Design and Prototyping of a Superheated Steam Electric Powered Propulsion System for CubeSats

Abstract

A water-based ResistoJet type propulsion system is designed for its use in CubeSats larger than 6U as an orbital maneuvering system. Designed to be self-contained in 1U, its electrically powered evaporator and high-temperature superheater systems are fed by a self-pressurized liquid water tank, thus characterized by simplicity due to the lack of pumps or external pressurizing systems. Moving parts and the use of toxic materials are minimized.
The analytical and parametric models introduced[1] allow an engineer to introduce the changes needed to adapt the propulsion system to different missions, maintaining efficiency. Steady-state thermodynamic and heat transfer analytical models are used, defining dimensions and materials of the inner components to meet the power and energy restrictions of a typical CubeSat's power system.
A future test plan is presented, taking advantage of the vacuum chamber available in the university. This allows for the characterization and validation of the different propulsion system components. Following the pandemics induced restrictions, our test plan will continue. Conversations for further TRL development are underway.

Working principle and requirements

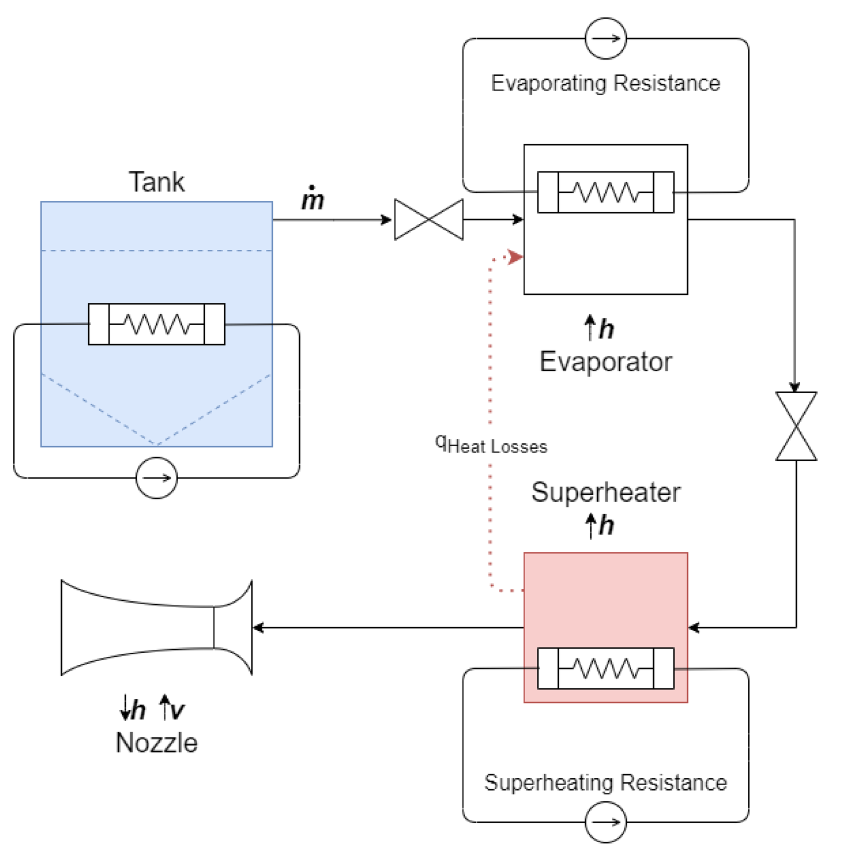

Figure 1: ResistoJet subsystems

Our ResistoJet is separated into 4 main subsystems and 2 on-off control valves. The heating loops work independently.

1. Propellant tank: pressurized by water vapor pressure at system's working temperature, eventually heated.
2. Water evaporator: with a membrane (fig 2) retaining propellant in position, evaporates the required mass flow.
3. Superheater: resistive wire raises the vapor temperature and contributes to evaporation by reusing radiation loses
4. Nozzle: convergent-divergent, EDM manufactured. Limits mass flow via throat orifice area and tank pressure.
5. Tank isolation valve.
6. Preheating and shut-off valve.

