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Review

# Review of vapor compression refrigeration in microgravity environments

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ABSTRACT

Using a vapor compression cycle for cooling in microgravity environments was already suggested in the 1970s to leverage the high coefficient of performance. Since then, only a few systems have operated in microgravity with scarce documentation of these flights. The lack of measured data and detailed documentation makes identifying the necessary next steps difficult for researchers entering the field of refrigeration in space. This paper provides a review of available literature for vapor compression systems flown in microgravity by outlining the history of vapor compression devices in space and presenting performance data. Moreover, gaps in the literature are highlighted and open questions are posed based on the reviewed material. Next steps of research are suggested to support and ultimately achieve reliable vapor compression refrigeration in space. Calculating equivalent masses for a fair comparison of different microgravity cooling technologies is proposed by capturing both energy consumption and used volume.

# Examen d'un système frigorifique à compression de vapeur dans les environnements en microgravité

*Mots-clés:* Cycle à compression de vapeur; Froid [artificiel]; Cycle diphasique; Microgravité; Gravité nulle; Vaisseau spatial

## 1. Introduction

Space exploration is currently supported by entities in politics, industry and academia. The global space economy was worth well above 300 billion USD in 2015, with approximately a quarter associated with government budgets and the rest being commercial revenues (Bryce Space 2017; Bockel, 2018). Frequent flights to the Moon, human missions to Mars and extraterrestrial habitats are primary goals for current space exploration development activities. One of the primary challenges in achieving these goals is the development of lighter weight, more energy efficient, and resilient thermal management systems for spacecraft.

To date, most spacecraft have been able to reject heat directly to the cold of space (via radiation) without a refrigeration system. However, future missions in hotter environments, certain regions of the Moon for example, will be different (Ewert and Bergeron, 2005). Even today, spacecraft often provide a refrigerated space to preserve biological samples or for other scientific purposes. Human space exploration missions or a trip to Mars will require a refrigerated space for long-term food storage. Current methods store astronaut food at ambient temperatures where it experiences a decay of nutritional value after long time periods (Smith et al., 2009; Cooper et al., 2017). Radiating against deep space is the most straightforward way to achieve low temperatures, e.g. the International Space Station (ISS) has pumped liquid ammonia and water loops to cool devices and space inside the ISS. However, depending on the desired cooling temperature, the radiator size and mass for heat rejection can become excessive.

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**Abbreviations**

| | |
|---|---|
| $A$ | surface area [m$^2$] |
| $CFC$ | chlorofluorocarbon, class of refrigerants |
| $CHF$ | critical heat flux |
| $COP$ | coefficient of performance [-] |
| $EOR/F$ | enhanced orbiter refrigerator/freezer |
| $f$ | subscript, liquid |
| $FBCE$ | flow boiling and condensation experiment |
| $Fr$ | Froude number [-] |
| $g$ | gravity [m/s$^2$] or as subscript for gaseous |
| $GLACIER$ | general laboratory active cryogenic ISS experiment refrigerator |
| $h$ | heat transfer coefficient [W/(m$^2 \cdot$ K)] |
| $HCFC$ | hydrochlorofluorocarbon |
| $ISS$ | International Space Station |
| $l$ | length [m] |
| L | liter |
| $M$ | mass of device [kg] |
| $M_{sys}$ | mass of refrigeration system [kg] |
| $M_{tot}$ | total equivalent system mass [kg] |
| $\Delta M_\eta$ | mass difference due to energy efficiency |
| $LSLE$ | life sciences laboratory equipment refrigerator/freezer |
| $MELFI$ | minus eighty-degree laboratory freezer for ISS |
| $MERLIN$ | microgravity experiment research locker/incubator |
| $MIR$ | space station operated by Soviet Union |
| $NASA$ | National Aeronautics and Space Administration |
| $OR/F$ | orbiter refrigerator/freezer |
| $\dot{Q}$ | heat transfer/cooling capacity [W] |
| $R$ | thermal resistance [K/W] |
| $RC$ | refrigerated centrifuge |
| $Re$ | Reynolds number [-] |
| $Ref$ | reference |
| $SABL$ | space automated bioproduct lab |
| $SBIR$ | small business innovation research |
| $SKV$ | air-conditioning unit in module Zvezda on ISS |
| $SP$ | subscript, single phase |
| $STS$ | space transportation system |
| $T_h$ | heat sink temperature [°C] |
| $T_l$ | heat source temperature [°C] |
| $TP$ | subscript, two-phase |
| $TSER$ | two-phase system experiment rack, part of the Chinese manned space program |
| $TRL$ | technology readiness level |
| $u$ | velocity [m/s] |
| $UA$ | UA-value of heat exchanger [W/K] |
| $USD$ | US-Dollar |
| $V_{ex}$ | external volume [L] |
| $V_{in}$ | internal volume [L] |
| $VCC$ | vapor compression cycle |
| $VCD-FE$ | vapor compression distillation flight experiment |
| $V_{sys}$ | total pressurized volume occupied by refrigeration system [$m^3$] |
| $\dot{W}$ | power draw [W] |
| $\dot{W}_{avg}$ | average electrical power [W] |
| $We$ | Weber number [-] |
| $X$ | Martinelli parameter [-] |

*Greek symbols*

| | |
|---|---|
| $\eta_{2nd}$ | second law efficiency [-] |
| $\lambda_{el}$ | equivalent mass per average electrical power [kg/kW$_{\mathrm{el}}$] |
| $\lambda_v$ | equivalent mass for volume [kg/m$^3$] |
| $\rho_g$, $\rho_f$ | density of gas, density of liquid [kg/m$^3$] |
| $\phi^2$ | two-phase frictional multiplier |

Therefore, there is a growing interest in refrigeration systems for space, which use cooling loops provided by the radiators as their heat sink. Fig. 1 shows the approximate configuration found on the ISS. Ammonia is used in the radiators, which exchanges heat with a water-cooling loop, which may be used by internal devices as a heat sink.

In particular, the demand for cryogenic temperatures, often for enabling sensitive sensors to collect critical measurements, has brought almost all types of cryogenic coolers into space. These are well summarized in Ross (2006) and Bar-Cohen (2016). The author of Ross (2006) writes that "*perhaps hundreds of millions of dollars have been expended examining every conceivable technology capable of providing long-life cooling. Stirling, Vuilleumier, Brayton, magnetic, sorption, and pulse tube – all have been researched in great depth.*" Led by reasons to enable measurements, these technologies have been investigated for application to refrigerated spaces in various scientific purposes. Along with cryogenic coolers, thermoelectric coolers and incubators are used in spacecraft as a reliable gravity independent technology. A few example devices are listed in Table 1 with temperature ranges and technology employed. Glacier was able to reach temperatures around −180 °C but was controlled to −160 °C to prevent oxygen condensation (Ruemmele, 2020).

