IPRO 304-A: Compact Climatization Units for Automotive Applications

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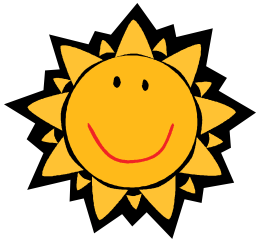
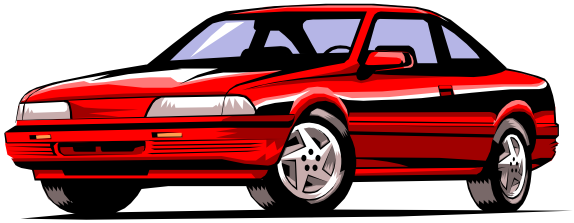
Introduction & Background

- 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 ºF

Pressure: atmospheric

Car:

Temperature: 120 °F

Pressure: atmospheric

$T_{DESIRED} = 90\ °F$

Calculation of Heat load

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

Φ	δ	Time	H	Z	I (W/m^2)	Description	I_{window} (45º from horizontal)	Radiation (W/m^2)
33.4	23.5	8	-60.0	53.0	602	Phoenix, summer, 8am	426	400
33.4	23.5	12	0.0	9.9	985	Phoenix, summer, noon	697	655
33.4	23.5	17	75.0	65.3	418	Phoenix, summer, 5pm	295	278

