IPRO 304-A: Compact Climatization Units for Automotive Applications

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Introduction & Background

- On a hot, sunny day, cars can become unbearably hot.
- The temperature increases due to solar radiation.
- This radiation can be used as an energy source to cool the car.
Defining the System

**Surroundings:**
- Temperature: 100 °F
- Pressure: atmospheric

**Car:**
- Temperature: 120 °F
- Pressure: atmospheric
- $T_{\text{desired}} = 90 \, ^\circ\text{F}$
Calculation of Heat load

- $P_{(atm)} = 1.00 \text{ atm}$
- $n = \frac{PV}{RT} = 108 \text{ moles air}$
- $\rho = \frac{MWn}{V} = 1.10 \text{ kg/m}^3$
- $m = MW*n = 3.13 \text{ kg air}$
- $Q_{HL} = mC_p(T_{\text{CAR}} - T_{\text{DESIRED}}) = 52 \text{ kJ}$
Solar Radiation

- **Insolation**
  - Variables: S, Zenith angle (Z), Latitude (Φ), Hour angle (H), Solar declination angle (δ)

- **Radiation heat load**
  - Variables: Angle from horizontal (θ), Emissivity (ε)

<table>
<thead>
<tr>
<th>Φ</th>
<th>δ</th>
<th>Time</th>
<th>H</th>
<th>Z</th>
<th>I (W/m²)</th>
<th>Description</th>
<th>I_{window} (45° from horizontal)</th>
<th>Radiation (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>33.4</td>
<td>23.5</td>
<td>8</td>
<td>-60.0</td>
<td>53.0</td>
<td>602</td>
<td>Phoenix, summer, 8am</td>
<td>426</td>
<td>400</td>
</tr>
<tr>
<td>33.4</td>
<td>23.5</td>
<td>12</td>
<td>0.0</td>
<td>9.9</td>
<td>985</td>
<td>Phoenix, summer, noon</td>
<td>697</td>
<td>655</td>
</tr>
<tr>
<td>33.4</td>
<td>23.5</td>
<td>17</td>
<td>75.0</td>
<td>65.3</td>
<td>418</td>
<td>Phoenix, summer, 5pm</td>
<td>295</td>
<td>278</td>
</tr>
</tbody>
</table>
Power System

- Solar Panel
  - Black body radiation
    - Windshield has a non-unit emissivity.
  - Aesthetics

- Battery (to regulate the solar panel)
  - Primary
  - Secondary
Power System: Description

- Solar radiation is variable
- Average power is 150 Watts
- Choices
  - NiCd, NiZn, Lead Acid, Li+
  - Memory Effect
  - Operating Temperature
Power System: Batteries

- What are they used for?
  - To power the compressor or freezer
- What is the voltage?
  - Approximately 12V
- For how long can the battery run?
  - 4 hours
- What is the current needed?
  - \[ I = \frac{P}{V} \Rightarrow \frac{150 \text{ Watts}}{12 \text{ Volts}} = 12.5 \text{ A} \]
  - \[ 12.5 \text{ A} \times 4 \text{ hr} = 50 \text{ Amp-hr} \]
Power System: Battery Choice

- **NiZn**
  - No Memory Effect
  - High Energy Density
    - 60 to 80 W h/kg
  - High Cycle Life
    - 500
  - Reasonable Cost
    - $30/cell
Available Space

- This image represents the basic frame that is available for the refrigeration / heat pipe systems.
- Note the positioning of the cooling chest and the compressor in the trunk of the car.
- This is an isometric view from the rear driver’s side of the car.
Strategy 1: Refrigeration Cycle
Refrigeration: Description

- Refrigerant: Ethyl chloride
- Pressure in and out of evaporator: 1.361 atm
- Vapor pressure of Ethyl chloride @68.31°F is 1.36 atm
Refrigeration: Description

- Heat load absorbed into evaporator in 15 min.: 735.1 Watts (44.11 KJ)
- Compressor work: 150.0 Watts
- Pressure out of compressor: 4.590 atm
- Temp into condenser: 187.5 °F
- Temp out of condenser: 140.0 °F
Refrigeration: System Layout

- Compressor
- ¼” Steel tubing
- Evaporator
- Condenser
- Compressor
Refrigeration: Specs

