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Assessing the Potential of Heat Pumps to Reduce the Radiator Size on Small Satellites

Nick S. Bennett [1,*] and Brian Lim [2]

[1] Centre for Advanced Manufacturing, University of Technology Sydney, Broadway, Sydney, NSW 2007, Australia
[2] Dandelions, Botany Road, Alexandria, Sydney, NSW 2015, Australia; brian@dandelions.cloud
* Correspondence: nicholas.bennett@uts.edu.au; Tel.: +61-2-9514-2995

Abstract: Future small satellites will demand high-performance on-board electronics, requiring sophisticated approaches to heat rejection beyond simply increasing the radiator surface area. An interesting alternative approach is to increase the surface temperature of the radiator, using a heat pump. In this study, calculations were carried out to compute the theoretical radiator size reduction potential enacted by having a heat pump as part of a satellite's thermal management system. The practical likelihood of a 'typical' vapor compression cycle (VCC) heat pump satisfying theoretical requirements was considered. In agreement with theoretical calculations, employing a 'typical' VCC heat pump could either increase or decrease the required radiator surface area. The choice of heat pump and its design is therefore crucial. A heat pump with a large temperature lift is essential for satellite radiator cooling applications, with the coefficient of performance (COP) being less important. Even with a low COP, such as 2.4, a 'typical' heat pump providing a large temperature lift, close to 60 °C, could reduce the satellite's radiator surface area by a factor close to 1.4. This is a significant potential reduction. The decision on whether to pursue this approach compared to alternatives, such as deployable radiators, should consider the relative complexity, cost, weight, size, reliability, etc., of the two options. The focus of this study is VCC heat pumps; however, the results provide performance targets for less mature heat pump technologies, e.g., caloric devices, which could ultimately be applied in space.

Keywords: heat pump; thermal management; satellite; vapor compression cycle; radiator

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1. Introduction

This coming decade will see an extraordinary increase in the number of small satellites deployed into low-Earth orbit (LEO) [1]. Access to LEO will be readily available, both in terms of the convenience of access and a reduction in flight costs [1]. This will enable an array of new and advanced missions for telecommunications, sensing, surveillance and astronomy, among others. The success of such missions relies on an increase in the functionality of on-board electronics. Often this is accompanied by an escalation of heat generation. In space, the reliability of electronics is of fundamental importance and is closely linked to temperature of operation, i.e., reliability decreases by 50% for every 10 °C increase in operating temperature [2]. Likewise, if elevated temperatures do not damage the electronics, their life span can still be significantly shortened [3].

The cooling of electronic components on satellites usually relies on directing heat to radiators located on the satellite's external surfaces by heat pipes or thermal straps. As cooling demands increase, radiator surface area must increase too, which can involve the use and additional complexity of deployable radiators [4]. An interesting alternative approach is to increase the surface temperature of the radiator, since radiated heat is proportional to the fourth power of temperature. However, this only works when the surface temperature remains less than the safe operating temperature of the on-board electronics, or alternatively, when active thermal management via a heat pump is used to provide a temperature lift between the electronics being cooled and the radiator.

Vapor compression cycle (VCC) heat pumps are used extensively for terrestrial applications, and studies have shown that they could be adapted for use in space. Indeed, there is a small body of previous work on the development of heat pumps for space and low-gravity-use cases:

St. Pierre [5] was the first to patent the design of a heat pump system for zero-gravity applications in 1987. Subsequently, in 1993, Woolley [6] generated a patent on a separation method and apparatus, which was used by Messaros and Verstracte [7] to develop a prototype Joule–Thomson cooler with very high reliability, ideal for space applications.

In 1997, Nikanpour et al. [8] considered the viability of heat pump technologies in terms of their suitability for lander/rover applications, with a 2 kW thermal load. They concluded that VCC and chemical heat pumps had the potential to meet the demanding temperature lift constraints of extracting heat at 276 K and rejecting it at 343 K.

In 2003, Domitrovic et al. [9] developed and tested a VCC heat pump suitable for microgravity, which performed with a COP of 4.5 while maintaining a 30.6 °C temperature lift.

