Large-scale Heat Rejection for Martian Settlements
ThermoMars IV

Sam Ross

1 Overview

- The relatively high latitude of Starship's proposed landing sites results in better-than-baseline performance of all heat rejection options due to lower environment temperatures. This is around 35% less system mass per unit heat rejection than the standard reference value provided.
- Forced-convection heat exchangers provide a far more effective alternative to radiators for heat rejection, particularly at low rejection temperatures where they have up to 90% less total system mass.
  - A conservative reference value for forced-convection heat exchanger Equivalent System Mass is $10\,\mathrm{kg/kW_{th}}$. This compares to a textbook reference of $121\,\mathrm{kg/kW_{th}}$ for generic Martian radiators.
  - Forced-convection heat exchangers require more operating power than radiators, so are even more effective with a less massive power system, but also introduce additional failure risks.
- Thermal energy storage, allowing heat rejection systems to exploit low night-time temperatures, bring no significant advantage for forced-convection heat exchangers but may be worthwhile for radiators.
  - The most mass-effective thermal energy storage option considered is a regolith thermal mass with brine heat transfer fluid, or a brine thermal mass.
- Heat pumps to increase the temperature of heat rejection are not an effective approach for reducing system mass for the majority of use cases.

2 Environmental Assumptions

Temperature data for thermal analysis was taken from the Mars Climate Database [1], which outputs temperatures on both an annual and diurnal cycle. Locations for analysis were based on proposed Starship landing sites [2]. From this, a maximum daily temperature of 235 K was assumed for both the regolith and atmosphere, with a daily minimum of 165 K for the ground and 195 K for the atmosphere. This corresponds to a hot summer day, as this is a worst-case for heat rejection system design. Winter cases, while equally challenging for overall thermal design, do not pose issues for the heat rejection system. These maxima and minima were fit to a sinusoidal-linear model (developed as part of the Syrtis thermal code [3]) with maximum temperatures occuring at 13:20 local time and minimum temperatures just before sunrise.

3 Heat rejection systems

Two practical closed-loop heat rejection alternatives are viable for Martian use - radiators and forced-convection heat exchangers (FCHX). The former uses radiative heat transfer to the cold regolith and Martian sky, the latter convection with the Martian atmosphere driven by a large fan.

Only radiators have been proven for space applications, although FCHX have been investigated for the use of Martian nuclear power systems [4]. One additional heat rejection mechanism is the melting of ice resources in an ISRU plant. This was not considered, as it imposes severe restrictions on landing location and is a fundamentally open-loop approach.

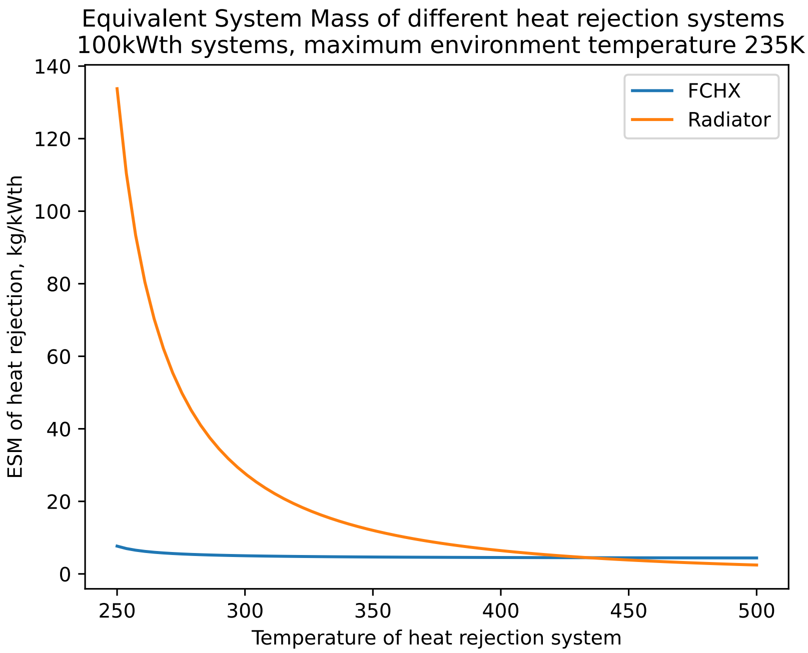

Figure 3.1: The Equivalent System Masses of radiators and FCHX in representative conditions, normalised to kg/kWth