The mentioned technologies can claim high technology readiness levels (TRLs) but are outperformed in energy efficiency by a vapor compression cycle (VCC) for the traditional refrigerator/freezer temperature range. VCCs exploit the phase change of a refrigerant to achieve high cooling or heating coefficient of performances (COPs) with their need pointed out multiple times in the literature (Chiaramonte and Joshi, 2004; Motil and Singh, 2004; Anderson, 2006; Hurlbert et al., 2004). Considering the decades of conducted microgravity two-phase flow research to support development of space borne two-phase cycles, it is surprising that vapor compression refrigerators are not yet standard in space. An important reason for the low TRL of two-phase cycles is the lack of accessible microgravity testing. Current facilities for experiments in reduced or microgravity are costly and difficult to access. Approaches leverage drop-towers and parabolic flights for short microgravity durations, while sounding rockets and spacecraft or space stations support longer and sustained microgravity environments (Brendel et al., 2019). None of these approaches achieves the microgravity environment by escaping the effect of Earth's gravitational field. Instead, due to free fall conditions, the payloads experience microgravity, which (Antar and Nuotio-Antar, 1993) describes as *dynamic weightlessness*.

Looking at flight experiences of the vapor compression cycle, efforts in the last 20 years have decreased rather than increased. Researchers wanting to make progress on this topic face great difficulties obtaining a clear overview of completed work. The few reports of VCC space flights are rarely included within indexed databases, are scattered over five decades and have never been summarized, making a review paper very beneficial. This paper summarizes existing information on VCC refrigeration under microgravity and poses open questions that should be addressed in future research efforts.

Over 300 publications and reports were considered for the review and many experts were consulted in gathering information. A large number of theoretical publications suggesting the use of vapor compression cycles in microgravity was not included in this review to maintain the focus on devices that have flown in microgravity.

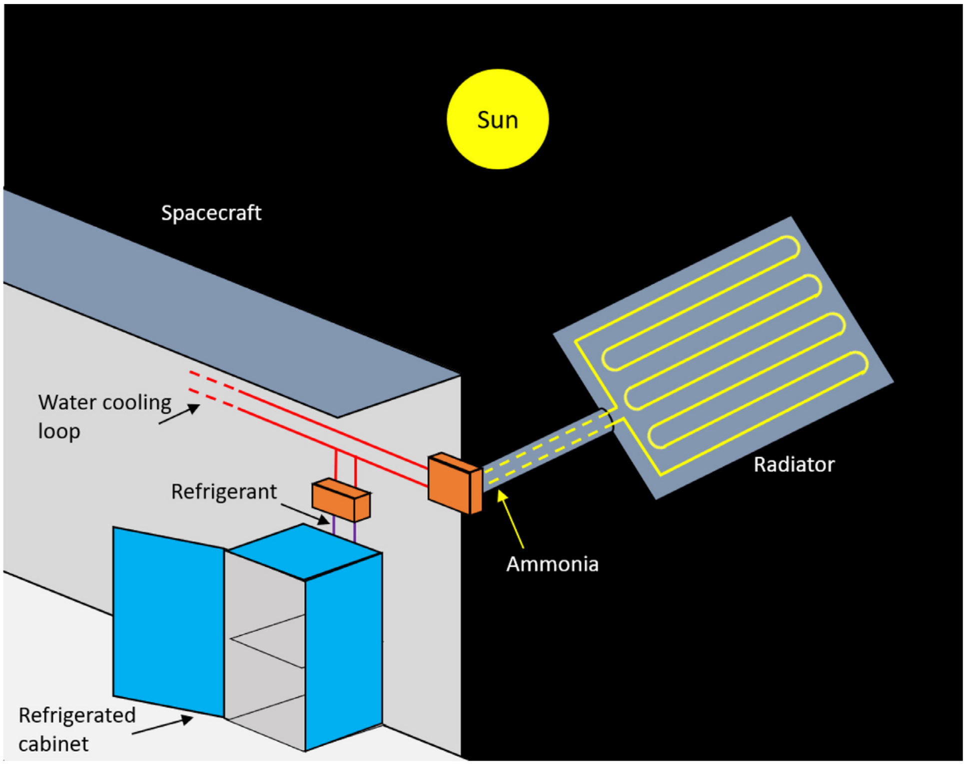

**Fig. 1.** Sketch of thermal connection of a refrigerated cabinet, internal cooling loop and radiator.

**Table 1**
Examples of devices for refrigeration in space.

| Name | Temperature range | Technology | Reference |
|---|---|---|---|
| Biorack | −17 °C to + 8 °C | Thermoelectric | (Manieri et al., 1996; Hartley, 2018) |
| MELFI | −95 °C to + 2 °C | Reversed Brayton | (Ravex et al., 2005; Hartley, 2018) |
| MERLIN | −20 °C to + 48 °C | Thermoelectric | (Hartley, 2018; Rouleau, 2019) |
| Polar | −95 °C to + 4 °C | Stirling | (Hartley, 2018; Rouleau, 2019) |
| GLACIER | −160 °C to + 4 °C | Stirling | (Hartley, 2018; Rouleau, 2019) |
| SABL | −5 °C to + 43 °C | Thermoelectric | (Niederwieser et al., 2015) |

## 2. History of vapor compression refrigeration in microgravity

Fig. 2 shows a timeline of documented events in the history of VCC in microgravity while Table 2 provides more details and references. All information is according to the best knowledge of the authors.

The idea to operate a terrestrial four component VCC in space emerged after the immense efforts of landing a human on the moon in the 1960s. One set of authors suggested a VCC with a direct condensing radiator (Williams et al., 1973) for microgravity. The authors flew the custom designed condensing radiator with a flow pattern visualization experiment on Keplerian trajectories using a C-135 aircraft in 1973. Three years later, a 400 page report was written about various cooling technologies and their applicability to three different zero-G cooling applications, including vapor compression technology in the final recommendations (Mosinskis, 1976). However, flight experiments are not reported. The first documented vapor compression refrigerator in space flew in 1982 supporting both freezer and refrigeration temperatures (Lipson, 1982). An off-the-shelf VCC with an oil-free diaphragm compressor was selected. All objectives were achieved satisfactorily and VCC technology was listed as being quite feasible for zero-gravity and development in this area should continue.

