Thermodynamics Final Report

ES – 305 R. Rodriguez

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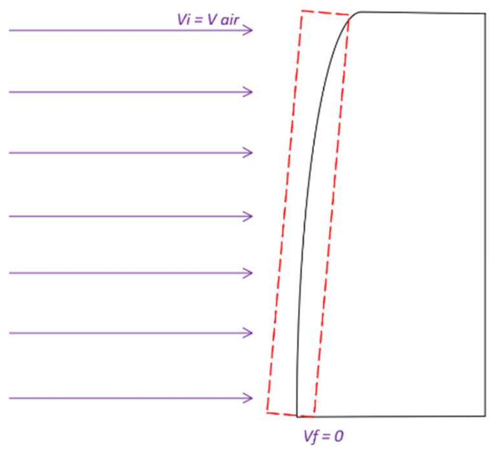
Adiabatic Wall Temperature:

Known: A F-22 is flying at a Mach number of 2.2 at an altitude of 30,000 feet above sea level. Consider the aircraft's external air temperature and velocity relative to the still air in this scenario.

Find: Determine the air temperature on the surface of a stationary object on the aircraft door where the air is considered stagnant due to boundary layer effects.

Schematic:



Properties:

State 1; Air	
$T_{alt} = 59 - (.00356620 \cdot 30000\ ft) = -47.9°F = 412.1°R$	❶
$P_{alt} = (14.969\ psia)(1 - (6.8754 \cdot 10^{-6} \cdot z)^{5.2559} \cong 14.969\ psia$	❷
$h_1 = 98.41\ Btu/lbm$	❸

Assumptions: The air will be stagnant on the outside of the door, steady state, streamline flow, neglect changes in potential energy, no additional work or heat is added to the system, air acts as an ideal gas, isentropic.

Solution:

$$mach = \frac{V}{\sqrt{KRT}} \rightarrow V_{air} = mach \cdot \sqrt{KRT}$$ ❹

$$V_{air} = (2.2)(\sqrt{(1.4)\left(\frac{1545}{28.96} \cdot \frac{ft \cdot lbf}{lbmol\ °R}\right)(412.1°R)\left(32.2\frac{ft}{s}\right)} = 2190.18\ ft/s$$

$$\frac{dE_{cv}}{dt} = \dot{Q} - \dot{W} + \dot{m}\left[h_1 - h_2 + \frac{v^2{}_1 + v^2{}_2}{2} + g(z_1 - z_2)\right]$$ ❺

$$h_2 = h_1 + \frac{v_1{}^2}{2} = \left(98.41\frac{Btu}{lb}\right) + \left(\frac{(2190.18)^2\frac{ft^2}{s^2}}{2}\right)\left(\frac{lbf}{\left(32.2lbm \cdot \frac{ft}{s^2}\right)}\right)\left(\frac{1Btu}{778lbf \cdot ft}\right)$$

$$h_2 = 194.15\frac{Btu}{lbm} \rightarrow T = 809.59\ °F$$ ❸

Comments: While this analysis assumes the air at the aircraft surface is fully stagnant due to boundary layer effects, in reality, the boundary layer may retain some motion, and turbulence or surface roughness could prevent complete conversion of kinetic energy into internal energy.

The assumption of steady-state flow eliminates the possibility of transient effects, such as those caused by changes in altitude, speed, or flight maneuvering, which can significantly impact local temperature and pressure. Treating the flow as isentropic neglects the presence of shock waves, which are likely at Mach 2.2 and would increase entropy, thereby reducing the actual stagnation temperature relative to ideal predictions.

