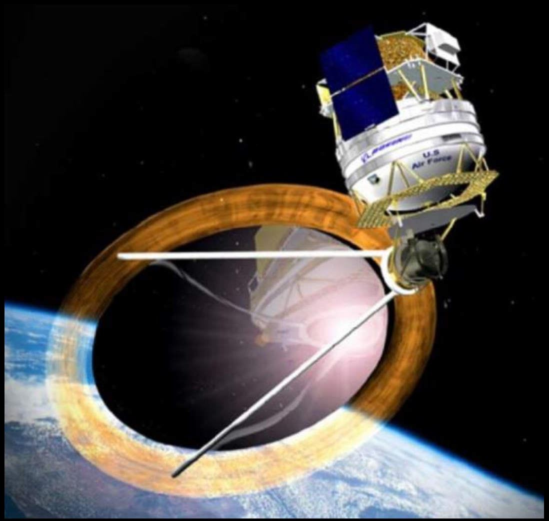
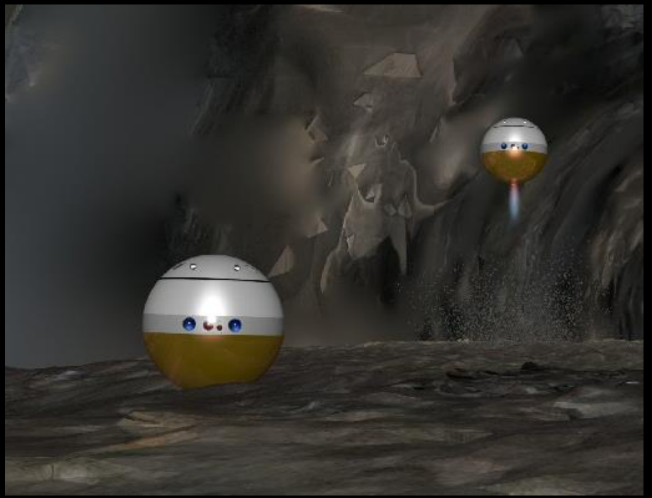




Water-enabled Propulsion Technologies for Interplanetary Travel and Surface Exploration and Prospecting

Jorge Martinez Dominguez
Space and Terrestrial Robotic Exploration (SpaceTREx) Laboratory
Aerospace and Mechanical Engineering Department
University of Arizona

Outline

- Introduction
- Motivation
- Solar Thermal Steam Propulsion
- System Overview
- Analysis
- Performance
- Conclusion

Introduction

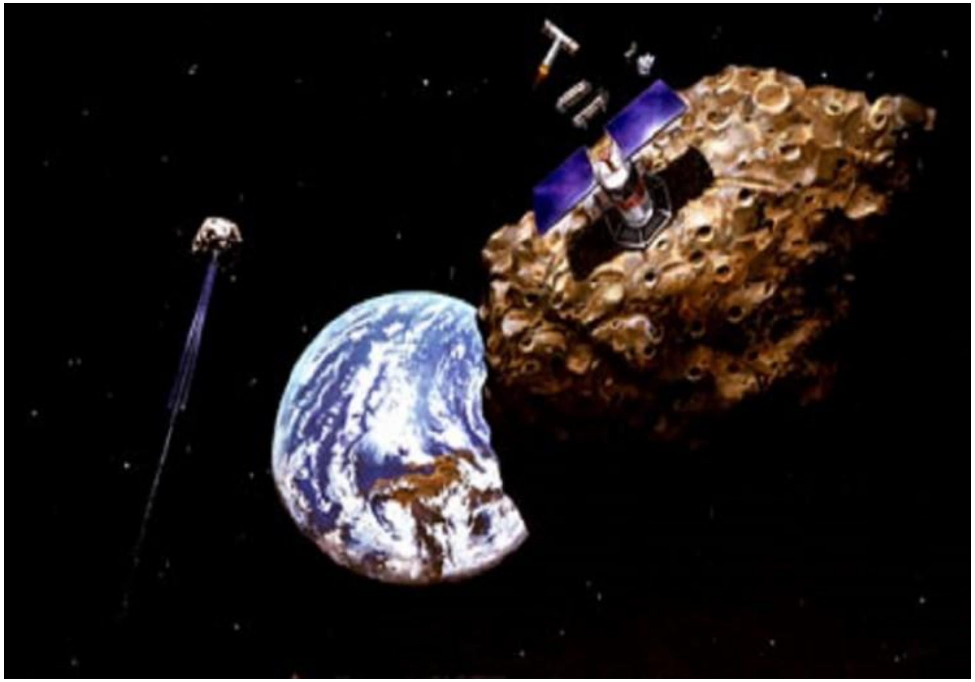
Why Space Exploration?

- Human need to understand where we came from
- Answer questions about habitability and astrobiology

Space Economy

- Activities and use of resources that benefits human beings
- Two factor for a sustainable space exploration
  - The use of off-world resources during the mission (ISRU)
  - The use of small, cheaper and expendable spacecrafts and robots

ISRU



Source: NASA

- In-situ resources to sustain:
  - Long Missions
  - Lower the cost
  - Routine movement
  - Economic viability
- Why water ?
  - Multiple sources in the inner solar system.

Small Satellites

- Reduced launch costs
- Reduced development times
- Easily manufactured
- Swarms of microsatellites to replace single large
- Quicker response when replacing a damaged satellite
- Workhorse for interplanetary travel

Small Satellites for Interplanetary Travel

- High Isp solutions have been developed
- Low thrust requires long waiting time, precise maneuvering and hard to achieve capture orbits
- Solar Thermal Propulsion represents a medium-range solution

Propulsion Type	Thrust	$I_{sp}(s)$
Hall/Ion	0.4 – 20 mN	300 – 3700
FEEP/Colloid	0.1μN – 1.5 mN	450 – 9000
Electromagnetic	0.03 – 2 mN	200 - 4000
Electrothermal	≤ 220 mN	50 – 250
Cold Gas	0.5 – 3 N	40 – 80
Monopropellant	0.1μN – 1.5 N	100 – 200
Bipropellant	0.1μN – 45 N	100 – 320
Decomposing Solid	No number available	230
Laser Micro. (ablation)	0.1μN	100 – 300
Laser Micro. (ignition)	1 – 10 mN	37 – 100
Laser Plasma	0.1 – 1 mN	500 – 1000
Hollow Cathode	0.1μN – 10 mN	50 – 1200
Solar Thermal (Concentrators)	56 mN – 1 N	200 – 1100
Solar Thermal **(Heat Exchanger-water)**	**32 – 33 mN**	**317 – 332**
Solar Thermal (Heat Exchanger-**hydrogen**)	**97 – 101 mN**	**951 – 995**
Solar Thermal (Heat Exchanger-**ammonia**)	**33 – 35 mN**	**326 – 341**
Solar Thermal (Heat Exchanger-**hydrazine**)	**24 – 25 mN**	**238 – 249**