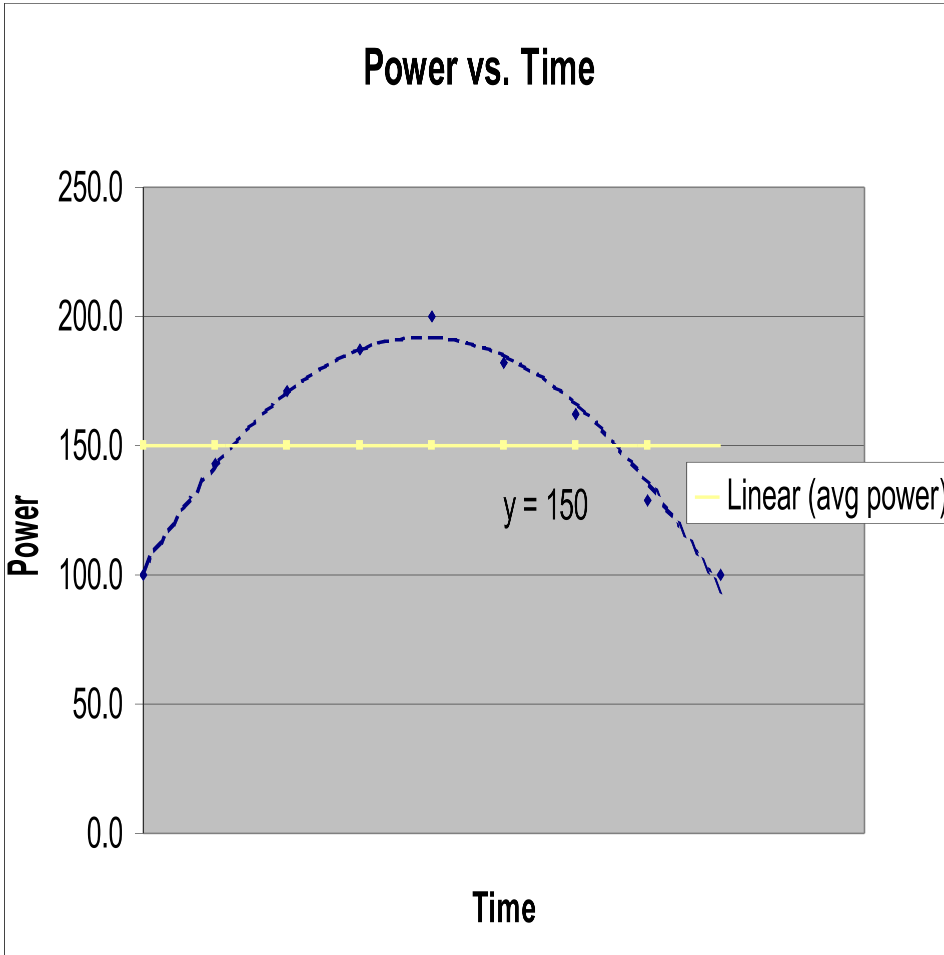
Power System

- 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



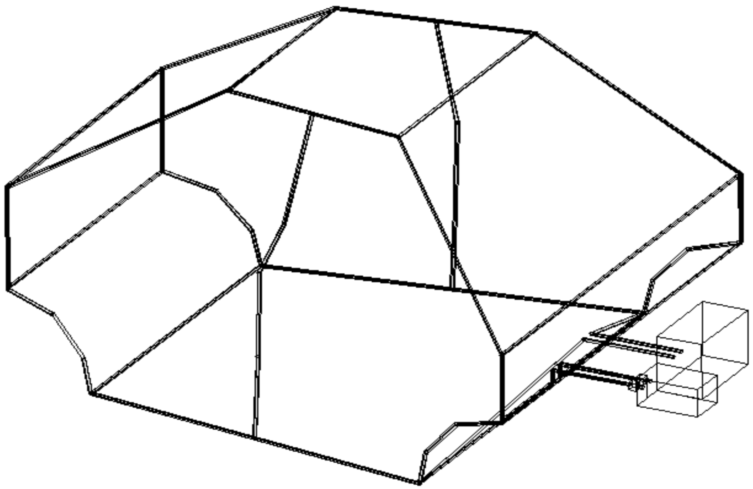
Power System: Batteries

- 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?
  - $I = P/V$ ➔ 150 Watts / 12 Volts = 12.5 A
  - 12.5 A x 4 hr = 50 Amp-hr