Cole et al. [10] reported, in 2006, preliminary work on a VCC heat pump for microgravity and lunar gravity to operate for heat loads from 5 kW to 15 kW, addressing requirements set out by NASA at that time. It is not clear whether a prototype, testing or further development was subsequently carried out.

In 2014, Bell et al. [11] described component and system models that were used to simulate the performance of a heat pump that could be used to cool the electrical components of a satellite. They found that the COPs that could be achieved were adequate over a wide range of operating conditions.

Brendel et al. [12] published a thorough review of VCC refrigeration in microgravity environments in 2021. This work encompassed not just heat pumps linked to satellites and satellite radiators, but covered an array of uses for refrigeration systems, such as food and medicine cooling for future human spaceflight missions. They concluded that few VCC refrigerators built for low gravity are discussed in the scientific literature, with a shortage of available data. They also identified the difficulty of testing in low-gravity environments as a bottleneck for the robust validation of designs. The review identified examples of other cold storage technologies used in space, such as Stirling cycle, reversed Brayton cycle and thermoelectrics. Subsequently, in 2022, the same group published experimental results from their own VCC refrigeration tests during parabolic flights [13,14].

Recently (2022), Pan et al. [15] carried out a performance evaluation of a VCC heat-pump design for a lunar habitat. This large system was designed for a 100 kW thermal load and the focus was on the impact of lunar dust on radiator performance.

In summary, much of the previous published work on heat pumps for satellite/space applications has tended to focus on the performance characterization of specific designs. However, heat pumps can be constructed to operate in a variety of ways, for example, in terms of their coefficient of performance (COP) or temperature lift.

The novelty of this study is that it provides an assessment for thermal engineers about which heat pump performance characteristics are the most beneficial. This is quantified in terms of radiator size reduction potential. The aim is not only for this to inform system designers about how to design for maximum performance, but it can also provide performance targets for less mature heat pump technologies, e.g., caloric devices, which could ultimately be applied in space.

2. Materials and Methods

The study is split into three parts: First, calculations are carried out to compare the radiator size difference enacted by having a heat pump as part of a satellite's heat rejection system, with a range of theoretical performance data. As a baseline, radiator size is compared to the case where no heat pump is used. The required performance is also compared to theoretical Carnot efficiency. Second, a compilation of performance data from

VCC systems in the scientific literature is plotted and a non-linear fit is derived, describing the performance that could be expected from heat pumps, at least based on their terrestrial performance. Finally, the potential radiator size reduction as a function of performance data is derived and discussed.

2.1. Theoretical Radiator Size Calculations

The internal temperature onboard a satellite in LEO is determined by the thermal balance of incoming and outgoing radiation, as well as internally generated heat. Incoming radiation components consist of direct solar radiation (Q_D), albedo from the Earth (Q_A), and the Earth's infra-red radiation contribution (Q_{IR}). This, in addition to heat from the internal electronics (Q_E), will be balanced by outgoing radiation from the satellites radiators (Q), i.e., $Q = Q_D + Q_A + Q_{IR} + Q_E$. These quantities will determine the internal satellite temperature, yet it is not constant, since each of these amounts will vary dynamically as a function of orbit attitude. The sum of Q_D, Q_A and Q_{IR} usually ranges up to 1400 W/m^2 during LEO, resulting in a temperature range of approximately +70 °C to −20 °C [16], neglecting significant internal heat. The power emitted by the radiator is described by the well-known equation [17]

$$Q = A\varepsilon\sigma\left(T_{rad}^4 - T_{space}^4\right) \quad (1)$$

where A is the radiator's area in m^2, ε is the radiator's emissivity, σ is the Stefan-Boltzmann constant, equal to 5.67×10^{-8} W/m^2 K, T_{rad} is the temperature of the radiator and T_{space} is the temperature of deep space, defined here as 3 K.

