CFD analysis for an improved concept of ventilation system for the Crew Quarters on board of the International Space Station

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ABSTRACT

The current concept of Crew Quarters (CQ) on board of the International Space Station (ISS) demonstrated the possibility of a private place with reduced noise levels compared to the relatively acoustically noisy ISS aisle way. However, several issues were recorded by NASA and ESA, the most important ones pertaining to the noise levels and the accumulation of CO_2 and dust. Currently, 13% and 6%, respectively of the total mass and volume of a CQ are allocated to acoustic reductions. Interplanetary missions, unlike the low orbit ISS, would likely not allow this level of mass and volume penalty. It is believed the CQ has good air flow but high CO_2 levels are attained inside the station when the Carbon Dioxide Removal Assembly (CDRA) is not functioning to its capacity. Our project QUEST is intended to propose a new concept of improved CQ design for better acoustical performance, increased the space dedicated to the crew member, reduced the total weight, improved efficiency of the air distribution and a supplementary personalized strategy of air diffusion for eliminating CO_2 from the breathing zone. This paper presents a CFD study in which a numerical model of the air flow inside this enclosure. The numerical model was developed as a preliminary approach by our team as one of our goals is to understand the flows occurring in the actual design of air diffusion system of the existing CQ on the ISS. The results are showing that for all three air flow rates at which the present system is designed to function, the resulting flow patterns and velocity distributions are likely to produce draught discomfort. In this case, it appears that lower velocity values at the inlet diffuser, distributed over a larger surface, as well as diffusers with improved induction would be a better choice.

KEYWORDS: *International Space Station, Crew Quarters Ventilation, Air distribution and comfort, Computational Fluid Dynamics*

NOMENCLATURE

Latin
DR – draught rate [%]
t – air temperature [°C]
Re – Reynolds number
Subscripts
head - surface of the head region on the virtual manikin body
neck - surface of the neck region
torso - surface of the torso region
shoulders - surface of the shoulders
arms - surface of the arms region
forearm - surface of the forearms region
hand - surface of the hands region
thigh - surface of the thighs region
leg - surface of the legs region
foot - surface of the feet region

1 INTRODUCTION

1.1 Problematics

Quality of life on space stations or inside spacecrafts has become more and more important, since the time spent by astronauts outside the terrestrial atmosphere has increased over the years. Furthermore, future stations and transportation vehicles will demand more comfortable life conditions for more and more space travellers, whether they are simple tourists or professionals. With the technological development, the aspect of comfort is starting to gain importance since the wellbeing has a major impact on health, concentration and performance capabilities on long term. Moreover, national space agencies are also developing programs for commercial flights. For example NASA's Commercial Crew Program was designed to facilitate the development of a United States commercial crew space transportation capability with the aim of accomplishing safe, reliable and cost-effective access to and from the International Space Station and low-Earth orbit, laying the basis for upcoming commercial transportation capabilities [1, 2]. The space agencies are seeking improved life support systems that provide new levels of reliability and environmental quality for passengers and settlers [3, 4]. Challenges include accomplishing suitable temperature and humidity, maintaining a proper supply of fresh air, necessary water, and improved hygienic systems that are easy to use under microgravity conditions. In the same time, the resting periods are important for the body health and a quality sleep is important for occupants to do their jobs properly, to react appropriately to emergencies, and keep their performance capabilities intact. Any improvement of the actual environmental conditions represents a step further for future space accommodation.

Habitability refers to the suitability of a dwelling for living [5]. Early space missions were often of short duration, and served to confirm that people were physically able to go into space, therefore the design criteria focused on issues of function, efficiency, reliability and, of course, safety. As mission duration increases, and as more individuals, from different cultures and professions gain experience living in space, the question of what contributes to a habitable crew accommodation becomes more complex. Oungrinis et al. [6] define two types of habitability: environmental habitability and perceived habitability. The environmental habitability is associated with the actual spatial settings and conditions created inside the spacecraft by the design layout, the materials, as well as by the interior equipment and ambient elements. The perceived habitability is associated with the personalized, mental representations that the astronauts recreate from the actual environmental settings and conditions. Other studies are pointing the importance of psychological adaptation to space living and how significant is to obtain normal, Earth conditions [2]. It is clear that surrounding conditions are really important, being vital to comply with Earth living state. Challenges include achieving proper temperature and humidity balance, maintaining a continuous supply of fresh air, fresh water, developing appealing and easy to prepare foods that are acceptable for different cultures, and improved hygienic systems that are easy to use and perform well under conditions of microgravity [7].