Power System: Battery Choice

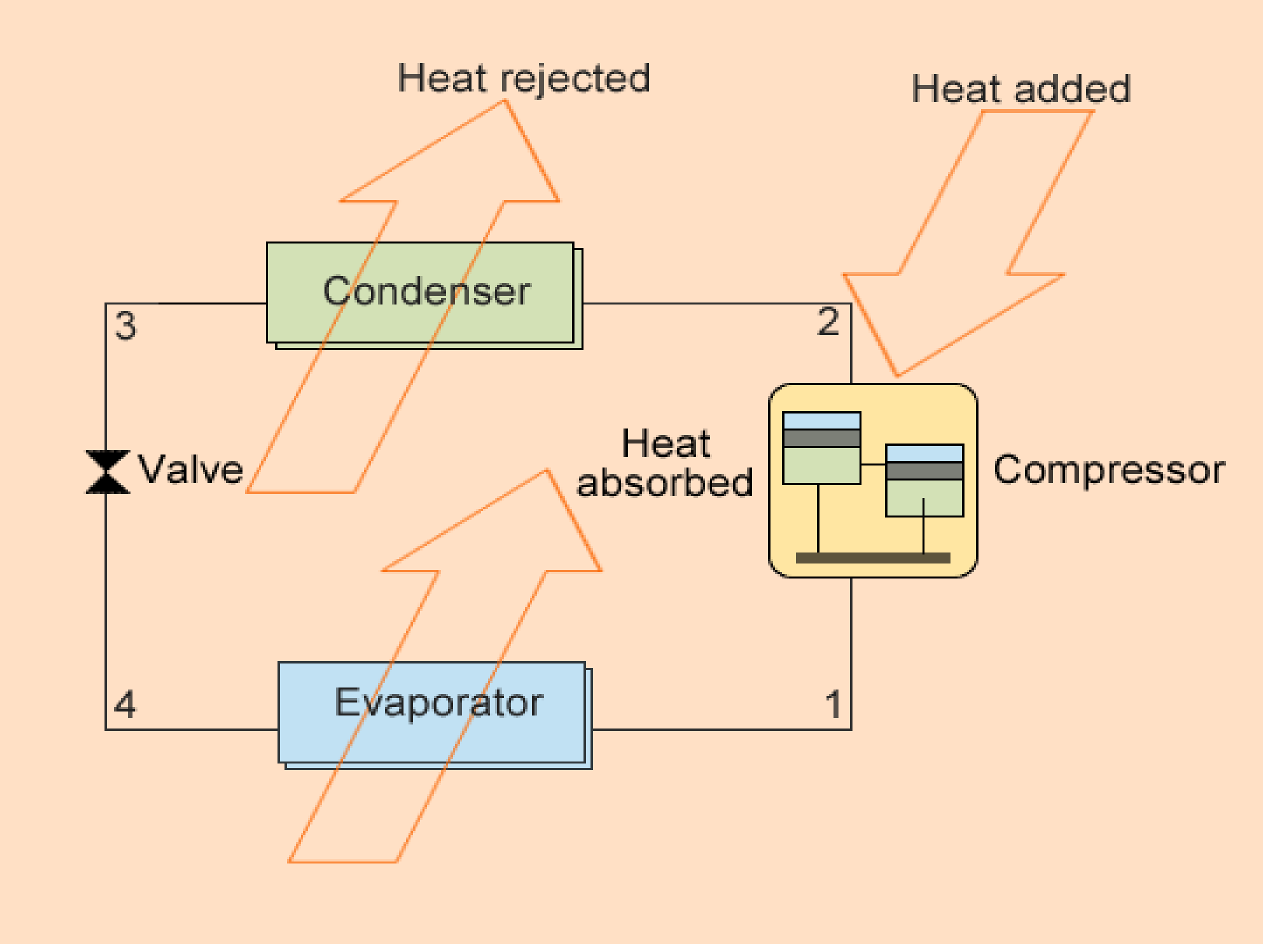
- NiZn
  - No Memory Effect
  - High Energy Density
    - 60 to 80 W h/kg
  - High Cycle Life
    - 500
  - Reasonable Cost
    - $30/cell

