SR555: Heat Transfer in Space Applications

Aerodynamic Heating-I

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Aerodynamic Heating

- **Definition:**
  - Kinetic energy of a space vehicle that is re-entering in the Earth's atmosphere is converted into heat
  - Significant only of velocity > 650 m/s
  - Occurs at stagnation point / line and skin of lifting/non-lifting surfaces

  - **Mechanisms:**
    - friction slows down molecules by shear force
    - chemical reactions occur in the boundary layer

Aerodynamic Heating

- **Effects:**
  - Heat penetrates skin, structure, and interior components
  - Weakening due to changes in crystal structure, melting, vaporization
  - Thermal stresses → additional mechanical stresses → more weight is required to withstand given stress / exotic materials
  - Dissimilar materials in close contact expand at different rate upon heating → unbalanced forces → mechanical stresses

Aerodynamic Heating

- **Definitions of parameters:**
  - **Recovery temperature (T_r):** in case of an insulated object, equilibrium temperature at which the heat transferred out from the inner viscous layer of boundary layer is balanced by the viscous work done on the layers
  - **Slip flow:** flow regime that appears at approximately 60 km altitude after the end of continuum flow regime (45-60 km). Slip flow is followed in turn by intermediate and free molecular flow regimes at even higher altitudes
  - **Stagnation point:** point at which flow comes to a halt (fluid velocity is zero) wrt a body in motion
  - **Static temperature:** unchanging temperature unaffected by heat from viscous shear / dissipation
  - **Transition point:** location on a moving object at which the surrounding fluid ceases to follow the surface, developing eddies and turbulence

Aerodynamic Heating

- **How to know if aerodynamic heating occurs:**
  - **Ground testing facility:** hardware to be tested, computer controlled heating, instrumentation, data acquisition, heat transfer calculations

Aerodynamic Heating

- **How to know if aerodynamic heating occurs:**
  - **Determine test specimen mission profile**
    - Trajectory, velocity, altitude programs as *f* (time)
    - Free-stream parameters: T_∞, P_∞, ρ_∞, M_∞ from standard atmospheric tables
    - body shape, attitude, and above parameters → potential flow parameters T_0, P_0, ρ_0, M_0
    - Local heat transfer coefficient (h) and recovery temperature (T_r) as *f*(time) from potential flow parameters, material properties, and characteristic length

Aerodynamic Heating

- **How to know if aerodynamic heating occurs:**
  - **Further steps**
    - Determine type of testing facility
    - **Determine instrumentation:** high-temperature strain gages, thermocouples, radiation pyrometers
    - Use h = f_1(time) and T_r = f_2(time) and program into computer → net heat inflow into test specimen must be same as in trajectory
    - **Begin tests:**
      - Monitor T_{wall}, surface strain, etc.
      - Record variations from design capabilities by operating onboard equipment during testing
      - Compare test specimen instrument data and test facility instrument data
    - **Inspections:**
      - Surface degradation, creep, fatigues, effects of thermal stresses
      - Operate onboard equipment in cold conditions → note variations from the design capabilities

Aerodynamic Heating

- **Heating methods employed in ground tests for aerodynamic heating:**
  - **Non-convective:** heating with/without application for external loads for a given time duration, cyclic loads (inertial and thermal), programmed heating and loading according to mission profile
    - **Radiant heaters:** quartz lamp (large, 150 btu/sec.ft^2, 450 F/s, Tmax = 3200 F); arc-image furnace (small, 2600 btu/sec ft^2, 8000 F/s, Tmax = 7000 F)
    - **Furnaces:** large (Tmax = 2000 F), small (Tmax = 5000 F)
    - **Electrical resistance heating:** small, 350 btu/sec ft^2, 1500 F, Tmax > melting point
    - **Induction heating:** large (3000 btu/sec ft^2, 9000 F/s, Tmax > melting point); small (25000 btu/sec ft^2, 75000 F/s, Tmax > melting point
    - **Electron beam heaters:** small, >100k btu/sec ft^2, > 300k F/s, Tmax > melting point
    - **Radiant heating is surface heating and closely simulates aerodynamic heating**
    - **Induction heating is NOT surface heating; develops high heating rates and temperatures. Depending on the frequency of heating current and material resistivity, heating is concentrated at a certain depth below the surface**