- **Evaporator:**
  - \( T_{\text{IN}} = 68.313 \) F
  - \( T_{\text{OUT}} = 68.314 \) F
  - Heat Duty = 735.1 W

- **Condenser:**
  - \( T_{\text{IN}} = 187.5 \) F
  - \( T_{\text{OUT}} = 140 \) F
  - Heat Duty = 885.1 W
Refrigeration: Heat transfer area

- $\Delta T_{LM} = (T_2 - T_1)/\ln(T_2/T_1)$
  - $\Delta T_{LM, EVAP} = 293.3242 \, K$
  - $\Delta T_{LM, COND} = 346.1768 \, K$

- $Q = U*A*\Delta T_{LM}$
- Heat Transfer Coefficient = 2.8 W/m$^2$*K
  - (Minimum value for still air)

- $A_{EVAP} = Q_{EVAP}/U*\Delta T_{LM, EVAP} = 0.895 \, m^2$
- $A_{COND} = Q_{COND}/U*\Delta T_{LM, COND} = 0.913 \, m^2$
Length of Steel Tubing

- \( V = \pi r^2L \)
- \( V_{\text{TOTAL}} = 2.02 \text{ liters Ethyl Chloride} \)
- \( A = 2\pi rL \)
- \( L_{\text{EVAP}} = 26.86 \text{ m} \)
- \( L_{\text{COND}} = 27.95 \text{ m} \)
- \( L_{\text{STRAIGHT}} = 8 \text{ m} \)
- Total Length of 0.21 inch Radius Tubing \( \cong 63 \text{ m} \)
## Refrigeration: Costing

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Size Range</th>
<th>Capacity Unit</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressor</td>
<td>150</td>
<td>Watts</td>
<td>$119.15</td>
</tr>
<tr>
<td>Valve</td>
<td>0.02</td>
<td>meters</td>
<td>$6.50</td>
</tr>
<tr>
<td>Solar Panel</td>
<td>150</td>
<td>Watts</td>
<td>$700.00</td>
</tr>
<tr>
<td>Ni-Zn Battery</td>
<td>12 x 2</td>
<td>Volts</td>
<td>$400.00</td>
</tr>
<tr>
<td>Stainless steel tube</td>
<td>63</td>
<td>meters</td>
<td>$339.00</td>
</tr>
<tr>
<td>Ethyl Chloride</td>
<td>2000</td>
<td>Grams</td>
<td>$141.50</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>$1706.15</strong></td>
</tr>
</tbody>
</table>
Refrigeration: Safety

- Ethyl Chloride:
  - Toxicity Levels: 30,000 μg/m³
  - Effects: Simple asphyxiant; anesthetic effect in high concentrations; forms toxic substances upon heating of combustion.
  - Corrosive in moist conditions; need to use stainless steel material.
Heat Pipes

Condenser
$T_{\text{cond}} = 83^\circ\text{F}$

Adiabatic Region

Evaporator
$T_{\text{evap}} = 40^\circ\text{F}$

Wick
Heat Pipes: Cooling Source

- Cooling/freezing ability from 40°F to 0°F
- Inside Dimensions: L 13.75" x W 7.5" x H 7.5"
- Power consumption: 0.9 - 3.9 Amps on a 12-Volt DC adapter
Heat Pipes: Cooling Source

- Power consumption: 3.0 Amps in refrigerator 12Volt AC adapter
- Cooling/freezing ability from 75°F to 25°F
- Self-contained and sealed against the environment
- Inside Dimensions: L 8.7" x W 5.3" x H 2.6"
Heat pipes: Working fluid

- Key properties
  - High latent heat
  - High surface tension

- Possible fluids

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Boiling point at 1 atm (°C)</th>
<th>Surface tension, $\sigma$, at 50 °C (N/m)</th>
<th>Liquid density, $\rho$, at 50 °C (kg/m³)</th>
<th>Liquid viscosity, $\mu$, at 50 °C (cP)</th>
<th>Latent heat, $L$, at 50 °C (kJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-11 (CCl$_3$F)</td>
<td>24</td>
<td>0.0153</td>
<td>1414</td>
<td>0.35</td>
<td>172</td>
</tr>
<tr>
<td>Pentane (n-C$_5$)</td>
<td>28</td>
<td>0.0127</td>
<td>596.0</td>
<td>0.187</td>
<td>348.9</td>
</tr>
</tbody>
</table>
Heat pipes: Wick material