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



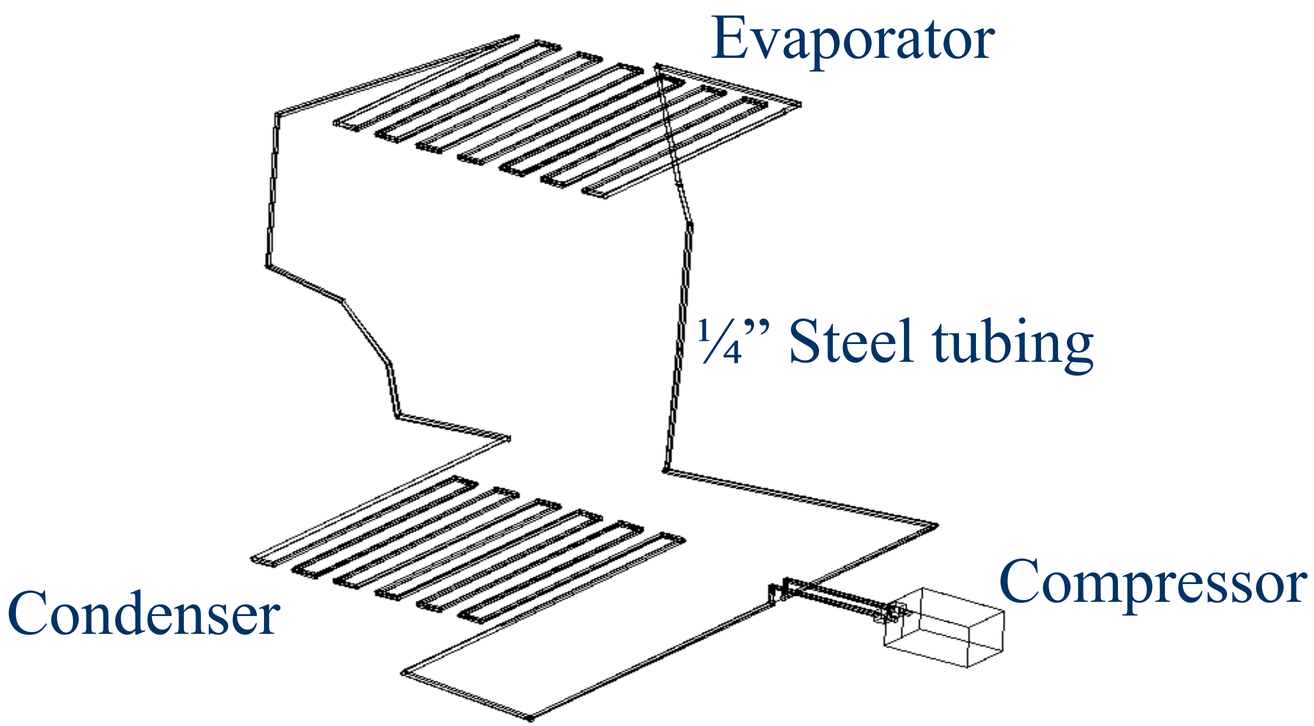
Refrigeration: Description

- Refrigerant: Ethyl chloride
- Pressure in and out of evaporator: 1.361 atm
- Vapor pressure of Ethyl chloride @68.31ºF 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 ºF
- Temp out of condenser: 140.0 ºF

Refrigeration: System Layout



Refrigeration: Specs

- Evaporator:
  - T_{IN} = 68.313 F
  - T_{OUT} = 68.314 F
  - Heat Duty = 735.1 W
- Condenser:
  - T_{IN} = 187.5 F
  - T_{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

- $V = \pi r^2 L$
- V_{TOTAL} = 2.02 Liters Ethyl Chloride
- $A = 2\pi rL$
- $L_{EVAP} = 26.86$ m
- $L_{COND} = 27.95$ m
- $L_{STRAIGHT} = 8$ m
- Total Length of 0.21 inch Radius Tubing $\cong$ 63 m