Aerodynamic Heating

- **Heating methods employed in ground tests for aerodynamic heating:**
  - **Radiant heating tests:**
    - Heat elements with high thermal inertia to constant temperature
    - Change heat flux by programming the distance between test item and heating elements
    - Keep distance between test specimen and radiator as constant
    - Rapidly change heat flux by using heating element of low thermal inertia and programming the power input to elements

Aerodynamic Heating

- **Heating methods employed in ground tests for aerodynamic heating:**
  - **Convective heating methods:**
    - **Useful up to low supersonic flights → true velocity, enthalpy, and heating rate could be simulated**
    - Better than radiant heating
    - **Resistance based tunnels:** small (55 btu/sec ft^2, 550 btu/lb, Tmax (total) = 2200 F)
    - **Ceramic heated tunnels:** small (300 btu/sec ft^2, 1100 btu/lb, Tmax (total) = 4000 F);
    - **Combustion heated tunnels:** large (180 btu/sec ft^2, 1400 btu/lb, Tmax (total) = 4000 F)
    - **Electron arc heating:** small (1000 btu/sec ft^2, 18000 btu/lb, Tmax (total) = 16000 F)

Aerodynamic Heating

- **Example of method for determining thermal environment from a mission profile:**
  - **Boundary layer assumption:** potential flow outside (neglect shear compared to inertia); viscous flow inside (shear and inertia are considered)
  - Assume required angle of attack, locally constant temperature and zero normal pressure gradient: $\partial p / \partial y = 0$
  - Use standard atmospheric tables: T_∞, P_∞, ρ_∞
  - Use trajectory / flight path coordinates and obtain h_∞ and V_∞

$$M_\infty = \frac{V_\infty}{\alpha_\infty} = \frac{V_\infty}{\sqrt{M_g R T_\infty}} \qquad \rho_\infty = \frac{P_\infty}{R_{sp,\infty} T_\infty}$$

Contd. …

Aerodynamic Heating

- **Example of method for determining thermal environment from a mission profile:**
  - **Obtain potential flow solutions:**
    - **Shapes:** cones, ogives, arbitrary shapes
    - **Methods:** CFD, Taylor-McCall equations, method of characteristics, conical shock expansion method
    - Solution for M_0, V_0, T_0, P_0, ρ_0 for each location on the body as a function of time t (0: outside boundary layer)
    - Compute Re_0 ($\mathrm{Re}_0 = (\rho_0 V_0 l_c)/\mu_0$), where μ_0 is obtained using Sutherland equations
    - Determine if the boundary layer is laminar or turbulent ($Re_0 > 10^6$)

Contd. …

Aerodynamic Heating

- **Example of method for determining thermal environment from a mission profile:**
  - **Calculations for skin temperature:**
    - **Local heat transfer rate into/out of a surface element:**

$$q_{local} = q_W + \cancel{q_E} + \cancel{q_N} - q_R$$

q_W: Aerodynamic heating

q_E: Internal heat generation

q_N: Solar radiation

q_R: Radiation from boundary layer and skin

$$\therefore q_{local} = q_W - q_R = h(T_r - T_W) - \varepsilon\sigma T_W^4$$

T_r: gas temperature in boundary layer on skin surface when convective heat transfer is zero

Contd. …

Aerodynamic Heating

- **Example of method for determining thermal environment from a mission profile:**
  - **Calculations for skin temperature:**
    - **Local heat transfer rate into/out of a surface element:**

Also, $\therefore q_{local} = C_{skin} t_{skin} \rho_{skin} \dfrac{dT_w}{dt}$

$$\therefore \frac{dT_w}{dt} = \frac{h}{t_{skin} C_{skin} \rho_{skin}} \left(T_r - T_w\right) - \frac{\varepsilon \sigma T_w^4}{t_{skin} C_{skin} \rho_{skin}}$$

Applies to laminar / turbulent boundary layer

Heat absorption capacity of skin

- h is determined using relations specific to laminar or turbulent boundary layers