Rearranging Equation (1), the temperature of the radiator can be calculated according to

$$T_{rad} = \sqrt[4]{T_{space}^4 + \frac{Q}{A\varepsilon\sigma}} = T_{elec\_rad} \quad (2)$$

where T_{elec_rad} is defined as the temperature of the internal electronics (the subscript "rad" denoting that this applies to the case with radiator cooling). Here, T_{elec_rad} is set equal to T_{rad}, which is of course an upper limit. In practice, T_{elec_rad} is likely to be higher in temperature; the subsequent temperature drop is a result of any heat transfer mechanism employed between the electronics and radiator, e.g., a thermal strap; however, this would be analogous for the system with or without a heat pump and is therefore ignored in this analysis.

For the case where a heat pump is used to remove heat from the electronics, a modification of Equation (2) is necessary to account for the additional heat resulting from the work carried out (W) by the heat pump, equal to $W = Q/COP$, where COP is the coefficient-of-performance of the heat pump. This leads to Equation (3),

$$T_{hp\_rad} = \sqrt[4]{T_{space}^4 + \frac{Q + \frac{Q}{COP}}{A\varepsilon\sigma}} = T_{elec\_hp\_rad} + T_{lift} \quad (3)$$

where T_{hp_rad} is defined as the temperature of the radiator when a heat pump is used and $T_{elec\_hp\_rad}$ is the temperature of the internal electronics (the subscript "hp_rad" denoting that this applies to the case using a heat pump and radiator). The additional term T_{lift} recognizes that in this case the radiator temperature would be elevated according to the temperature lift imposed by the heat pump.

In the first part of this study, T_{elec_rad} and T_{rad} were calculated using Equation (2) by setting Q = 650 W, A = 1 m^2 and σ = 0.95, giving a temperature of 58.3 °C. $T_{elec\_hp\_rad}$ was then set equal to 58.3 °C and the non-linear solver engine in Microsoft Excel was used to calculate the required radiator area for combinations of heat-pump COPs and temperature lifts, through the range 0 < COP ≤ 12 and temperature lifts of either 10 °C, 20 °C, 30 °C or 40 °C.

In a second step, the radiator area was set equal to 1 m^2 and the solver was used to calculate the required COP to make $T_{elec\_hp\_rad}$ equal to 58.3 °C, as a function of temperature lift, in the range 0 °C < $T_{lift} \leq 40$ °C.

2.2. Heat-Pump Performance Data

In the second part of the study, a compilation of VCC heat pump performance data from 22 studies in the scientific literature was extracted and plotted, covering a range of COPs and temperature lifts. A polynomial best-fit line was formulated in the form y = intercept + Ax + Bx^2. This was carried out using the Fitting Tool in OriginPro software.

2.3. Radiator Size Reduction Potential

In the final part of the study, the polynomial fit devised in Section 2.2 was used to create pairs of COP and T_{lift} data as inputs into Equation (3). Again $T_{elec\_hp\_rad}$ was set equal to 58.3 °C and Excel's non-linear solver engine was used to calculate the radiator size required in each case to reject the necessary quantity of heat (=Q + (Q/COP)). In all cases, an area ratio was calculated to indicate the potential radiator size reduction by dividing the area of the radiator with no heat pump, i.e., 1 m^2, by each of the calculated areas for the various heat-pump performance conditions.

3. Results

3.1. Theoretical Radiator Size Calculations

Figure 1 is a plot of a theoretical calculated radiator area versus heat pump COP. Each line represents the area–COP relationship for a constant heat pump temperature lift of either 10 °C, 20 °C, 30 °C or 40 °C. In all cases, the calculated radiator area is achieving a temperature of 58.3 °C for $T_{elec\_hp\_rad}$. The radiator area can be compared to that which is required when T_{elec_rad} is also equal to 58.3 °C, i.e., A = 1 m^2.