Forced-convection systems have a dramatically lower weight than radiators, due to their substantially greater heat transfer per unit area. A vertically oriented Martian radiator can provide around $300\,\mathrm{W/m^2}$ of heat loss, while heat transfer on a heat exchanger element can exceed $4000\,\mathrm{W/m^2}$. In addition, FCHX do not suffer as large a peformance penalty during diurnal variations as they are only affected by air temperature variations. Radiators additionally suffer a significant performance reduction when illuminated (even obliquely) by sunlight. As such, the equipment weight of a radiator may be as much as thirty times higher than the equivalent heat exchanger.

However, FCHX achieve this performance at the expense of greatly increased power consumption compared to radiators. A radiator system requires power only to pump coolant through the tubing arrays, and so might achieve a coefficient of performance (heat loss divided by power consumption) of 250 or higher. In comparison, the large fans of a FCHX increase power consumption and reduce coefficient of performance to 20-30. Due to the comparatively high baseline mass equivalency of power on Mars, this difference in power consumption reduces the performance gap between radiators and FCHX to 5-10 in relevant operating ranges. The performances of FCHX and radiators are shown in Figures 3.1 and 3.2, for the system Equivalent System Mass at a given maximum environment temperature, and overall system mass across a range of temperatures respectively.

3.1 Heat Rejection Modelling Approach

To model the radiators for this work, a direct physics-based approach was used, based upon the work of John Dzenitis (presented in [5]). The heat balance in $\mathrm{W/m^2}$ was calculated as the

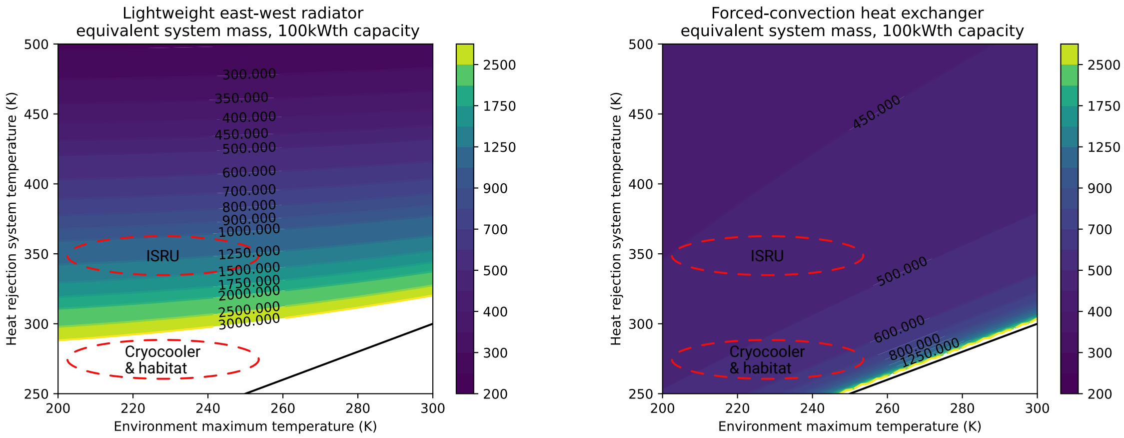

Figure 3.2: The modelled total mass of lightweight radiators and forced-convection heat exchangers in Martian conditions for a 100kWth heat rejection load. Heat exchangers outperform radiators by a factor of 8-10 for habitat-relevant temperatures and by a factor of 2-3 at ISRU-relevant temperatures

greybody emissive heat loss, with heat inputs from direct and indirect solar input as well as thermal absorption from the regolith and atmosphere. This resulted in an overall small error relative to the reporting of Dzenitis' results, particularly when the sunlight falls on the radiator at a highly oblique angle, which was deemed to be acceptable. The pumping power and mass both implemented values and correlations from [5].

Due to the complexity of FCHX, a correlation-based approach was instead used to determine their performance under arbitrary conditions. Select system mass results of Colgan [4] were digitised and converted to functions of cooling power, ambient air density and temperature difference between heat exchanger and ambient. Power consumption due to the forced convection fan and coolant pump were determined in similar fashions. These correlations matched the input data to acceptable accuracy.