Over the last two-and-a-half decades, the International Space Station's Environmental Control and Life Support System (ECLSS) has grown and evolved in size, complexity, and capability [8]. The functions that it performs today are many of those that will need to be performed in the future aboard spacecraft and habitats that will enable long duration human exploration missions to destinations beyond low earth orbit. Regardless of the particular deep space destination, it is widely accepted that highly reliable ECLSS systems that depend minimally on expendable equipment will be required [8]. Crew members working aboard the ISS operate in a high risk environment, with very limited access to outside resources and as such, their safety is paramount at all times. Their comfort plays a major role in all of this, as a rested crew operating in a comfortable environment is less prone to human error.

Currently, on the International Space Station (ISS) are installed several personal Crew Quarters (CQ) for the crew members [9-11]. Four of them are installed for instance in the Node 2 United States On-orbit Segment (USOS), also called Harmony Node [5]. These particular CQs are the newest design of personal space on board of the ISS. Functionally a CQ provides an acoustically quiet and visually isolated area in which crew members can sleep, relax, and retreat to a private area (Figures 1 and 2).

The crew quarters (CQ) on board the International Space Station provide a private place with reduced noise levels in comparison to the ISS aisle way. These spaces are meant to improve crew comfort by offering an intimate space where they can sleep and from which they can communicate with family and friends. However, these modules are not entirely without problems. As NASA and ESA have recorded, noise levels, CO_2 and dust accumulation are frequently occurring issues [12, 13]. Information regarding these issues, mainly comes in the form of crew member comments, most of which have indicated the need for reducing the acoustic signature of the ventilation system incorporated in the CQ module [10]. Other comments are concerned with headaches after waking up, which are believed to be caused by the accumulation of CO_2 in the sleeping area when the Carbon Dioxide Removal Assembly (CDRA) is not working properly [14]. Lastly, dust accumulation presents a problem in regard to obstructing the

air flow sensors that are monitoring the flow variation in order to prevent asphyxiation hazards [12, 15].
Our observations indicate that the current USOS CQ design can be improved at several levels in regard to acoustical performance, air distribution efficiency and dedicated crew member living space. In addition to these improvements, a supplementary personalized strategy for air diffusion could aid in reducing the CO_2 levels around the breathing zone. These improvements are the objective of the QUEST research project developed by our research team.
There are few studies presented in the literature, displaying results from numerical simulations of the heat and mass transfer phenomena associated to the air flows inside the CQ. 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. This paper presents a numerical model of the air flows inside this enclosure which was developed as a preliminary approach by our team.

Figure 1: USOS Crew Quarters installed on Node 2 of the International Space Station [5]

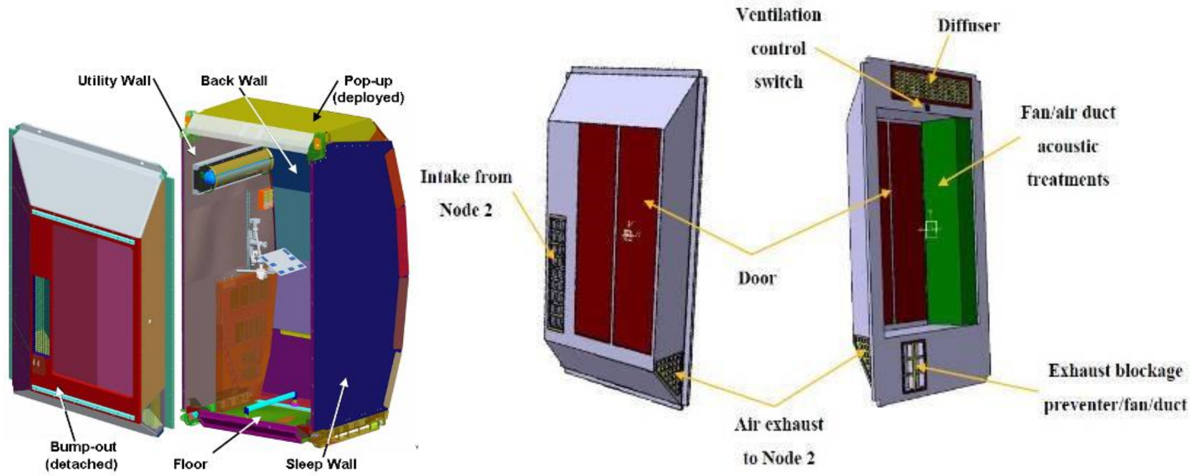

***Figure 2: a) Sketch of the CQ indicating the relative bump-out, pop-up and rack volumes [16], b) CQ bump-out (exterior view on left, interior view on right) illustrating general airflow and ventilation components in its current configuration* [16]**