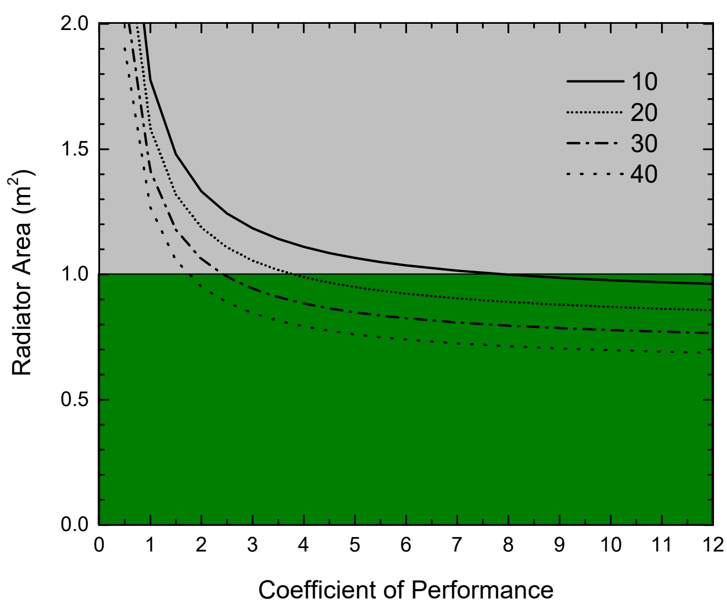

Figure 1. Theoretical radiator area versus heat pump coefficient of performance (COP). Each line represents the relationship for a heat pump temperature lift of either 10 °C, 20 °C, 30 °C, or 40 °C. In all cases, the calculated radiator area gives a surface temperature of 58.3 °C. The radiator area is compared to the radiator area with no heat pump, i.e., 1 m^2.

The reader can observe that there are both cases where theoretically the heat pump can reduce the required radiator surface area (green zone), and where it actually increases the required radiator size. The latter tends to occur for a very low heat pump COP. What is clear from the figure is that a heat pump with a large temperature lift is essential for satellite radiator cooling applications, with the COP being less important. For example, when the temperature lift is only 10 °C, a COP of approximately 7.6 is required for the heat pump to bring a net benefit in terms of radiator size reduction. However, raising the COP still higher, say to 12, is of limited benefit. One can see that the solid line is relatively flat at that point and even extremely high COPs (>>12) will yield next-to-no additional reduction in radiator size. In contrast, it is apparent that increasing the temperature lift has a much larger relative benefit. For example, if comparing the solid and dotted lines, raising the temperature lift from 10 °C to 20 °C has the same impact as increasing the COP from 3.6 to 7.6.

In Figure 1, each of the COP–temperature lift requirements are purely hypothetical. There is no consideration of whether these values can be achieved by heat pumps either theoretically or practically. In Figure 2, the theoretical possibility is addressed by comparing the required heat pump performance to Carnot efficiency. The dotted line shows the COP calculated for a heat pump operating with Carnot efficiency, i.e., $COP = T_C/(T_H - T_C)$. Here, T_C was set equal to 331.45 K, to match 58.3 °C—the value of both $T_{elec\_hp\_rad}$ and T_{elec_rad}. T_H was varied to give the desired temperature lift ($T_{lift} = T_H - T_C$).

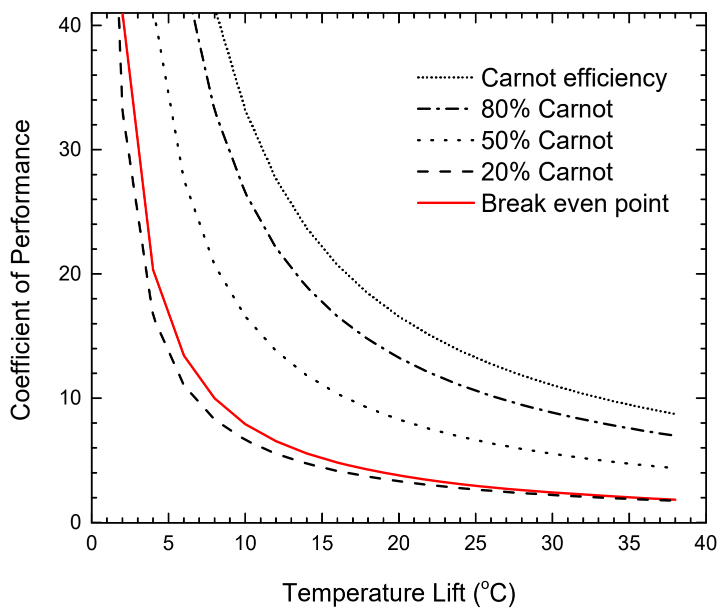

Figure 2. Coefficient of performance (COP) versus temperature lift for heat pumps operating at 100%, 80%, 50% and 20% of the theoretical Carnot maximum. The red (solid) line represents the required performance to make the radiator surface temperature equal to 58.3 °C when a heat pump is used. T_C = 331.45 K.

