty U_\infty^2 S C_D$
- In terms of Aerodynamic heating, it varies as the cubic of the velocity. i.e. $\dot{q}_w \simeq \frac{1}{2}\rho_\infty U_\infty^3 C_H$

· In order for us to understand the effect of Aerodynamic heating, we may first introduce C_H.

§. Stanton number (C_H)

· In hypersonic flight, we introduces a dimensionless heat transfer coefficient called as Stanton number ;

$$C_H \equiv \frac{\dot{q}_w}{\rho_e u_e (h_{aw} - h_w)} = \frac{\text{Heat conduction}}{\text{Heat convection}}$$



↳ Energy is transferred by Electromagnetic..

; where

ρ_e : Local density at the edge of the BL at the given point

u_e : Local Velocity at the edge of the Boundary Layer

$\dot{q}_w$: Heat transfer rate per unit area at a given point on the body surface, i.e. $\dot{q}_w = -k\frac{dT}{dy}$ by Fourier's law

h_w : Enthalpy of the gas at the wall

h_{aw} : 〃 when the wall temperature is the adiabatic wall temperature

· You may be wondering ;

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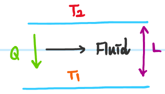
- Why stanton number was introduced even though Nusselt number were already there ?

↳ the ratio of convective to conductive heat transfer normal to the boundary.

- The Nu is usually known as average Nusselt number. For instance,



$$Nu = \frac{h \Delta T}{K \frac{\Delta T}{L-0}} = \frac{hL}{K}$$

; where { h : convective heat transfer coeff. of the flow
K : thermal conductivity of the flow
L : characteristic length

- However, in hypersonic flow, the heat transfer at every point on the boundary surface would be totally different.

∴ The average value would not be a good idea for the hypersonic flow analysis.

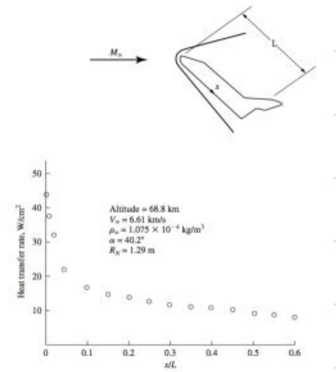


Figure 14.21 Experimental data for the local aerodynamic heating rate along the windward centerline of the space shuttle. Data from Zoby (Reference 102).

· Going back to the effect of Aerodynamic heating, recall that ;

$$\dot{q}_w \simeq \frac{1}{2} \rho_\infty U_\infty^3 C_H$$

- So, where does it come from ?

- Think about the total enthalpy of the freestream : $H_0 = H_\infty + \frac{1}{2} m U_\infty^2$

$$\Leftrightarrow h_0 = h_\infty + \frac{1}{2} U_\infty^2$$

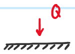
$$\simeq \frac{1}{2} U_\infty^2 \text{ at hypersonic speeds } (\because U_\infty \text{ is very large})$$

- Then,

(e.g. T_{aw} is about 12% less than T_0 in the freestream for high M laminar flow over a flat plate)

$$C_H \equiv \frac{\dot{q}_w}{\rho_e U_e (h_{aw} - h_w)} \simeq \frac{\dot{q}_w}{\rho_e U_e (h_0 - h_w)} \quad ; \; h_{aw} \simeq h_0 \text{ because of } T_{aw} \simeq T_0$$

$$\simeq \frac{\dot{q}_w}{\rho_e U_e h_0} \quad ; \; h_0 >>> h_w$$



; T_w < Melting temperature

(i.e. T_w is usually much smaller than T_0 at high Mach number)

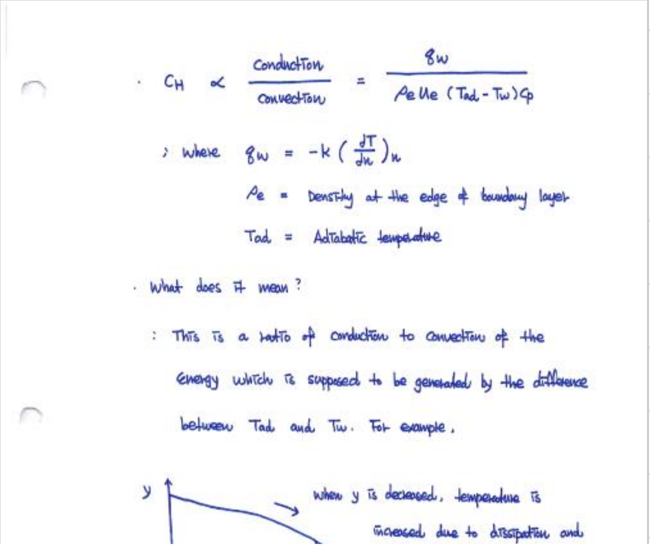
$$\simeq \frac{\dot{q}_w}{\rho_e U_e \frac{1}{2} U_e^2}$$

Hence, $\dot{q}_w \simeq \rho_e U_e^3 \frac{1}{2} C_H$

cf. Aerodynamic heating occurs when ;

$T_\infty < T_w < T_{ad,w}$

∴ Conversion of K.E. to heat via viscous force



· $C_H \propto \frac{\text{Conduction}}{\text{Convection}} = \frac{q_w}{\rho_e U_e (T_{ad} - T_w) C_p}$

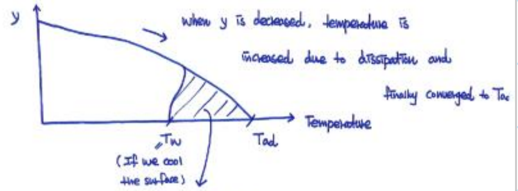
; where $q_w = -k \left(\frac{\partial T}{\partial n} \right)_w$

ρ_e = Density at the edge of boundary layer

T_{ad} = Adiabatic temperature

· What does it mean ?

: This is a ratio of conduction to convection of the energy which is supposed to be generated by the difference between T_{ad} and T_w. For example,



Enthalpy (= energy), $(T_{ad} - T_w) C_p$

When $(T_{ad} - T_w) C_p$ is generated, how much to convection or to conduction. This can be described by Stanton number

§. Blunt vs. Slender bodies in Hypersonic flow

- All successful entry vehicles in practice have utilized rounded noses and rounded leading edge.
- The concept that a blunt body would reduce Aerodynamic heating in comparison to a slender body was first advanced by H. Julian Harvey Allen in 1951.
- According to the Blunt body theory,

cf. Heating to sphere is larger than cylinder (∵ Relieved effect)

$$\dot{q}_w \propto \frac{1}{\sqrt{R}}$$

; where R is the nose radius at the stagnation point

↔ the stagnation point is frequently (but not always) the point of maximum heat transfer rate.

- This implies that ;

To minimize Aerodynamic heating, the vehicle must be a blunt body. (having a blunt nose)

- He proved it mathematically by using similarity solution.
- At the same time, it was experimentally verified