In the past forty years, 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 of "Predicted Mean Vote" and "Predicted Percentage of Dissatisfied" [17].
Fanger started form the hypothesis that at thermal comfort state, the human body balance between the heat produced, consumed and transferred to the environment. The most important parameters that can influence the thermal comfort state were analyzed and then introduced in the equation of thermal balance of the human body (*heat exchanged with the environment by radiation, convection, conduction, respiration and perspiration*). The result was an index that can predict a thermal vote of the occupants in certain indoor conditions, which is the *Predicted Mean Vote* (PMV) index [17].
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 [17]. 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 *Predicted Percent of Dissatisfaction* (PPD), indicating the percentage of occupants in thermal discomfort. A value of 10% of the PPD index corresponds to a range between -0.5 and +0.5 for PMV. Measurements proved that even for the PMV = 0, about 5% of occupants will feel a degree of discomfort.
Draught rate study begins with the study of Fanger and Pedersen [18] that displayed the effect of the air velocity fluctuations on the sensation of discomfort. Later, Fanger and Christensen [19] made correlations for the local turbulence intensity of the indoor air flow with thermal discomfort sensation in an index called "*Draught Rate*" (DR). Their studies were oriented to the study of the effect of air turbulence intensity on the sensation perceived by humans. This sensation was then translated in a local thermal comfort model, opening the local investigation series. The Draught Rate is an index that depends on the mean velocity, temperature but also on the air turbulence intensity value.
An extensive study on thermal comfort models for indoor spaces and vehicles can be found in [20].

1.2 Technical requirements

The total deployed volume of a CQ is around 2.1 m^3 and it was desirable to provide as large a habitable volume for the crew member as possible with the respect of the configuration to a standard US rack volume [5, 16, 21]. The structure of a CQ is divided into three main areas: bump-out, rack, and pop-up (Figure 2). To maximize the amount of interior volume, the bump-out and pop-up were designed to contain key features for operation as well as to provide additional headroom. Currently, the ventilation system provides airflow at three different flow rates, allowing crew members to adjust airflow to their preferred settings. The CQ are not connected to the ISS fluid loop connections, instead they are using in cabin air from Node 2 for ventilation. The CQ ventilation system utilizes a double flux fan system, where Node 2 cabin air is pulled into the CQ with the fan located in the intake duct, pushed into the CQ interior volume, and a second fan in the exhaust duct pulls air out through the CQ exhaust air grille. The ventilation system's main objective is to flush the carbon dioxide concentration, which in high levels represents an asphyxiation hazard. Inside the CQ, the air receives the crew member's metabolic heat (considered to be between 100 and 132 W) and the electronics heat (around 153 W) [5, 16, 21]. The air is then directed though the CQ exhaust duct outlet and directed parallel to the rack face and down the aisle way toward the Node 2 CCAA air return. The CQ air intake and exhaust directions are consistent with the general Node 2 air circulation, which allows the CCAA smoke detector to identify combustion events within the CQ. Additionally, these intake and exhaust directions minimize recirculation of air between CQ which would result in some CQ interiors not receiving adequate cooling. The primary vehicle level interface ventilation requirements for the CQ are: 0.42-5.1 m^3/min of airflow and exhaust air velocity lower than 1.2 m/s.

2 RESULTS AND DISCUSSION

2.1 Numerical model

The geometrical model was built using the SolidWorks software. It was than imported in the Ansys Design Modeler. The numerical simulation was carried out in Ansys Fluent. The mesh grid was composed of 1.43 million tetrahedral elements and the boundary layer consists of 5 layers (Figure 3). A grid independence test was carried out on for different grids: 0.7, 1.14, 1.43 and 2.12 million elements. Given the fact that for 1.43 and 2.12 million elements grid we did not observe a noticeable difference we chose to work with the smaller grid from computational reasons. Also, for the chosen mesh the maximum value for the wall y+ in the interest domain was 3.18. For the pressure-velocity coupling we utilized the coupled algorithm [22]. A second order upwind scheme was used to calculate the convective terms in the equations, integrated with the finite volume method. The turbulence model used for the numerical simulation was SST k-ω since from our previous researche we have established that is an appropriate turbulence model to use for indoor air circulation [23]. This is because SST k-ω model takes into consideration flows where both the boundary layer as well as the free stream are taken into account.