Also plotted in Figure 2 are the COP values for heat pumps operating at 80%, 50% and 20% of the theoretical maximum. The red (solid) line represents the required COP to make $T_{elec\_hp\_rad}$ equal to 58.3 °C, as a function of temperature lift, with T_{lift} set in the range 0 °C < $T_{lift} \leq 40$ °C, and the radiator area set equal to 1 m^2. Figure 2 shows that the so-called break-even point occurs close to the 20% Carnot efficiency line. This suggests that not only should it be possible to source a heat pump with suitable performance to break-even in terms of radiator size, it should also be feasible to design a heat pump that can bring a significant radiator size reduction.

3.2. Heat-Pump Performance Data

A deeper insight can be gained into the practical likelihood of developing a suitable heat pump by investigating the performance data in the scientific literature. A total of 22 research articles were accessed [18–39], and experimental VCC heat pump performance metrics were extracted. This led to 195 separate data points, which are presented in Figure 3 as COP versus temperature lift. It should be noted that (i) all of the data come from heat pumps that were designed for and operated under terrestrial conditions; (ii) while the temperature lift is correct, the top temperature on the high side of these heat pumps is generally lower than what would be required for the satellite radiator surface temperature, i.e., being better suited to domestic heating applications; and (iii) that data from other types of heat pump are not considered. The polynomial best-fit line to the data has the equation $y = 10.25769 + 0.25214x + 0.00202x^2$.

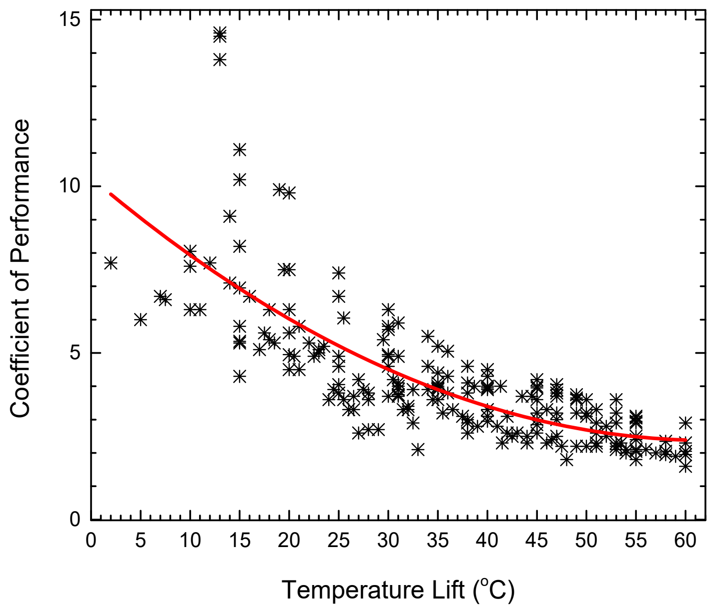

Figure 3. Symbols represent a total of 195 data points from 22 experimental research articles [18–39] demonstrating vapor compression cycle heat pump performance metrics, plotted as the coefficient of performance (COP) versus temperature lift. The red (solid) line is a polynomial best-fit line with equation $y = 10.25769 + 0.25214x + 0.00202x^2$.

3.3. Radiator Size Reduction Potential

Using the polynomial fit, COP and T_{lift} data were input into Equation (3). An area ratio was calculated to indicate the potential radiator size reduction by dividing the area of the radiator with no heat pump, i.e., 1 m^2, by each of the calculated areas for the various heat pump performance conditions. In Figure 4, the area ratios are plotted versus the COP and temperature lift that might be expected for a 'typical' heat pump.

