Buildings in space!
To boldly model what no building physicist has modelled before

Sarah Brown[1], Ian Beausoleil-Morrison[1], Marie-Josée Potvin[2]
[1]Carleton University, Ottawa, Canada
[2]Canadian Space Agency, St-Hubert, Canada

Abstract

Habitats for humans on planets other than Earth are quickly becoming a reality. There have been very few studies documented in literature that use simulation tools to evaluate the thermal performance and indoor environmental quality (IEQ) of habitats in space, and none with the robust validation and level of detail provided by building simulators of Earth-bound buildings. In looking at the existing models and practices used in building performance simulation (BPS), it was found that the reduced gravity, the expanded radiation spectrum, and the new atmospheres surrounding habitats in space are problematic when considering using existing BPS tools to model buildings outside of Earth.

Introduction

Many government space agencies have committed to returning astronauts to the Lunar surface in the near future (USA by 2024; China & Russia in the next 5 years) and plans are in motion to prepare for the long journey to Mars thereafter. Extended human habitation on planets other than Earth is coming quickly and the successful completion of this venture requires a multidisciplinary approach. There has been a lot of focus over the years from the aerospace and medical communities on the pressing issue of radiation exposure of astronauts during extended exploration outside of Earth's protective atmosphere. Part of the protection plan for astronauts involves the suitable design and operation of living environments. Although building physicists have extensively researched and modelled earthly buildings and their mechanical systems up to now, there's been no documented interest from the community to move this knowledge off world. The purpose of this paper is to start a discussion among building physicists on simulating buildings in space and to evaluate in what ways the building physics and the building simulation communities are prepared to tackle extraterrestrial buildings and in what ways they are not. The article starts with a critical review of existing space habitat simulations documented in literature followed by a brief description of the environments proposed for off-Earth habitats (the Moon, Mars, and the space in between). The ways in which the indoor and outdoor environments of extraterrestrial habitats differ from those on Earth are highlighted and these noted differences are used in a discussion on how building performance simulation (BPS) models and tools would need to be adapted for extraterrestrial buildings.

Space simulations to date

Detailed energy and indoor environmental quality (IEQ) models of space habitats are not well documented in academic literature. The closest comparison found to a detailed building physics model is the Virtual Habitat (V-HAB) tool that has been under development at the Technical University of Munich since 2006 (Czupalla et al. (2015); Pütz et al. (2019)). Programmed in MATLAB, the purpose of V-HAB is to simulate the performance of life support systems (LSS) in extraterrestrial buildings with a particular focus on the management and conversion of waste products. In addition to V-HAB, there are scattered CFD models looking specifically at air movement and pollutant dispersion in sections of the ISS and the majority of these investigations are from the early 2000s (Lin et al. (2000); Son et al. (2005); Smirnov and et. al. (2006)). A recent series of CFD studies focused specifically on CO_2 concentrations around sleeping astronauts in the crew quarters (CQs) and investigated improved ventilation configurations in the CQs to prevent dangerous levels of CO_2 buildup (Georgescu et al. (2020, 2021)).

Many of the CFD models encountered in literature do not provide detailed validation of model performance to measured data from the ISS leading to questions regarding model accuracy. Some studies mention that flight data or measured data was used to validate the model but fail to show comparisons of model results to measured data. In lieu of having measured data to calibrate models, some research groups have attempted to replicate sections of the ISS on Earth either in full-scale and/or reduced scale models and use measured data from these setups to calibrate CFD models (Wang et al. (2018); Georgescu et al. (2020)). It is observed, however, that the ability of CFD models to capture the novelties of heat and mass transfer in space when gravity effects are reduced or negligible is not substantially defended. This is true of the non-CFD models surveyed as well. The developers of V-HAB note in Zhukov et al. (2011) that all models used in V-HAB are based on data for Earth's gravitational field. These Earth-based models are then generically used in Czupalla et al. (2015) to predict mass transfers on the ISS and Mars which experience vastly different forces of gravity in comparison to Earth. The general impression given by the studies documented in literature is that more comparison to measured data from the ISS is necessary to show that current practices of modelling heat and mass transport in reduced gravity environments result in accurate reflections of reality. The existing studies and practices would also benefit from model input sensitivity analyses.