These models were used to generate the plots of Figure 3.2 which describes the total system mass (physical mass plus equivalent system mass of the power requirements) of both radiators and FCHX with variations in maximum environment temperature and heat rejection system temperature.

4 Thermal Energy Storage

Thermal energy storage works on the principle of heating a high heat capacity medium during the day, when radiators and FCHX are relatively inefficient, and cooling them using either rejection system at night. This means the rejection system can be sized to reject the overall heat rejection of one day (with the majority occuring at night), rather than sized for the worst-case minute of an operating day.

A thermal energy system must comprise a thermal mass, which can be a fluid or solid. If a solid thermal mass is used then a heat transfer fluid must be used to efficiently heat and cool the thermal mass. Since a thermal energy storage system is inherently high-mass, systems have only been considered where their thermal mass and heat transfer fluid can be obtained from ISRU rather than imported. The three TES options considered are a crushed-regolith thermal mass with either liquid carbon dioxide or brine heat transfer fluid, and a brine thermal mass.

4.1 Effect on Heat Rejection Performance

Using thermal storage to bring the heat rejection system from ”worst-case” to ”average” performance characteristics has a strong positive effect on performance, more so for radiators than heat exchangers. As discussed above, radiators’ mass scales much faster as the radiator temperature and environment temperature approach each other. Using TES to reduce the effective average environment temperature seen by the radiator dramatically improves performance - this is shown in Figure 4.1. In regimes relevant for habitat heat rejection, a 50% reduction in radiator mass is achievable using TES. Radiators have a less pronounced reduction, of around 10% in these temperature ranges, as shown in Figure 4.2. These models still assume a worst-case for diurnal variation (local summer) since storing the accumulated energy for several days or weeks is likely to be infeasible.

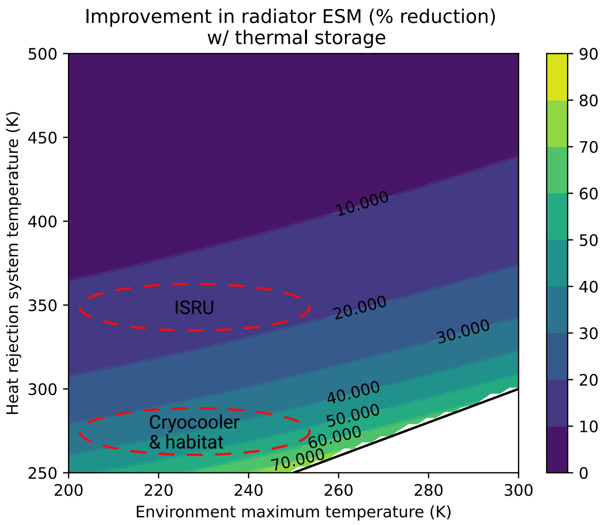

Figure 4.1: Percentage reduction in ESM in heat rejection radiators from using average rather than worst-case loading, as would be obtained with

One alternative that may be considered for TES is running a heat rejection system at night only, with all heat produced during the day stored. This would allow the system to reach lower temperatures without the use of heat pumps. Nighttime air temperatures at the candidate Starship landing sites are around 40K lower than daytime, and the nighttime radiative environment temperature around 53K lower. Rejecting all heat with this approach is unlikely to be optimal since the rejection system’s capacity must be at least double the nominal heat output, but it may be viable for small heat loads that require a low temperature such as carbon dioxide acquisition.

4.2 TES Analysis

Three TES systems were analysed to find their required import mass and power input for operation. These alternatives were crushed regolith thermal mass with liquid/supercritical carbon dioxide heat transfer fluid, crushed regolith with brine heat transfer fluid, and brine thermal mass. Brine is needed, rather than pure water, to achieve the low temperatures needed on the cold side of the TES system. Regolith, carbon dioxide, water and salts can all be obtained from the Martian atmosphere and soil.

