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Thesis: Forced-convection waste heat rejection for Mars surface applications

# Background and Motivation

- Crewed Mars missions will require >40kWe, nuclear fission power systems, such as NASA's Kilopower, are ideal for this application due to their high power density
- Current designs use a radiator for waste heat rejection, however the radiator contributes significantly to the overall system mass and size and requires high rejection temperatures, increasing mission cost and reducing scientific payload capacity and power cycle thermal efficiency
- A forced-convection heat exchanger transferring waste heat to the Martian atmosphere may significantly reduce overall system mass
    - Higher heat transfer coefficient
    - More compact design as surface area does not require sky exposure, reducing deployment complexity
    - Weaker rejection temperature dependence
    - Scalable to lower-power and lower-temperature applications such as cryofuel refrigeration, ISRU plant cooling, habitat thermal regulation
- Challenges:
    - Martian atmospheric conditions (~600 Pa, 220K, 95% $CO_2$) drastically reduce heat transfer coefficient and fan performance
    - Very little data exists on heat exchanger performance at low Reynolds, high Knudsen number, or on high head coefficient fan performance at low Reynolds, high Mach number

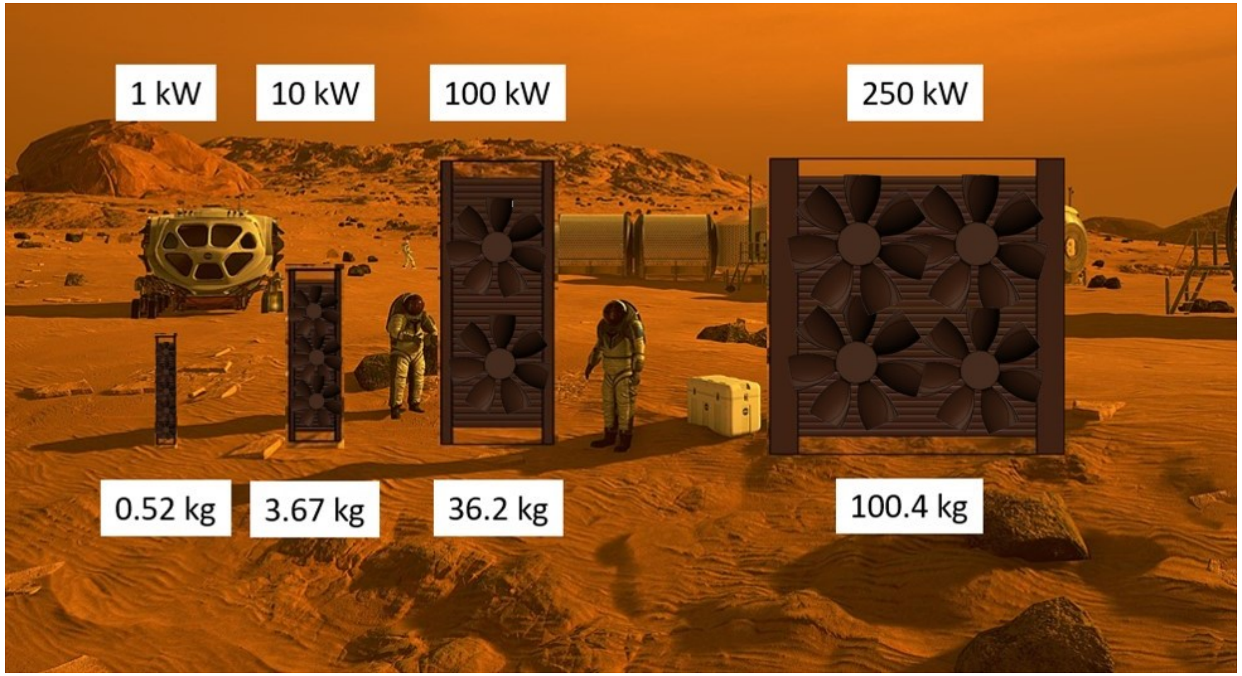


