Preliminary Numerical Studies for the Improvement of the Ventilation System of the Crew Quarters on Board of the International Space Station

Florin BODE[1,2], Iinca NASTASE*[,1], Cristiana CROITORU[1], Mihnea SANDU[1], Angel DOGEANU[1], Ioan URSU[3]

*Corresponding author
[1]CAMBI, Technical University of Civil Engineering of Bucharest, Romania,
B-dul Lacul Tei nr. 122 – 124, cod 020396, sector 2, Bucuresti,
ilinca.nastase@utcb.ro*, cristiana.croitoru@cambi.ro,
mihneasandu2010@gmail.com, Angeld_ro@yahoo.com
[2]Technical University of Cluj Napoca, Romania,
Memorandumului street, nr. 28, Cluj-Napoca, 400114, Jud. Cluj, Romania,
florin.bode@termo.utcluj.ro
[3]INCAS – National Institute for Aerospace Research "Elie Carafoli",
B-dul Iuliu Maniu 220, Sector 6, Bucharest 061126, Romania,
ursu.ioan@incas.ro

DOI: 10.13111/2066-8201.2018.10.2.13

Received: 17 March 2018/ Accepted: 29 April 2018/ Published: June 2018

Abstract: *The current concept of Crew Quarters (CQ) aboard the ISS has several issues as recorded by NASA and ESA, the most important ones pertaining to the noise levels and the accumulation of CO2. 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. This paper presents numerical models of the airflow inside the enclosure which were developed as a preliminary approach of our team to aid in the proposal of two different air distribution strategies for the CQ existing on the ISS. The CFD models feature a simplified and detailed version of al thermal manikin which simulates the posture of the human body during sleep and recreational activities. These preliminary simulations were run for a zero-gravity scenario and are concerned mainly with the airflow parameters and temperature buildup inside the CQ.*

Key Words*: Ventilation inside cabins, International Space Station, CFD, thermal comfort, air quality*

1. INTRODUCTION

This study concerns the current concept of Crew Quarters (CQ) aboard the International Space Stations' (ISS) Node 2 "Harmony". With the advancements in space research and the experience gathered through years of exploration and study, the duration of space missions has steadily increased. This increase comes with a cost, the spacecraft and systems aboard needing to be efficient and robust in the long term. At the end of the day though, humans are at the centre of it all and thus they also need to operate at peak performance in a manner sustainable over long periods of time [1, 2]. Human error aboard a spacecraft presents as great a risk as any equipment malfunction. Although training can help dealing with short term stressful situations, it is not a viable solution in the long term. Thus, the concept of the CQ was born. A place where the astronauts can unwind and rest, offering some much needed privacy akin to a home and a quiet place to sleep away from the general noisiness of the ISS aisleway. The design of a functional CQ must tackle several technical challenges. First of all, it needs a functioning ventilation system to compensate the lack of natural convection found in microgravity. Second, since it can be compared to a confined space it needs good acoustic isolation in order to mitigate the vibrations felt throughout the structure of the CQ and the direct noise coming from the ventilation system. Last but not least, all of the systems need to be as energetically efficient as possible, while having a long lifespan and offering easy access to manual intervention as well as redundancy protection. The current CQ solution was designed to fit inside the standard rack spaces present on the ISS, [3, 4]. The ventilation system is composed of two axial fans, one used for the introduction of air into the CQ, the other for its extraction. Each of the two fans is individually capable of supplying the airflow parameters necessary for avoiding asphyxiation hazards in case one of the fans breaks down and the alarm system malfunctions. The interior of the CQ as well as the ducting of the ventilation system is acoustically isolated. Despite all this, the system is not perfect and reports consistently indicate the presence of the following issues. The primary issue is that astronauts wake up presenting symptoms of CO_2 intoxication. Reports also mention temperature increases above the comfort level. A common solution for these problems is setting the fans to their highest speed setting, but this in turn causes acoustic levels to rise, hampering the astronauts' sleep. From our preliminary studies we found that at 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. Two different cases are evaluated by means of numerical simulations in order to ascertain the performances of the proposed system. One of the cases concerns the airflow inside the cabin for a simplified geometry of the human body resting within. The second case, studies the airflow as well as temperature parameters for a human resting in the natural position assumed in microgravity conditions. The two cases will be compared to each other with the aim of highlighting the difference between the simplified and the complex geometries. The end goal is to obtain information which can be used to further improve the models. In a later stage of the project these improved case studies will be validated with experimental data and once this is done they will be used to test different adjustments to the ventilation system aimed at optimizing the parameters of the internal artificial atmosphere.

