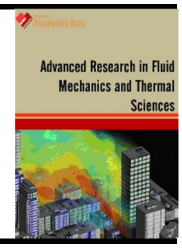
Penerbit Akademia Baru

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage: www.akademiabaru.com/arfmts.html
ISSN: 2289-7879



Parametric Study to Determine Optimum HVAC in a Hospital Operation Theatre

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ARTICLE INFO

Article history:
Received 22 February 2018
Received in revised form 8 April 2018
Accepted 25 April 2018
Available online 27 April 2018

Keywords:
Operation Theatre (OT), Computational Fluid Dynamics (CFD), Heat Ventilation and Air Conditioning (HVAC), Phoenics

ABSTRACT

Computational Fluid Dynamics (CFD) simulation inside an Operation Theatre (OT), considering real world conditions such as temperature and airflow movement in the OT environment is carried out. Simulation is carried out using Phoenics software to predict the flow velocity and temperature distribution inside the OT. Parametric study is done to determine the most suitable inlet and outlet configuration. Only one out of the six cases provided the required cooling and reduced recirculation. Results indicated that the entire ceiling inlet with eight outlets was the best case, for further studies to be carried out considering contaminants.

1. Introduction

A hospital consists of various departments such as OR, obstetrics, isolation, pathology, radiology, sterile service department etc., [1]. Each of these departments need specialised HVAC design to meet their specific requirements. HVAC in an OT is for the sole purpose of maintaining the Indoor Air Quality (IAQ) by minimizing infection and comfort of patient and staff [2]. The design and maintenance of a clean operating room depends on the following factors, establishing the location of air intake, type of humidifier used, air cleaning, temperature and humidity inside the OT [3, 16]. As per the recommended US department of health guidelines, the OT should have positive pressure and greater than 15 Air changes per hour Air changes per hour (ACH) [4]. Lower and higher humidity levels affect the human comfort. Khalil [5] discussed the importance of effective HVAC design Figure 1, to obtain the required conditions inside OR (Operating Room) to maintain the humidity for better IAQ. Khalil [6] Further discussed the importance of designing energy efficient HVAC design.

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The OR is equipped with large inlet and outlet vents for effective air changes. Air changes per hour (ACH) are carried out to reduce the effect of contaminants. A detailed guideline in designing of HVAC facility is provided in the, ASHRAE HVAC design manual for hospitals and clinics, [2] and ANSI/ASHRAE/ASHE Standard 170-2008 [7]. Figure 2 shows the ventilation system design of a typical OR

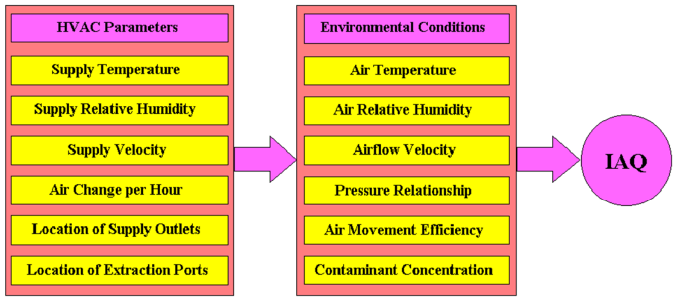


Fig. 1. Parameters to maintain IAQ of OR [5]

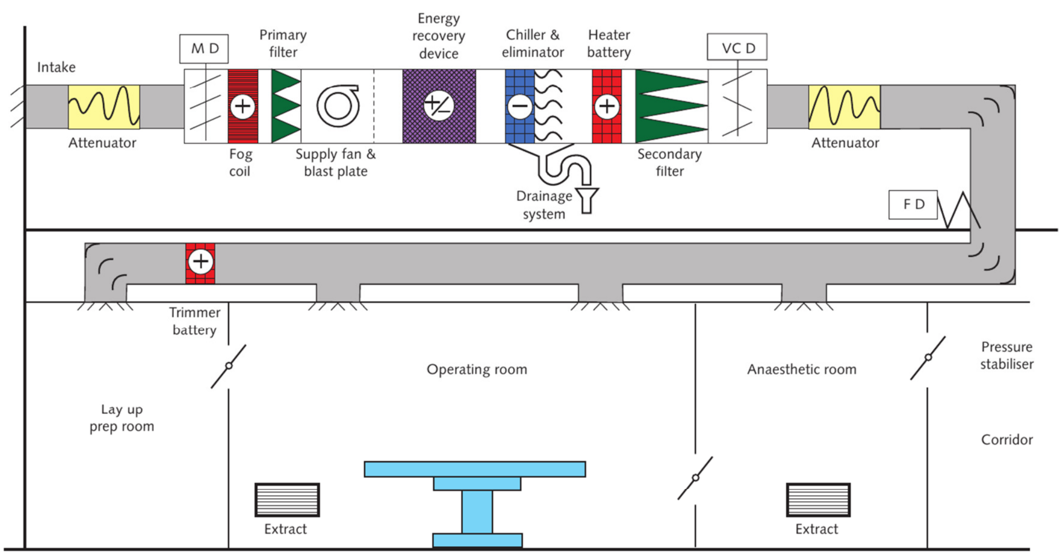


Fig. 2. Typical OR ventilation system layout [1]