Source: Scharfe et. al. 2009

Need for Multifunctional Materials to Support Long Duration Missions

- Adopting a common, high-performance yet green propulsion solution has major benefits
- Maximal multi-functionality from few materials.
- The resource can be readily replenished
- Water is an excellent candidate
  - Propulsion, power, thermal control, radiation shielding, life-support
  - Compelling choice for fuel

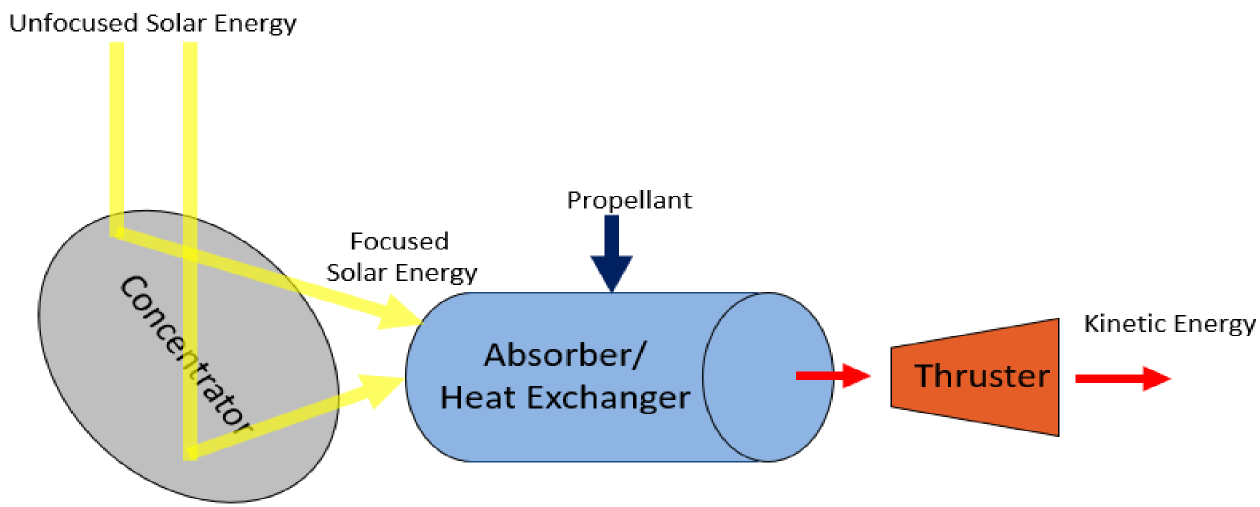
Objective

- Detect market gap and improve capabilities
  - ISRU
  - Compact, small technology
- Apply these concepts to refine previous model
  - Interplanetary travel: STP
- Propulsion systems modelling and performance analysis

Approach

- Analytical approach
- Computer simulations
  - Matlab
  - ANSYS
- Analyze performance

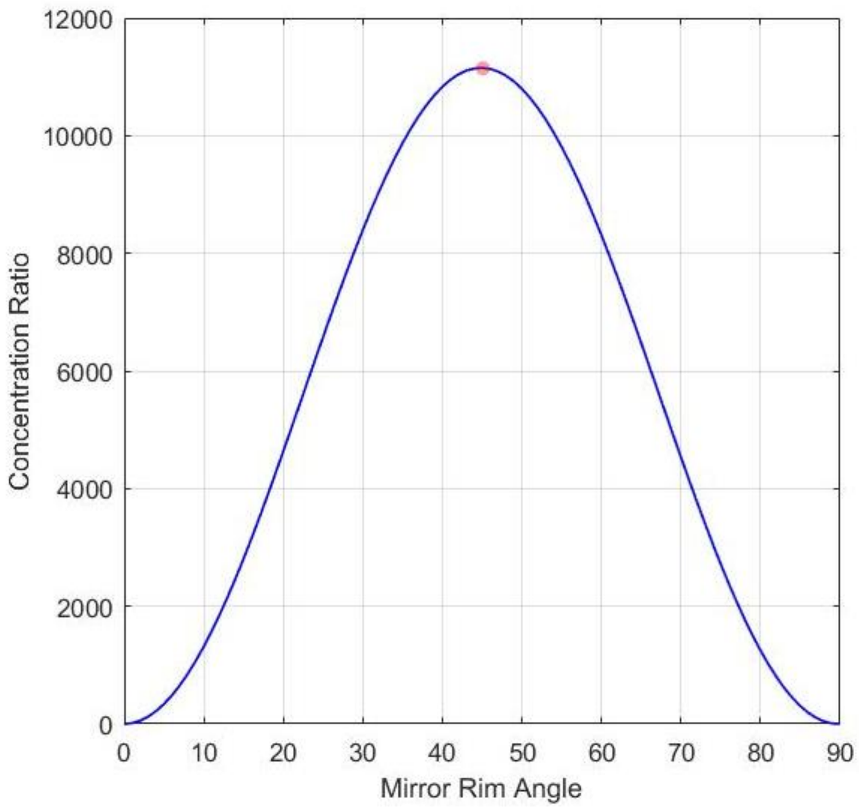
Solar Thermal Propulsion (STP)



