A Numerical Analysis of the Air Distribution System for the Ventilation of the Crew Quarters on board of the International Space Station

Florin Bode[1,2], Ilinca Nastase[2], Cristiana Verona Croitoru[2], Mihnea Sandu[2], Angel Dogeanu[2]

[1]CAMBI Research Center, Technical University of Civil Engineering Bucharest, 021414 Bucharest, Romania
[2]Technical University of Cluj Napoca, Department of Mechanical Engineering 400020 Cluj - Napoca, Romania

Abstract. Quality of life on the International Space Station (ISS) has become more and more important, since the time spent by astronauts outside the terrestrial atmosphere has increased in the last years. The actual concept for the Crew Quarters (CQ) have demonstrated the possibility of a personal space for sleep and free time activities in which the noise levels are lower, but not enough, compared to the noisy ISS isle way. However, there are several issues that needs to be improved to increase the performance of CQ. Our project QUEST is intended to propose a new concept of CQ in which we will correct these issues, like the noise levels will be lower, more space for astronaut, increased thermal comfort, reduce the CQ total weight, higher efficiency for the air distribution, personalized ventilation system in CQ for the crew members in order to remove CO_2 from the breathing zone. This paper presents a CFD study in which we are comparing the actual and a proposed ventilation solution for introducing the air in CQ. A preliminary numerical model of the present configuration of the air distribution system of the Crew Quarters on board of the ISS, shows the need for an improved air distribution inside these enclosures. Lower velocity values at the inlet diffuser, distributed over a larger surface, as well as diffusers with improved induction would appear to be a better choice. This was confirmed through the development of a new model including linear diffusers with a larger discharge surface. In this new configuration, the regions of possible draught are dramatically reduced. The overall distributions of the velocity magnitudes displaying more uniform, lower values, in the same time with more uniform temperatures. All these observations allow us to consider a better mixing of the air inside the enclosure.

1 Introduction

Space is one of the most extreme environments imaginable. Outside ISS, the wall temperature will vary from 121°C (Sun facing side) to -157°C (dark side)[1]. Due to the fact that the time spent by astronauts on ISS has increased over the years, quality of life has become a matter that needs to be improved. Furthermore, future space stations and long range transportation space ships will demand for more comfortable life conditions for both crew members and travellers. Over the last two-and-a-half decades, The International Space Station's Environmental Control and Life Support System (ECLSS) has developed in size, complexity, and capability continuously from the beginning [2]. ISS crew members are living and working in a high-risk environment, and their comfort plays a major role in ISS proper operation, because a rested crew member operating in a comfortable environment is less prone to human error.

Nowadays, on the ISS operates several personal Crew Quarters (CQ) for the crew members [3-5]. The most advanced form all CQ are four of them which are installed in the Harmony Node (also known as Node 2) [6]. Functionally, the role of a CQ is to provide a quiet private place in which crew personnel can sleep or relax in the free time (Figure 1 and Figure 2).

However, there are several issues that needs to be improved to increase the performance of CQ. NASA and ESA admitted that on ISS, higher noise levels, CO2 and dust accumulation are frequently occurring issues [7, 8]. From our observations we believe that the current CQ design can be improved in order to reduce the noise levels, increase the personal space for astronaut, increased thermal comfort, reduce the CQ total weight, higher efficiency for the air distribution, personalized ventilation system in CQ for the crew members in order to remove CO_2 from the breathing zone. These improvements are the objective of the QUEST research project developed by our research team.

One of the goals of our project is to understand the flows occurring in the actual design of air diffusion system of the existing CQ on the ISS. Our team has experience on studying the air flow through different types of diffusers. This paper presents a CFD study in which we are comparing the actual and a proposed ventilation solution for introducing the air in CQ [9-11].