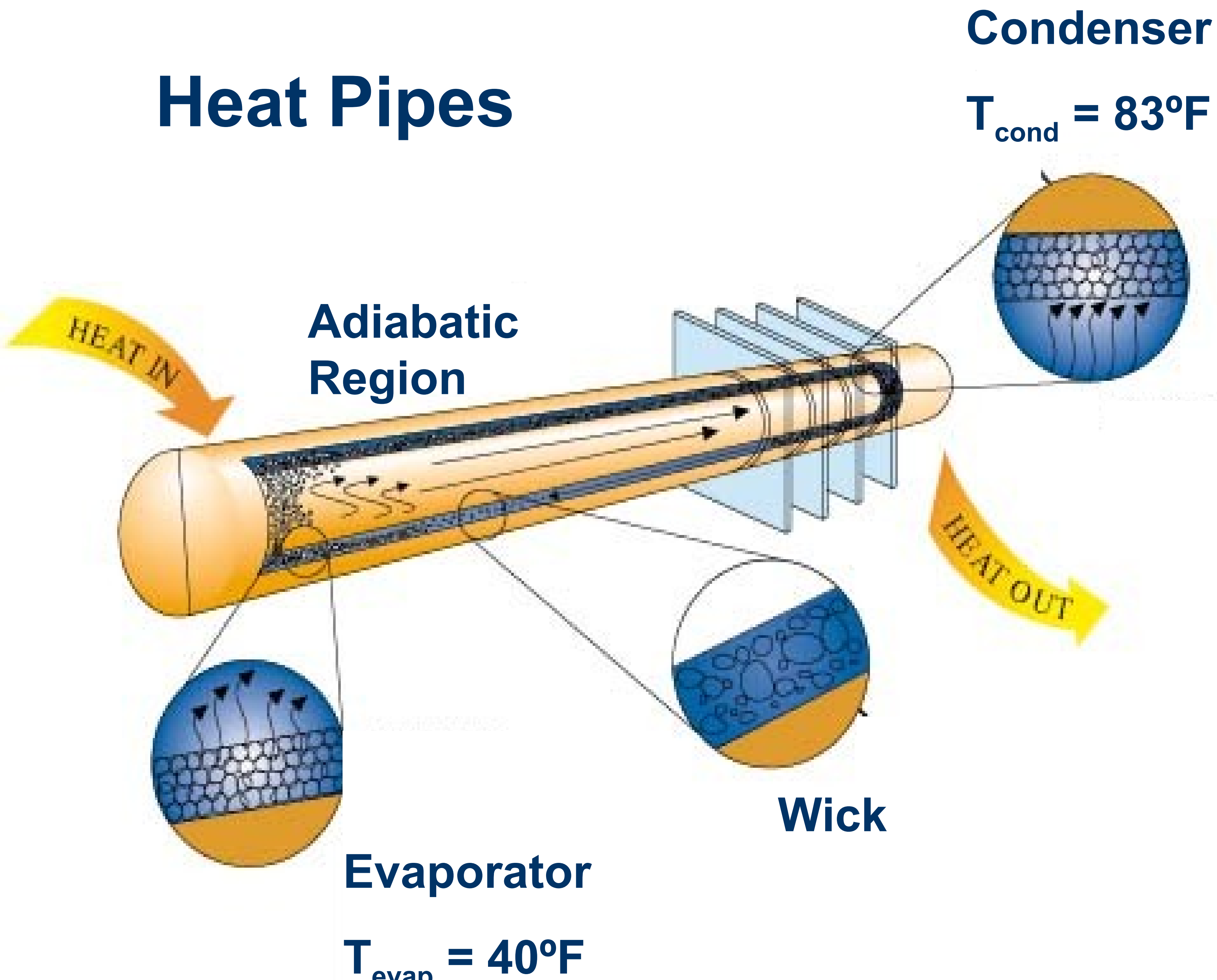
Refrigeration: Costing

Equipment	Size Range	Capacity Unit	Cost
Compressor	150	Watts	$119.15
Valve	0.02	meters	$6.50
Solar Panel	150	Watts	$700.00
Ni-Zn Battery	12 x 2	Volts	$400.00
Stainless steel tube	63	meters	$339.00
Ethyl Chloride	2000	Grams	$141.50
		Total	**$1706.15**

Refrigeration: Safety

- Ethyl Chloride:
  - Toxicity Levels: 30,000 μ g/m^3
  - 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_{cond} = 83ºF
Adiabatic Region
HEAT IN
HEAT OUT
Wick
Evaporator
T_{evap} = 40ºF

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

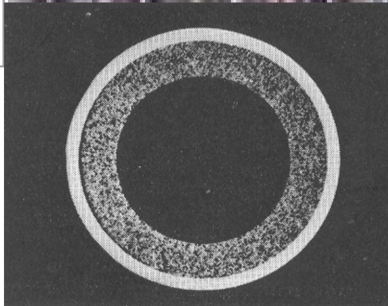
- Key properties
  - High latent heat
  - High surface tension
- Possible fluids

Fluid	Boiling point at 1 atm (ºC)	Surface tension, σ_l, at 50 ºC (N/m)	Liquid density, ρ_l, at 50 ºC (kg/m³)	Liquid viscosity, μ_l, at 50 ºC (cP)	Latent heat, L, at 50 ºC (kJ/kg)
R-11 (CCl_3F)	24	0.0153	1414	0.35	172
Pentane (n-C_5)	28	0.0127	596.0	0.187	348.9