- Solar Concentrator
- Volumetric Receiver
- Convergent-Divergent Nozzle

STP: System Overview

- Parabolic Dish Concentrator



- High Concentration Ratio

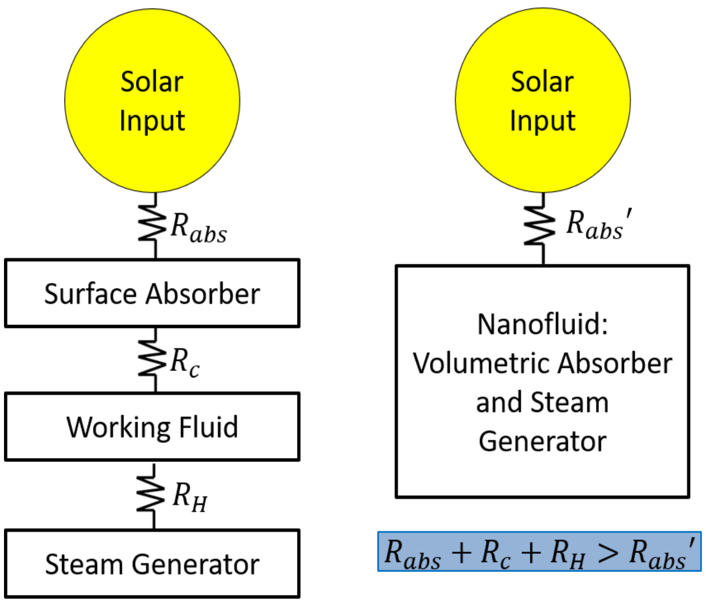
$$C = \frac{A_c}{A_r}$$

- Rigid and Inflatable options

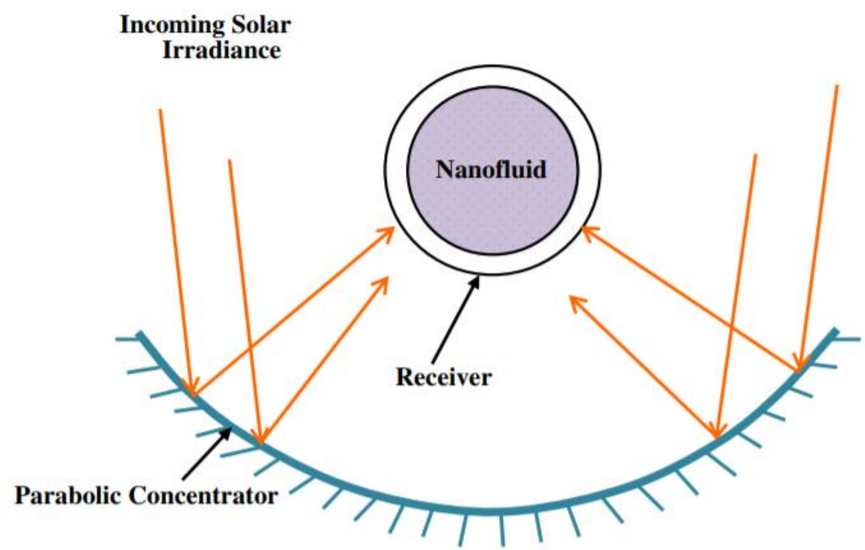
- Design:
  1) Select a desired C
  2) Select a desired R
  3) Compute the focal length necessary

STP: System Overview

- **Solar Receiver**



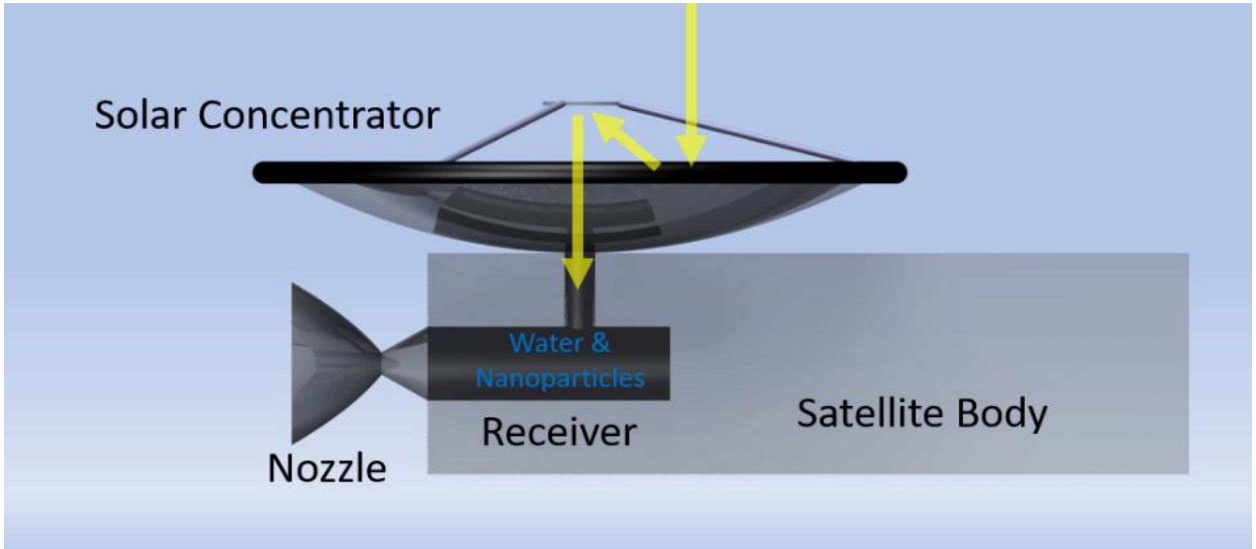
Indirect Direct



$$R_{abs} + R_c + R_H > R_{abs}'$$

STP: System Overview

- Solar Receiver

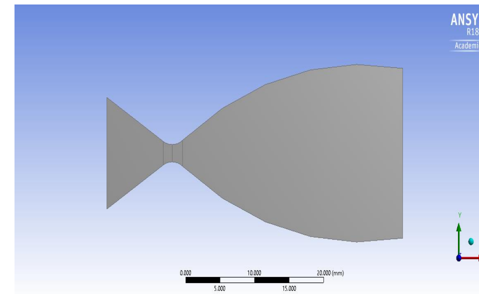


Direct Gain STP Concept

- Volumetric heating
- Thermal Isolation
- Impure water

STP: System Overview

- **Thruster: Operating Conditions**



Nozzle Design	
Chamber Temperature (K)	$T_c = 2500$
Chamber Pressure (bar)	$p_c = 6$
Mass flow rate (g/s)	$\dot{m} = 1$
Specific Heat Ratio	$\gamma = 1.32$
Expansion Ratio	$\varepsilon = 100$
Nozzle Throat Temperature (K)	$T_t = 2145$
Nozzle Throat Pressure (bar)	$p_t = 3.24$