Given that space exploration and its associated research is dominantly industry and government space agency driven, it's possible that more detailed and robust building physics models exist but they are not publicly documented or available. Even so, there is clearly an opportunity for building simulation experts to help develop more detailed building models for space infrastructure. Habitats in space could greatly benefit from the detail and validation practices that have been used for years to model earthly buildings.

Descriptions of proposed off-Earth building environments

Before starting the discussion on BPS tools and their applicability to space, it's important to understand a little bit about the new worlds being proposed for the habitats that will need to be simulated. In this article, there are two types of habitats that will be considered - habitats fixed to a celestial surface and habitats existing in open space (such as orbiting space stations and transport vessels required for deep space exploration). The celestial bodies most prominently being considered for feasible human habitation outside of Earth are the Moon and Mars. Table 1 lists some characteristics of each that will be useful for the discussions to follow.

The most significant difference between the indoor and outdoor environments of buildings on Earth and buildings in space is the force of gravity experienced by each. Referring to Table 1 Earth is significantly larger and denser than the Moon and Mars. As a result, the surface gravity of the Moon and Mars are only a fraction of that which we experience on Earth (17% of Earth's surface gravity for the Moon and 38% of Earth's surface gravity for Mars).

When analyzing habitats that orbit celestial bodies the concept of microgravity or "freefall" needs to be considered. Orbiting bodies still experience a percentage of the surface gravity created by the celestial body around which it is orbiting. This means that orbiting objects are "falling" towards the celestial body due to gravity. But when an object has sufficient momentum in a tangential direction to gravity, the object will experience a "prolonged fall". The prolonged falling of an orbiting habitat and everything in it means that everything - including the air inside - is falling at the same rate. If everything is falling at the same rate then, in the moving frame of reference of the habitat, nothing inside is moving. This is what gives the impression of being weightless on the ISS and is also the reason that orbiting bodies are an artificial environment of no gravity. This is a complicated concept and the interested reader is directed to Albrecht-Buehler (1992) for additional information on the topic. When considering a habitat that is moving in space between planets but isn't actively orbiting a celestial body, the local gravity imposed on the habitat by nearby bodies will need to be considered. A significant amount of time would likely be spent far away from significant celestial bodies and therefore the habitat would be in a negligible gravity field.

In addition to the differences in gravity, the radiation in space is different from that which we experience on Earth's surface. Earth is protected from much of the harmful radiation in space by its atmosphere and strong geomagnetic field. The ozone, O_2 and N_2 molecules present in Earth's atmosphere absorb a significant portion of the Sun's high energy UV radiation that is incident on the top of the atmosphere (Barrett (2005)). Earth's atmosphere also protects humans from the even higher energy gamma rays and X-rays that come from the most energetic sources in our universe - neutron stars, black holes, supernova explosions, and galactic rays (Schönfelder (2001); Hayakawa and Matsuoka (1964)). In addition to these categories of high energy electromagnetic (EM) radiation, there is also particle radiation (alpha, beta, and neutron radiation) in space originating from solar flares and other galactic mechanisms that Earth is mostly protected from by its geomagnetic field (Durante and Cucinotta (2011)). Due to the Moon's near negligible atmosphere and Mars' significantly reduced atmosphere in comparison to Earth, as well as the insignificant geomagnetic fields these celestial bodies possess in comparison to Earth, the spectrum of radiation experienced on the Moon and Mars is different than that with which we're familiar with on Earth. It should also be noted that with increasing distance from the Sun, solar radiation levels incident on celestial bodies decrease (refer to the *Solar Irradiance* values in Table 1). For habitats existing between ce-

Table 1: Comparison of celestial body characteristics between Earth, the Moon, and Mars.