In the last five decades, extensive investigations and experiments involving human subjects have resulted in methods for predicting the degree of thermal discomfort of people exposed to a certain environment. One of the most well-known and widely accepted method is Fanger's "Comfort Equation" and his practical concepts

* Corresponding author: ilinca.nastase@utcb.ro

of "Predicted Mean Vote" and "Predicted Percentage of Dissatisfied" [12].

Fanger's hypothesis relies on the thermal balance between the heat produced, consumed and transferred to the environment when the human body finds itself in a state of neutrality. The most important parameters that can influence the thermal comfort state were considered to be the metabolic rate, the clothing thermal resistance, the air temperature, velocity, humidity, pressure and turbulence intensity [12-15].

Figure 1 : Crew Quarters installed on ISS Harmony node [16]

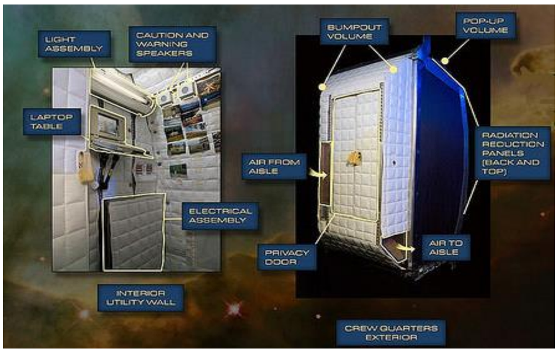


Figure 2: CQ in its actual structure [3]

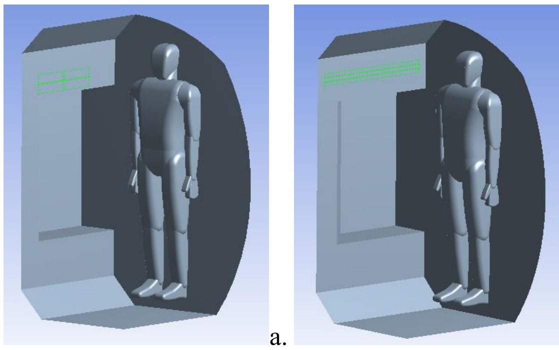
When the heat balance equation proposed by Fanger is satisfied, the heat generated by the human body is dissipated without having an increase or a decrease in the human body [12]. PMV index values are between -3 and 3. These values quantify the average opinion of a group of subjects on the state of comfort. Associated with this parameter, is the index PPD, indicating the percentage of occupants in thermal discomfort.

Fanger and Christensen [17] proposed correlations for the local turbulence intensity of the indoor air flow with the thermal discomfort sensation in an index called "Draught Rate" (DR). The Draught Rate is an index that depends on the mean velocity and temperature but also on the air turbulence intensity value. DR values are divided in four regions of values corresponding to a classification of the indoor ambiance regarding its comfort level. This way, a values of DR≤15% are associated to the zones with a high standing quality of the ambiance, values of 15%≤ DR≤20% are corresponding to a good quality of the ambiance, values 20%≤ DR≤25% are corresponding to an acceptable quality of the ambiance and values of DR>25% correspond to unacceptable conditions to regions where the sensation of draught might create a serious discomfort. More information on thermal comfort models for indoor spaces and vehicles can be found in [18].

The CQ total volume is around 2.1 m^3 and is limited to the size of a standard US rack volume [6, 19, 20]. The actual ventilation system provides adjustable airflow at three different flow rates. The CQ ventilation system's main purpose is to lower the carbon dioxide concentration, which in high levels represents an asphyxiation hazard. Another role of the CQ ventilation system is to remove the heat generated in the CQ which is composed from crew member's metabolic heat (100-132 W) and the electronics heat (around 153 W) [6, 19, 20]. The primary ventilation requirements for the CQ are: 0.42-5.1m^3/min of airflow and exhaust air velocity lower than 1.2 m/s.