Figure 1: Current configuration of CQ on board of ISS

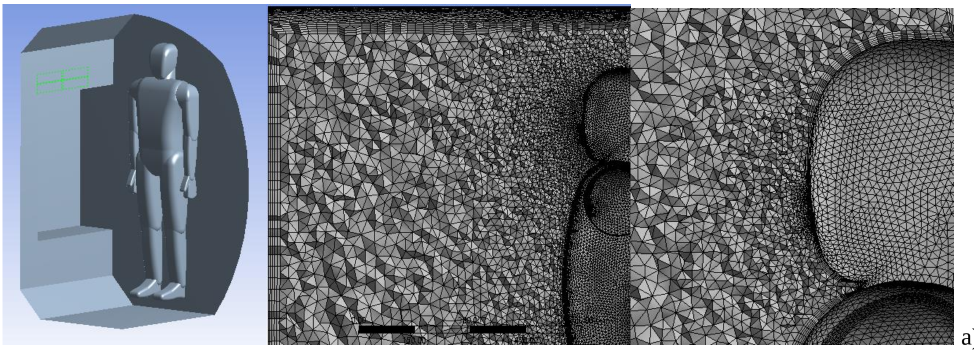
2. METHODS

2.1 Technical requirements of the studied cabin

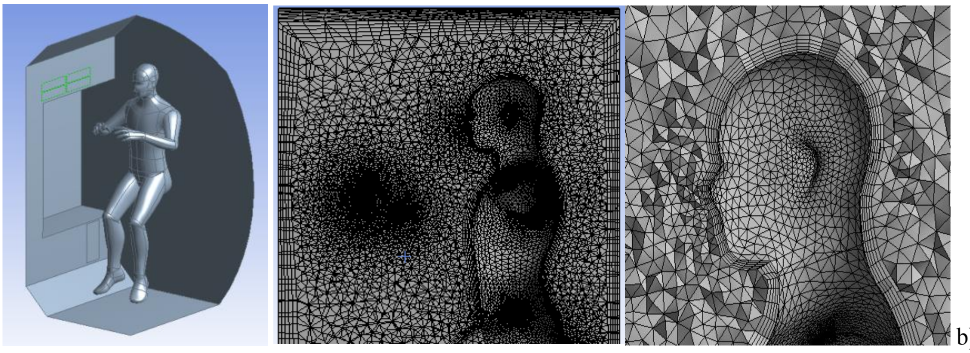
The total deployed volume of a CQ is around 2.1 m^3 and it was desirable to provide as large a habitable volume for the crew member as possible with the respect of the configuration to a standard US rack volume [3, 5, 6]. The structure of a CQ is divided into three main areas: bump-out, rack, and pop-up (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) [3, 5, 6]. 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.

2.2 Numerical methods

The CQ geometrical model along with the virtual manikins were built using the SolidWorks software in Figure 2. Other numerical studies concerning the ventilation in CQ on ISS can be found in [7, 8] Two cases were considered: Case 1 – existing ventilation solution with simplified human body model and Case 2 – existing ventilation solution with anatomic human body model in neutral position generated by the zero gravity. Unstructured tetrahedral meshes were generated for both studied cases. Case 1 was already presented in detail in [7]. This configuration of the air diffuser is composed by four rectangular regions, each of them having independent vertical and horizontal guiding vanes [3, 5, 6]. For the Case 1 the unstructured tetrahedral mesh has 4.8 million elements, for Case 2 the mesh has 5.7 million cells. In both cases there are 9 cells in the boundary layer region near the walls.



a)



b)

Figure 2: Geometries and details of the used mesh grids: a) case 1, b) case 2

The air distribution solution uses four rectangular regions as inlets. Each region is equipped with independent vertical and horizontal guiding vanes, allowing for the adjustment of the flow entry direction.

For the boundary conditions, we imposed three mass flow rates corresponding to the three positions of the fan controller: low, medium and high, 108 m^3/h, 138 m^3/h and 196 m^3/h [3], respectively.

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.