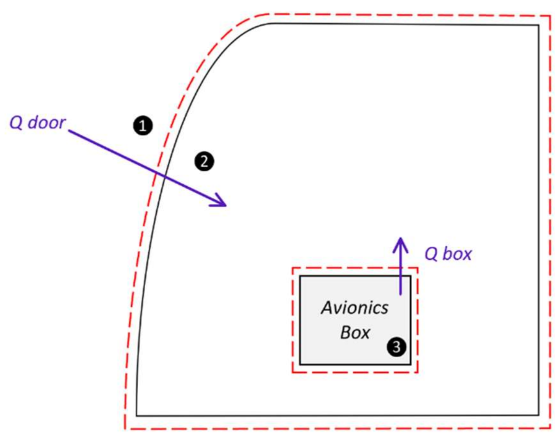
Total Heat Transfer:

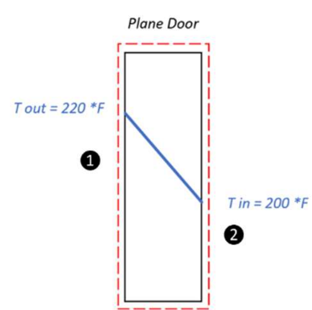
Known: A sealed and well-insulated compartment is exposed to two internal sources of heat: conduction through an aluminum door and electrical power dissipation from an internal electronic box. The door is constructed from Aluminum 6061-T6, with a uniform thickness of 0.25 inches and a surface area of 638.1 in^2. The outside surface of the door is exposed to an external temperature of 220°F, while the interior surface is at 200°F. The electronic box operates at a current of 15.5 amps and a voltage of 28 volts.

Find: The total heat transfer to the compartment.

Assumptions: Uniform material and thickness, linear temperature gradient across the width of the door, 100% efficiency of electrical energy to heat, well insulated compartment

Schematic:





Properties:

State 1; Al 6061-T6	State 2; Al 6061-T6	State 3; Box
$T_{out} = 220°F$ $k = 96.51 \frac{Btu}{ft \cdot hr \cdot °F}$ 6	$T_{in} = 200°F$ $k = 96.51 \dfrac{Btu}{ft \cdot hr \cdot °F}$	$I = 15.5\ amps$ $V = 28\ volts$ $\eta_{th} = 1.00$

Solution:

$$Q_{door} = -kA\frac{dt}{dx} = -kA\Delta T$$ ❼

$$Q_{door} = -\left(96.51\frac{Btu}{ft\cdot hr\cdot {}^\circ F}\right)(638.1\ in)\left(\frac{1\ ft}{144in^2}\right)\left(\frac{(200-220)^\circ F}{(.25in)\left(\frac{1ft}{12in}\right)}\right)$$

$$Q_{door} = 410553.54\frac{Btu}{hr}$$

$$Q_{box} = \dot{W} = P = IV$$ ❽

$$Q_{box} = (15.5\ amps)(28\ volts) = 434\ watts$$

$$Q_{box} = (434\ watts)\left(\frac{1\frac{Btu}{hr}}{3.14\ watts}\right) = 1481.7\frac{Btu}{hr}$$

$$Q_{tot} = Q_{door} + Q_{box}$$

$$Q_{tot} = (410553.54 + 1481.7)\frac{Btu}{hr}$$

$$Q_{tot} = 412035.24\ Btu/hr$$

Comments: While this analysis assumes the door and the electrical box are the only sources of heat within the compartment, in reality, there could be additional contributions such as radiation from external surfaces, minor air leakage, or heat generation from other electronic components.

The assumption of linear temperature distribution across the door simplifies the conduction equation and allows for direct use of Fourier's Law in one dimension. However, this overlooks potential temperature variations due to non-uniform material properties, temperature-dependent conductivity, or localized hot spots on the door caused by uneven external exposure (e.g., sunlight or aerodynamic heating).

The assumption of perfect insulation eliminates any losses to the surrounding environment. In practical applications, even well-insulated systems experience some degree of heat leakage, especially through seams, fasteners, or mounting points, which could affect the internal energy balance over time.