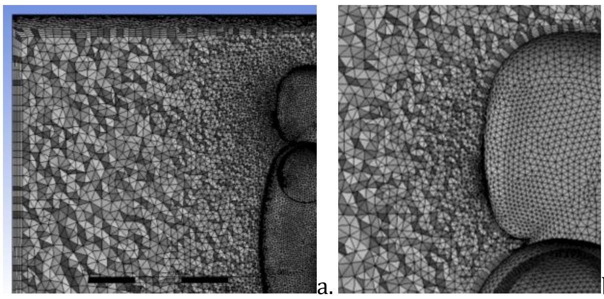
2 MATERIAL AND METHOD

The CQ geometrical model along with the virtual manikin was built using the SolidWorks software in Figure 3. Unstructured tetrahedral meshes were generated for both studied cases. The actual ventilation solution study of the CQ (Figure 3a) was already presented in [21]. This configuration of the air diffuser is composed by four rectangular regions, each of them having independent vertical and horizontal guiding vanes [6, 19, 20]. The proposed ventilation solution is presented in Figure 3b. The main difference between the presented solutions in Figure 3 is the replacement of the axial fan solution with a tangential fan solution.



a. b.

Figure 3: Studied geometrical model a. Actual ventilation solution - Case 1 b. Proposed ventilation solution - Case 2



a. b.

Figure 4: Computational mesh for case 2
a. General view b. Close-up view

For the proposed ventilation solution (Case 2), a new mesh was generated consisting of 5.8 million elements. A boundary layer of 5 layers was generated (Figure 4 a and b).

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Ansys Fluent was the software used for the numerical modelling. For the pressure-velocity coupling, Fluent provides four segregated types of algorithms (SIMPLE, SIMPLEC, PISO, Fractional Step) and a coupled one. For this study we used coupled algorithm which offers some advantages over the segregated approach because it contains a robust and efficient single phase implementation for steady-state flows, with superior performance compared to the segregated algorithms [22]. A second order upwind scheme was used to calculate the convective terms in the equations, integrated with the finite volume method. SST k-ω was the turbulence model used for the numerical simulation due to our experience in using this model for indoor air circulation [23]. The reason is that in SST k-ω turbulence model, for flows, both the boundary layer as well as the free stream are considered.

For the boundary conditions, we imposed three mass flow rates corresponding to the three positions of the fan controller: low, medium and high, respectively 108 m^3/h, 138 m^3/h and 196 m^3/h [20]. The Reynolds numbers at the exit of the air vents based on streamwise mean velocity and on the equivalent diameter (De_1= 1.144m) were Re_1= 4462, Re_2=5692, and Re_3=8098. The inlet turbulence intensity was imposed at: 5.6%, 5.43% and 5.19%, being calculated using the empirical relation proposed by Jaramillo [24]. The present configuration of the air diffuser is presented in [6, 19, 20] and is composed by four rectangular regions, each of them having independent vertical and horizontal guiding vanes. Inspired by [20] we considered that the air flow is deflected equally towards right and left in the horizontal plane with a 45° angle respectively, and in the same time the air flow is deflected equally towards the 'up' and 'down' in the vertical plane with a 45° angle as well.

For the cases 1, 2 and 3 we have considered that the air flow is deflected right and left on the horizontal and up and down on the vertical with a 45° angle [20]. Case 1, 2 and 3 are corresponding to the flow rates of 108 m^3/h, 138 m^3/h and 156 m^3/h. For the cases 4 and 5 the air was deflected 45° angle down, through an improved linear diffuser. This case is associated with an idea of a first level improvement of the air distribution system in the CQ. This way, we propose to keep the actual configuration of the inlet and the exhaust ducting parts but renounce to the ducting and abatements that are situated along the door of the CQ. This will be possible using transverse flow (cross-flow) fans. The inlet and the outlet grilles inside the CQ cabin will be kept at the same locations. The inlet air grille to the Node 2 cabin will be placed on the 'upper' chamfered part of the bump-out while the exhaust air grille will be kept at the same position on the lateral flat side of the bump-out.