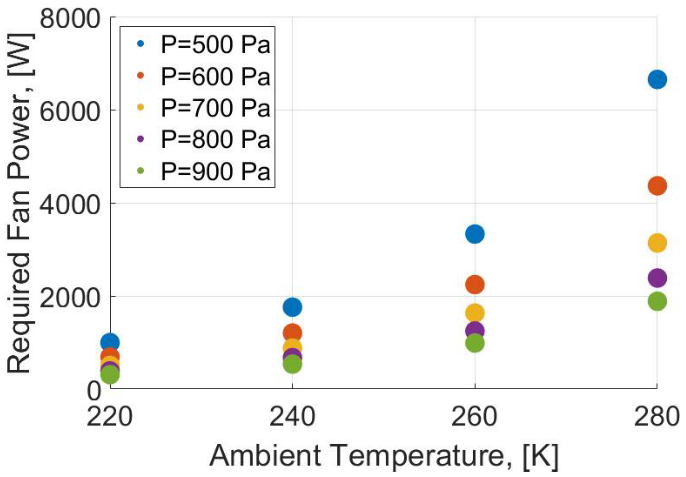

Illustration of heat exchangers optimized for various heat rejection loads. Background image credit: NASA

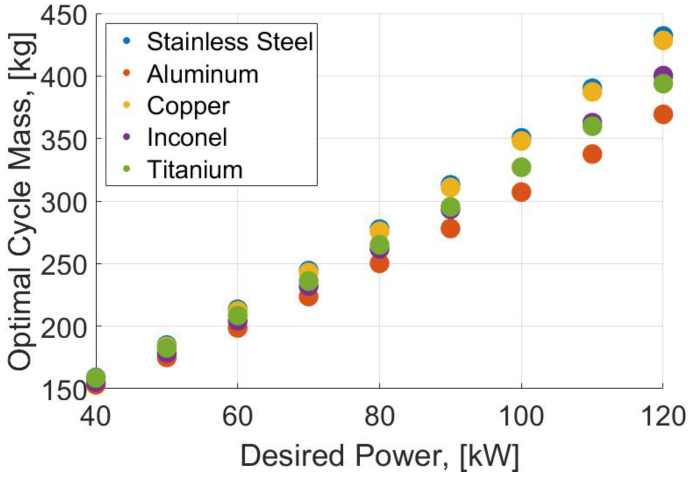
# Modelling

- Modelled cross-flow heat exchanger using effectiveness-NTU method and existing Nu and Eu correlations for low-Reynolds number tube banks
- Optimized HX design to minimize mass, including mass penalty for required fan power
- Integrated model with existing fission power cycle model to minimize overall system mass
- Use of HX instead of radiator reduces predicted system mass by 80%, frontal area by 94%, minimum cycle temperature by 42K
- Optimal HXs have no fins, very small tubes, few rows to minimize required fan pressure rise
- Aluminum HX lightest across range of cycle output power
- HX optimized for average Mars conditions can operate across typical annual range of atmospheric conditions by increasing fan power

| Performance Parameter | Radiator | Air cooling HX |
|---|---|---|
| Mass Flow Rate [kg/s] | 1.14 | 0.664 |
| Heat Rejection Temperature [K] | 404 | 361.8 |
| Minimum Cycle Temperature [K] | 414 | 329 |
| Maximum Cycle Temperature [K] | 900 | 900 |
| Cycle Efficiency | 0.27 | 0.361 |
| Recuperator Mass [kg] | 111 | 29.8 |
| Heat Rejection Mass [kg] | 570 | 26.8 |
| Reactor Mass [kg] | 101 | 102.5 |
| Combined Mass [kg] | 782 | 159 |
| Area, [m$^2$] | 84 | 5.29 (frontal area) |