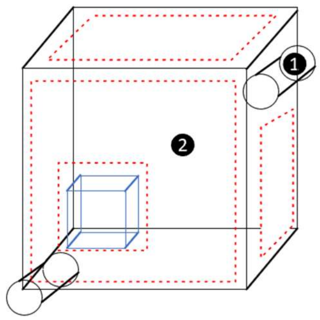
Lastly, assuming that all electrical power from the box is converted into heat may slightly overestimate its thermal contribution, as some energy could be used for light, motion, or stored in capacitors, depending on the box's function.

Pipe Diameter and Mass Flow Calculations:

Known: The air in the compartment has to be maintained at 160*F and 15 psig.

Assumptions: Steady state, no additional work on the system, well insulated, neglect changes in potential and kinetic energy, incompressible flow.

Schematic:



Properties:

State 1; Air	State 2; Air
T = 40*F P = 15 psig = 19.7 psia h = 119.48 Btu/lb	T = 160*F = 620*F P = 15 psig = 19.7 psia h = 148.28 Btu/lb

Solution:

$$Mach = \frac{V}{V_s} \rightarrow V = mach \cdot V_s = (.2)\left(1096\frac{ft}{s}\right) = 219.2\frac{ft}{s}$$ 4

$$\rho = \frac{P}{R{\cdot}T} = \frac{(19.7psia)\,(144in^2)}{\left(\frac{1545}{28.96}\right)\frac{ft{\cdot}lbf}{lbmol\,°R}{\cdot}(500°R)} = .1063\frac{lbm}{ft^3}$$ 9

$$\frac{dE_{cv}}{dt} = \dot{Q} - \dot{W} + \dot{m}\left[h_1 - h_2 + \frac{v^2{}_1 + v^2{}_2}{2} + g(z_1 - z_2)\right]$$ 5

$$\dot{m} = -\frac{\dot{Q}}{h_1 - h_2} = -\frac{(412035.24)\frac{Btu}{hr}}{(119.48 - 148.28)\frac{Btu}{lbm}} = 14306\frac{lbm}{hr} = 3.974\frac{lbm}{s}$$

$$\dot{m} = \rho AV \rightarrow A = \frac{\dot{m}}{\rho V} = \frac{(3.974)\frac{lb}{s}}{\left(.10634\frac{lbm}{ft^3}\right)(219\frac{ft}{s})} = .1706\,ft^2$$

Additional Calculations:

$$d_i = \sqrt{\frac{4A}{\pi}} = .466\,ft \cong 5.5\,in$$

$$A = .1706\,ft^2 \cdot \frac{144in^2}{1\,ft^2} = 24.56\,in^2$$
$$A_{hole} = \frac{A}{\#\,of\,holes} = \frac{24.56}{4} = 6.14\,in^2$$

$$d_{hole} = \sqrt{\frac{A_{hole} \cdot 4}{\pi}} = \sqrt{\frac{6.14 \cdot 4}{\pi}} \cong 2.75\,in$$

Comments: Since the flow is assumed to incompressible you can solve for the velocity of the air flowing into the compartment by using a Mach number of .2. The density variation at this level would be relatively negligible.

Using the First Law of Thermodynamics and the assumptions made you can solve the conservation of energy equation for an open system for mass flow. Relating this equation to the mass flow equation of volumetric flow rate times density you can solve for the area of the pipe.

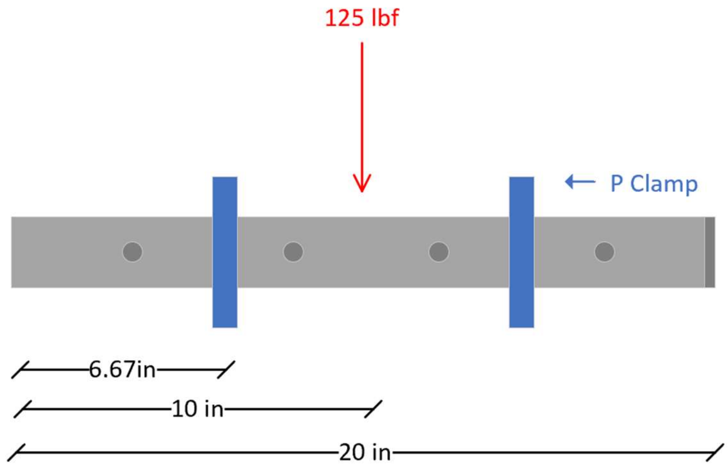
If you reduce the size of each pipe outlet but increase the number of outlets, the total combined area of all outlets must stay the same to maintain the same flow rate. This ensures the system can handle the same volume of fluid.