In the case 4 we tested the medium flow rate of 138 m^3/h, and in the case 5 we tested the high flow rate of 156 m^3/h. We considered to present here only the two highest flow rates that were recorded to produce problems in terms of local air speed discomfort. The inlet air temperature was in all cases 18°C corresponding to the air taken from Node 2. The heat flux from the walls was equivalent to 150 W (imposed wall temperature was 22 °C). On the different zones of the virtual manikin inside the CQ we imposed the temperatures from Table 1.

Table 1. Temperatures imposed on the manikin surface

t	t_{head}	t_{neck}	t_{torso}	$t_{shoulders}$	t_{arms}	$t_{forearms}$	t_{hand}	t_{thigh}	t_{leg}	t_{feet}
°C	36	35	34	34	33	32	30	32	30	28

3. RESULTS AND DISCUSSION

Figures 5, 6 and 7 are presenting the distributions of the velocity magnitude, air temperature, of the in-plane vectors, and of the predicted percentage of dissatisfied regarding the draught sensation in the coronal plane of the virtual manikin in the first three cases (cases 1, 2 and 3). These three cases are corresponding to the current situation of the air distribution system in the CQ on board of the ISS.

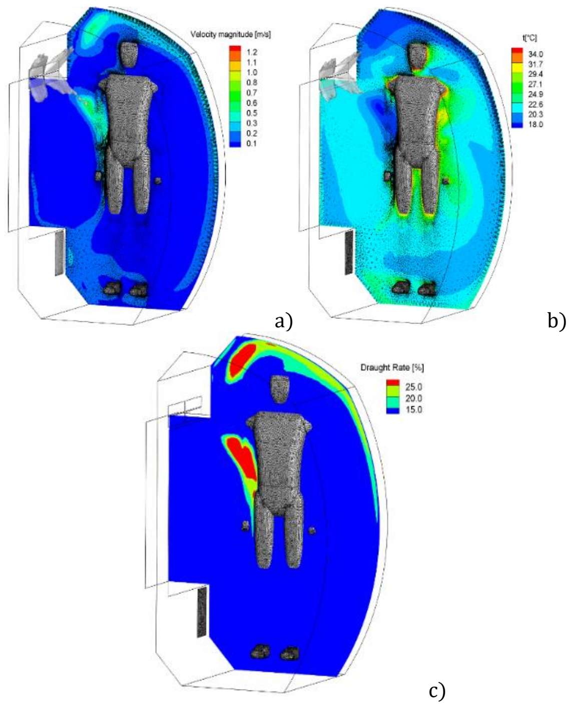

Figure 5: Distributions in the coronal plane of the virtual manikin – case 1 - 108m^3/h : a) velocity magnitude, b) air temperature, c) DR – predicted percentage of dissatisfied regarding the draught sensation

On the velocity magnitudes distributions in the coronal plane we superimposed iso-values of the velocity magnitude in the entire cabin corresponding to 0.6 m/s. On the temperature distributions in the coronal plane we superimposed iso-values of the temperature in the entire cabin corresponding to 18°C. Figures 8 and 9 are presenting the same distributions for the cases 4 and 5 corresponding to the medium flow rate and the proposed new air distribution strategy.

For the first three cases, the global pattern of the flow inside the CQ is changing dramatically with a relatively slight variation of the inlet velocity. In the region of the head and of the chest, fairly high values of the velocity magnitude from the point of view of limitations imposed by the thermal comfort standards, suggest that a sensation of thermal discomfort might occur. This is confirmed by the distributions of the draught rate.