	Equitorial Radius (km)	**Mean Density** ($km\,m^{-3}$)	**Surface Gravity** ($m\,s^{-2}$)	**Surface Pressure** (kPa)	**Sidereal Day Length** (h)	**Solar Irradiance**[b] ($W\,m^{-2}$)
Earth[a]	6378.1	5513	9.78	101.3	23.9	1361
Moon[a]	1738.1	3344	1.62	3e−13	655.7	1361
Mars[a]	3396.2	3934	3.71	0.6	24.6	586.2

[a] Data obtained from NASA's planetary fact sheet on Earth (Accessible Here), the Moon (Accessible Here), and Mars (Accessible Here)

[b] This refers to the average intensity of solar energy reaching the top of the atmosphere.

lestial surfaces, there are no natural shields protecting habitats and their occupants from the harsh radiation of space. A final radiation related difference between Earth and the other environments proposed for habitats in space that impacts BPS is the length of sidereal day experienced which, for planets, is a function of how quickly they spin on their axes and, for orbiting bodies, is a function of the revolution speed of their orbit. For habitats moving in deep space, there won't be the same cyclical exposure to the Sun that is seen by planets and orbiting bodies. Once again looking at Table 1, Mars experiences a slightly longer day than we have on Earth (about 24.6 hours in comparison to Earth's 23.9 hours) and the Moon experiences a significantly longer day (about 655.7 hours or 27.3 Earth days). The ISS orbits Earth every 90 minutes and therefore will experience about 16 days every Earth day.

The outdoor atmospheres in space are very different from the N_2 and O_2 rich air that we have on Earth. The Moon has a near negligible atmosphere which can be seen from the very low atmospheric pressure listed for the Moon in Table 1. The atmosphere that does exist is estimated to be composed of 26% He, 26% Ne, 23% H_2, 19% Ar, and some other gases in trace amounts. Mars has a more significant atmosphere than the Moon but still a much less significant atmosphere than Earth. Mars' atmosphere is 95% CO_2 and is prone to dust storms. Cloud formation has also been documented in Mars' atmosphere (Vicente-Retortillo et al. (2015)).

Looking now at the gas composition and pressure of the indoor environment, it is possible that extraterrestrial habitats will be kept at Earth's atmospheric pressure of 101.3 kPa and typical air composition. There is, however, considerable research going into the feasibility of extended human survival at lower atmospheric pressures. It would be beneficial from a design perspective to have the interiors of habitats at lower pressures that are closer to that of the environment in which they are located. Most notably, a reduced indoor-outdoor pressure difference requires less intensive construction practices. However, reduced pressures mean that the percentage of O_2 in the indoor environment needs to be increased to support human physiological needs (Paul and Ferl (2006)). Thus, depending on design, extraterrestrial habitats could reflect the typical pressure and gas composition of earthly buildings or could make use of low-pressure, O_2-rich environments.

Building performance simulation

BPS tools have the models and functionality capable of accurately simulating heat and mass transfer processes in buildings. Until now, BPS tools have been designed with Earth buildings in mind. In the sections to follow, models and practices used for heat and mass transfer will be examined through the lens of a building researcher looking to model extraterrestrial habitats.

Zoning and mass transfers

CFD has been a popular choice for space habitat simulations to date and this choice is likely driven by the detailed resolution CFD can provide for a single zone. CFD is available in some BPS programs but is not commonly employed due to the knowledge and experience needed to properly configure CFD models and boundary conditions (Beausoleil-Morrison (2021)). More commonly, BPS programs assume thermal zones are well mixed (uniform temperature, pressure, and composition). This assumption works well for many studies on Earth but is less reflective of reality in space. The accuracy of assuming a well-mixed zone in space most significantly depends on the level of gravity present and the extent of mechanical ventilation in the habitat forcing air mixing. Without gravity, buoyancy-driven airflows are non-existent and in reduced gravity environments (such as the Moon and Mars) the impact of natural airflows will be reduced. Thus air mixing in space depends significantly on mechanical ventilation and chemical diffusion (which is a very slow process). Temperature gradients in still fluids of the same composition (e.g. air at different temperatures) will degrade by conduction and radiation between the molecules only. As a result, buildings in low gravity fields will have significant temperature and gas composition variation in a single geometric zone unless mechanical equipment is used for mixing.