The next refrigerators in space flew multiple times during the 1990s with satisfactory performance and had the abbreviations OR/F, EOR/F and LSLE (see Table 2 for more details). Fig. 3 shows a picture of two LSLE refrigerators. Shuttle flight STS-40 was the first flight for OR/F and LSLE refrigerator/freezers. While no performance data was published from the flights, a few sources provided insights into the machines. First, NASA published hardware guides, which are very brief descriptions of the systems (NASA, 2018a,b). Secondly, a project overview (Cairelli, 1995) and a technology assessment (Gaseor et al., 1996) both briefly describe OR/F, EOR/F and LSLE and state that "*The systems have an expected life of a few hundred hours and are reconditioned between missions*". In the comparison of cooling technologies for spacecraft (Gaseor et al., 1996), the authors conclude that VCC refrigeration is not suitable because of demands for "*substantially longer life, higher reliability, less maintenance and no CFCs.*" Although the coolant mechanisms performed satisfactorily, the report also notes that frost accumulation was a significant problem with the potential to increase maintenance work of the crew or reduce efficiency.

On STS-40 a manufacturing problem led to an OR/F fan motor burnout and melted a plastic component that released a noxious gas (Schmalholz, 2020). On the same flight, but probably unrelated, there was a refrigerant leak into the secondary containment; however, refrigerant was not released into the cabin (Schmalholz, 2020). The LSLE units also had problems on STS-40 due to moisture in the refrigerant loop freezing at the capillary tube, but operators were able to keep at least one unit running at all times and complete the mission (Schmalholz, 2020). Accord-

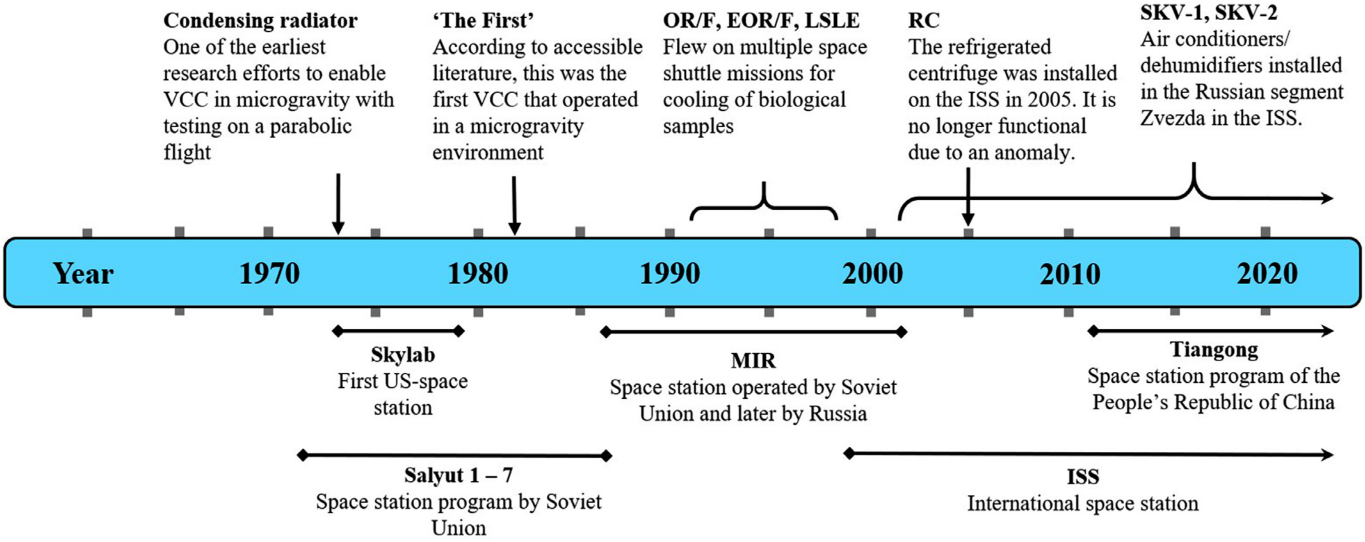

**Fig. 2.** History of vapor compression cycles in microgravity.

**Fig. 3.** LSLE refrigerators were flown in the 1990s on space shuttles.

ing to Boyle and Heimann (1992)), both OR/F and LSLE showed anomalies during SLS-1 and temporarily lost their cooling capability. The refrigeration cycle in these devices had to be double contained because a release of refrigerant into the cabin would have resulted in exceedance of the Spacecraft Maximum Allowable Concentration (SMAC) of the gas. Shuttle post-flight reports (Goodman et al., 2015) state that these systems produced notable vibration and acoustic noise, the former being loud enough to interfere with flight crew conversations and even causing headaches. It appears that the setbacks of OR/F, EOR/F and LSLE, while not directly related to VCC operation in microgravity, may have led to reduced confidence in VCC technology for space applications.

The next remarkable device is the VCD-FE (vapor compression distillation flight experiment), a device to generate potable water from urine (Hutchens and Graves, 2004). Although not a cooling cycle, the machine is included here because it connects an evaporator, compressor and condenser, all present in a VCC. The experiment was conducted on STS-107 in 2003, which was the tragic last flight of space shuttle Columbia (and also carried EOR/F; Schmalholz, 2020). For this reason, a large portion of the experimental data was lost, but the authors still concluded from directly transmitted data that "*the technology is well suited for microgravity operation.*" The machine stands out by its heat exchanger design: "*To achieve phase separation in microgravity, the evaporator/condenser and product water collector rotate.*" The urine processor assembly was installed on the ISS, has operated successfully since 2008 on the ISS and reclaimed more than 18,400 L of water (Carter et al., 2019). The duty cycle is around 25% and the evaporator rotates at 220 RPM. When the machine is turned off, a demister prevents liquid from migrating into the suction line.