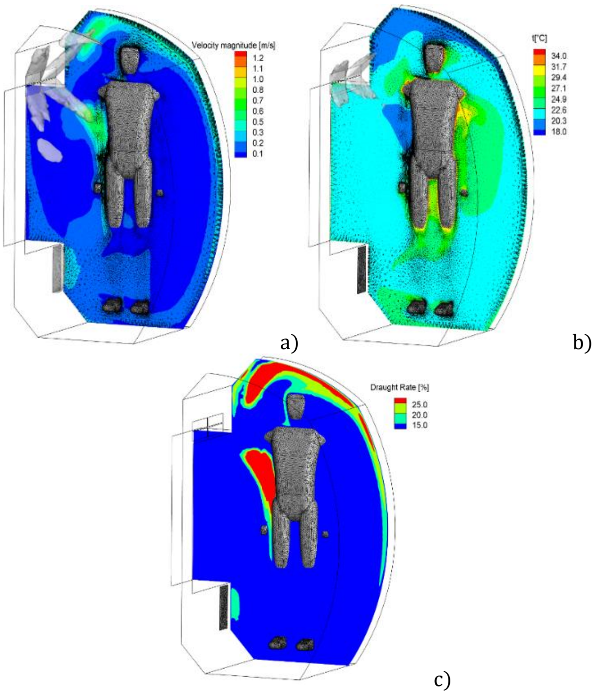

Figure 6: Distributions in the coronal plane of the virtual manikin – case 2 - 138m^3/h : a) velocity magnitude, b) air temperature, c) DR – predicted percentage of dissatisfied regarding the draught sensation

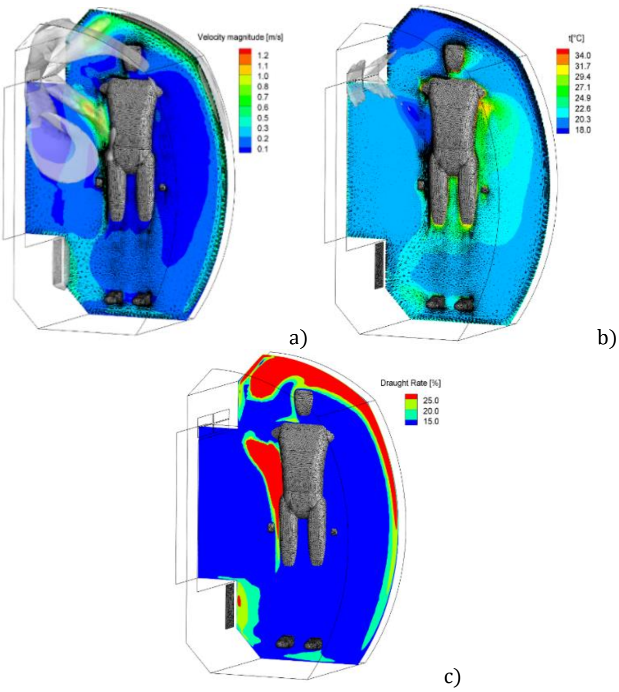

Figure 7: Distributions in the coronal plane of the virtual manikin – case 3 - 196m3/h: a) velocity magnitude, b) air temperature, c) DR – predicted percentage of dissatisfied regarding the draught sensation

The regions of possible draught are dramatically reduced in the case of the new linear diffusers. The flow is introduced with lower mean velocities over a larger surface, and the flow is oriented away of the head of the occupant. The overall distributions of the velocity magnitudes in Figure 8 and 9 are displaying lower values, more uniform than in the previous cases. In the same time we could observe more uniform temperature distributions inside the CQ. All these observations allow us to consider a better mixing of the air inside the enclosure.