Contd. …

Aerodynamic Heating

- **Example of method for determining thermal environment from a mission profile:**
  - **Calculations for skin temperature:**
    - **Solution of equation** $\frac{dT_w}{dt} = \frac{h}{t_{skin} C_{skin} \rho_{skin}} (T_r - T_w) - \frac{\varepsilon \sigma T_w^4}{t_{skin} C_{skin} \rho_{skin}}$

Assumptions:

--radiation loss is small

--short-duration, high-speed flight

--skin temperature reaches equilibrium

$$\therefore \frac{dT_w}{dt} = 0 \longrightarrow \therefore \varepsilon \sigma T_{w,e}^4 = h(T_r - T_w) \longrightarrow \because LHS \to 0 \longrightarrow \therefore T_r = T_{w,e}$$

Aerodynamic Heating

- **Example of method for determining thermal environment from a mission profile:**
  - **Calculations for skin temperature:**
    - **Solution of equation** $\frac{dT_w}{dt} = \frac{h}{t_{skin}C_{skin}\rho_{skin}}(T_r - T_w) - \frac{\varepsilon\sigma T_w^4}{t_{skin}C_{skin}\rho_{skin}}$

Difficulties:
--we do not know how T_r behaves
-Or
-when radiation loss is significant

Need to measure h

Need to model behavior of T_r

Aerodynamic Heating

- **Example of method for determining thermal environment from a mission profile:**
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    - **Solution of equation** $\frac{dT_w}{dt} = \frac{h}{t_{skin} C_{skin} \rho_{skin}} (T_r - T_w) - \frac{\varepsilon \sigma T_w^4}{t_{skin} C_{skin} \rho_{skin}}$

Measurement of h:

--take nose cone of missile as an example

-Use cones of different vertex angles; measure T_r and h in supersonic wind tunnel

↓

Use empirical equations

↓

h

Aerodynamic Heating

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Modeling for T_r:

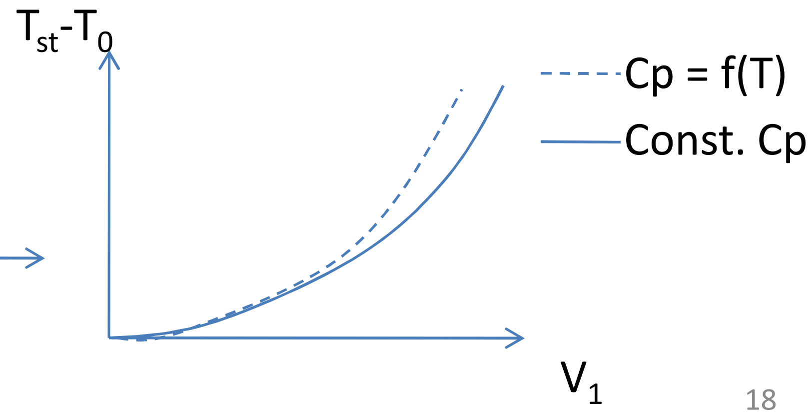
--use measurements of T_r

--isentropically stagnant air at the tip of nose cone has T_{st} (stagnation temperature)

$$\int_{V_1}^{0} V dV + \int_{T_0}^{T_{st}} J \rho C_p dT = 0$$

(Bernoulli equation)

$$\therefore T_{st} - T_0 = \frac{1}{2} \frac{V_1^2}{J \rho C_p}$$



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  - **Calculations for skin temperature:**
    - **Solution of equation** $\frac{dT_w}{dt} = \frac{h}{t_{skin} C_{skin} \rho_{skin}} (T_r - T_w) - \frac{\varepsilon \sigma T_w^4}{t_{skin} C_{skin} \rho_{skin}}$

Modeling for T_r:

--use measurements of T_r

--isentropically stagnant air at the tip of nose cone has T_{st} (stagnation temperature)

$\int_{V_1}^{0} V dV + \int_{T_0}^{T_{st}} J \rho C_p dT = 0$ (Bernoulli equation) $\longrightarrow \therefore -\int_{V_1}^{0} V dV = \int_{T_0}^{T_{st}} J \rho C_p dT \longrightarrow \therefore \frac{V_1^2}{2} = J \rho \int_{T_0}^{T_{st}} C_p dT$

Define c, recovery factor: $c = \frac{T_r - T_0}{T_{st} - T_0} \longrightarrow (T_r - T_0) \propto (T_{st} - T_0)$