**Table 2**
References of vapor compression refrigeration in microgravity.

| Name/Project | Flight/Launch/Facility | Temp. range and Fluid | Compressor | Application | Comments |
|---|---|---|---|---|---|
| N/A | Mission participation1982: STS-4 | Freezer −13.8 °C to 18.8 °C / Condenser 36.4 °C to 40.7 °C R12 (Lipson, 1982) | Oil-free diaphragm compressor (Lipson, 1982)<br>Single stage, 100 BTU/h (Schmalholz, 2020) | Life Sciences experiments and future need for food storage (Lipson, 1982) | Completed three functional test objectives: capture freezer heat exchanger dynamics, long term freezer temperature stability, and freeze a sample, store, and return to earth frozen (Lipson, 1982) |
| OR/F (Orbiter Refrigerator/ Freezer) | Mission Participation (OR/F or EOR/F, 1991 - 1998):<br>STS-40, STS-47, STS-55, STS-58, STS-71, STS-95 Mir-18 (NASA 2018), STS-107 (Schmalholz, 2020) | −20°C to 4°C (NASA, 2018)<br>CFC refrigerant (Cairelli, 1995) | Oil-free diaphragm compressor (Jimenez, 2019),<br>2-stage, 4 cylinders (Schmalholz, 2020) | Biological samples and solutions. (NASA 2018) | Internal volume: 36 L (NASA, 2018)<br>Released noxious gas during STS-40 (Matney et al., 1993) due to a manufacturing problem resulting in a melted component (Schmalholz, 2020). |
| EOR/F (Enhanced Orbiter Refrigerator/Freezer) | | −22°C to 10°C (NASA 2018)<br>CFC refrigerant (Gaseor et al., 1996),<br>HCFC for linear compressor (Gaseor et al., 1996) | Oil-free diaphragm compressor (Cole et al., 2006; Jimenez, 2019)<br>2-stage, 4 cylinders (Schmalholz, 2020). A linear compressor flew once (Jimenez, 2019) on IML-2 (Gaseor et al., 1996). | Biological samples and solutions. (NASA 2018) | Based on OR/F but subjected to enhancements for example on compressor/motor, electronics, acoustic padding (NASA 2018) and condenser (Schmalholz, 2020). |
| LSLE (Life Sciences Laboratory Equipment Refrigerator/ Freezer) | Mission participation (1991 - 1998): STS-40, STS-42, STS-47, STS-58, STS-71, STS-78, STS-90, Mir-18 (NASA 2018) | −22°C to 10°C (NASA 2018)<br>CFC refrigerant (Gaseor et al., 1996) | Oil-free diaphragm compressor (Jimenez, 2019),<br>2-stage, 4 cylinders (Schmalholz, 2020) | Freeze perishable samples (blood, urine, saliva). (NASA 2018) | Internal volume: 71 L. Two modules were often flown together, one in freezer and one in refrigerator mode (NASA 2018). |
| VCD-FE (Vapor compression distillation flight experiment) | STS-107, Successor currently operating aboard ISS (Carter et al., 2019) | Contaminated water at sub-atmospheric pressure (Carter et al., 2019) | Oil free rotary lobe compressor (Carter, 2019) | Urine processor for potable water generation | Not a VCC, but an evaporator and a condenser were coupled through a compressor. Successful microgravity operation until present (Carter et al., 2019). Both heat exchangers and product water container rotate to achieve phase separation. |
| SKV-1/SKV-2 | ISS | Exact temperature range unknown<br>R218 | Micro-compressor with cylinder-piston group, contains lubricant but separated from refrigerant by a bellows (Goerig, 2001) | Air cooling and dehumidification (Goerig, 2001) | Installed on ISS for many years. Needed occasional maintenance and leaked refrigerant (Perry, 2003; Williams and Gentry, 2009). |
| RC (Refrigerated Centrifuge) | Installed on ISS. Launched on STS-114 on July 26th, 2005. (NASA 2019) | 4°C to 20°C (NASA 2019)<br>Original centrifuge ran on R404A (Grzyll and Cole, 2000), but the refrigerant may have changed during the design process. | Oil-less hermetic reciprocating compressor. Modification of an existing compressor. Compressor may have been further modified before launch (Grzyll and Cole, 2000). | Maintain rotor chamber temperature of centrifuge (NASA 2019) | "Cooling became unavailable soon after the start of on-orbit operation", but the reasons are unclear. Refrigeration operations were certified for only up to 60 min (NASA 2019). |

Two additional vapor compression cycles are in the Russian Module Zvezda of the International Space Station with the names SKV-1 and SKV-2. Information about the systems are scarce in scientific papers but together with other documents and websites some insight can be gained. The systems each have a charge of about 750 g of R218 (Perry, 2003), an uncommon refrigerant for terrestrial applications partially due to its high global warming potential (Mühle et al., 2010). The system can dehumidify at a rate of approximately 0.45 kg/h and has a steady-state power consumption of 350 W (Wieland, 1998). The exact date of commissioning is unknown, but the systems must have been installed in 2001 because a refrigerant leak was detected and documented

**Fig. 4.** Astronaut using the refrigerated centrifuge (NASA, 2019).

(Perry, 2003). Leaks also occurred in 2008 (Williams and Gentry, 2009) and 2014 (Russian News Agency, 2014). A compressor failure was reported for 2008 (Williams and Gentry, 2009) and heat exchanger maintenance or repair was conducted around 2003 (Williams and Gentry, 2004) and again foreseen in 2009 (Spaceref 2009). Wieland (1998) also gives the expected life cycle for the compressors and heat exchangers as 10,000 and 31,000 h, respectively. The overall system lifetime, assuming replacement of components at scheduled intervals, is estimated at 133,000 h (Goerig, 2001). The SKV systems stand out by oil-lubricated compressors. However, the oil and the refrigerant are kept separated by a bellows, such that the oil does not circulate through the cycle (Goerig, 2001). Goerig (2001) also provides a schematic of the systems.

The latest attempt for VCC cooling in space was launched in 2005 on STS-114, the next consecutive STS flight after the loss of space shuttle Columbia. This time, the VCC was part of a refrigerated centrifuge (RC). A device description on a NASA website states "*The RC is designed to provide refrigeration with temperatures that range from ambient ISS temperature to* 4 °C, *but cooling became unavailable soon after the start of on-orbit operations.*" The reason for cooling unavailability is referred to as an "*anomaly*" but not further described. Fig. 4 shows a picture of the installed RC. After STS-114, no additional VCC microgravity flight experiences are documented in the literature except the continued operation of SKV-1 and SKV-2, which had been installed prior.

In summary, the idea of VCC refrigeration in space is old, but only a few projects achieved microgravity operation and none are documented in detail. Efforts seem to have declined since 2005. A NASA Small Business Innovative Research (SBIR) project on oil-free VCC cooling for cold stowage of food in space was started in 2017 (Rohleder et al., 2018).