In zones with significant and consistent mechanical ventilation it's likely sufficient to assume a well-mixed zone, but there will be areas in a space habitat that won't have significant air movement. For example, CQs (where astronauts sleep) will need to have well designed airflow systems that maintain adequate air movement without creating uncomfortable drafts. A simulation of the CQs on the ISS employing the well-mixed assumption would likely not flag a CO_2 concentration problem since the average concentration of the zone could be below acceptable levels. But a CFD model would be able to highlight that the CO_2 is dangerously concentrated around the astronaut's sleeping head as was seen in Georgescu et al. (2020). In these types of low air-movement spaces, CFD capabilities built into BPS tools is likely needed to capture the composition and temperature variations within the zone being analyzed. Another option is to divide single geometric zones into many separate thermal zones and to create an airflow network (AFN) between the smaller zones, however this requires significant knowledge of the airflow behaviour within a zone. CFD models are likely the best way to look at zones that are expected to not be well mixed but the models and practices used in implementing CFD need to be validated for low gravity environments.

Space habitats are designed to avoid significant infiltration/exfiltration between the habitat and the surrounding environment. This is critical to human survival and so only inter-zonal mass transfers and HVAC mass transfers need to be considered. BPS modelling approaches for infiltration will not be necessary. Along this same train of thought, IEQ is a big concern as we submerge humans into deadly atmospheres and expose them to new environmental hazards. The ability to model various air pollutants and their movement throughout a habitat is an important capability for BPS tools to have when modelling buildings in space. Many BPS programs are able to model various gases through bulk air movement using AFNs however diffusion and buoyancy-driven airflows between different gases are not considered in these networks. Additionally, the ability to model solid particle dispersion and movement is not currently possible in BPS tools. A concern for Lunar and Martian habitats is the possibility of Lunar and Martian dust getting into the habitats as astronauts enter and leave the habitat (Kobrick and Agui (2019)). Many CFD programs are able to simulate particle movement and it would be beneficial to add this capability to BPS tools as it will help inform building design decisions in space applications.

As was mentioned, AFNs can be used to model pollutant and air movement between zones. The components used to connect nodes in an AFN are derived from fundamentals but are mostly implemented in BPS tools as empirical models for specific opening types. These empirical models are derived from experiments done on Earth and are therefore specific to Earth's gravitational field. The validity of these models in other gravitational fields and for fluids other than air at Earth's atmospheric pressure would need to be investigated. This same conclusion applies to HVAC models implemented in BPS tools. Many BPS models used to define HVAC systems are empirical and derived from experiments of HVAC equipment on Earth. Proper modelling of life support systems is critical to properly modelling the indoor environment of a space habitat and many of these systems are not a part of the Earth HVAC repertoire (e.g. CO_2 zeolite adsorption filtration systems; urine and feces processing systems) and the ones that are common between Earth and space habitats use models specific to Earth's gravity. Some examples of HVAC processes that would need to be considered are phase change and two-phase forced convection which are documented as occurring differently in reduced gravity conditions (Sundén and Fu (2017); Guo et al. (2014)). Thus new HVAC models for systems in space would need to be developed and validated to successfully model an extraterrestrial habitat. The work done on V-HAB (Zhukov et al. (2011)) is perhaps a good place to start in this venture.

Conduction

Fourier's law of conduction, which is the fundamental equation used for calculating conduction heat transfer in buildings, still applies in space (thankfully universal laws are, by definition, applicable across the universe). It is common in BPS simulations to approximate the multi-dimensional, multi-mode heat transfer process across a building material as a 1-dimensional conduction-only process (Beausoleil-Morrison (2021)). The conduction-only simplification can cause issues for more porous materials (where convective and radiative heat transfer become more significant) and for materials exposed to extreme temperatures that differ from the temperature at which their effective conductivity was determined (Berardi and Naldi (2017)). Some BPS tools (EnergyPlus and ESP-r) allow users to input temperature varying effective conductivities to better approximate the actual heat transfer processes at play. For space applications, it is argued that effective conductivities should be re-evaluated in reduced gravity and varying atmospheric pressures and compositions to see how the actual conductivity changes as a function of these environmental conditions.

The conduction-only assumption becomes particularly problematic in building materials with gas gaps or vacuum gaps. To more accurately model gas gaps in building materials, some dedicated individuals will model the gap as a separate thermal zone in order to capture the convective and radiative heat transfer processes occurring. This same process could be used for a vacuum gap (which is more common in space buildings) however the only heat transfer process in a vacuum is radiation. It would be best to modify BPS tools to couple a radiation model to a transient conduction model in order to properly quantify the heat moving through such building materials. The proper modelling of vacuum spaces will be particularly important for window models in environments will little to no atmosphere.