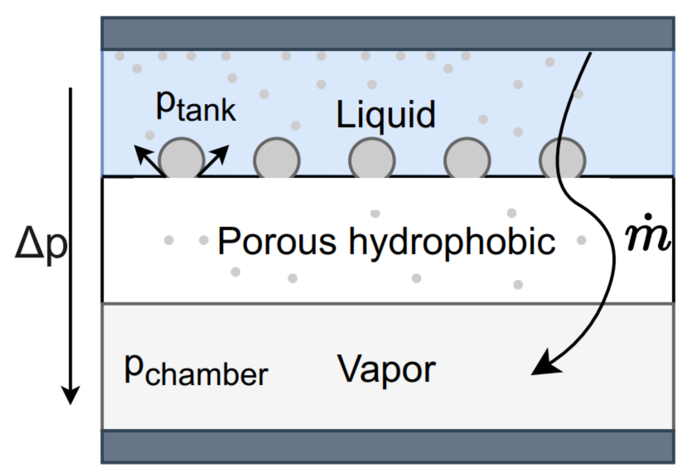

Figure 2: PTFE hydrophobic filter

A design example is presented for a 6U CubeSat, allocating 1U for the propulsion system and a reduced tank. Total amount of propellant carried depends ultimately on the system's specific impulse and the mission's required ΔV.

The main design restrictions are the energy and power available, provided by the satellite's power bus.
Lowest propellant tank temperature, and thus working pressure, can be estimated by the expected inner sat's temperature. Tank temperature is not expected to drop significantly due to mass flow, as the evaporator feeds on liquid water.

Obtained thrust will be a result of system's power and heating efficiency.
A target of 200s specific impulse is set.

Satellite bus units	6U
Propulsion system units	<1U
Allocated battery capacity	80Wh
Available power	50W (~67%)
Target thrust	> 15mN
Target I_{sp}	200s

Table 1: ResistoJet example specs

Design process

Analytical, steady state simulation models are used to design the device and are interdependent according to **figure 3**.
1-D fluid, nozzle and thermal circuit sub-models are interconnected, determining the mass flow, thrust and specific impulse of the propulsion system, as well as heat losses and required power to be dissipated by the heating wires. Efficiencies and electric variables such as required currents or voltages are calculated at later steps.
This modelling strategy allows for quick changes in every iteration (e.g., convection or friction coefficients, duct geometries, components connections), making the design process fast and versatile.