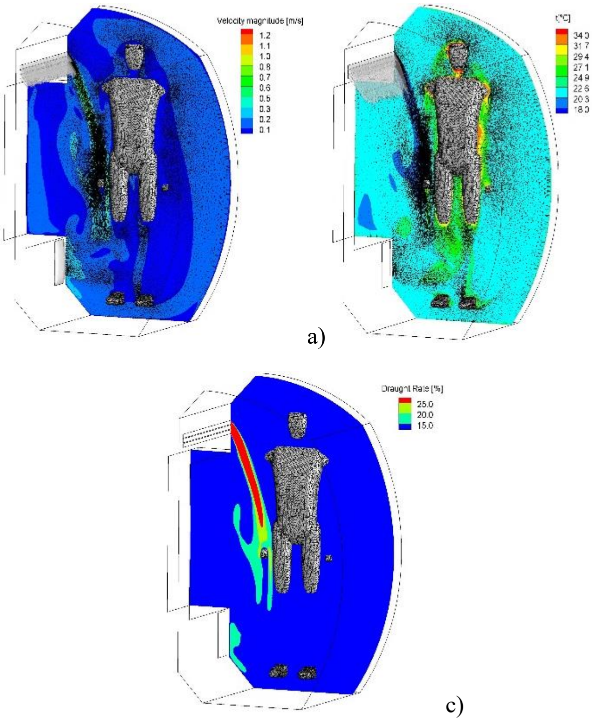

Figure 8: Distributions in the coronal plane of the virtual manikin – case 4 - 138m^3/h: a) velocity magnitude, b) air temperature, c) DR – predicted percentage of dissatisfied regarding the draught sensation

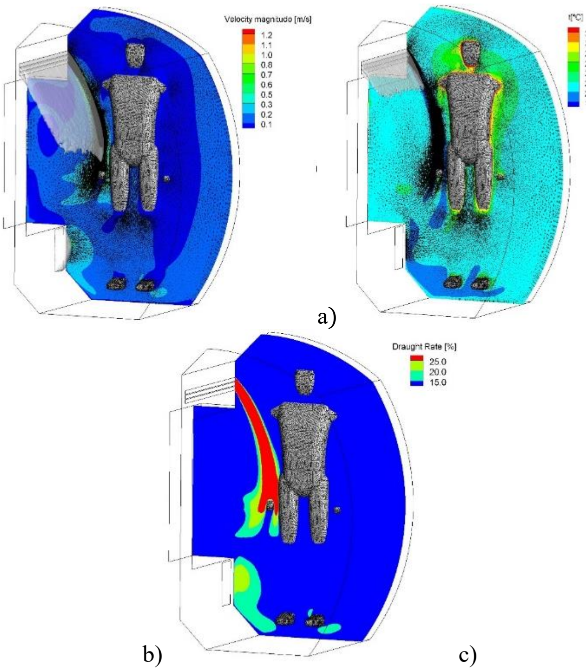

Figure 9: Distributions in the coronal plane of the virtual manikin – case 4 - 138m^3/h: a) velocity magnitude, b) air temperature, c) DR – predicted percentage of dissatisfied regarding the draught sensation

CONCLUSIONS

From our preliminary numerical study representing the testing of a model of the present configuration of the air distribution system of the Crew Quarters on board of the ISS, it appears that the need for an improved air distribution inside these enclosures is obvious. This way, lower velocity values at the inlet diffuser, distributed over a larger surface, as well as diffusers with improved induction would appear to be a better choice. This was confirmed through the development of a new model including linear diffusers with a larger discharge surface.

In this new configuration, the regions of possible draught are dramatically reduced. The overall distributions of the velocity magnitudes displaying more uniform, lower values, in the same time with more uniform temperatures. All these observations allow us to consider a better mixing of the air inside the enclosure.

Other further improvements, like a supplementary PV ventilation system, can aid in diminishing the issues with CO2 accumulation during the sleeping hours. A combination between the general ventilation system in the CQ module and a personalized ventilation system with an adjustable air diffuser will allow us to obtain good air quality near the crew member in any conditions and further improve thermal comfort by covering the need for fresh air without having to lower the overall temperature inside the CQ module. This configuration has to be tested next.