Pipe Properties:

Known: The pipe is required to support a 125lbf, 10 inches from the wall. There are P-Clamps 1/3 and 2/3 the length of the pipe. The cap on the end of the pipe is welded together.

Find: Required supports, safety factor, and outside diameter.

Schematic:



Assumptions: Material is consistent, clamps are identical

Properties:

Pipe ; Aluminum 6061-T6
$\sigma_y = 40000\ psi$ ⓾ $d_i = 5.5\ in.$ $d_o = 5.6\ in.$ $t_w = .05\ in.$

Solution:

$M = F\ x\ d = (125\ lbf)(3.33) = 412.25\ lbf \cdot in$ ⓫

$I = \frac{\pi({d_o}^4 - {d_i}^4)}{64} = \frac{\pi(5.6^4 - 5.5^4)}{64} = 3.36\ in^4$ ⓬

$\sigma = \frac{M \cdot c}{I} = \frac{(412.25 lbf \cdot in)\cdot(2.8\ in)}{3.36\ in^4} = 346.9\ lbf/in^2$ ⓭

$SF = \frac{\sigma_y}{\sigma_a} = \frac{40000\ psi}{346.9\ psi} = 115.3$

Additional Diagrams:

Fig 1.1

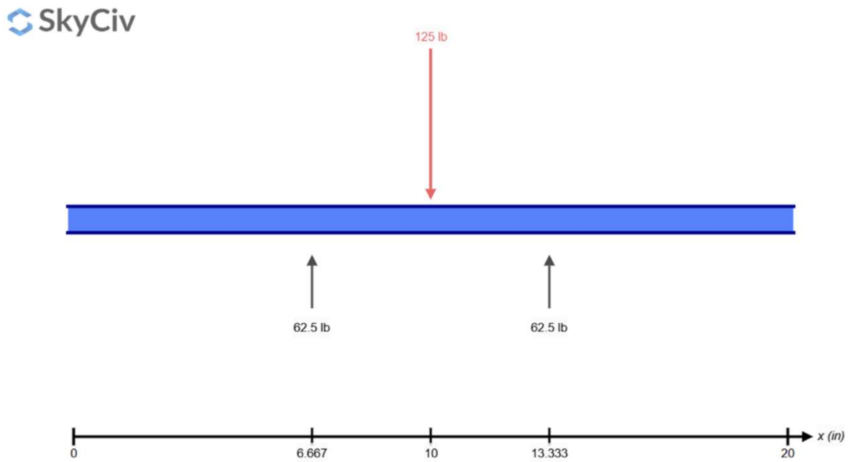


Fig 1.2

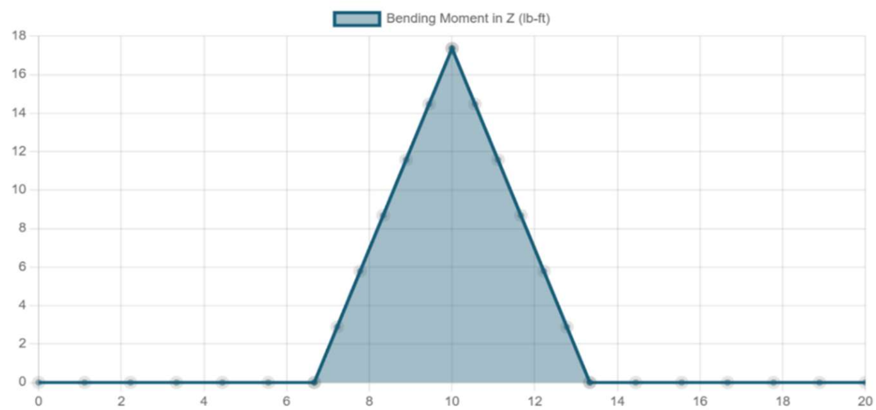
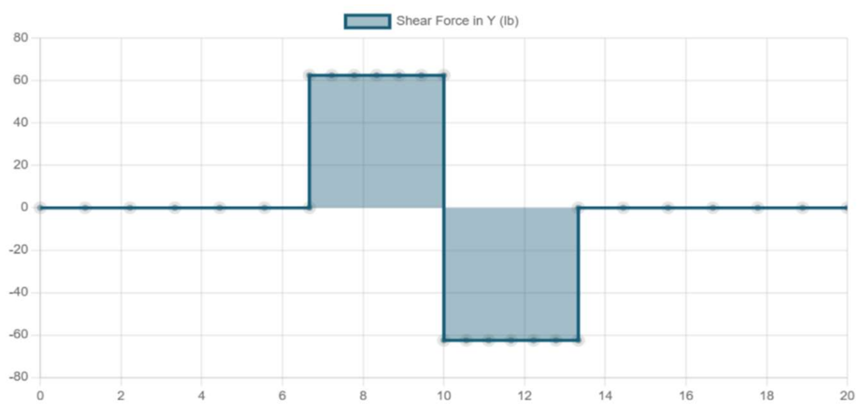


Fig 1.3



Comments: To minimize deflection under load, the hanging pipe is supported by two P-clamps spaced at one-third intervals along its total length. The pipe extends 20 inches from the wall, with the first clamp positioned 6.67 inches from the wall and the second clamp placed another 6.67 inches further along the pipe. This evenly distributed support helps prevent excessive bending and reduces the risk of the pipe exceeding its yield strength.

While a large safety factor like 115.3 guarantees a very safe design, it may not always be necessary for all applications. Aerospace engineers need to balance safety with efficiency, cost, and weight. A more typical safety factor, likely between 1.5 and 3, would suffice for most structural components, unless the design specifically requires additional reliability due to critical, high-risk factors. It’s important to evaluate the trade-offs and adjust the safety factor according to the performance requirements and operating conditions of the system.