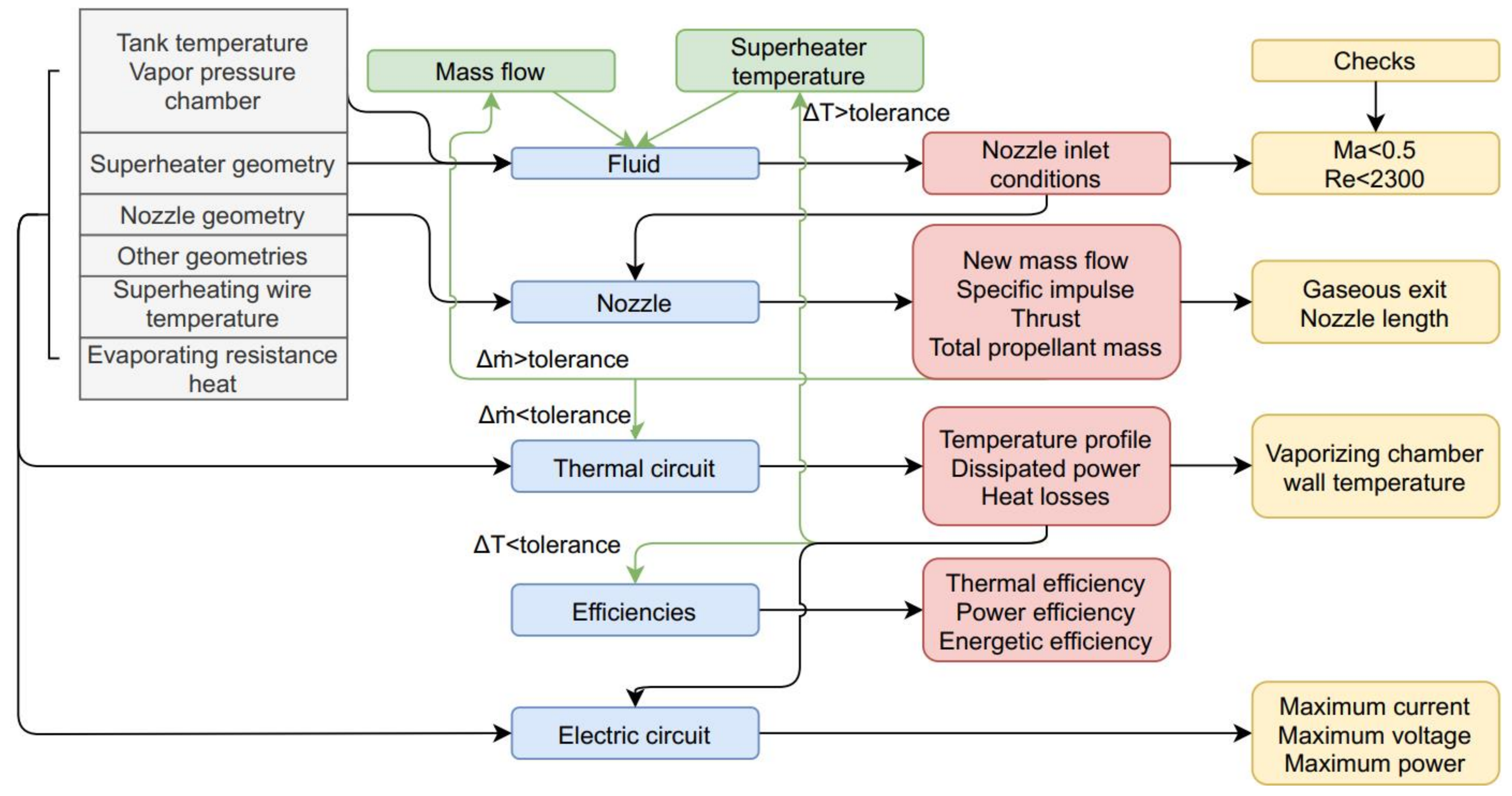

Figure 3: Simulation logic used to (re)design a mission-customized propulsion system

Proposed example design

Most significant design characteristics:

- Nested components following the natural temperature gradient minimize heat transfer loses, allowing for an efficient high temperature core.
- Independent power control for evaporator and superheater resistances, carefully selected power rates allow for a wide range of stable operation points.
- Both evaporating resistance and superheater losses used as sources for evaporation.
- Static evaporator with a hydrophobic mesh retaining liquid in position, allowing only the passage of steam bubbles; pressure gradient as motor.
- Low conductivity ceramics as structural support.
- Ultra low conductivity materials to insulate superheater from low emissivity lids.
- Melting joints provide for a safe and rigid launch configuration.
- Superheater's outlet placed collinear to nozzle, avoiding unnecessary fluid cooling.