## 3. Performance data of space coolers

In section 2, the history of vapor compression technology in microgravity has been qualitatively described. Unfortunately, baseline COP values for refrigerators that operated in space are rarely found in the literature although they would be of great value to VCC researchers. The sparse data available to the authors is shown in Table 3. Mass, volume and COP data for EOR/F and LSLE was acquired in personal communication with a NASA engineer (Ruemmele, 2020). The exact procedures of collecting the performance data were not documented and may be design values instead of actual measurements. SABL is included as a recently built thermoelectric space cooler for comparison. A screenshot from a thermodynamic modeling software in Niederwieser et al. (2015) indicates that SABL can provide a COP of 0.26 at a controlled temperature of −5 °C and an ambient temperature of 25 °C. To compare the devices against typical terrestrial freezers, data of a commercial freezer has also been included in Table 3. The COP values for each device may not include defrost-cycles, fans or lights, and should therefore only be considered as a rough estimate. Since the COP values capture different cabinet and ambient temperatures, they are here normalized using the second law efficiency. The COP is directly given for SABL and calculated for the other devices from the cooling capacity $\dot{Q}$ and the compressor power draw $\dot{W}$ as

$$COP = \frac{\dot{Q}}{\dot{W}}. \tag{1}$$

The second law efficiency $\eta_{2nd}$ is the ratio of the actual COP to the maximum theoretical COP (Carnot efficiency) for the given heat source and heat sink temperatures, $T_l$ and $T_h$, respectively:

$$\eta = \frac{COP}{\frac{T_l}{T_h - T_l}} \tag{2}$$

EOR/F and LSLE achieved second law efficiencies of 0.11–0.17, which is low for a vapor compression freezer but still higher than the efficiency of thermoelectric cooling. The terrestrial reference freezer shows that second law efficiencies above 0.3 may be achieved with vapor compression technology. Looking at the ratio of net mass over storage volume, the commercial refrigerator freezer is significantly below EOR/F and LSLE. The reference freezer also outperforms EOR/F and LSLE in needing an external volume only twice as large as the internal volume. The differences can partially be attributed to the additional refrigerant containment measures required for EOR/F and LSLE. Where safely possible, future space coolers should attempt light weight fabrication and small volume penalties to keep the total equivalent system mass to a minimum.

## 4. Liquid-gas two-phase flow at microgravity

Over the last few decades, a considerable body of literature has accumulated on microgravity two-phase flow. Relevant literature has been reviewed and summarized multiple times so that a detailed listing is avoided here. Instead, four review efforts helpful for an engineer working on microgravity VCCs are shown in Table 4. Surprisingly, decades of microgravity two-phase flow research have not yielded a validated heat transfer correlation. Currently planned experiments may provide such a correlation, among them the Flow

**Table 3**
Mass, volume and COP data for space cooling devices.

| Device | $V_{ex}$ | $V_{in}$ | $M$ | $M/V_{in}$ | $T_l$ | $T_h$ | $\dot{W}$ | $\dot{Q}$ | $COP$ | $COP_c$ | $\eta_{2nd}$ | Ref |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| [-] | [L] | [L] | [kg] | [kg/L] | [°C] | [ °C] | [W] | [W] | [-] | [-] | [-] | [-] |
| EOR/F | 159 | 34 | 50.4 | 1.5 | 4.0 | 27 | 100 | 205 | 2.1 | 12.2 | 0.17 | (Ruemmele, 2020) |
| | | | | | −22 | 27 | 160 | 117 | 0.7 | 5.2 | 0.14 | (Ruemmele, 2020) |
| LSLE | 267 | 71 | 77.0 | 1.1 | 4.0 | 27 | 130 | 205 | 1.6 | 12.2 | 0.13 | (Ruemmele, 2020) |
| | | | | | −22 | 27 | 200 | 117 | 0.6 | 5.2 | 0.11 | (Ruemmele, 2020) |
| SABL | | 27 | | | −5.0 | 25 | | | 0.3 | 8.9 | 0.03 | (Niederwieser et al., 2015) |
| Reference freezer | 957 | 501 | 90.0 | 0.2 | −18 | 32 | | | 1.7 | 5.1 | 0.33 | (Gomes, 2020) |

**Table 4**
Two-phase flow at microgravity review studies.

**Basil N. Antar, 1993,** (Antar and Nuotio-Antar, 1993)
Chapter seven in this book focuses on liquid-vapor two-phase flows and highlights the drift flux. Gravity is said to play an important role in specifying the shape of the liquid-vapor interface, but dedicated zero-gravity heat transfer correlations are not discussed. Experimental results for pressure drop at microgravity and earth gravity are presented and show little difference. Chapter nine on fluid management in space describes how to contain, position or pump fluid in microgravity by leveraging certain geometries. These results are mainly applied to liquid propellant tanks.

**Kamiel Gabriel, 2007,** (Gabriel, 2007)
This book extensively compares measurements and models on flow patterns, pressure drop, heat transfer coefficients and other topics. Some conclusions reached are that frictional pressure drop is higher in microgravity but the difference is very small throughout different flow regimes and the heat transfer coefficients are only markedly different for low flow velocities and low qualities. A couple of general effects of microgravity are described:
The slip-velocity is reduced in microgravity which leads to fewer interactions between phases and suppresses turbulence. The lower slip velocity also increases the void fraction.
The lack of gravity decreases boiling heat transfer because without buoyancy forces, bubbles generate less turbulence.

**Issam Mudawar, 2017,** (Mudawar, 2017)
This publication reviews two-phase flow at microgravity and focuses among others on boiling and condensation mechanisms as well as results from recent parabolic flights. Adiabatic two-phase flow, pool boiling, as well as the critical heat flux (CHF) are also discussed, and the review presents criteria for a minimum flow velocity required to make the CHF independent of gravity (originally in (Zhang et al., 2004)). Microgravity testing platforms and the Flow Boiling and Condensation Experiment (FBCE) are also described. It is concluded that past experiments have "*failed to yield reliable, long-duration, steady state data, and flow visualization records for flow boiling and flow condensation.*"

**Ramaswamy Balasubramaniam, 2019,** (Balasubramaniam et al., 2019)
This review paper is a follow up to a review in 2006 (Balasubramaniam et al., 2006). Both the pressure drop and the heat transfer of two-phase flow are discussed in detail in separate chapters. It is concluded for two-phase flow boiling that "*correlations in which low gravity has a significant effect on the heat transfer are yet to be developed and tested*" (Balasubramaniam et al., 2019). The authors therefore point to heat transfer correlations that were developed for normal gravity. One chapter is written on startup, transients and system instabilities and the review suggests correlations for heat transfer and pressure drop, and discusses components and phenomena such as piping bends, phase separators, system transients and flow instabilities.