Heat pipes: Wick material

- Pore size vs. permeability

Wick material and mesh size	Pore radius, r (mm)	Wire diameter, d_w (mm)	Porosity, ε(%)	Permeability, K (m^2)
Stainless steel, 403 mesh	0.019	0.025	36	1.9×10^{-11}
Stainless steel, 101.6 mesh	0.08	0.09	41	4.3×10^{-10}
Copper powder, sintered, 45-56m	0.009		52	1.74×10^{-12}



Heat pipes: Heat flow

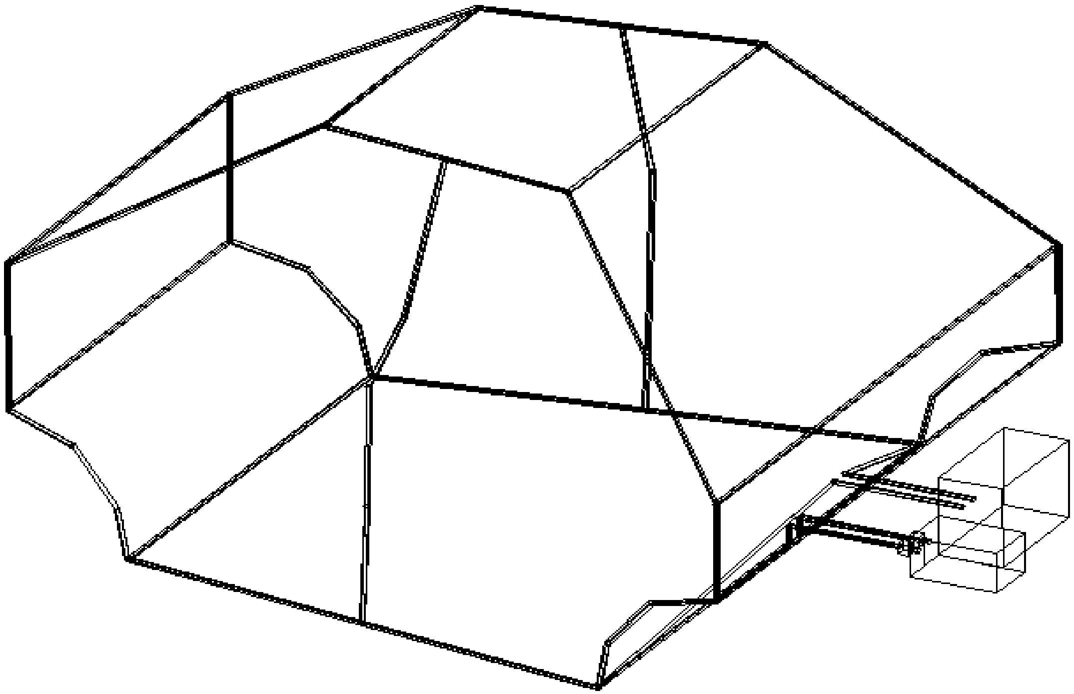
- From pressure balance, $(\Delta P_c)_{max} = \Delta P_l + \Delta P_g$
- Mass flow rate,

$$m = \rho_l A_w K / \mu_l l_{eff} * (2\sigma_l / r - \rho_l g l_{eff} \sin\phi)$$

- Heat flow = mass flow * Latent heat

Description	m (kg/s)	Q (W)	$W/1.5m^2$	Total W	Layers
4 layers 400 ss wick, ga, 45º	2.9E-06	1.05	157	471	3
6 layers 400 ss wick, ga, 45º	4.3E-06	1.57	236	707	3
8 layers 400 ss wick, ga, 45º	5.8E-06	2.09	314	628	2
10 layers 400 ss wick, ga, 45º	8.7E-06	3.14	471	943	2

Placement of Heat pipes



Heat Pipes: Costing

Equipment	Size Range	Capacity Unit	Number	Cost
Aluminum pipe	0.4	meters	300	$1594.49
Stainless steel Mesh	0.915 x 30.49	meters		$7.00
n-pentane	0.00379	m^3		$50.00
Cooler	0.22 x 0.134 x 0.066	m	1	$400.00
			Total	**$2051.49**

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.