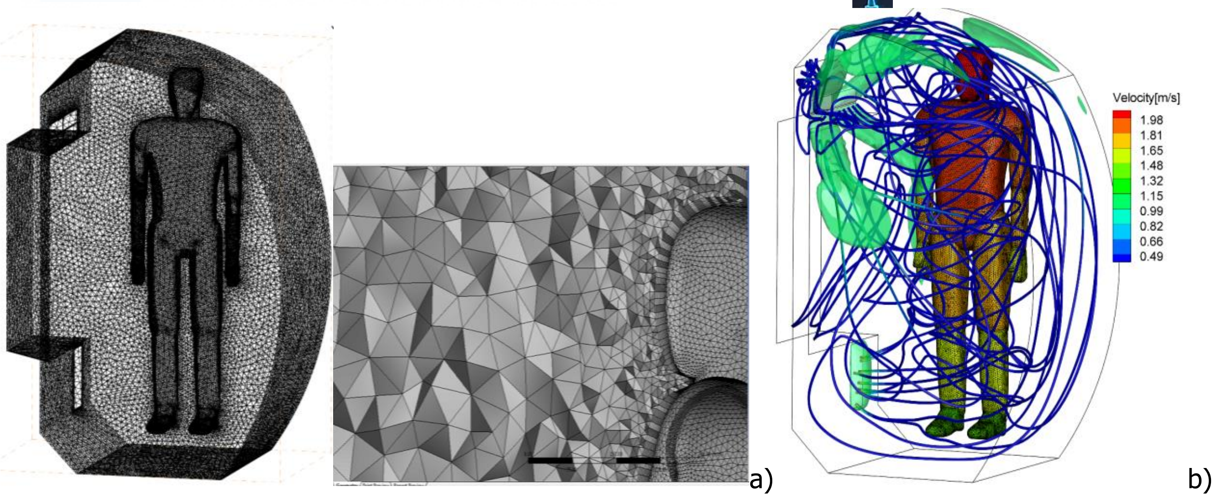

Figure 3: a) Computational grid details, b) case corresponding to the medium fan velocity: pathlines coloured by velocity magnitude, body surface coloured by temperature, and isosurface of the velocity magnitude of 0.6 m/s

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 156 m^3/h. 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 [5, 16, 21] and is composed by four rectangular regions, each of them having independent vertical and horizontal guiding vanes. Inspired by [16] 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.
The inlet air temperature was 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 following temperatures: t_{head} =36 °C, t_{neck}=35 °C, t_{torso}=34 °C, $t_{shoulders}$=34 °C, t_{arms} =33 °C, $t_{forearms}$=32 °C, t_{hand}=30 °C, t_{thigh}=32 °C, t_{leg}=30 °C, t_{feet} =28 °C.
Figure 3b is presenting iso-values of the velocity magnitude corresponding to 0.6 m/s and pathlines in the case corresponding to the medium velocity.

2.2 Results

Figure 4 1 and 2 is presenting the distributions of the velocity magnitude, and of the air temperature, of the in-plane vectors in the coronal plane of the virtual manikin for the three positions of the fan controller. Figure 4 3 is presenting the distributions of the predicted percentage of dissatisfied regarding the draught sensation.
One could observe that the global pattern of the flow inside the CQ is changing dramatically with the variation of the inlet velocity with a small amount. In the region of the head and of the chest, relatively high values of the velocity magnitude suggest that a sensation of thermal discomfort might occur. This is confirmed by the distributions of the draught rate in Figure 4 3. The spatial distributions of the *DR* are divided in four main regions as indicated in the legend from the same figure. These four regions correspond to a classification of the indoor ambiance regarding its comfort level. This way, the blue color (*DR*≤15%), is associated to the zones with a high standing quality of the ambiance and the red color (*DR*>25%) corresponds to unacceptable conditions to regions where the sensation of draught might create a serious discomfort.
The resulting flow patterns and velocity distributions are likely to produce draught discomfort for all the three positions of the fan controller. These results are comforting us regarding to the need of an improved solution for the air distribution inside the CQ.