Nozzle Geometry	
Hot chamber Diameter (cm)	$D_i = 2$
Convergence half-angle (mm)	$\theta_c = 30°$
Nozzle Throat Diameter (mm)	$D_t = 1.84$
Throat exterior Radius (mm)	$R_{ext} = 2.6$
Divergence half-angle (mm)	$\theta_d = 35°$
Exhaust Diameter (mm)	$D_e = 18.4$
Nozzle Length (mm)	$L = 43$

STP: Analysis

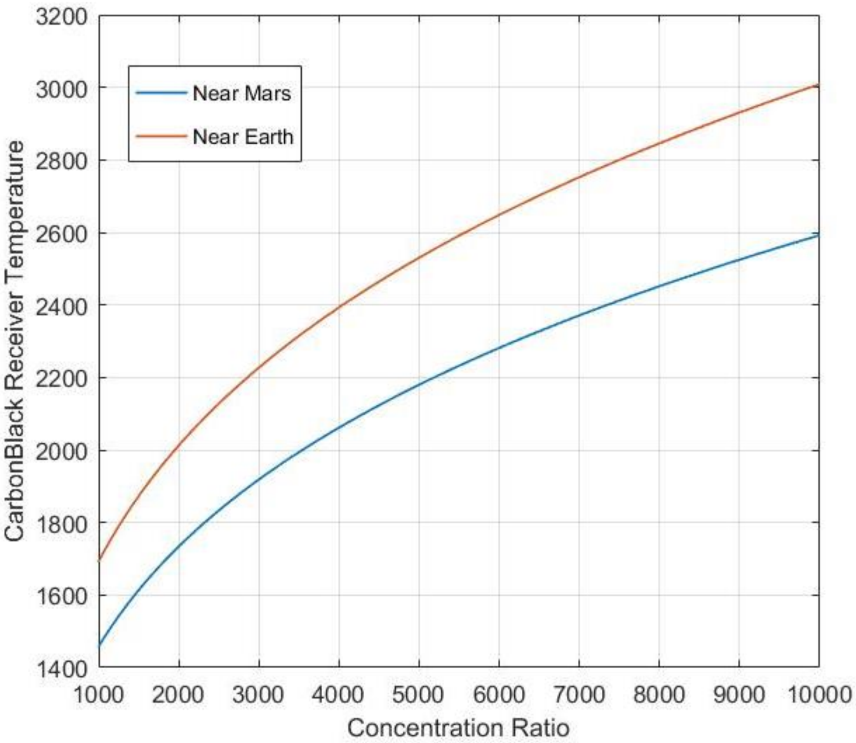
- **Carbon-black Receiver**

Thermal Equilibrium

$$T_R^4 = \left(\frac{\alpha \gamma C I_{solar}}{\varepsilon \sigma} + T_{amb}^4 \right)$$

Source: Surrey Nanosystems

Up to 99% absorptivity



STP: Analysis

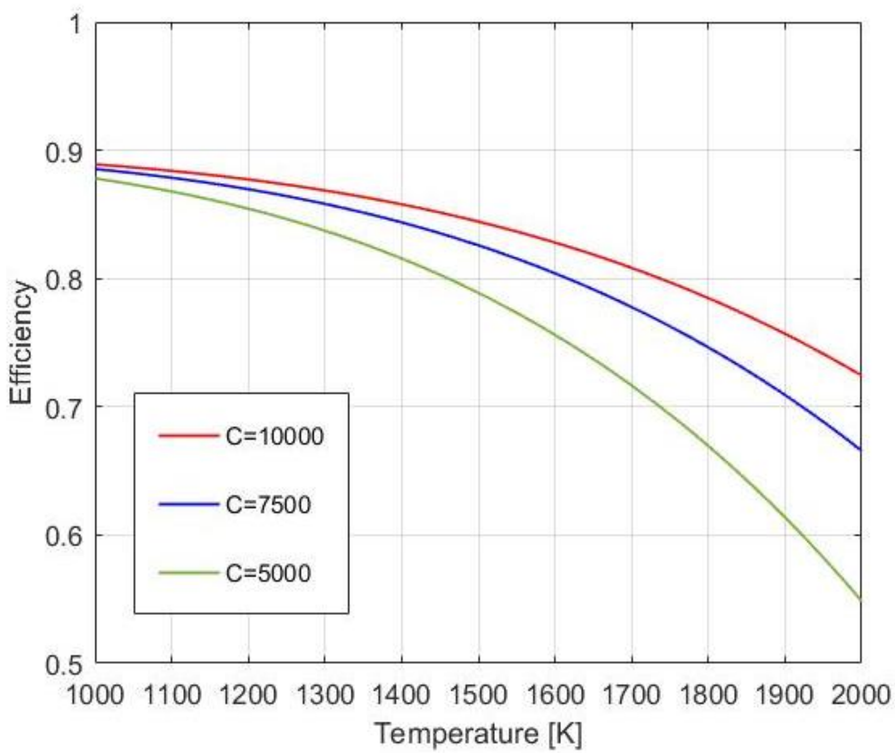
- **Carbon-black Receiver**

  - **Receiver Efficiency**

$$\eta = \frac{Q_{useful}}{Q_{in}} = \alpha - \frac{\varepsilon\sigma\left(T_R^4 - T_{amb}^4\right)}{\gamma C I_{solar}} - \frac{U_L(T_R - T_{amb})}{\gamma C I_{solar}}$$