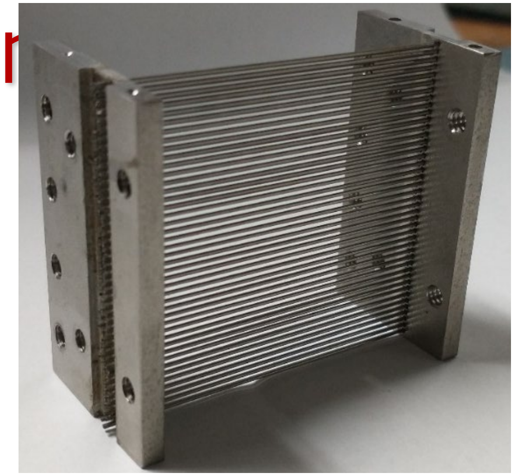
| Optimal HX Geometry | Value |
|---|---|
| Atmospheric Pressure [kPa] | 0.6 |
| Heat Load [kW] | 71.0 |
| Inlet Temp, [K] | 394 |
| Outlet Temp, [K] | 324 |
| Length, [mm] | 1485 |
| Tubes/row | 3100 |
| Tube Diam [mm] | 0.569 |
| Height, [mm] | 3528 |
| Depth, [mm] | 2.3 |
| Tube rows | 2 |
| Fan Power, [W] | 1039 |
| Air-side Pressure Loss, [Pa] | 11.95 |
| Optimal Mass, [kg] | 27.7 |



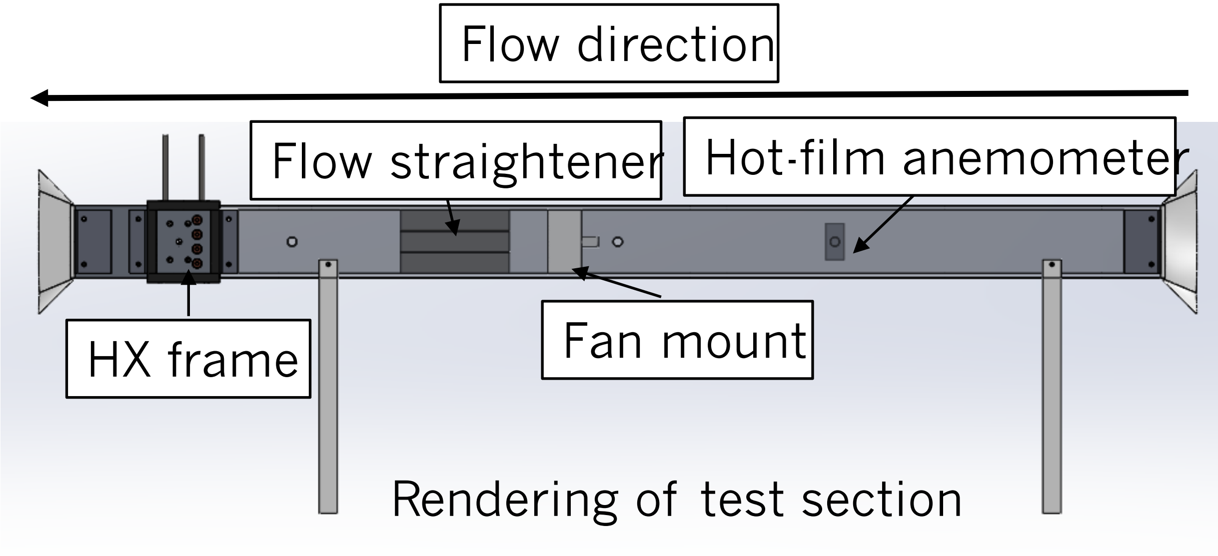
# Experimental Validation

- Constructing low-pressure test facility to operate prototype HXs in Mars-like environment
- Will collect HX pressure loss and conductance data for range of fan speeds, heat loads, and ambient pressures for various HX designs
- Tests will be carried out in a vacuum glovebox filled with low-pressure $CO_2$
- Experimental HX is 1.75”x1.75”, consists of 2 rows of 43 0.02” diameter tubes, will be heated via electrical resistance



Prototype heat exchanger

Vacuum glovebox




Rendering of test section