- Pore size vs. permeability

<table>
<thead>
<tr>
<th>Wick material and mesh size</th>
<th>Pore radius, r (mm)</th>
<th>Wire diameter, d_w (mm)</th>
<th>Porosity, ε (%)</th>
<th>Permeability, K (m^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless steel, 403 mesh</td>
<td>0.019</td>
<td>0.025</td>
<td>36</td>
<td>1.9 × 10^{-11}</td>
</tr>
<tr>
<td>Stainless steel, 101.6 mesh</td>
<td>0.08</td>
<td>0.09</td>
<td>41</td>
<td>4.3 × 10^{-10}</td>
</tr>
<tr>
<td>Copper powder, sintered, 45-56m</td>
<td>0.009</td>
<td></td>
<td>52</td>
<td>1.74 × 10^{-12}</td>
</tr>
</tbody>
</table>
Heat pipes: Heat flow

- From pressure balance, \((\Delta P_c)_{\text{max}} = \Delta P_l + \Delta P_g\)
- Mass flow rate,
  \[ m = \rho \bar{A}_w \frac{K}{\mu} l_{\text{eff}} \left( 2\sigma /r - \rho gl_{\text{eff}} \sin \phi \right) \]
- Heat flow = mass flow * Latent heat

<table>
<thead>
<tr>
<th>Description</th>
<th>m (kg/s)</th>
<th>Q (W)</th>
<th>W/1.5m²</th>
<th>Total W</th>
<th>Layers</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 layers 400 ss wick, ga, 45°</td>
<td>2.9E-06</td>
<td>1.05</td>
<td>157</td>
<td>471</td>
<td>3</td>
</tr>
<tr>
<td>6 layers 400 ss wick, ga, 45°</td>
<td>4.3E-06</td>
<td>1.57</td>
<td>236</td>
<td>707</td>
<td>3</td>
</tr>
<tr>
<td>8 layers 400 ss wick, ga, 45°</td>
<td>5.8E-06</td>
<td>2.09</td>
<td>314</td>
<td>628</td>
<td>2</td>
</tr>
<tr>
<td>10 layers 400 ss wick, ga, 45°</td>
<td>8.7E-06</td>
<td>3.14</td>
<td>471</td>
<td>943</td>
<td>2</td>
</tr>
</tbody>
</table>
Placement of Heat pipes
# Heat Pipes: Costing

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Size Range</th>
<th>Capacity Unit</th>
<th>Number</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum pipe</td>
<td>0.4 meters</td>
<td>meters</td>
<td>300</td>
<td>$1594.49</td>
</tr>
<tr>
<td>Stainless steel Mesh</td>
<td>0.915 x 30.49 meters</td>
<td>meters</td>
<td></td>
<td>$7.00</td>
</tr>
<tr>
<td>n-pentane</td>
<td>0.00379 m³</td>
<td>m³</td>
<td></td>
<td>$50.00</td>
</tr>
<tr>
<td>Cooler</td>
<td>0.22 x 0.134 x 0.066 m</td>
<td>m</td>
<td>1</td>
<td>$400.00</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>$2051.49</strong></td>
</tr>
</tbody>
</table>
Heat Pipes: Safety

- n-Pentane
  - Extremely flammable liquid and vapor
  - Vapor may cause flash fire
  - Harmful or fatal if swallowed or inhaled
  - Affects central nervous system
  - Causes irritation to skin, eyes and respiratory tract
  - Toxicity in 8-Hour Time Weighted Average (TWA), 1000 ppm
Results and Conclusions

- In the refrigeration system, 735.1 Watts of heat is being extracted while only 655 Watts are coming into the car.
- It is possible to design the heat pipe system to match the heat load. It would require 300 – 400 heat pipes of ~ 2 Watts each.
- Both systems are feasible but not cost efficient.
Recommendations

- Find a Better Refrigerant.
- Find a Less Expensive Battery.
- Better Integration of the Refrigeration Cycle in the Car’s Frame.
- Further optimize the heat pipe system.