Three types of ventilation design are considered; 1. Cross flow 2. Impinging or vertical flow 3. Plenum. The aim is to have Laminar Air Flow (LAF) to prevent the mixing of contaminants. The cross flow system is one where in the diffuser is located on one wall and the exhaust vents are located on the other. In case of impinging or vertical flow, the diffuser is located on top of the operating table. Both the designs provide Ultra Clean Ventilation (UCV) Figure 3 and are equipped with High-Efficiency Particulate Air (HEPA) filters [8]. In Plenum ventilation the clean air is forced in columns from various overhead locations. Air quality has to be maintained in the OR's to reduce the infection to the patient and OR staff. It has been a concern that blood borne pathogens from infected patients may affect the health of OR staff. The primary sources of bacteria are skin scales, facial hair, ears and clothing from the patient as well as the staff [9, 10].

Study by Balaras *et al.,* [11] considering 20 OR's in 10 hospitals in Greece with focus on the temperature, humidity and ventilation inside the OR, showed that the majority of the audited hospitals did not meet the health standard requirements. This shows the importance of HVAC auditing of hospitals is the need of the hour. An efficient design to control the airflow movement, in an operating room can be achieved through CFD. CFD studies in HVAC design are helping in energy efficient design by providing better solution for wall insulation, avoid leak in piping and duct system [12]. The four interrelated parameters which need to be considered for HVAC design in an OR are airflow, thermal comfort, contamination/aerosol control and heat dissipation.

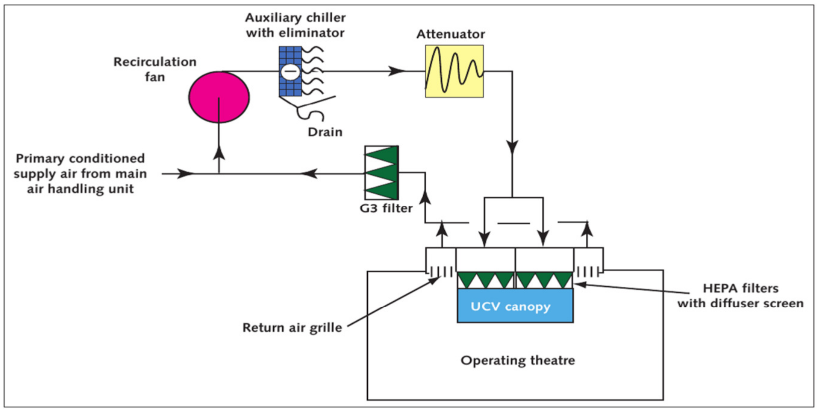


Fig. 3. UCV Theatre [1]

A review by Chow and Yang [13] on the design of HVAC system for OR discussed the importance of LAF. Melhado *et al.*, [14] conducted an in-depth review considering the effect of three different ventilation systems; 1. Vertical 2. Horizontal 3. Mobile, they also report of a combined system, where in LAF is combined with linear system to create two zones in an OR Wong *et al.*, [16]. They concluded that LAF ventilation was most effective in preventing the contamination. The above reviews are clearly showed that CFD application is currently needed in OR/OT research. The current review gives an in-depth insight into the studies implementing CFD in designing of OR. In the current work, we have conducted a parametric study considering various inlet and outlet, sizes and positions for an operation theatre (OT). An analysis has been carried out to determine the best case scenario, which provides adequate cooling and thermal comfort.

Horizontal airflow

Case 1: We have two inlets and two outlets. The inlets are located at the top of the side wall and the outlet at the bottom of the opposite side as shown in Figure 4. The size of the inlet and outlet vents is 0.6m x 1.2 m.

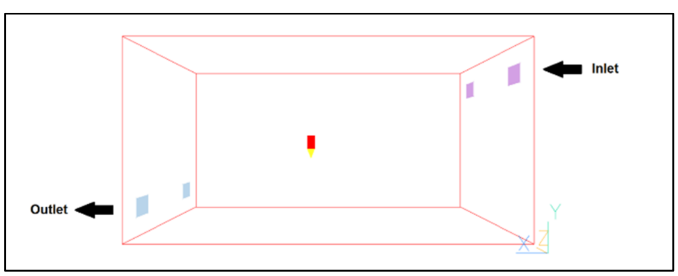


Fig. 4. Two inlets and two outlets

Case 2: In this case, we have two inlets and four outlets. The size of the inlet and outlet vents remains same as mentioned previously. The extra outlet vents added on the opposite wall are exactly parallel with the inlet on opposite wall, as shown in Figure 5.