$$\uparrow \boldsymbol{T_r} \quad \downarrow \boldsymbol{\eta}$$

  - **Higher radiation losses**
  - **Higher heating time**



STP: Analysis

- **Steam generation**

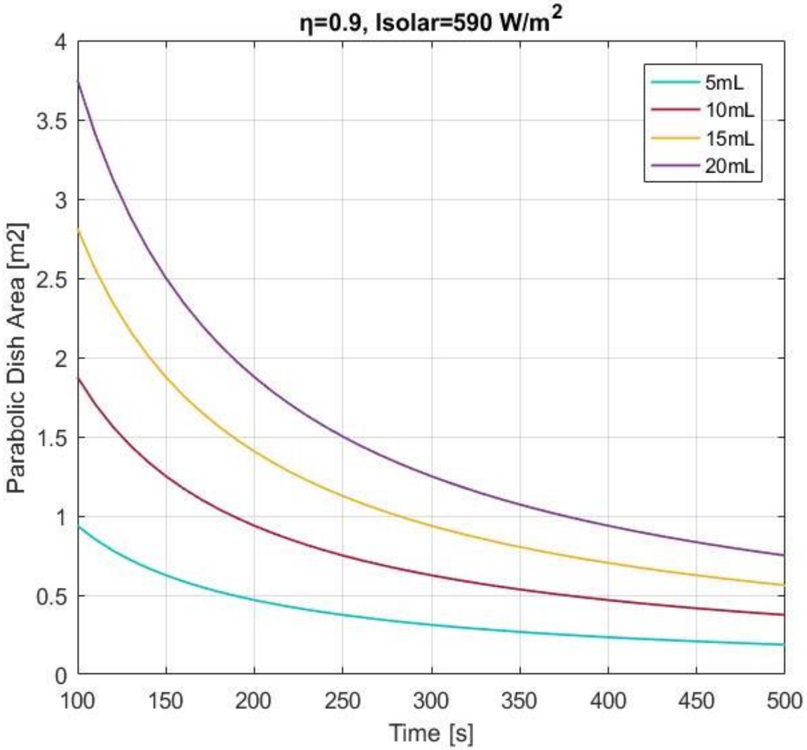
  - **How efficiently do the nanoparticles transmit the heat to the water?**

$$\eta(t) = \frac{\left(c_{p_w} m_w + c_{p_n} m_n\right) \Delta T + \int_0^t m_s h_{lv} dt + c_{p_s} m_s \Delta T}{\eta_c \int_0^t I_{solar} A_{ab} dt}$$

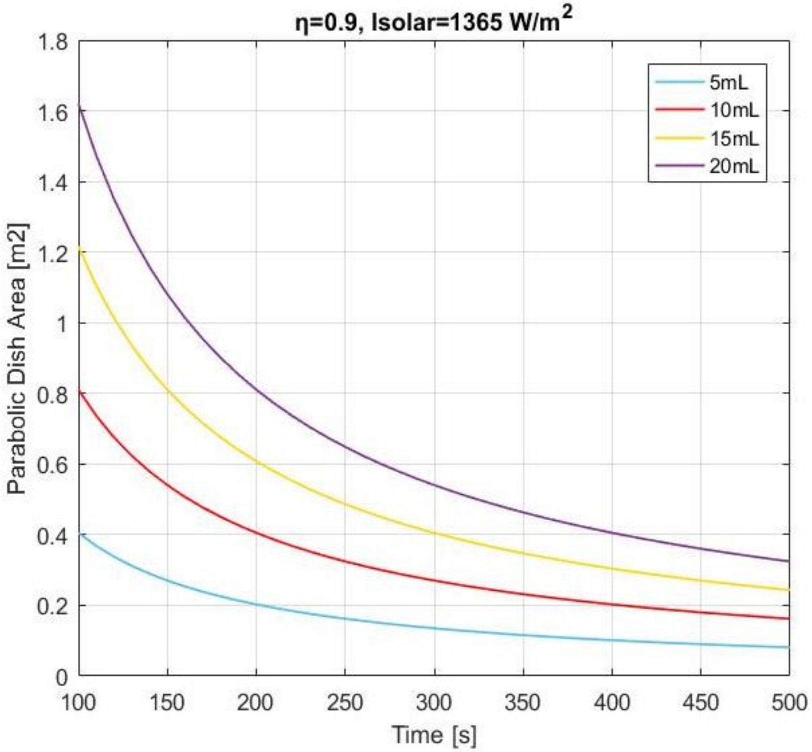
  - **Experimental work on low concentration ratios, for gold nanoparticles, show efficiencies $\boldsymbol{\eta = 0.8 - 0.9}$.**

  - **Further experimentation is needed for carbon nanoparticles and high concentration ratios, but a similar photothermal efficiency is expected.**

STP: Time Need to Achieve 2500 K



Mars



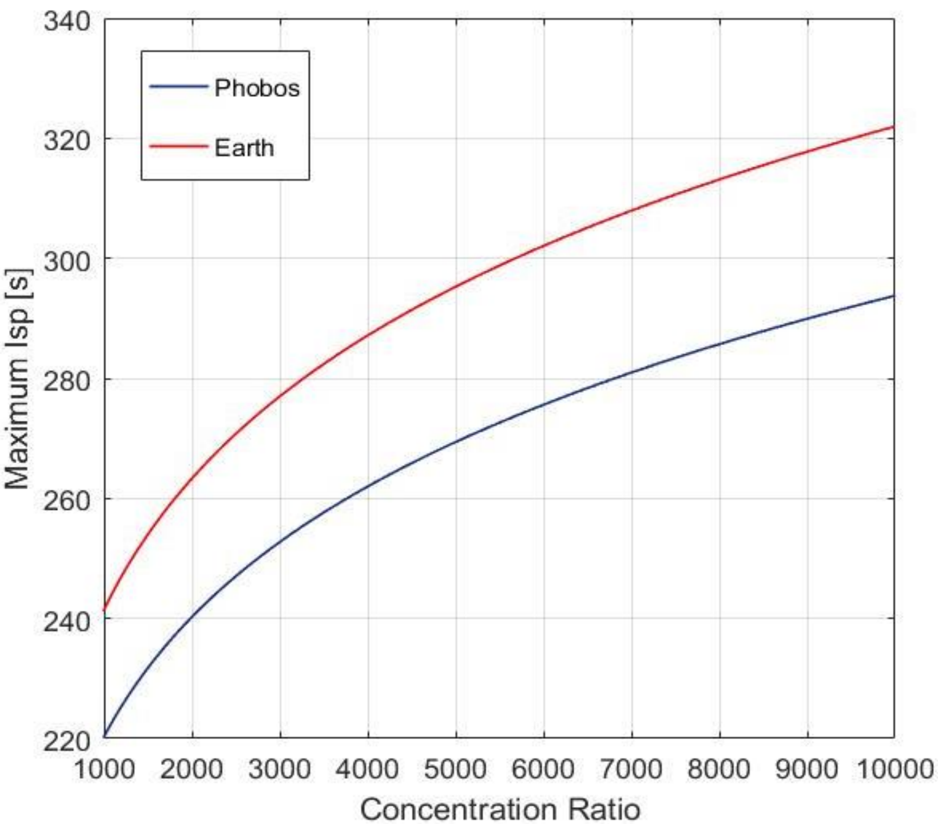
Earth

STP: Performance

- Specific Impulse
  - **ANSYS model showed only a 5% difference with the analytical work**