Crushed regolith was analysed using techniques for packed bed chemical reactors, particularly the Wakao correlation for heat transfer and Ergun equation for pressure drop. The transient behaviour of the regolith particles was analysed using the Heisler chart for non-dimensional

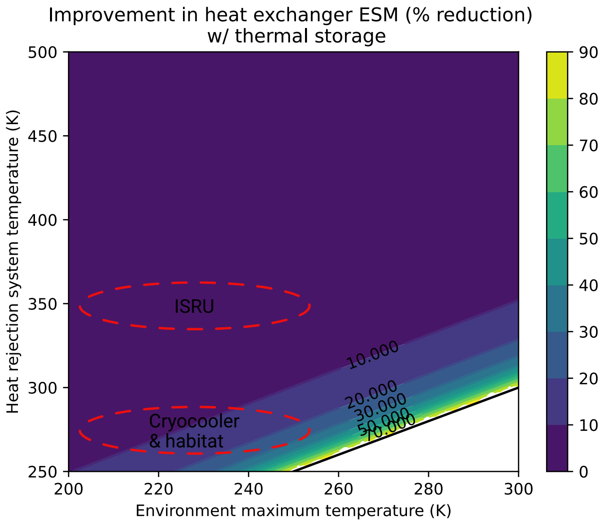

Figure 4.2: Percentage reduction in ESM in heat rejection FCHX from using average rather than worst-case loading, as would be obtained with

convection/conduction transients of a sphere. This assumes a uniform spherical packed bed, which is unlikely to be an accurate reflection for a bed of unprocessed regolith, but is a reasonable approximation for initial design.

Supercritical carbon dioxide and regolith is the highest mass of the options considered, due to the high pressures required to prevent the carbon dioxide boiling when used to cool a hot thermal mass. This high-pressure thermal mass vessl (which must contain around 70 bar) is substantially heavier than the 1 bar required for brine. As a result, the carbon dioxide-based system is around ten times heavier than brine-based regolith. A fully liquid system is of approximate comparable weight to a regolith-brine system, but has substantially smaller volume due to the better volumetric thermal energy density of water. The numerical performance characteristics are summarised in Table 4.1. While regolith and brine performs marginally better than pure brine, the reduced size and simpler operational concept may favour the latter.

System	Thermal mass (kg)	Vessel dimensions	Imported ESM (kg)	ESM performance $kg/kW_{th}h$
Regolith-CO2	30000	1.6m diameter 17m length	4000	4
Regolith-Brine	45000	1.5m diameter 30m length	300	0.3
Brine	18000	3.2m diameter spherical tank	330	0.33

Table 4.1: The performances of different thermal energy storage systems with a capacity of 1MWth-hr, or 100kWth for 10 hours

4.3 Overall Performance Analysis

The data from the above sections was combined to determine the effectiveness of a TES heat rejection system. A 100 kW_{th} average heat load was assumed, with 500 $kW_{th}h$ of storage - equivalent to 12 daytime hours with the heat rejection system at 60% average load, and 12 nighttime hours at 140% load. This is of course a crude analysis and will be more variable with precise diurnal environmental temperature which is not suitable for the current analysis. Each of the three options considered was compared to a no-TES system, for both of radiators and FCHX as the heat rejection system. All of these analyses neglect the weight of the heat exchangers which transfer heat from hot equipment to the cold heat transfer fluid, and from hot heat transfer fluid to the cold heat rejection system, but these are expected to be relatively lightweight compared to the considered components. The results are presented in Table 4.2.

Heat rejection	Storage	Rejection ESM kg/kW_{th}	Storage performance $kg/kW_{th}h$	System mass (kg)
Radiator	None	55.4	N/A	5540
	Regolith/CO2	27.7	4	4770
	Regolith/Brine	27.7	0.3	2920
	Brine	27.7	0.33	2935
FCHX	None	5.6	N/A	560
	Regolith/CO2	5	4	2500
	Regolith/Brine	5	0.3	650
	Brine	5	0.33	665

Table 4.2: The overall system performance for heat rejection systems with different thermal energy storage options

As expected, radiators benefit the most from TES with brine-based energy storage reducing the overall by almost 50%. FCHXs have less performance gain with a non-TES system being marginally lighter under the assumed heat loads (which may not be the case). However the use of thermal storage may not be worthwhile to gain marginal performance at the expense of operational complexity and additional points of failure - particularly for FCHX where gains are small.