Convection

The well-mixed assumption for zones that is commonly implemented in BPS tools allows convective heat transfer to be calculated using Newton's law of cooling (Beausoleil-Morrison (2021)). This method presents only one challenge in determining the convective heat transfer in a BPS simulation - establishing an appropriate convection coefficient. Although there are theoretical equations derived from boundary layer analysis that can be used to solve for convection coefficients, these only exist for simple flows over simple geometries. For more complex and realistic scenarios, such as those experienced in a building environment, there is still a dependence on obtaining convection coefficients from empirical formulas (Bergman et al. (2011)). This is the strategy implemented in BPS programs for determining the convection coefficients for all surfaces.

Convection is classified into two main categories - natural convection and forced convection. Natural convection is driven by density differences and buoyancy forces whereas the fluid motion resulting in forced convection is generated by an external source (such as fans or HVAC). Empirical convection models used in BPS programs for building surfaces are developed from experiments in Earth's gravitational field, with air passing over different surfaces at different orientations, all at Earth's atmospheric pressure (Peeters et al. (2011); Mirsadeghi et al. (2013)). The internal convection models are divided into natural convection, forced convection, and mixed convection (both natural and forced). All external convection models consider the forced convection generated by wind however only a few consider the natural convection that becomes non-negligible at low windspeeds when there's a significant external surface-air temperature difference. This brings up an important point for the discussion of the applicability of existing convection models in space - even when forced convection is present, there is always buoyancy-driven effects that need to be considered as well. Of course, these buoyancy-driven effects are small when fluids are moving at high velocities and forced convection takes over however it's important to remember that buoyancy forces are still present even when convection is classified as "forced".

Buoyancy effects on convection heat transfer is the main issue in moving existing convection correlations implemented in BPS tools to space. As was discussed in the *Zoning and mass transfers* section, buoyancy effects are non-existent in spaces with no effective gravity (such as the ISS and habitats moving through deep space). On the Moon and Mars, where surface gravity is 17% and 38% of Earth's surface gravity, buoyancy effects will be existent but reduced. So the impact of natural convection on its own will be eliminated or significantly reduced for buildings in space. The performance of forced convection in space will depend on how significant the buoyancy component is for a given situation. Regardless, new convection models will need to be developed in microgravity, on the Moon, and on Mars to account for the varying gravity fields. At a minimum, a study would need to be done to investigate a convection coefficient correlation form in which gravity could be input as a variable.

In addition to the variance in gravity between space environments and Earth, the chemical composition of the outdoor and indoor environments needs to be considered. The convection correlations currently implemented in BPS programs are all derived from experiments with air. When considering extraterrestrial buildings, CO_2 and O_2 rich fluids need to be considered. Convection coefficients are functions of Nusselt number (Nu) and Nu is a function of Reynolds (Re) and Prandtl (Pr) numbers (Bergman et al. (2011)). These non-dimensional numbers are calculated using fluid properties and so different fluids will result in different convection coefficients for similar flow rates and geometries. The extent of the variance in convection coefficients between the fluids anticipated in and around space habitats needs to be investigated. There are also significant dust storms documented on Mars (Banfield and et. al. (2020)) and the impact of significant concentrations of Martian dust in the atmosphere on convection heat transfer at external surfaces needs to be quantified.

When simulating the ISS, habitats moving in deep space, and habitats on the Moon, the atmospheres are negligible or non-existent and so external convection can be neglected. Mars has a more substantial atmosphere than the Moon but still a significantly less dense atmosphere than Earth. The ability to neglect external convection for Martian buildings will need to be investigated more closely than in the case of the Moon. For all external environments, the level of accuracy needed for external convection models will depend on the insulation level of the proposed habitats. If habitats are substantially insulated, then the external environment might have a negligible impact on predicting the energy usage and indoor air temperature of a building.

