Present State and Future Of Environmental Control Systems in Space

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Space is becoming the next medium for business opportunities, advancements in technologies and exploration for inhabiting planets, moons and areas outside our planet. Companies are developing systems that would permit short-term and, eventually, long-term human inhabitation of the moon, Mars and other extraterrestrial bodies; start-up firms are focusing on capsules and rockets for human spaceflight.[1,2,3] With regulations relating to space launch and travel established and continually being reviewed in numerous countries,[4,5] ASHRAE has an opportunity to propose standards, guidelines and codes relating to the indoor environment of extraterrestrial transport vessels, waypoint stations and buildings.

Environmental Control Systems: An Outer Space Perspective

The regulation of indoor air environments in extraterrestrial structures will need to be adjusted because the exterior environment of deep space is a near vacuum, with temperature extremes ranging from approximately −200°F to 200°F (approximately −129°C to 93°C).[6] Objects in space are ubiquitous, varying in size from frozen gas or liquid droplets to meteors and asteroids, and these objects travel in a wide range of directions and at various speeds. Space objects traveling at high velocities relative to travel vessels in deep space may potentially damage thermal management machinery and accompanying accessories exposed to space.

The vacuum condition in outer space limits the options for heat rejection mechanisms to thermal radiation and the lack of gravity significantly, which affects how to effectively cool and heat the spacecraft's interior environment. Due to the lack of resources and limited ability to send more supplies, reuse of air and water in deep space structures is vital. HVAC technologies used in Earth applications will need to be modified to accommodate deep space.

Similarly, environmental control equipment for planetary environments would vary planet by planet. Atmospheric conditions and gravity of planets differ from the outdoor environments on Earth, resulting in varying compositions of gases and radiation and differing temperature ranges. Depending on the planet,

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limited amounts of water and gases that create human breathing air may be present. With space agencies interested in sending humans to the moon and Mars,[1,3] understanding their atmospheric conditions would be ideal to modify current HVAC technologies for facilities there.

The moon's atmosphere is far less dense than Earth's and is comparable to the conditions on the outer edges of the Earth's atmosphere encountered by the International Space Station (ISS) in low-Earth orbit. Gases mainly found on the moon's atmosphere include helium-4, deuterium (hydrogen-2), methane, ammonia, carbon dioxide, and differing isotopes of neon and argon. Gravity is present on the moon, although it's 16.5% of the Earth's gravity.[7] Heat transfer and rejection equipment developed for the ISS may be a starting point for developing environmental control equipment for lunar facilities.

In contrast, the atmosphere on Mars is mostly composed of carbon dioxide, nitrogen and argon,[8] and the gravity on the planet is about 38% that of Earth's.[9] Atmospheric pressure on Mars is much lower than Earth's, and the planet's increased distance from the sun, compared to the Earth, results in lower surface temperature.[10] Assessing each planet's surface conditions for human inhabitation is necessary to develop and manufacture HVAC equipment for the respective planet.

Harsh environmental conditions necessitate accurate thermal management systems for spacecraft.[11] Several studies have been devoted to direct and inverse heat transfer techniques for measurement and monitoring of the spacecraft's surface temperature and critical parameters under extreme conditions such as atmospheric entry[12] and other similar applications.[13–15] While keeping spacecraft safe during space missions is critical and challenging, maintaining a livable condition for the astronauts is even more complex. On Earth, HVAC systems are considered important because they provide thermal comfort for the occupants of built environments. For outer space applications, however, proper environmental control is not just about comfort, but survival. The ISS is an excellent example for environmental control needs in space, with three to six crew members onboard for long durations. Providing a livable and comfortable condition for the crew members is critical at ISS, and various challenges in this regard must be addressed including temperature control, ventilation, oxygen production and water.

A Living Example: The International Space Station

The ISS is at an altitude of about 260 miles (418 kilometers) and orbits the Earth in about 92 minutes,[6] with temperature extremes for deep space as noted earlier. A significant amount of heat is also generated inside ISS by the hundreds of electronics and equipment onboard, which lead to a massive cooling load.[6] The large temperature gradients as the result of the harsh environment and significant internal loads necessitate effective temperature control systems for ISS.

Temperature control at the ISS is performed using a combination of passive techniques and an active thermal control system.[6] Passive techniques include the use of multilayer insulation (MLI), surface coatings with selected radiative properties and heaters and heat pipes. The active thermal control system consists of cold plates, heat exchangers, ammonia and water as coolant fluids and radiators to maintain appropriate internal and external temperatures.