Figure 4 demonstrates that employing a 'typical' heat pump could either increase or decrease the required radiator area onboard a satellite. The choice of heat pump and its design is therefore crucial. Choosing a heat pump with a relatively high COP but lower temperature lift results in a worse radiator reduction potential. For example, even with a high COP, close to 10, the associated temperature lift of a 'typical' heat pump would mean that a larger radiator would likely be needed if a heat pump was used. In contrast, even with a low COP, such as 2.4, a 'typical' heat pump could provide a large temperature lift, close to 60 °C, and therefore it is feasible that the satellite's radiator could be reduced by a factor close to 1.4. This is a significant potential reduction.

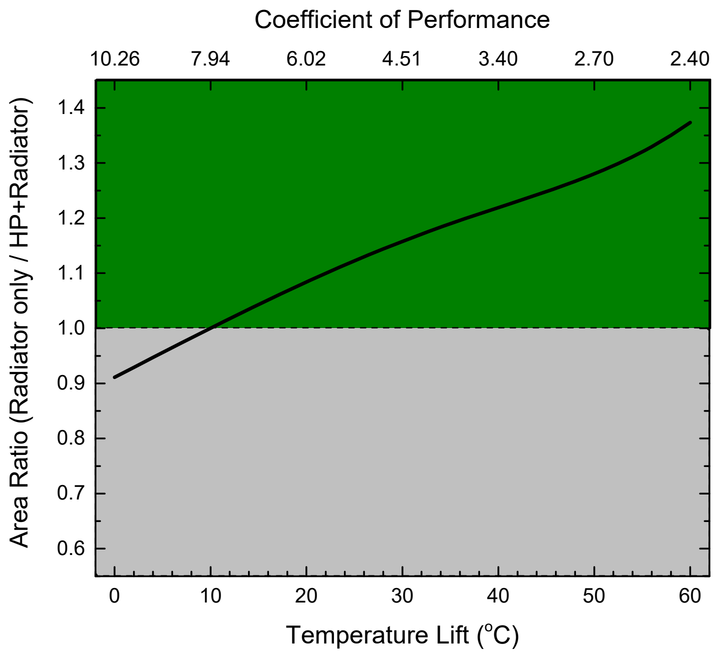

Figure 4. Area ratios plotted versus the coefficient of performance and temperature lift that might be expected for a 'typical' heat pump. Area ratios indicate the potential radiator size reduction by dividing the area of the radiator with no heat pump, i.e., 1 m^2, by each of the calculated areas for the various heat-pump performance conditions using the polynomial equation $y = 10.25769 + 0.25214x + 0.00202x^2$ from Figure 3.

3.4. Discussion

Ultimately, it is likely that for high performance electronic components, which generate significant heat, a heat pump could be designed to either reduce the required radiator size, or indeed to provide enhanced heat rejection without reducing the size of the radiator.

It is likely that some of the VCC heat pump designs already developed and tested for space, such as that by Domitrovic et al. [9], could provide a radiator size reduction. In their case, the heat pump performed with a COP of 4.5, while maintaining a 30.6 °C temperature lift. By cross-checking this information with Figure 4, we can observe that it not only agrees well with the performance metrics of a 'typical' heat pump in terms of COP and temperature lift, but it also could produce a radiator reduction of about 15%.

It should be noted that while previous heat pump designs have been tested to demonstrate their suitability for micro-gravity (such as reference [9]), despite their temperature lift being adequate, the top temperature on the high side of these heat pumps is generally lower than what would be required for the satellite radiator surface temperature. This difference will be crucial to consider when designing a suitable satellite heat pump system, e.g., when choosing a suitable refrigerant. This requirement is unlikely to hinder the feasibility of the heat pump idea since refrigerants exist, e.g., carbon dioxide (R744), which can be used to reach higher output temperatures—this is something already exploited in heat pump water heaters.

Creating a custom VCC heat pump for small satellites would require the additional complexity of creating a more sophisticated heat pump thermal management system and the decision on whether to pursue this route compared to a deployable radiator system might ultimately require consideration of the relative complexity, cost, weight, size, reliability, etc., of the two options.