Boiling and Condensation Experiment (FBCE) (Mudawar, 2017), or the Two-phase System Experiment Rack (TSER), which is part of the Chinese Manned Space program (Hao, 2016).

### 4.1. System considerations

Two-phase flow heat transfer coefficients and pressure drop are necessary for predicting system-performance, but authoritative microgravity correlations are not yet available. However, it does not appear that there is excessive pressure drop or the dysfunction of flow boiling and condensation under microgravity when compared to gravity on earth. Even in microgravity, two-phase flow heat transfer coefficients are expected to be much larger than single phase heat transfer coefficients. For refrigerant to liquid heat exchangers the thermal resistances are the inverse of the product *hA*, which consists of the heat transfer coefficient and the surface area. Because this product is significantly higher for two-phase flow than for single phase flow, the two-phase thermal resistance is smaller than the single phase resistance, $R_{TP} \ll R_{SP}$, where $R_{TP}$ and $R_{SP}$ are the two-phase and single phase thermal resistance, respectively. Therefore, the uncertainty of the refrigerant heat transfer coefficient should have a minor impact on the overall calculated UA using the following equation:

$$UA = \frac{1}{R_{SP} + R_{TP}} = \frac{1}{\frac{1}{(hA)_{SP}} + \frac{1}{(hA)_{TP}}} \tag{3}$$

Mosinskis (1976) generally supports this reasoning. It may not hold true for refrigerant to air heat exchangers where the airside surface area can be orders of magnitudes larger than the refrigerant side surface area such that $R_{TP} \ll R_{SP}$ is no longer true.

When uncertainty in the heat transfer coefficients is unacceptable, reducing pipe diameter at the cost of a higher pressure drop is an option to enforce high flow velocities (Brendel et al., 2019). High flow velocities are widely acknowledged to make the two-phase flow regime and its heat transfer coefficients independent of flow orientation and gravity magnitude. What is still unclear, however, are the minimum flow velocities required for each application. The following section discusses this topic more.

Generally speaking, the importance of heat transfer coefficient, flow regime and pressure drop of two-phase flow is subordinate to the overall robustness of two-phase flow devices in zero-gravity. Macroscopic events like the movement of liquid through pipes, potentially towards the compressor, are a greater concern. The behavior of a two-phase mixture in an evaporator during a start-up in microgravity is unclear, too.

## 5. Thermal gravitational scaling of two-phase flow and systems and gravity independent two-phase flow

The concept of thermal gravitational scaling, sometimes also referred to as similarity or similitude, is one possible attempt to predict microgravity flow characteristics based on terrestrial experiments, not unlike estimating the performance of large industrial systems from laboratory sized test setups. This can also be worded as in Ungar (1998): "*…experiments are constructed so that microgravity-like behavior is obtained.*" The concept could be of tremendous value because expensive microgravity testing would be reduced. An early work on the topic is a book from 1950, quite thoroughly discussing similitude not only for fluids but also for electric circuits, mechanics, acoustics and other fields (Murphy, 1950). The concept received considerable attention tailored to cooling systems in the 1990s (Ungar, 1998; Delil, 2001; Crowley and Sam, 1991; Hurlbert, 2000) when plans for a two-phase cooling loop for the ISS emerged.

Delil (2001) generally proposed to match dimensionless numbers of an intended application in micro- or reduced gravity (prototype) by a terrestrial experiment (model). The author points out that even for single phase flow, perfect similarity is very difficult to achieve and since two-phase flow is characterized by many more dimensionless parameters, scaling becomes more difficult. However, comparisons based on distorted scaling may also be of value. Delil (1991) describes 18 dimensionless numbers that were later described in Delil (2001) as "*the most complete set for two-phase flow*". The Froude number for single phase flow can be used for an intuitive example to understand the fundamental idea. It relates the flow velocity $u$, the gravitational acceleration $g$ and a characteristic length $l$:

$$Fr = \frac{u}{\sqrt{gl}} \tag{4}$$

If reduced gravity is to be explored but experiments at reduced gravity are not possible, the flow velocity in a test setup on earth could be increased to reach the Froude number that reduced gravity would have generated. Frequently, adjusting a dimensionless number will cause a mismatch in other dimensionless numbers, such that perfect similarity, i.e. a match of all relevant dimensionless numbers, is very difficult (Delil, 1989).

The work of Ungar (1998) derives a scaling method based on the Buckingham Pi theorem for the frictional pressure drop of two-phase flow in microgravity. The pressure drop is shown to be a function of eight variables in three dimensions such that the Buckingham Pi theorem states there should be a relationship between six dimensionless groups. The suggested six dimensionless groups are $\phi_g^2, Re_f, Re_g, We_f, We_g, \rho_g/\rho_f$ with the option to swap one of the dimensionless groups with the Martinelli Parameter $X$. Additionally, criteria for gravity insensitivity are suggested using the Froude and Bond numbers. The paper concludes that a horizontal ground experiment designed to mirror a two-phase system in microgravity with the same geometry would have to satisfy the criteria of gravity insensitivity, have an identical $\rho_f/\rho_g$-ratio and "*match the range and interrelationship of* $Re_f$, $Re_g$, $We_g$, $\rho_g/\rho_f$, $X$". The paper includes a sample calculation in which R134a at a temperature of 295 K is shown to match Cyclopentane at 342.5 K.

The work of Crowley and Sam (1991) proposed a different scaling method. For the five different phenomena "flow regime", "pressure drop", "evaporator two-phase heat transfer", "condenser 2 phase heat transfer" and "condenser single phase heat transfer", different scaling parameters were used and the ratio of these parameters for R11 and Ammonia was calculated. Based on the results, the author concluded that R11 is *"an excellent simulant of the behavior expected with Ammonia"*. R11 was therefore chosen as the refrigerant for variable gravity tests of a two-phase loop utilizing parabolic flights on the NASA KC-135 aircraft. A total of about 150 parabolas were flown and data is presented that shows that the pressures and temperatures were affected by the changing gravity but also that the two-phase loop remained operational.

Hurlbert et al. (2004) collected a large dataset for two-phase flow pressure drop at different gravity levels. Generally, the study found that the Euler number, containing pressure drop, for a given fluid, saturation temperature and flow regime can be scaled in a simple power law relationship with the Froude number. For annular type flows, the functional form for the two-phase flow pressure drop was found to contain the term $1/g^{0.38}$.