Radiation

Many of the existing resources and modelling practices in BPS programs to simulate radiation heat gains and losses at building surfaces are easily translated into space applications due to their independence of many environmental variables. Starting with material properties, ASTM standard E903 (ASTM International (2020)), states that the solar absorptivity, reflectance and transmittance of materials need to be determined over the complete solar spectrum from 300 nm to 2500 nm. This covers most of the EM radiation seen in space but omits the higher energy rays (X-rays and gamma rays) that are not significant on Earth but are prevalent in space. Therefore, when considering heat gains from EM radiation in buildings, new absorptivity characteristics will need to be determined for the higher energy EM radiation that will be incident on building surfaces. Something else to consider when looking at radiation in space is if/how to account for energy gains/losses from the particle radiation that is present in space. From literature, the main concerns with particle radiation are the biological/health hazard they present as well as the degradation threat they pose to materials. The energy impact of these particles on materials is a complicated process (Durante and Cucinotta (2011)) that requires a significant understanding of particle physics and the associated energy change in building materials from the particle radiation expected in space needs to be quantified before it is discounted from BPS programs.

A key part of accurately simulating radiation heat gains in buildings is accurately simulating how much EM radiation is hitting the building's surface over time. On Earth, this process is done using solar angles and understanding the Earth's position relative to the Sun and a building's position on Earth. For space habitats fixed to other planetary surfaces, solar angle relationships specific to those planets will need to be programmed into BPS programs. The ability to quantify solar angles for orbiting habitats that don't have a fixed orbit or for habitats travelling between planets is complicated and will need to be carefully mapped out and custom programmed into a BPS program. Gamma rays, X-rays, and particle radiation do not exclusively come from the Sun and so their collision paths on a habitat are harder to predict. Additional research into predicting the locations of irradiance by these higher energy radiation sources will need to be done.

The solar irradiance considered in BPS programs is split into the diffuse component and the beam component. On Earth, the diffuse component of solar radiation comes from atmospheric scattering and from ground reflection. The variation in ground reflectivity on other planets will need to be quantified. Can constant values for ground reflectivity be used for planets such as the Moon and Mars or is there geographical and seasonal variation like we have on Earth? What are appropriate values for the ground reflectivity on those planets? These questions will need to be answered via experimental work. Looking now at atmospheric scattering of irradiance, the Moon has a negligible atmosphere and so there will likely be no diffuse solar irradiance from atmospheric scattering. The same is true for habitats orbiting or travelling between planets. On Mars, there is a more significant atmosphere that will play a role in creating diffuse solar irradiance. The amount of dust in the Martian atmosphere is documented as affecting radiation levels at the planet's surface (Vicente-Retortillo et al. (2015); Häder and Cabrol (2018)). The dust absorbs certain wavelengths (preferentially shortwave less than 650 nm) and also contributes to scattering (scattering both shortwave and longwave radiation) which means more dust results in more diffuse radiation (Vicente-Retortillo et al. (2015)). The diffuse component of solar irradiance created by atmospheric scattering can be measured using a pyranometer and so this would be a measured input in a weather file. However, new solar irradiance measurement tools may need to be investigated for Mars' unique atmosphere since dust deposition on pyranometers will make accurate measurements a challenge (the low gravity on Mars and the electrostatic charge of the dust make it deposit and stick to everything).

Isotropic diffuse sky models have been shown to lack accuracy for earthly applications (Perez et al. (1990)), so most BPS tools make use of anisotropic diffuse sky models that consider circumsolar brightening and horizon brightening. All such models are empirical and have been calibrated using measured data from certain locations on Earth. These types of models are likely not needed for the Moon and spacecraft traveling between planets since the effects modelled by the sky models are caused by the presence of an atmosphere. However, new models of these types would be required for Mars' atmosphere.

The methods currently employed for calculating radiation transfer through transparent assemblies in BPS programs should hold true in space. Most BPS programs aren't able to simulate the spectral transmissivity of windows, but the spectral properties of the bulletproof glass used on the ISS should be investigated to see if this omission is acceptable for modelling transparent assemblies in space. The glass used on the ISS is much thicker than what's typically used in Earth window constructions and the need for protective glazings (which can cause windows to preferentially transmit wavelengths (Beausoleil-Morrison (2021))) is much higher in the toxic radiation environment off-Earth. If spectral transmissivity is deemed an important feature to model, then the spectral distribution of incoming irradiance for environments in space would also need to be quantified and programmed into BPS tools if this is not a feature that's already available. If we look at how BPS programs are prepared to model EM radiation at internal surfaces once it passes through a transparent assembly, it's clear that the methods typically employed by BPS tools for determining the distribution of beam and diffuse solar irradiance on zone surfaces (described in Sections 3.4 and 3.5 of Beausoleil-Morrison (2021)) still apply.