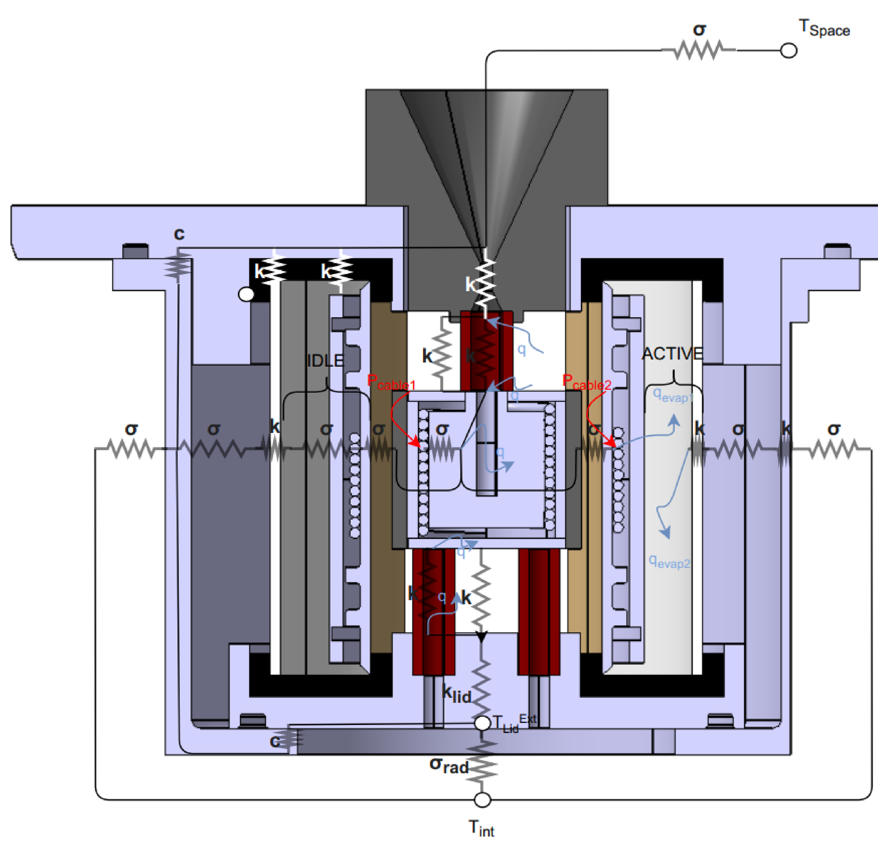

Figure 4: Final device design, showing a superimposed thermal model

ISP	204 sec
Thrust	19 mN
Mass Flow	36 g/h
Evaporating power	8 - 0 W
Superheating power	42 W
Superheating current (max)	6 A
Superheating voltage (max)	7 V
Power efficiency	80.66 - 86.33 %
Energetic efficiency	54.79 - 62.82 %
Ideal thermal efficiency	41.96 - 44.82 %
Real thermal efficiency	37.77 - 40.33 %

Table 2: Model performance marks

Table 2 shows performance results for our design example, where the target specific impulse of 200s is achieved.
Power conversion efficiency above 80% -due to low heat losses- results in an increased mass flow and a thrust of 19mN, for a 50W total power input.
Energy efficiency suffers, as ResistoJet systems need preheating.
Real thermal efficiency is a bit lower due to nozzle efficiency, and nozzle shortening to avoid sublimation of the fluid.

Experimental setup

Taking advantage of the department's previous experience with ResistoJet design and testing[2], an un-nested version of our device has been built.
Our custom-built vacuum chamber can work with propulsion systems expelling condensing gases at different flow rates.

The simplified propellant system is being tested now, including the hydrophobic filter for water-steam phase separation.
Optically measuring stable mass flow with a micro graded syringe; mN thrust range with a micro load-cell, adding a mechanical amplifier for increased sensibility. Electrical power, temperatures and pressures complete the test setup.