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References

1. NASA, https://science.nasa.gov/science-news/science-at-nasa/2001/ast21mar_1. 2001.
2. Robert M. Bagdigian, et al. *International Space Station Environmental Control and Life Support System Mass and Crewtime Utilization In Comparison to a Long Duration Human Space Exploration Mission*. *International Conference on Environmental Systems ICES*. 2015. Seattle,
3. Schlesinger, T.P., B.R. Rodriguez, and M.A. Borrego, *International Space Station Crew Quarters On-Orbit Performance and Sustaining Activities.* AIAA Journal, 2013.
4. Broyan, J.L., S.M. Cady, and D.A. Welsh, *ISS Crew Quarters Ventilation and Acoustic Design Implementation.* AIAA Journal, 2010.
5. *NASA Reference guide to the ISS* https://www.nasa.gov/pdf/508318main_ISS_ref_guide_nov2010.pdf. 2010.
6. Fairburn, S. and S. Walker, *'Sleeping With the Stars'–The Design of a Personal Crew Quarter for the International Space Station*. 2001, SAE Technical Paper.
7. Matty, C.M., *Overview of Carbon Dioxide Control Issues During International Space Station/Space Shuttle Joint Docked Operations.* American Institute of Aeronautics and Astronautics, 1976.
8. https://www.newscientist.com/article/dn9379-noisy-iss-may-have-damaged-astronauts-hearing/.
9. Amina Meslem, et al., *Optimization of a Lobed Perforated Panel Diffuser - A Numerical Study of Orifice Arrangement.* The International Journal of Ventilation, 2012. **11**(3): p. 16.
10. Bode, F., A. Meslem, and C. Croitoru, *Numerical simulation of a very low Reynolds cross-shaped jet.* Journal Mechanika 2013. **19**(5): p. 6.
11. Bode, F., et al., *The influence of the Inlet angle of vehicle air diffuser on the thermal comfort of passengers.* ENERGY and ENVIRONMENT (CIEM), 2017 p. 442-446.
12. Fanger, P.O., ed. *Thermal Comfort-Analysis and Applications in Environmental Engineering*. ed. C.D.T. Press. 1970.
13. *ISO 7730 - Ergonomics of the thermal environment.* 2005.
14. Djongyang, N., R. Tchinda, and D. Njomo, *Thermal comfort : A review paper.* Renewable and Sustainable Energy REviews, 2010. **14**: p. 2626-2640.
15. Nilsson, H.O., *Thermal comfort evaluation with virtual manikin methods.* Building and Environment, 2007. **42**(12): p. 4000-4005.
16. NASA, https://spaceflight.nasa.gov/gallery/images/station/crew-26/html/iss026e012169.html. 2010.
17. Fanger, P.O. and N.K. Christensen, *Perception of draught in ventilated spaces.* Ergonomics, 1986. **29**(2): p. 215 - 235.
18. Croitoru, C., et al., *Thermal comfort models for indoor spaces and vehicles—Current capabilities and future perspectives.* Renewable and Sustainable Energy Reviews, 2015. **44**(Supplement C): p. 304-318.
19. Adams, C. *Four Legs in the Morning: Issues in Crew-Quarter Design for Long-Duration Space Facilities*. in *28th International Conference on Environmental Systems, Danvers, MA.* 1998.
20. Broyan, J.L., M.A. Borrego, and J.F. Bahr. *International Space Station USOS Crew Quarters Development*. in *08ICES-0222*. 2008.
21. Florin Bode, et al., *Analysis for an improved concept of ventilation system for the Crew Quarters on board of the International Space Station*, in *6th CEAS Air & Space Conference*. 2017: Bucharest.
22. Ansys Inc, https://www.sharcnet.ca/Software/Ansys/17.0/en-us/help/flu_th/flu_th_sec_uns_solve_pv.html.
23. Danca, P., et al., *On the Possibility of CFD Modeling of the Indoor Environment in a Vehicle.* Energy Procedia 2017. **112**: p. 656-663.
24. Jaramillo, J.E., et al., *Numerical study of plane and round impinging jets using RANS models.* Numer. Heat Transfer Part B 2008. **54**: p. 213-237.