$$I_{sp} = \sqrt{\frac{2\gamma}{\gamma - 1} R_g T_c \left(1 - \left(\frac{p_e}{p_c}\right)^{\frac{\gamma-1}{\gamma}}\right) + \varepsilon R_g T_c \frac{p_e}{p_c}}$$

$$\boldsymbol{I_{sp} = 240 - 320}\ \text{s}$$

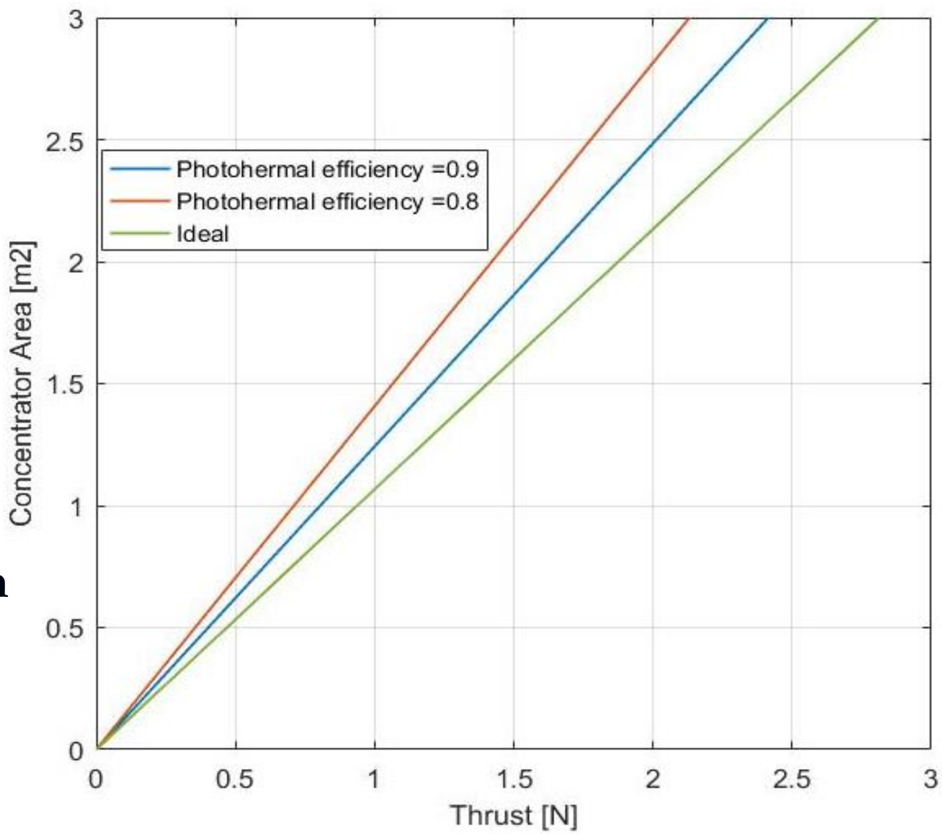


STP: Performance

- Thrust
  - The components efficiency allows us to compute the thrust

$$\eta_{opt}\eta_{pt}A_c I_{solar} = \frac{1}{2} T v_e$$

  - $\boldsymbol{T \sim 1N}$ with 1 $\boldsymbol{m^2}$ concentrator
  - Easily scalable
  - The overall efficiency of the system is ~0.7, higher than the ~0.4 of available electrothermal water technologies.



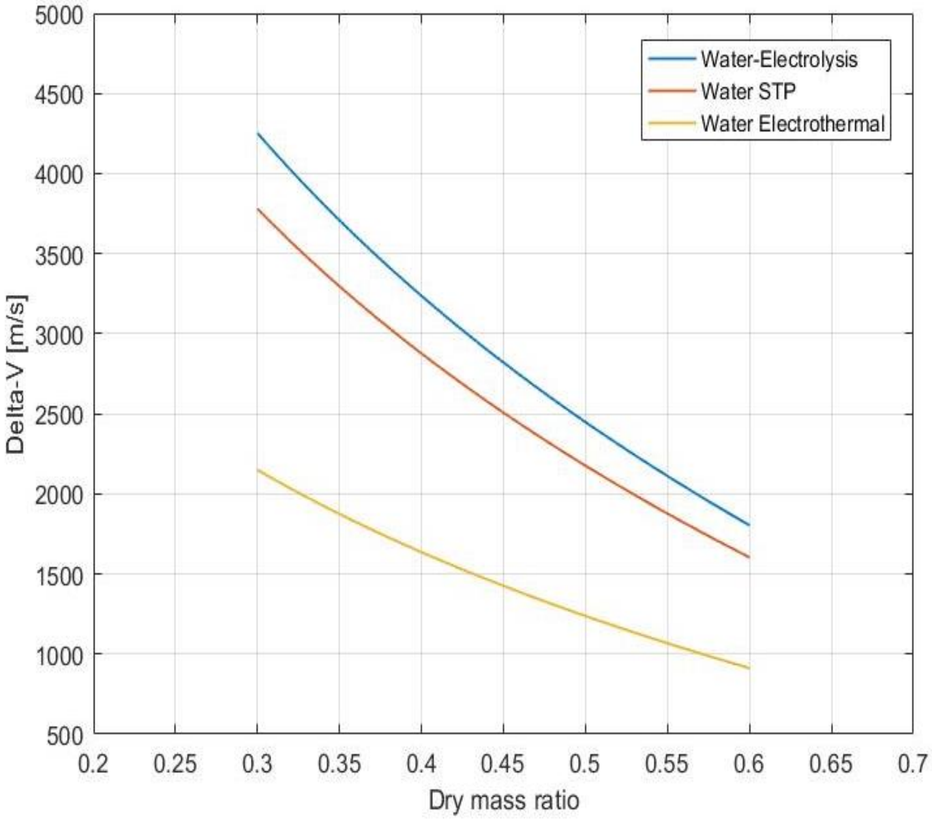
STP: Performance

- **Delta-v**

  - Tsiolkovsky rocket equation

$$\Delta v = v_e \ln \frac{m_0}{m_f}$$

  - Maximum $\boldsymbol{\Delta v}$ ~4 km/s at a 0.3 dry mass ratio
  - It approaches water electrolysis propulsion systems
  - Offer a superior performance than water electrothermal propulsion