An extreme case of scaling is when gravity has a negligibly small impact on the two-phase flow. A system could be built and tested terrestrially but would still perform equally in microgravity. Multiple different criteria have been put forward already for gravity independence of two-phase flow (Zhang et al., 2004; Ungar, 1998; Hye, 1985; Brauner, 1990; Zhao et al., 2000; Zhao et al., 2002; Bower and Klausner, 2006; Baba et al., 2011; Konishi et al., 2013; Lee et al., 2014; Del Col et al., 2014; O'Neill et al., 2017; Zhang et al., 2018), but they have not been extensively tested on heat exchangers, potentially with multiple circuits, or complete two-phase cycles.

Despite existing studies on similitude and scaling, there are still open questions and the research field could yield valuable results if methods are proposed and proven correct.

## 6. Design considerations for vapor compression systems in microgravity

Eight years of operation in microgravity by OR/F, EOR/F and LSLE and almost 20 years of operation of SKV-1 and SKV-2 demonstrate refrigerators and freezers are generally operable in microgravity. Nevertheless, Gaseor et al. (1996) pointed out that future system requirements "*call for substantially longer life, higher reliability* [and] *less maintenance*". A number of unknowns and open issues are related to reliable designs for VCC systems for microgravity environments. For example, cooling by the RC became unavailable soon after on-orbit operation due to an anomaly, but the causes were never identified. Also, OR/F, EOR/F, LSLE and SKV-1 and SKV-2 did not operate seamlessly. The following paragraphs discuss cycle features or operational conditions that can lead to VCC system damage in microgravity and provide some suggestions for future research that could give a better understanding of design for reliability of these systems. Additionally, noise and vibration are discussed because of severe problems on past flights.

### 6.1. System start up and off nominal conditions

During operation of a VCC, the vapor-quality continuously increases in the evaporator and decreases in the condenser along the flow direction. With normal operation of the expansion valve, the evaporator will provide superheated vapor to the compressor. However, once the system is turned off, the location of the liquid in the system is unknown. Small maneuvers of the spacecraft, capillary forces, temperature induced pressure differences as well as charge distribution at shutdown makes the location of the liquid very difficult to predict. A compressor at start-up with liquid at the suction port could take in large amounts of incompressible liquid into the compression chamber. Although some compressors can tolerate a liquid flooded start, this generally should be avoided for reliable operation over several years. Developing a system to prevent flooded start-up in microgravity is suggested for desirable compressor life.

### 6.2. Compressor lubrication

Most practical and theoretical approaches to VCC in microgravity propose an oil-free compressor because a gravity fed oil-sump does not function in space. This problem was first highlighted in 1984 by Hye (1984) as well as later on in Gaseor et al. (1996) and Ma et al. (2015). Moreover, removing oil from a cycle can enhance heat transfer and improve heat exchanger efficiencies. The development of high-performing, oil-free compressors at pressure ratios greater than 10 for refrigeration should therefore be continued. On the downside, oil-free compressors have a decreased performance with increased leakage paths and frictional losses. Some compressor designs achieve lubrication without a gravity-fed system and could be viable for microgravity operation. Instead of relying on a sump, oil can reach moving parts as a mist within the refrigerant vapor entering the compressor suction port. The entrained oil mist in the refrigerant vapor flow should not be impacted in microgravity. As a precursor to microgravity testing, compressors relying on lubrication mist could be tested at different orientations. If the performance is equal in all orientations, the compressor lubrication should indeed be body-force independent and suitable for microgravity. Rönnkvist and Heinås (2001) tested mist lubrication for a bearing test rig and achieved consistent mist creation under all operating conditions.

Increased bearing temperatures were found but not to a concerning extent. Dunaevsky confirmed through long-term durability experiments that the oil circulating through the system “enables a reliable lubrication of various friction interfaces of the compressor…” (Dunaevsky, 2009). In Rönnkvist and Heinås (2001) and Dunaevsky (2009), only the abstracts were accessible to the authors and limited details were available. A remaining concern with mist lubrication is the continuous return of oil throughout the cycle. However, it has been suggested that a VCC operating well with oil in a horizontal position should also operate well in microgravity. An absence of gravity generally enhances the oil-transport by the refrigerant (Hasan, 2020). Dedicated microgravity compressor development or testing is not summarized here due to the focus on the system but more details can be found in the following sources: Rohleder et al. (2018), Grzyll and Cole (2000), Hye (1984), Hye (1983), Scaringe et al. (2002), Chen et al. (2014), Gerner et al. (2015), and Sun et al. (2016).

### 6.3. Expansion valves

Throughout the practical and theoretical work on microgravity VCCs, the expansion valve is rarely discussed. It is at this point unclear from an experimental point, whether a thermal, electronic, or passive expansion device is best to regulate flow in space applications and if there is any difference when comparing terrestrial and space applications. The expansion valve shall ensure a constant and low superheat at the evaporator outlet, an experimental validation of which requires several minutes of operation. Hence, the test can almost exclusively be performed on an orbital spacecraft, because even commercial sounding rockets offer only approximately 3 min of zero-gravity testing time. However, such a test is currently not given a high priority.

### 6.4. Dehumidification of air

Generally, single phase flow regimes are not affected by gravity because of the homogeneous density. However, a second phase can occur in air to refrigerant evaporators when water condenses. Without the force of gravity, there exists no natural mechanism for condensed water to drain off an evaporator air-coil. Depending on the humidity infiltration and flight duration, the problem is significant in both freezer and refrigerator modes. The condensed water will freeze on the outside of the evaporator coil requiring defrosting to avoid a reduction of the evaporator air flow. Gravity-independent dehumidification, possibly desiccants or a condensed water removal system will be needed for evaporator air-coils. However, desiccants may impact the scientific samples in the refrigerated cabinet and should therefore be selected carefully. Similar to the expansion valve, the appropriate experiments for validating a dehumidifying technology likely require long testing times such as are available on an orbital spacecraft. It should be noted that SKV-1 and SKV-2 successfully dehumidify air, but a detailed documentation of the technology is not known to the authors.

### 6.5. Noise and vibration

In 2015, a book about acoustics and noise control in space crew compartments was published (Goodman et al., 2015). The book mentions OR/F and LSLE multiple times for their problematic noise. In particular LSLE was a continuous source of noise in Spacelab and even interfered with the crew communication to the ground. The noise levels were at times above 70 dBA and were among the noisiest devices on the spacecraft causing headaches and sleep problems for the crew.