Conclusion: This project applied core principles of thermodynamics to analyze the thermal and fluid behavior in a compartment system in an F-22 aircraft. Through a series of structured calculations and justified assumptions, we determined the adiabatic wall temperature experienced by a stationary surface at Mach 2.2 to be approximately 809.6°F, accounting for energy conversion from high-speed airflow. We then evaluated the total heat transfer into a sealed compartment due to both conduction through an aluminum door and internal electrical dissipation, yielding a combined heat input of over 412,000 BTU/hr.

To maintain desired internal conditions of 160°F and 15 psig, we analyzed the necessary air mass flow rate and inlet area. The resulting design called for multiple airflow holes, each approximately 2.75 inches in diameter, ensuring steady-state temperature regulation. Lastly, structural integrity of the pipe system used for airflow distribution was validated using mechanical stress analysis. The calculated safety factor of 115.3 confirmed the aluminum pipe’s suitability for the load conditions, emphasizing both reliability and overdesign margin.

Overall, this analysis highlights the importance of integrating thermodynamic and structural considerations in aerospace systems design. Realistic assumptions, while simplifying complex systems, also illustrate the need for careful interpretation of results, especially under extreme conditions such as supersonic flight. The methods and findings in this report offer a practical framework for future thermal management and structural planning in high-performance aircraft environments.

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Figure 1.1 – 1.3 SkyCiv. (n.d.). *SkyCiv structural analysis software*. SkyCiv Engineering. : Moment and Shear Diagrams