STP: Performance

- **Delta-v**
  - Tsiolkovsky rocket equation

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Comparison between Water-based Propulsion Systems		
Photovoltaic Electrolysis Propulsion System	$I_{sp} = 360$	$T = 3.5\ N$
Solar Thermal Steam Propulsion	$I_{sp} = 320$	$T = 3.1\ N$
Electrothermal Water Propulsion	$I_{sp} = 182$	$T = 1.8\ N$

Conclusion

- Developed a refined Solar Thermal Steam Propulsion concept for spacecraft
- Better performance than water-based electrothermal technologies, and comparable to water electrolysis
  - Major implications
- Delta-v on the 4km/s range required from LEO to Phobos
  - LEO to Earth-Mars transfer 3.6 km/s
  - Aerocapture and aerobraking to Phobos transfer and 0.5 km/s to Phobos surface
- Adapted the technology to power surface vehicles, and a ballistic hop mobility was shown for a quad-engine configuration

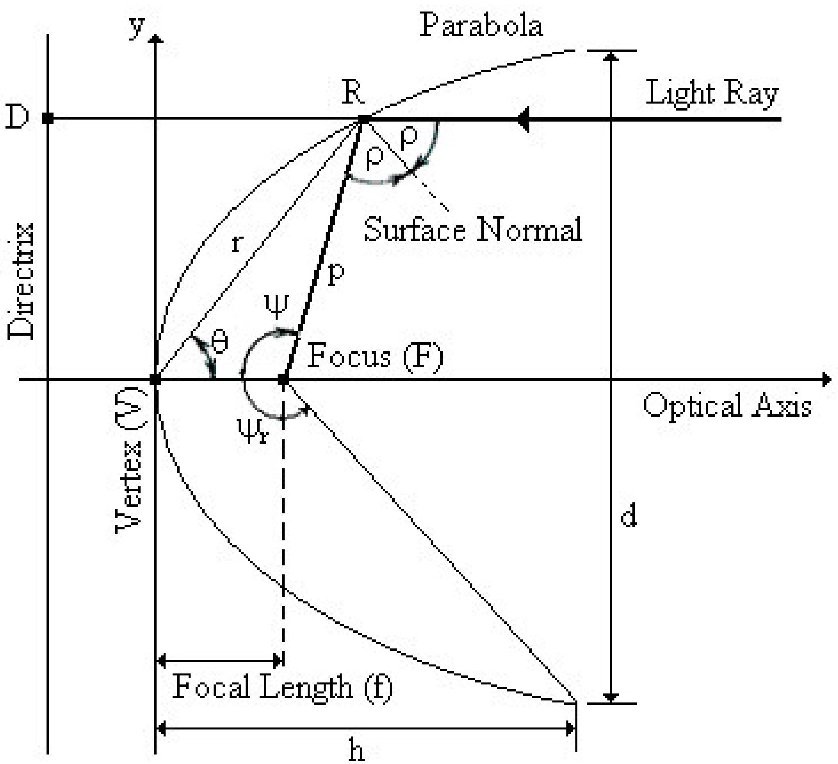
Contributions

- Refine understanding and analysis of STSP
- Develop an scalable model for STSP
- Develop a dynamic model for ballistic hopping of a quad-engine configuration robot

Backup Slides

STP: System Overview

- **Parabolic Dish Concentrator**

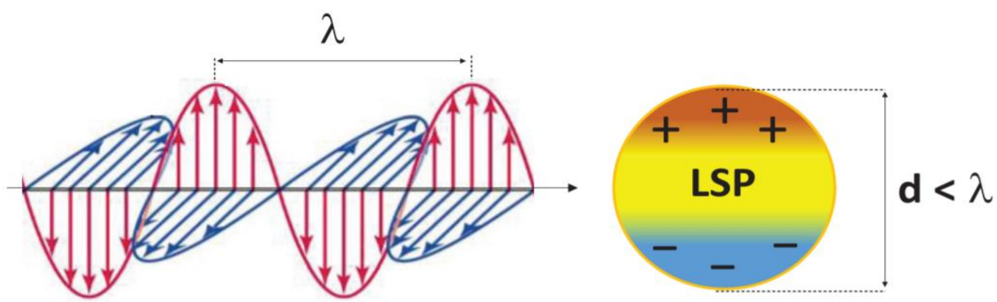


OPTICS

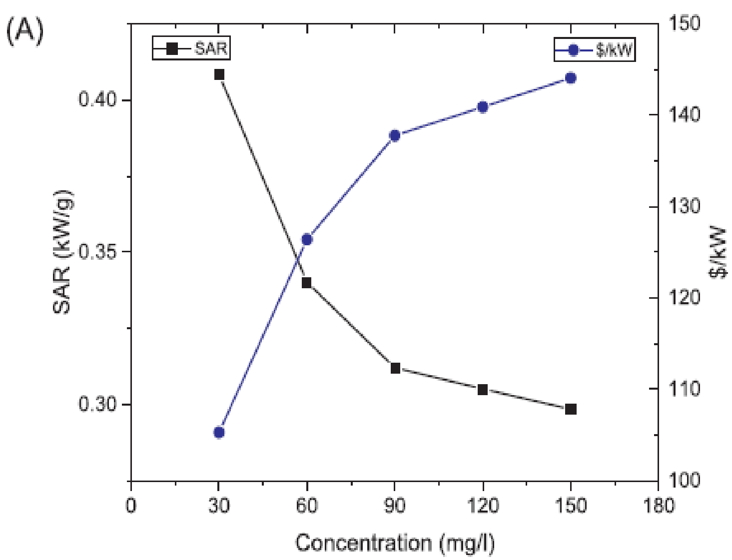
$$C_g = \frac{A_c}{A_r} = \frac{\sin^2 \Psi_r \cos^2(\Psi_r + \theta_s + \theta_f)}{\sin^2(\theta_s + \theta_f)}$$