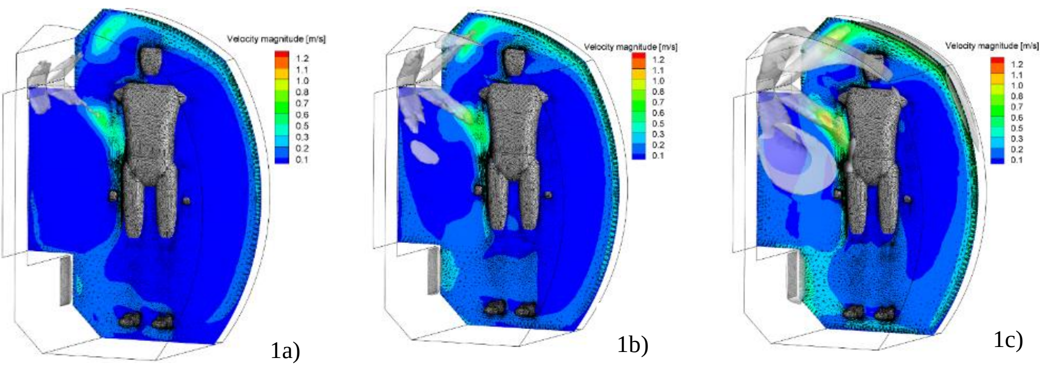
Table 1. Temperatures imposed on the manikin surface

t	t_{head}	t_{neck}	t_{torso}	$t_{shoulders}$	t_{arms}	$t_{forearms}$	t_{hands}	t_{thighs}	t_{shins}	t_{feet}
°C	36	35	34	34	33	32	30	32	30	28

3 RESULTS AND DISCUSSION

Figure 3 presents the distributions of the velocity magnitude in the coronal plane of the virtual body and the iso-surfaces of the velocity magnitude corresponding to 0.6 m/s. First of all, when regarding these results one must take into account the fact that the placement of the virtual body of the manikin is different inside the CQ. Thus, the velocity distributions in the coronal are completely different.

A slight difference between Case 1 and Case 2 is also occurring between the iso-surfaces of the velocity magnitude but this has to be an effect of the different mesh grid itself.



1a) 1b) 1c)

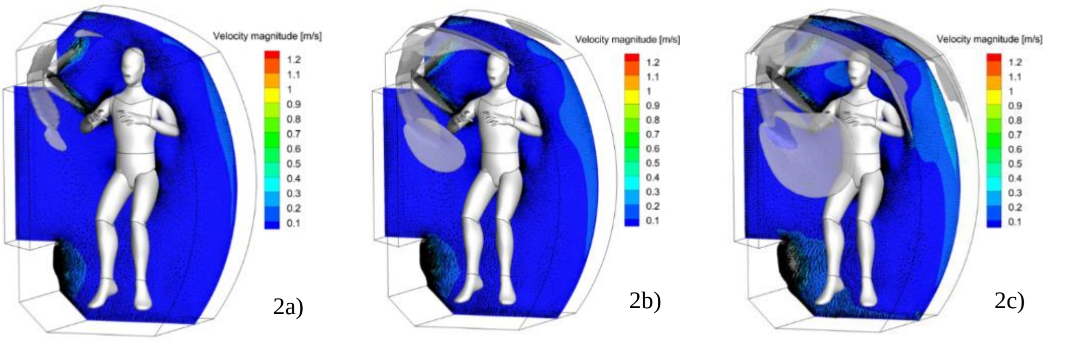


Figure 3: Velocity magnitude distributions and iso-surfaces of the velocity magnitude corresponding to 0.6 m/s: 1) Case 1, 2) Case 2; a) 108 m^3/h, b)138 m^3/h, c) 196 m^3/h

We are searching for cases in which air velocity values might surpass comfort levels. NASA recommendation is that 66% of velocity values fall within the 0.46-0.7 m/s range [9]. As seen above, for each of the three flow values assumed (108 m^3/h, 138 m^3/h and 196 m^3/h) the velocity magnitude profile is different. The first case presents higher air velocities near the head and at the manikin's right-hand side, while the second lacks these higher air velocities. This is due to the positioning of the manikin in each of the cases and due to the airflow direction. The second manikin being positioned in what is essentially a stagnation region, these results are not surprising. 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 from Figure 5.

The temperature distributions in the coronal plane are presented in Figure 3 and for Case 2 they display higher overall temperature values. Once again, the explanation is found in the position of the manikin and this time in its posture as well.