Models and material emissivity values used for longwave radiation exchange between internal surfaces of Earth buildings should be unaffected since gravity doesn't affect radiation heat transfer and the gas composition expected indoors should still be accurately modelled using the assumption in BPS programs that all mediums within a building do not participate in radiation exchange (Beausoleil-Morrison (2021)). In modelling longwave radiation at external surfaces, however, there is a need to determine an effective sky temperature (T_{sky}) that is used to approximate the longwave radiation exchange of an external surface with the atmosphere, clouds, and deep space (Beausoleil-Morrison (2021)). The models currently employed to calculate T_{sky} are empirical and are based on pyrgeometer measurements taken on Earth. As a result, similar empirical models will need to be developed for the Moon and Mars. The variation of T_{sky} for habitats that are moving within the solar system should also be investigated. Mars offers a unique challenge in determining an appropriate value for T_{sky} since its atmosphere is mostly CO_2 (which preferentially absorbs longwave radiation around 15 μm) and can contain significant amounts of dust (which, mentioned above, scatters longwave radiation). As such, Mars' atmosphere could be more participatory in longwave radiation exchange than Earth's atmosphere. It is therefore possible that a more complicated spectral analysis is needed to accurately model longwave radiation exchange at external surfaces on Mars.

Conclusion

BPS tools in their current state are not prepared to model buildings in environments other than Earth but the foundation for such a venture is strong in BPS tools. Many of the modifications needed involve adjusting the empirical models that are currently implemented for new models that are derived for the new environments under consideration. Partnerships with space agencies to obtain measured data and experimental opportunities in reduced gravity are key to developing the practices and models needed to simulate buildings in space.

The authors would summarize important tasks/research areas to pursue moving forward as follows:

- Develop new methods for calculating the effective radiant temperature of exterior environments that consider the impact of atmospheric gases, clouds, and atmospheric dust in space.
- Develop empirical models for predicting the distribution of sky diffuse solar irradiance.
- Develop new empirical convection models for the environments anticipated in space.
- Investigate material properties and thermal impacts of the high energy EM radiation and particle radiation that will be encountered in space.
- Improve the ability of BPS tools to model convection and radiation heat transfer within the transient conduction analysis of building materials.
- Add the ability to model solid particle movement within and between zones.
- Develop new effective conductivities for building materials in the conditions anticipated in space.
- Improve/expand on the CFD capabilities in existing BPS tools or develop coupling abilities between BPS tools and CFD-specific tools. At a minimum, modelling strategies for zones that are not well mixed should be investigated.

The hope is that this paper convinces readers of the interesting avenues that can be taken in the quest to model extraterrestrial buildings. This is a research area that is in its infancy and offers years' worth of projects that could have very real impacts moving forward.

References

Albrecht-Buehler, G. (1992). The simulation of microgravity conditions on the ground. *Gravitational and Space Biology 5*(2), 3–10.

ASTM International (2020). ASTM E903-20, Standard Test Method for Solar Absorptance , Reflectance , and Transmittance of Materials Using Integrating Spheres.

Banfield, D. and et. al. (2020). The atmosphere of Mars as observed by InSight. *Nature Geoscience 13*(3), 190–198.

Barrett, J. (2005). Greenhouse molecules, their spectra and function in the atmosphere. *Energy and Environment 16*(6), 1037–1045.

Beausoleil-Morrison, I. (2021). *Fundamentals of building performance simulation.* Routledge.

Berardi, U. and M. Naldi (2017, jun). The impact of the temperature dependent thermal conductivity of insulating materials on the effective building envelope performance. *Energy and Buildings 144*, 262–275.

Bergman, T. L., A. S. Lavine, F. P. Incropera, and D. P. DeWitt (2011). *Fundamentals of Heat and Mass Transfer, 7th Edition* (7th ed.). Hoboken, NJ : John Wiley & Sons, Inc.