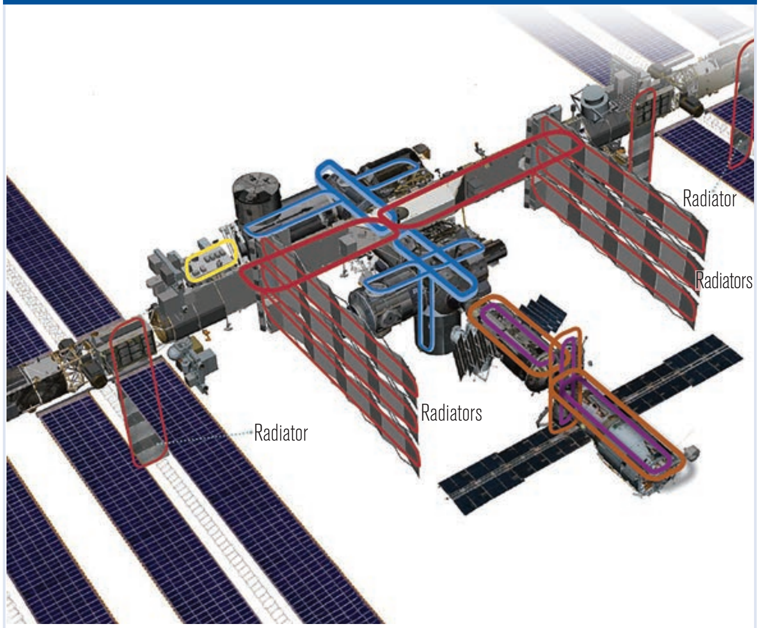
The surface of the ISS, apart from windows, is covered by MLI that slows down the heat transfer rate through an effective use of multilayer radiation shields. MLI used for ISS consists of an outer cover (aluminized biaxially oriented polyethylene terephthalate), followed by several reflector layers (double aluminized poly [4,4'-oxydiphenylene-pyromellitimide]), separated by polyester netting.[16] The multilayer structure of the insulation allows nearly 100% reflection of incident heat flux. However, it is not adequate to maintain livable conditions inside the ISS due to the large internal loads. An active thermal control system addresses this challenge (*Figure 1*).

The ISS active thermal control system consists of two loops with water and ammonia as their working fluids. Water circulates through the interiors and use cold plates and heat exchangers to absorb heat. The heated water then transfers its thermal energy content to another loop, which uses ammonia as the working fluid. Ammonia, as a widely used refrigerant, is selected due to its desired thermal characteristics and mainly because of its low freezing temperature of −107.9°F (−77.7°C). The ammonia then circulates in tubes throughout six large 6 ft by 10 ft (1.8 m by 3 m) radiator panels and cools down before circulating back to the interior. The radiator panels allow effective heat dissipation to deep space.[17]

Ammonia is also used to provide cooling for the photovoltaic panels that are responsible for electricity generation. This is because the efficiency of solar arrays decreases when they operate at elevated temperatures.[18] An additional radiator is used for each of the four pairs of solar arrays for heat dissipation and maintaining an appropriate operating temperature.

Effective control of air quality and airflow inside ISS is also of great significance. The spacecraft maximum allowable concentrations (SMACs) for short term (up to 24 hours) and long term are determined and published considering human space flight requirements.[19] Trace chemical contaminants resulting from equipment off-gassing and human metabolism and cleaning materials used prior to the flight must be properly addressed to avoid air quality issues for spacecraft cabins. For this purpose, a combination of passive and active contamination control methods have been successfully tested and used for ISS.[20]

FIGURE 1 Schematic of the active thermal control system for ISS.[22]



The ability of the contamination control system must be tested and verified using trace contaminant control (TCC) analysis. Through this analysis, the spacecraft is subjected to an off-gassing test, and the trace contaminant load is determined while comparing the load against the active contamination control system's capabilities.

The environmental control and life support system (ECLSS) is responsible for water recovery and oxygen generation at ISS.[21,22] The water recovery system (WRS) recycles crew member urine and cabin humidity condensation into drinkable water. The oxygen generation system (OGS) produces oxygen through electrolysis of water for the crew members at an adjustable level according to need.

The free convection process, which allows natural airflow circulation on Earth, does not occur in zero gravity. Sufficient airflow must be induced to avoid cold spots and the resulting condensation and microbial growth.[14] Maintaining a proper balance between the generation and removal of volatile trace contaminants is also essential in the indoor air quality of the spacecraft cabin.[23]

To enhance quality of life on ISS, crew quarters (CQ) are personal spaces for sleep and leisure for the crew with lower levels of noise and enhanced thermal comfort and personalized ventilation.[24] Addressing issues such as noise, carbon dioxide and dust accumulation[25] in ISS and particularly CQs are studied in several research studies and various improvement methods are investigated.[26–30]

Spacesuits and Environmental Control

Unlike on Earth, where HVAC is only considered a necessity for the built environment, astronauts require proper environmental control inside and outside the spacecraft cabin. Spacesuits allows astronauts to work outside the spacecraft for an extended amount of time by protecting them from excessive temperatures[31,32] and space dust as well as providing the needed interior spacesuit pressure, oxygen for breathing and water to drink. The spacesuit currently in use by NASA for space walks outside the ISS is the extravehicular mobility unit (EMU).[33] The EMU consists of 16 layers of protection, including a liquid cooling garment with 300 ft (91 m) of chilled water tubing woven to the garment to control the inside temperature; a pressure garment to maintain a proper pressure; and thermal micrometeoroid garment to reflect solar irradiation and protect the astronaut from space dust.