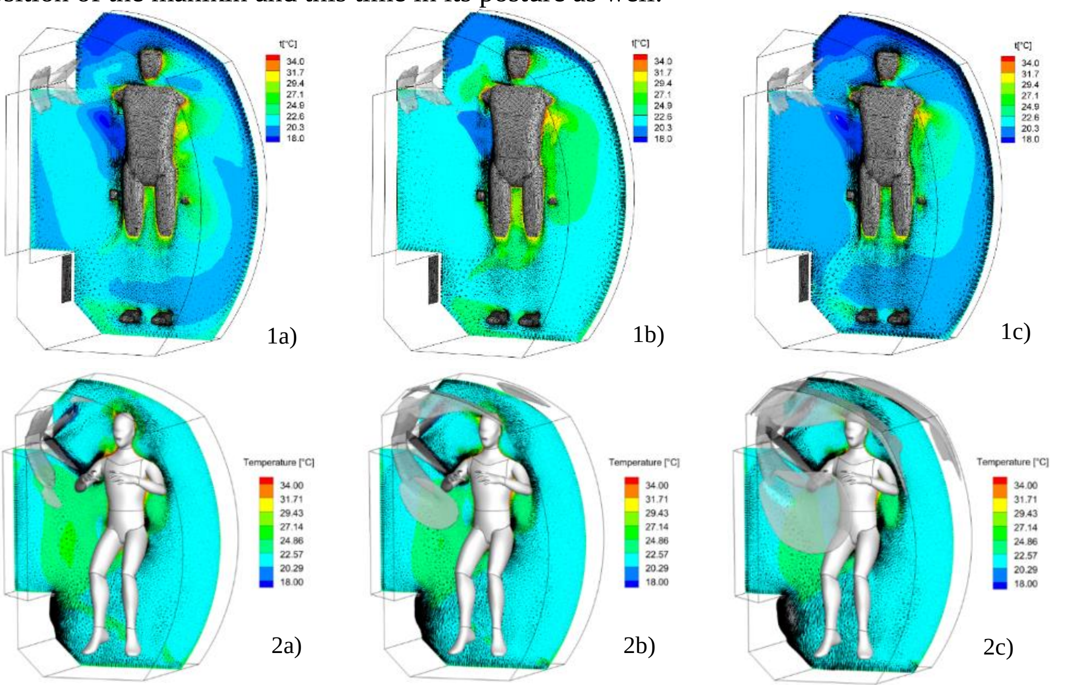


Figure 4: Air temperature distributions1) Case 1, 2) Case 2; a) 108 m^3/h, b)138 m^3/h, c) 196 m^3/h

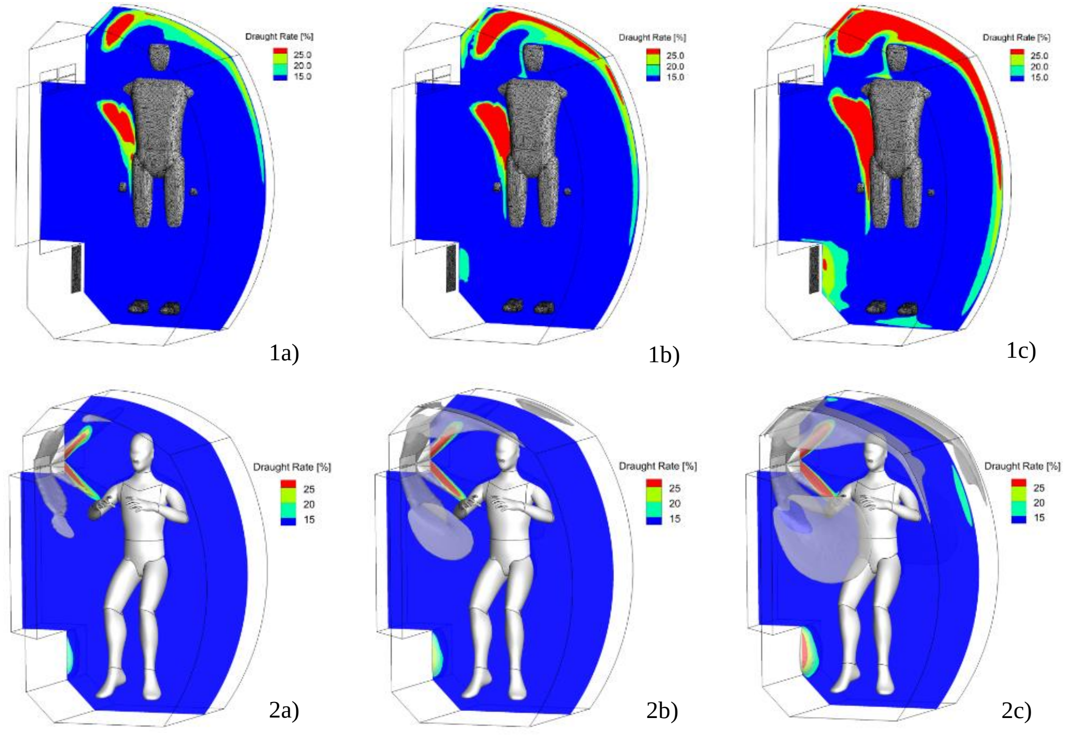


Figure 5: Draught rate: 1) Case 1, 2) Case 2; a) 108 m^3/h, b) 138 m^3/h, c) 196 m^3/h

Since the first manikin is close to the wall and is situated in the path of the air current, a great temperature difference is found between the right-hand side and the left-hand one. This temperature difference being of almost ten degrees in the last case, negatively affects the comfort levels.