Compressors usually cause vibrations due to their rotating parts, the effect of which is more or less harmful depending on the application. Satellites that take precise measurements or spacecraft on which vibration sensitive experiments are conducted are two examples. For these cases, the magnitude of the compressor vibration and its propagation would need to be investigated and mitigated as needed.

**Table 5**
Equivalent mass for energy and volume in spacecraft design.

| Type | Value | Equivalent mass |
|---|---|---|
| Energy | 1 $\boldsymbol{kW_{el}}$ | 83 kg |
| Volume | 1 $\boldsymbol{m}^3$ | 67 kg |

### 6.6. Refrigerant

Most spacecraft are an almost closed environment such that any accidentally released refrigerant can stay within the spacecraft for a long time. Toxicity and flammability are therefore to be considered when selecting a refrigerant as well as safety measures. Some spacecraft use a high temperature catalyst which may have the potential to break down refrigerants into toxic gases. The amount of refrigerant may be limited to reduce this concern and impact the system design.

## 7. Fair comparison of cooling technologies for space applications

If energy efficiency was not important in cooling onboard spacecraft, then current approaches based on thermoelectric elements, the Stirling cycle and the Reversed-Brayton Cycle would be better choices because of high Technology Readiness Levels (TRLs). However, energy efficiency is indeed very important because spacecraft with a lower overall energy consumption can be designed with smaller solar panels and radiators. Said in another way, energy consumption can be converted to an equivalent mass. Similarly, occupied pressurized volume can be converted to an equivalent mass as well. Pressurized volumes are the internal parts of the spacecraft that the crew can access without a spacesuit. Considering a refrigerator as an example, the equivalent mass ($M_{tot}$) of the refrigeration system is the sum of the mass of the refrigeration technology, an equivalent mass associated with the energy system used to power the refrigerator and reject heat back into space, and an equivalent mass associated with the volume of the refrigeration technology. Equivalent mass is a good proxy for cost in many cases since it dictates launch cost. NASA has typical equivalence values for energy consumption and volume as shown in Table 5, which can be obtained from Anderson et al. (2018) (Table 3.4 (Power plus thermal control, nominal) and Table 3.6 (ISS Module, nominal)). The equivalence value for required power accounts for both harvesting and rejecting energy and the equivalence value for volume is that of an ISS type module.

Equivalent masses can be used as a single metric for comparing different cooling technologies. For example, if technology ‘A’ requires 2 kW power and has a mass of 100 kg, while technology ‘B’ requires only 1 kW for the same cooling capacity but has a mass of 200 kg, then technology ‘A’ would be preferable on a total, equivalent system mass basis, $100\text{kg} + 2 \cdot 83\text{kg} < 200\text{kg} + 83\text{kg}$ (assuming both technologies require the same volume). If the volumes are different, too, the equivalent mass needs to account for that. An equivalent total mass is suggested as the significant parameter on which space cooling technologies with equivalent cooling capacity and cold temperatures should be evaluated:

$$M_{tot} = M_{sys} + \dot{W}_{avg}\lambda_{el} + V_{sys}\lambda_{v} \tag{5}$$

where

| | |
|---|---|
| $M_{tot}$ | Total equivalent system mass [kg] |
| $M_{sys}$ | Mass of refrigeration system [kg] |
| | (assuming the refrigeration enclosures are similar for different cooling technologies, the enclosure mass does not need to be accounted for) |
| $\dot{W}_{avg}$ | Average electrical power [kW] |
| $V_{sys}$ | Total pressurized volume occupied by refrigeration system [$m^3$] |
| | (assuming the refrigeration enclosures are similar for different cooling technologies, the enclosure volume does not need to be accounted for) |
| $\lambda_{el}$ | Equivalent mass per average electrical power [$kg/kW_{el}$] |
| $\lambda_v$ | Equivalent mass for volume [$kg/m^3$] |

Eq. (5) consists of three terms, which account for the physical refrigeration system mass, the average power consumption over a meaningful number of ON/OFF cycles, and the occupied pressurized volume of the refrigeration system. The consideration of all three terms yields a fairer comparison between different cooling technologies versus comparing only the second term. The equivalent mass could also be applied to compare a single refrigeration technology versus increases in spacecraft radiator areas, which can support lower temperatures via direct radiation to space. Eq. (5) should be used for equal cooling capacities and cold temperatures. Alternatively, both sides of the equation can be divided by the cooling capacity for a comparison of technologies with different capacities.

Eq. (5) can be illustrated in a small example. It is assumed that a cooling capacity of $\dot{Q} = 300\,\text{W}$ at a heat source temperature of $T_l = -20^\circ\text{C}$ and a heat sink temperature of $T_h = 20^\circ\text{C}$ is needed. A vapor compression prototype ($\eta_{VCC} = 0.3$) is compared with an alternative technology ($\eta_{ALT} = 0.1$). Using Eqs. (1) and (2), the equivalent mass benefit due the different COPs can be found as:

$$\begin{aligned}\Delta M_\eta &= M_{tot,VCC} - M_{tot,ALT}\\ &= \lambda_{el}\left(\dot{W}_{VCC} - \dot{W}_{ALT}\right)\\ &= \frac{\lambda_{el}\dot{Q}}{\frac{T_l}{(T_h - T_l)}}\left(\frac{1}{\eta_{VCC}} - \frac{1}{\eta_{ALT}}\right)\end{aligned} \tag{6}$$

For the given parameters, this results in $\Delta M_\eta = -26\text{kg}$. Hence, disregarding volume differences, the vapor compression cycle could be up to 26 kg heavier than the alternative technology and would still be preferable on an equivalent mass basis as in Eq. (5).

## 8. Conclusions

Very few vapor compression cycle (VCC) refrigerators that have flown in microgravity are published in the open literature and none of the devices are documented in detail. After decades of work on microgravity VCCs, there is only a small body of knowledge available. The vapor compression refrigerators flown in microgravity are summarized in this paper and available details about their design and experienced problems are highlighted.

Additional effort is required to enable reliable VCC refrigeration in microgravity. A conceivable risk for VCCs in microgravity is liquid entering the compression chamber. A modification or design to prevent this potential problem should be developed. Furthermore, research should explore the suitability of oil-free versus oil-lubricated compressors, microgravity dehumidification for air-cooling applications and different expansion devices. Additional investigations on thermal gravitational scaling could yield guidance for the design of microgravity VCCs. Furthermore, it is suggested that future space cooling technologies be compared by their equivalent total mass, accounting for their physical mass, energy consumption and used volume.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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