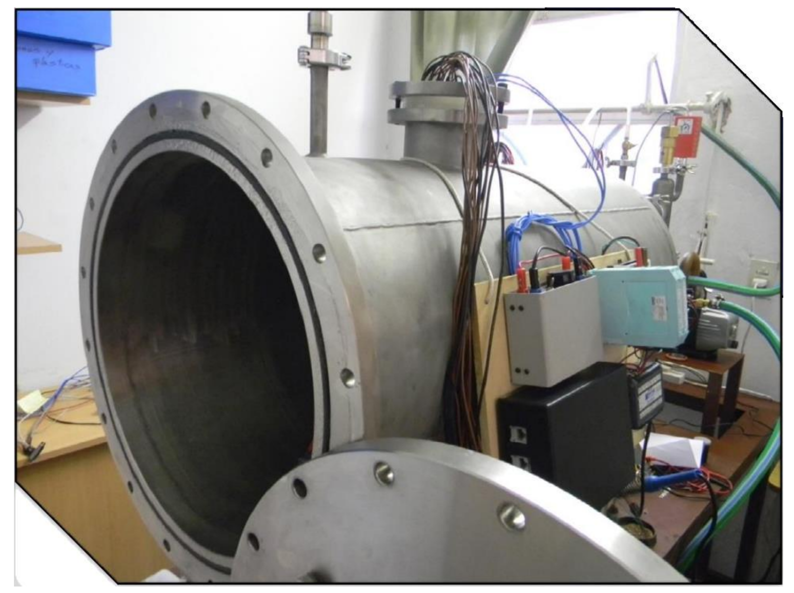

Figure 5: Propulsion-ready vacuum chamber and instrumentation

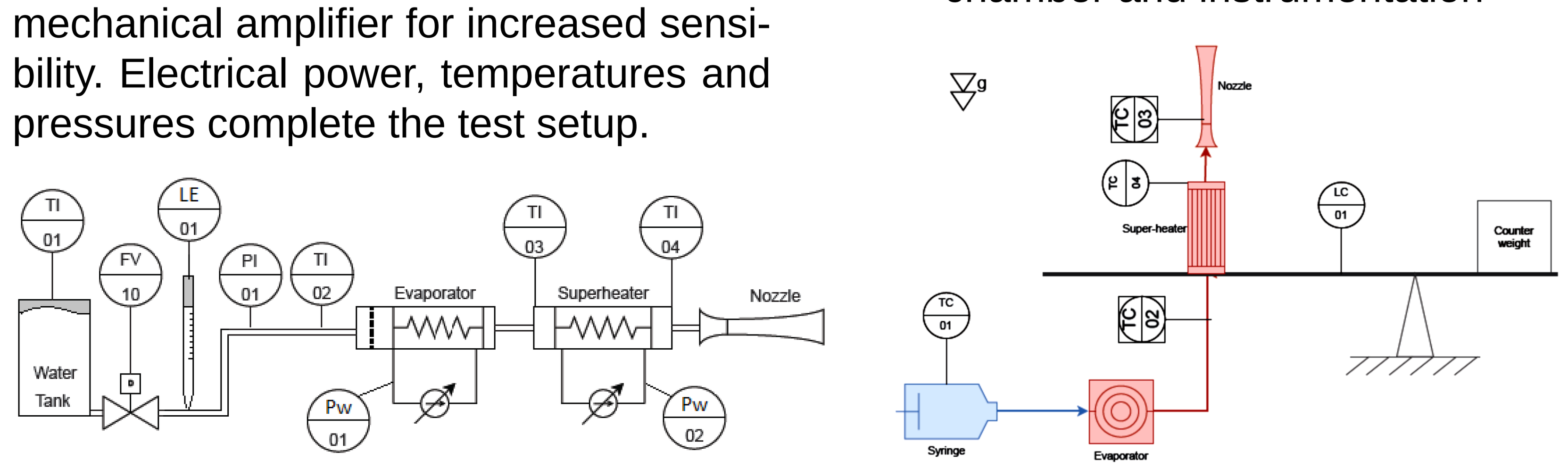

Figure 6: Un-nested test setups, for measuring stable mass flow and thrust

Conclusions and outlook

- A simple, easy to control, green propellant propulsion system has been designed, using minimum moving parts and complying with typical mission requirements.
- Competitive energy and power efficiency values have been reached for typical mission ISP, power and thrust requirements.
- A parametric model has been developed, allowing for mission managers added flexibility and for propulsion engineers to adapt to different mission profiles.
- Experimental results are being collected at the time, in order to fine-tune the methodology and parameters, and to achieve more accurate design results.

References

[1] Giraudy, T., Scarone, F.: "Design and Prototyping of a Superheated Steam Powered Propulsion System for CubeSats", Degree Thesis, ITBA, 2021
[2] Pedreira, P. H, Lauretta, J. R., D'hers, S.: Planar Nozzles for Controllable Microthrusters, Journal of Aerospace Engineering, Vol. 30, 2017

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