The back of the EMU contains the life support system including oxygen and water storage, pressure and flow regulator, electricity generator and carbon dioxide removal system. Carbon dioxide produced by astronauts through breathing can quickly build up in the confined space inside the spacesuit. An effective carbon dioxide removal system using lithium hydroxide canisters is located on the back of the spacesuit, which maintains a healthy condition for the astronauts.

Prospects and Concluding Remarks

Whether it is a single spacesuit, space capsules, spacecrafts or ISS, environmental control has been and continues to be a critical component of space missions, and it is becoming more important as the quest for interplanetary manned missions grows. With space travel and extraterrestrial habitation soon becoming a reality, ASHRAE is in a unique position to provide industry direction for indoor environmental quality (IEQ) standards for these facilities.

Because decision-making in space and planetary expeditions is necessary for mission success and crew survival, especially in emergencies, IEQ becomes a more important element in optimizing appropriate environmental conditions for optimum cognitive functions. The Society can build on research assessing human cognitive function in relation to gases deemed to contribute to lower IEQ, such as carbon dioxide exposure to individuals who would be trained for the rigors of space travel.[34]

Much of the content from ASHRAE research and in ASHRAE standards and guidelines can be translated to extraterrestrial facilities, but further research and work would need to be done to adapt today's technologies for the environments that will be encountered in space. Of particular interest for research and industry guidance would be the following topics.

Refrigerants and refrigerant cycles. Known refrigerants and refrigeration cycles would need to be reassessed for use in space and extraterrestrial environments, with a heightened focus on refrigerant safety and maximization of refrigerant system life cycle. Furthermore, refrigerant system maintenance would need to consider the competence of crew members and the required tools and resources to repair such systems, which may or may not be abundant based on training and the availability of supplies at various space and extraterrestrial locations.

Machinery resilience. HVAC equipment for extraterrestrial facilities would need to endure natural elements that are different from Earth's atmosphere, everything from near vacuum conditions and high-velocity objects in deep space to weather disturbances of varying intensities on planets and habitable extraterrestrial bodies (such as dust storms and thermal tides on Mars).[8,35]

Air treatment and revitalization. Inhospitable outdoor conditions will require extraterrestrial HVAC systems to filter and treat air for 100% reuse. Expanding on past research of gas separation and reuse and air purification for space application will be necessary to maximize resource reuse on space voyages and planetary colonies and to minimize transport of gases for human habitat sustainment.[36–38] Additionally, research on ultraviolet germicidal irradiation of airstreams may provide a solution for eradicating organisms, microorganisms and viruses in reused air.[39]

Systems with simpler maintenance and repair procedures. As more people go to space, people need to know how to maintain systems without much training. The availability of expert technicians to maintain and repair extraterrestrial HVAC systems will vary. Unlike on Earth, where HVAC mainly provides comfort cooling, the malfunction of extraterrestrial HVAC systems may result in loss of life.

Effective heat removal/addition methods and systems for future built environments. In view of the major differences between environments at different planets, appropriate methods and systems must be developed with consideration of each specific environment to provide adequate heating and cooling for the built environments in an efficient manner. The presence/absence and type of atmosphere, solar irradiance and gravity are among the factors that must be considered in developing passive and active strategies for effective heating and cooling of built environments in space.

With the development of refrigerants and equipment most effective in various extraterrestrial environments by industry, ASHRAE can build on this work to create standards for rating the performance of environmental control systems and components for extraterrestrial and space applications. Furthermore, ASHRAE can develop design guides for space and extraterrestrial structures that address minimal to no energy consumption while maintaining appropriate conditions for IEQ and resilience against exterior elements.

The built environment in space and on other planets where resources are limited or minimal will demand a mindset of using closed-cycle resource processes, maximizing reuse and minimizing building waste. The thought process by built environment professionals of designing and constructing net zero energy buildings in space and on other planets, while being conscious of occupant health and safety, is not a luxury but vital to success.

ASHRAE has an opportunity to make history and propel the manufacturing of extraterrestrial vessels and facilities by creating industry standards that would help make human space and interplanetary travel viable, comfortable and safe.

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