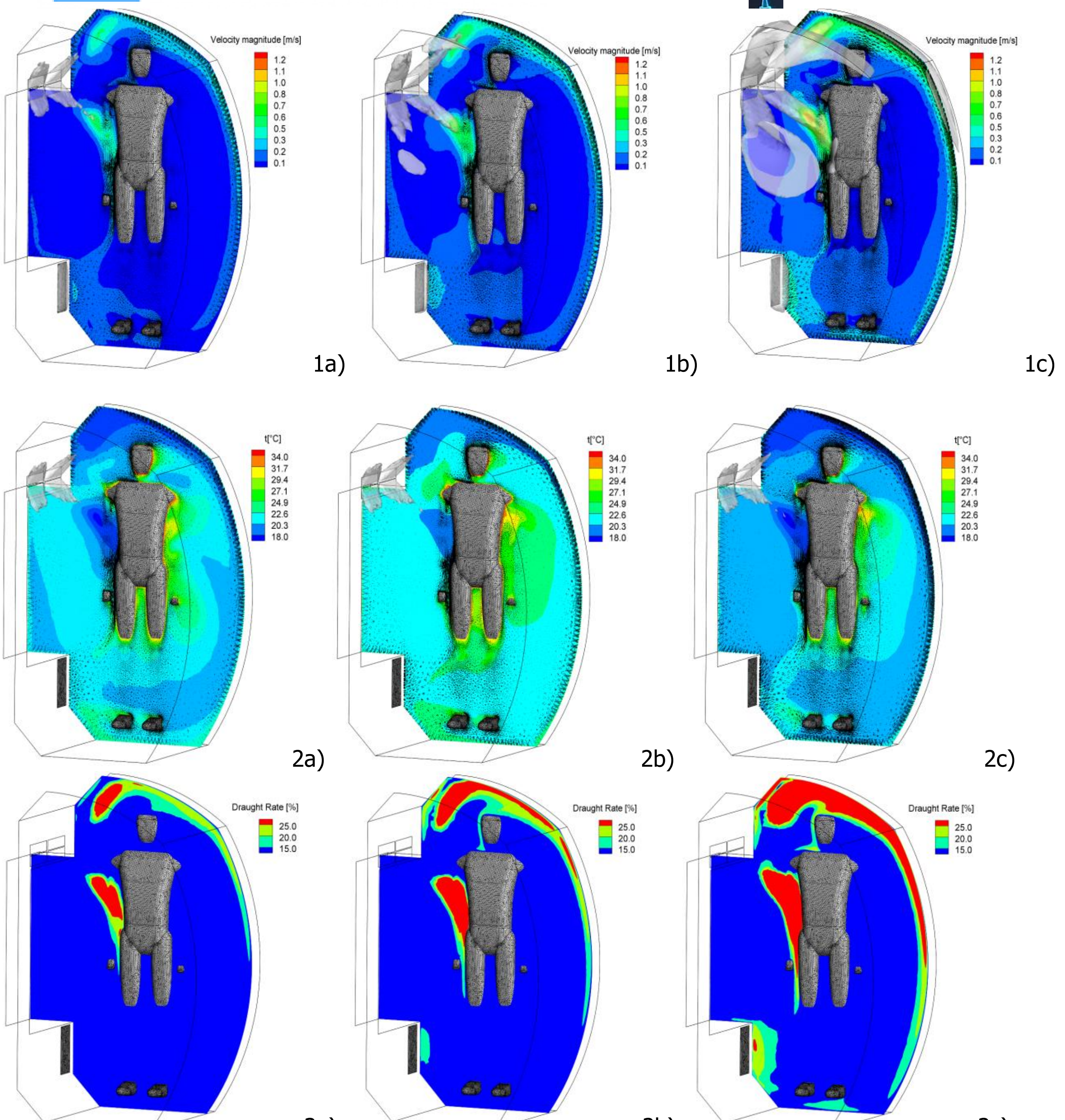

Figure 4: Distributions in the coronal plane of the virtual manikin: 1) velocity magnitude, 2) air temperature, 3) DR – predicted percentage of dissatisfied regarding the draught sensation, a) low fan velocity, b) medium fan velocity, c) high fan velocity

3 CONCLUSIONS

From our preliminary numerical study, it appears that the need for an improved air distribution inside the CQ is obvious. This way, lower velocity values at the inlet diffuser, distributed over a larger surface, as well as diffusers with improved induction would be a better choice, in our opinion. Ventilation flow rates could also be improved, allowing crew members to lower the temperature inside the CQ more than was previously possible if they so desire, without compromising acoustic comfort. Further improvements can aid in diminishing the issues with CO_2 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.

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