The second manikin being in a looser posture and being surrounded by the air jets presents smaller differences in temperature between the left and right sides. In both cases an increase in local temperature can be observed in the upper area of the body between the torso and the arms, as well as around the shoulders and the head region.

Figure 4 below, shows the comparison of the draught rates. As predicted, the first case presents higher draught rate due to the measuring plane being in the region of the room where the airflow is directed. High draught rates can be observed on the right-hand side in all of the 3 variations of the first case, while the last two also present high values for the head region. The second case presents no discernible increase in draught rate around the manikin for any of the three flow rates. This fact is due to the positioning of the manikin inside the airflow dead zone.

The previous results clearly display that the realism of a model could influence the obtained results and indirectly a design conception. In our case, an improved solution of the ventilation system must take into account this realistic position of the human body. Its posture and location within the CQ must be correlated with the airflow direction of the diffuser in order to achieve satisfactory comfort parameters. This is by far the most important factor to consider. Studies on thermal comfort for indoor spaces and vehicles can be found in [10, 11]. The manikin in the neutral posture offers an advantage in the sense that it is easier to evaluate the temperature levels on different body regions while also being more representative of actual resting period conditions.

4 CONCLUSIONS

The cases presented in this study highlight the importance of the correlation between the body posture and the position within the CQ. A general conclusion to be drawn is that the ventilation solution must be highly customizable. A way to improve the comfort could be the use of lobed jets as a solution for the air introduction [12, 13]. Being adaptable to a wide range of situations while meeting the required safety standards is paramount. Improving the comfort levels is a high priority subject as the stress generated from uncomfortable situations, when built up, can not only affect working performance but might also endanger lives.

The increased velocity obtained by aiming the flow directly at the body definitely improves the CO_2 accumulation issues but is prone to cause discomfort, thus future research might consider finding a configuration that reasonably increases air velocity without significantly impacting body temperature and draught rates. For our part, the research presented herein shall be correlated with experimental data, when said data will be available, and will serve as a sort of baseline. Upon this correlation of data, the ventilation configuration and the numerical model shall be continuously improved. This paper, regarding the comfort aboard spacecraft, is also a means to bring to attention an avenue of research which hasn't yet been fully explored and it is our team's belief that said avenue cannot be tackled too soon.

ACKNOWLEDGEMENTS

This work was supported by a grant of the Romanian space agency ROSA, QUEST – Advanced air diffusion system of the crew quarters for the ISS and deep space habitation systems, STAR-CDI-C3-2016-577.

REFERENCES

[1] * * * NASA. *https://www.nasa.gov/exploration/commercial/crew/index.html*.

[2] * * * NASA. *https://www.nasa.gov/mission_pages/station/research/news/national_lab_enables_research*.

[3] J. L. Broyan, M. A. Borrego and J. F. Bahr., *International Space Station USOS Crew Quarters Development*. in *08ICES-0222*. 2008.

[4] J. L. Broyan, S. M. Cady and D. A. Welsh, International Space station Crew Quarters Ventilation and Acoustic Design Implementation, *AIAA Journal*, 2010.

[5] C. Adams, *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.

[6] S. Fairburn and S. Walker, *'Sleeping With the Stars'–The Design of a Personal Crew Quarter for the International Space Station*, SAE Technical Paper, 2001.

[7] F. 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, Bucharest, 2017.

[8] F. Bode et al., *A Numerical Analysis of the Air Distribution System for the Ventilation of the Crew Quarters on board of the International Space Station*, E3S Web Conf., **32**: p. 01006, 2018.

[9] * * * *NASA Space Flight Human-System Standard, vol. 2, rev. A, Ch. 6*, 2015.

[10] C. Croitoru et al., Thermal comfort models for indoor spaces and vehicles—Current capabilities and future perspectives, *Renewable and Sustainable Energy Reviews*, **44** (Supplement C): p. 304-318, 2015.

[11] C. Croitoru, et al. *Numerical and experimental modeling of airflow and heat transfer of a human body*. in Roomvent 2011, Trondheim, Norway.

[12] A. Meslem et al., Optimization of a Lobed Perforated Panel Diffuser - A Numerical Study of Orifice Arrangement, *The International Journal of Ventilation*, **11**(3): p. 16, 2012.

[13] F. Bode, A. Meslem and C. Croitoru, Numerical simulation of a very low Reynolds cross-shaped jet, *Journal Mechanika*, **19**(5): p. 6, 2013.