Czupalla, M., A. Zhukov, J. Schnaitmann, C. Olthoff, M. Deiml, P. Plötner, and U. Walter (2015). The Virtual Habitat – A tool for dynamic life support system simulations. *Advances in Space Research 55*(11), 2683–2707.

Durante, M. and F. A. Cucinotta (2011). Physical basis of radiation protection in space travel. *Reviews of Modern Physics 83*(4).

Georgescu, M. R., A. Meslem, and I. Nastase (2020). Accumulation and spatial distribution of CO2 in the astronaut's crew quarters on the International Space Station. *Building and Environment 185*(September), 107278.

Georgescu, M. R., A. Meslem, I. Nastase, and L. Tacutu (2021). An alternative air distribution solution for better environmental quality in the ISS crew quarters. *https://doi.org/10.1080/14733315.2021.1975062*.

Guo, H., X. Liu, J. F. Zhao, F. Ye, and C. F. Ma (2014, dec). Experimental study of two-phase flow in a proton exchange membrane fuel cell in short-term microgravity condition. *Applied Energy 136*, 509–518.

Häder, D.-P. and N. A. Cabrol (2018). *From Habitability to Life on Mars*. Elsevier.

Hayakawa, S. and M. Matsuoka (1964). Part V. Origin of Cosmic X-Rays. *Progress of Theoretical Physics Supplement 30*, 204–228.

Kobrick, R. L. and J. H. Agui (2019, jul). Preparing for planetary surface exploration by measuring habitat dust intrusion with filter tests during an analogue Mars mission. *Acta Astronautica 160*, 297–309.

Lin, C. H., C. H. Son, and R. H. Horstman (2000). CFD studies on the ECLSS airflow and CO2 accumulation of the International Space Station. *SAE Technical Papers* (724).

Mirsadeghi, M., D. Cóstola, B. Blocken, and J. L. M. Hensen (2013). Review of external convective heat transfer coefficient models in building energy simulation programs: Implementation and uncertainty. *Applied Thermal Engineering 56*, 134–151.

Paul, A.-L. and R. J. Ferl (2006). The biology of low atmospheric pressure - implications for exploration mission design and advanced life support. *Gravitational and Space Biology 19*(2), 3–18.

Peeters, L., I. Beausoleil-Morrison, and A. Novoselac (2011). Internal convective heat transfer modeling: Critical review and discussion of experimentally derived correlations. *Energy and Buildings 43*(9), 2227–2239.

Perez, R., P. Ineichen, R. Seals, J. Michalsky, and R. Stewart (1990). Modeling daylight availability and irradiance components from direct and global irradiance. *Solar Energy 44*(5), 271–289.

Pütz, D., C. Olthoff, J. Schnaitmann, and U. Water (2019). Development Status of the Virtual Habitat (V-HAB) Simulation System. In *49th Int. Conference on Environmental Systems*, Number July.

Schönfelder, V. (2001). *The universe in gamma rays.* Springer.

Smirnov, E. M. and et. al. (2006). CFD Modelling of Cabin Air Ventilation in the International Space Station: A Comparison of RANS and LES Data with Test Measurements for the Columbus Module. *Int. J. of Ventilation 5*(2), 219–227.

Son, C. H., E. H. Turner, E. M. Smirnov, N. G. Ivanov, and D. S. Telnov (2005). Integrated computational fluid dynamics carbon dioxide concentration study for the international space station. *SAE Technical Papers 114*.

Sundén, B. and J. Fu (2017). Microgravity Heat Transfer. *Heat Transfer in Aerospace Applications*, 155–177.

Vicente-Retortillo, Á., F. Valero, L. Vázquez, and G. M. Martínez (2015). A model to calculate solar radiation fluxes on the Martian surface. *J. of Space Weather and Space Climate 5*.

Wang, C., J. Liu, W. Shang, H. Sun, J. Li, and F. Fan (2018). Experimental and numerical study of space station airflow distribution under microgravity condition. *Building and Environment 144*(August), 268–280.

Zhukov, A., M. Czupalla, M. Knifka, P. Ploetner, and T. Stuffler (2011). Status of the correlation process of the V-HAB simulation with ANITA ISS data. *41st Int. Conference on Environmental Systems 2011, ICES 2011* (July), 1–13.