5 Heat pumping for improved heat rejection performance

A persistent concept in spacecraft heat rejection is the heat pump assisted radiator, which uses electrical power to increase the temperature of heat rejection and thus reduce the mass of radiators or FCHXs. This is particularly pertinent for high temperature space environments such as the Lunar equator during local day, or missions to the inner planets where the minimum achievable radiator temperature may be greater than the temperature for cooling vehicle systems. To explore the effectiveness of heat pumping for Martian heat rejection a parametric heat pump model based on existing literature [5] was used for analysis.

The heat pump model requires three inputs: efficiency of the heat pump (expressed relative to Carnot efficiency, and generally greater than 100%), specific weight of compressors and specific weight of heat exchangers both relative to transferred heat. Efficiency relative to Carnot was assumed by Hanford and Ewert to be 50% for kilowatt-scale heat pumps in the late 1990s. With advances in technology over the past decades and the assumed performance improvements at larger scales, efficiencies from 50% to 70% were assumed to be realistic. The compressor specific weight follows Hanford and Ewert's analysis, with a weight equal to $31.83P^{0.476}$ with P being input electrical power in kilowatts. This model seems to overpredict compared to commercially available compressor units but is used as a conservative limit. Finally, Hanford and Ewert assume a heat exchanger weight of $2.72\,kg/kW_{th}$. A contact with Reaction Engines Limited (REL), a company specialising in extremely lightweight aerospace heat exchangers, claimed that a 100-fold improvement in weight should be possible with their current technology. This lightweight alternative was used in heat pump modelling.

The results of this analysis are shown in Figure 5.1, with baseline masses of radiators and FCHX rejecting at 270 K shown as a dot. Due to the low mass of FCHX, the power requirement of heat pumps makes them a poor choice in all usage cases. Radiators, having a higher mass and a substantial performance penalty for low rejection temperatures (see Figure 3.1) do benefit from heat pumps under a narrow range of operating conditions - a system which must be cooled to relatively low temperatures, a lightweight heat exchanger and very efficient compressor increasing the rejection temperature by less than 100 K. In this range, the 70%-efficient heat pump is operating with a coefficient of performance between 2.1 and 4.4. Decreasing the mass of the power system would increase this operating range or decrease the required heat pump efficiency, but is unlikely to ever make heat pumps and FCHX a viable combination. Furthermore, including the mass of energy storage needed to operate the heat pump overnight reduces performance - although the lower environment temperatures mean heat pumping may not be needed at night.

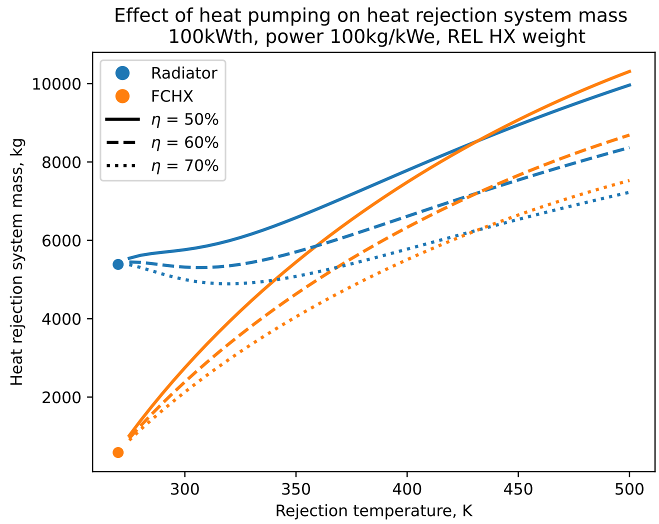

Figure 5.1: The performance of thermal rejection systems utilising heat pumps with a range of performance parameters.

Despite this poor performance there is some argument for including a heat pump as a redundant system for scenarios where heat rejection from essential systems like ECLSS is challenging. A 100 kW heat pump system with 50 K of lift would weigh less than 250kg and would allow ECLSS to operate even during high temperature events like dust storms. This may be preferable as an operational concept compared to alternatives but requires more evaluation. Additionally, heat pumping may be an entirely necessary technology to reduce power demands for inherently low-temperature processes like liquefaction of cryogenic propellants.

References

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