The focus of this study has been VCC heat pumps; however, this study could also provide performance targets for less mature heat pump technologies, e.g., caloric devices, which could ultimately be applied in space.

An example is a solid-state heat pump such as thermoelectric Peltier modules. These are solid-state heat pumps that reject heat from one side of the module to the other, while consuming electrical energy. Peltier modules have found a variety of applications terrestrially. Their solid-state nature—and lack of moving parts—makes them attractive for space applications due to increased reliability, lifetime and reduced vibration. On the other hand, Peltier devices have a much lower coefficient of performance than competing active cooling technologies, which often stifles their uptake in applications. As an initial test of their suitability, a review of performance data for commercial modules available from a range of vendors was carried out [40–42]. This considered both single modules and multi-stage architectures, where often the temperature lift is significantly higher. Our initial market scan suggests that no currently available products would have a combination of COP and temperature that would make them suitable as a heat pump for radiator size reduction. Extensive research into high performance thermoelectric materials is underway, suggesting a possibility in the future [43].

Caloric heat pumps are a less mature technology that could also be considered. Caloric phenomena occur where a phase transition causes an entropy change in a solid refrigerant, creating an adiabatic temperature change. The phase transition is prompted by a change in an external field applied to the material. Changes can result from a changing magnetic field, electric field, mechanical stress or hydrostatic pressure, creating various caloric effects, i.e., magneto-caloric, electro-caloric, elasto-caloric and baro-caloric. By allowing heat generated during phase transition to be rejected, but then allowing the solid refrigerant to absorb heat from the system during the reverse transition, a heat pump cycle can be built on either of these caloric effects [44]. In terms of their respective viability for space heat pump applications, the current state-of-the-art for elasto- and electro-caloric devices suggests that their demonstrated heating/cooling power is currently too low [45,46]. There are very few studies on the experimental validation of baro-caloric heat pumps, and this technology is currently far from the required technology readiness to be considered for space applications [47]. Magneto-caloric heat pumps might be a feasible technology for space-based heat pumps, given some of the studies in the scientific literature. For example, the work of Johra et al., used a cascaded magneto-caloric design to numerically demonstrate a heat pump capable of generating a 50 °C temperature lift and a COP of 2.78 [48]. These performance characteristics are in line with the performance of VCC heat pumps, and if experimentally demonstrated, would meet the requirements of a heat pump able to reduce the radiator size on a satellite.

4. Conclusions

Calculations were carried out to compute the required radiator size enacted by having a heat pump as part of a satellite's heat rejection system, for a range of theoretical heat-pump performance data. As a baseline, this was compared to the radiator size where no heat pump was used, with the ratio defined as the 'radiator size reduction potential'. There were both cases where, theoretically, a heat pump could reduce the required radiator surface area and where it increased the required radiator size. Theoretically, a heat pump with a large temperature lift is essential for satellite radiator cooling applications, with the COP being less important.

The practical likelihood of developing a suitable heat pump was considered by investigating the experimental performance data for VCC heat pumps. In agreement with theoretical calculations, employing a 'typical' VCC heat pump could either increase or decrease the required radiator area. The choice of heat pump and its design is therefore crucial. Choosing a heat pump with a relatively high COP but lower temperature lift results in a worse radiator reduction potential. In contrast, even with a low COP, such as 2.4, a 'typical' heat pump providing a large temperature lift, close to 60 °C, could feasibly reduce the satellite's radiator size by a factor close to 1.4. This is a significant potential reduction.

Creating a custom VCC heat pump for small satellites would require additional complexity. The decision on whether to pursue this route compared to an alternative, such as a deployable radiator, would require the consideration of the relative complexity, cost, weight, size, reliability, etc., of the two options.

The focus of this study has been VCC heat pumps; however, this study also provides performance targets for less mature heat pump technologies, e.g., caloric devices, which could ultimately be applied in space.

Future work should consider the transferability of terrestrial heat pump technologies for space applications and assess their relative suitability. Likewise, heat pumps should be compared to alternatives, such as deployable radiators, by comparing the relative financial cost, complexity, weight, size, reliability, etc.

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