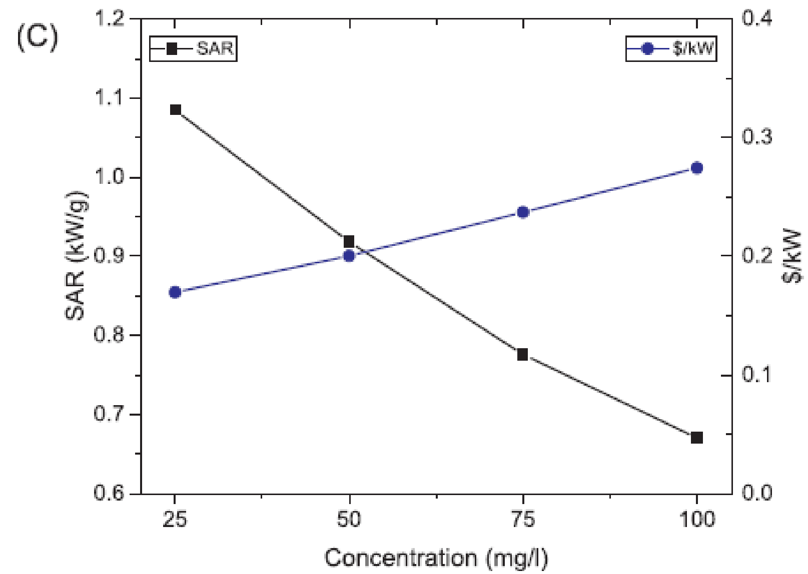
- Ψ_r : **Rim angle**
- θ_s : **Solar half-angle**
- θ_f : **Angular form error**

Gold vs Carbon Nanoparticles



Plasmonic Resonance

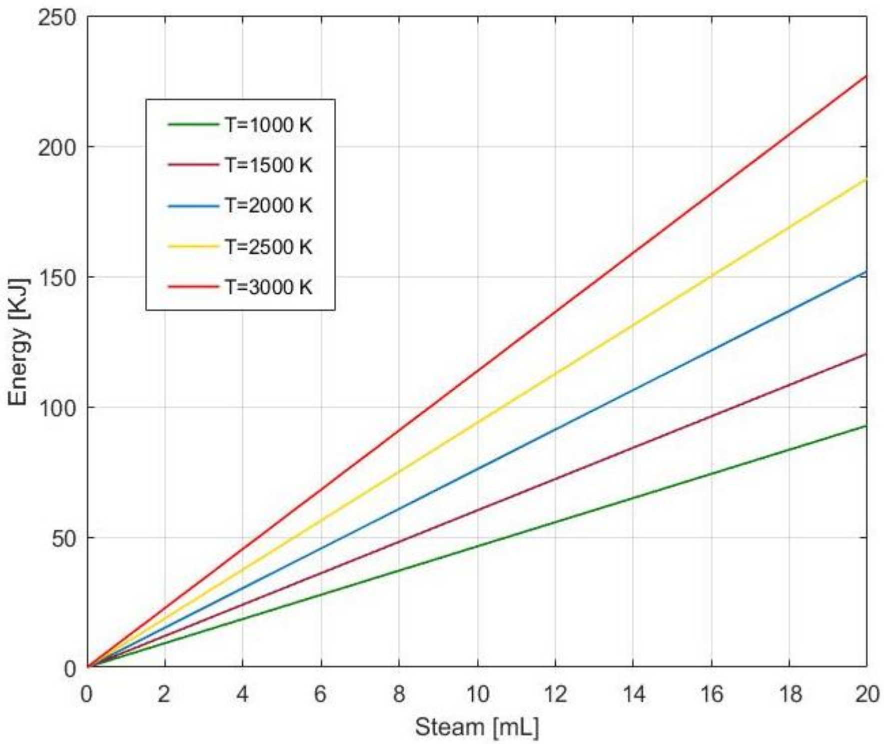




STP: Analysis

- **Steam generation**
  - How much heat is needed to produce the desired superheated steam?

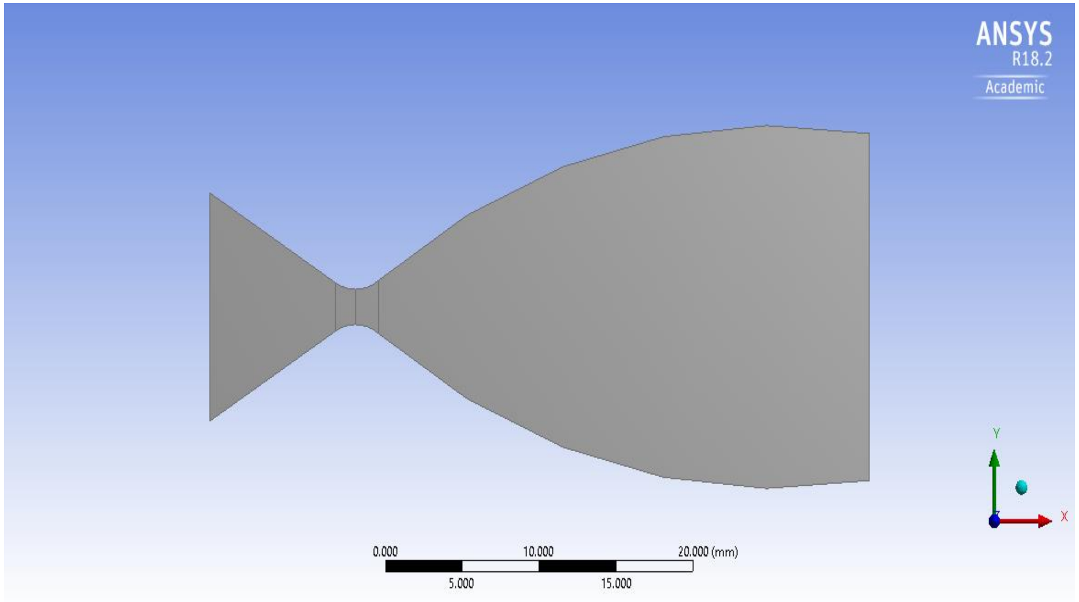
$$E \sim m_w c_{p_w}(T_b - T_0) + m_w h_{lv} + m_w c_{p_s}(T_f - T_b)$$



  - Most of the energy is employed in the phase change
  - Nanofluids enhanced heat capacity

STP: System Overview

- **Thruster: Bell-shape nozzle**



$$A_t = \frac{\dot{m}}{p^*}\sqrt{\frac{R_g\,T^*}{\gamma}}$$

$$x = a\,y^2 + b\,y + c$$

$$x_{exit} = a\,R_e^2 + b\,R_e + c$$

$$L = \frac{R_g(\sqrt{\varepsilon} - 1)}{\tan\alpha_c} + R_{ag}\frac{\cos(\theta_n - \alpha_c) - \cos\alpha_c}{\sin\alpha_c}$$

Performance Tested on ANSYS Fluent

ANSYS Fluent Model