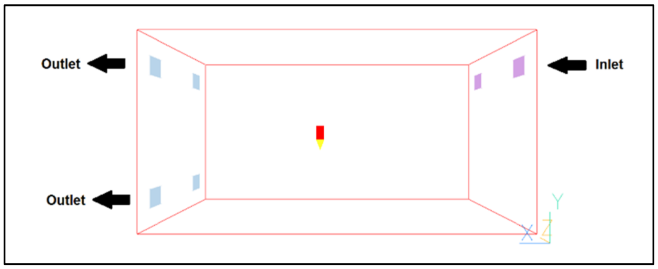


Fig. 5. Two inlets and four outlet vents

Case 3: In this case we have placed four inlets and four outlet vents, of same size parallel to each other on the side walls of the OT, as shown in Figure 6.

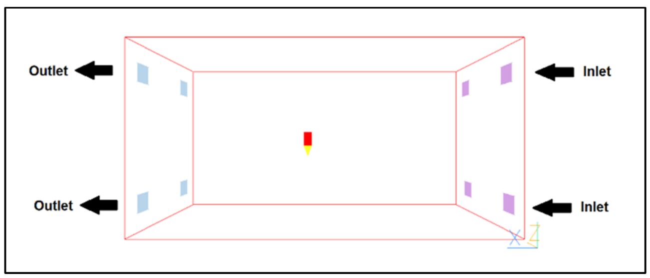


Fig. 6. Four inlet and four outlet vents

The main aim for the above three cases, is to determine the effectiveness of cooling in case of horizontal airflow.

Vertical Airflow

The following three cases have been designed, to study the effectiveness, of the OT cooling for vertical inlet conditions.

Case 4: This is the most common OT setup. The inlet is located at the ceiling in the central region. The inlet has same dimension as of 4m x 4m. The eight outlet vents are located on the side walls, four at the bottom and four at the top, as shown in Figure 7. The outlet vent size is 0.6m x 1.2 m.

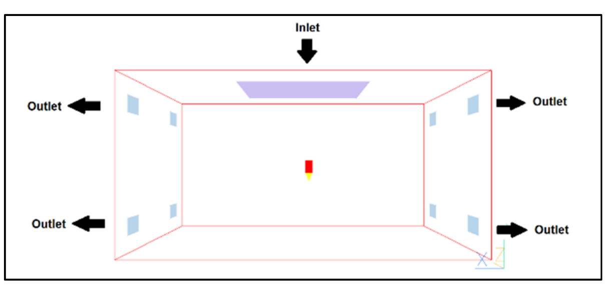


Fig. 7. Inlet at central ceiling with eight outlets

Case 5: In this case we have considered the entire ceiling as the inlet for OT. There are eight outlet vents four on either of the side walls as shown in Figure 8. Four of the outlet vents are placed at the bottom of the wall and four at the top, in order to effectively cool the room, and remove the contamination. From our literature review we found that, this kind of setup effectively suppress, the movement of the contaminants around the OT.

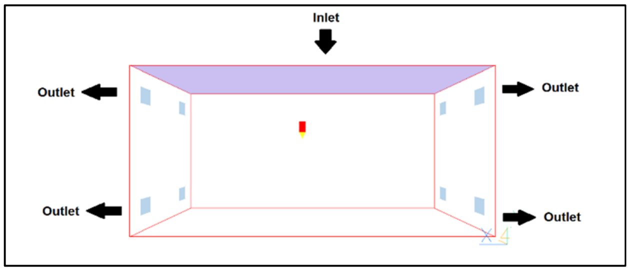


Fig. 8. Ceiling Inlet and Eight outlets

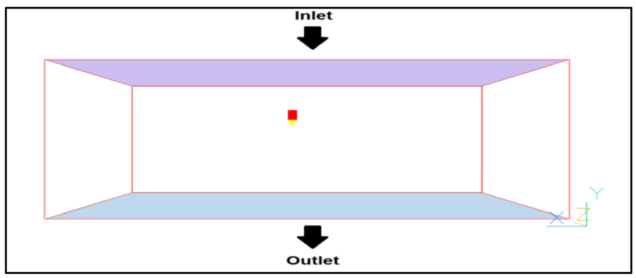


Fig. 9. Ceiling Inlet and Floor outlet

Case 6: In this setup we are simulating flow considering the ceiling as the inlet and the outlet is the entire floor Figure 9. This setup was designed to visualize the effectiveness of a new setup, compared to the conventional setup.

2. Validation Study

In this section the validation of the current CFD study is carried out with the previous experimental and simulation work. The rectangular room with 7m length, 7m width and 3m in height is created like the work of Romano *et al*., [15] Figure 10 (a). The hospital environment consists of three inlets with varying velocities. The air is injected at low speed 0.25 m/s, medium speed 0.35 m/s and high speed at 0.45 m/s. The distance between each inlet is about 54mm. A total of 8 extraction grilles are placed inside the OT, as shown in the Figure 10 (b). The room is kept at a positive pressure of 15 pa and the air is extracted at a rate of 6.63 m/s in between the main and service doors.

Grid Independence Study

Grid Independence study is carried out for the domain by varying the mesh size. In the current study low density, medium density and high-density mesh size is used. The low-density mesh has a grid size of 30 x 34 x 41, the medium density mesh has a grid size of 38 x 41 x 49 and high mesh density 46 x 50 x 59, as shown in Figures 11, 12 and 13.

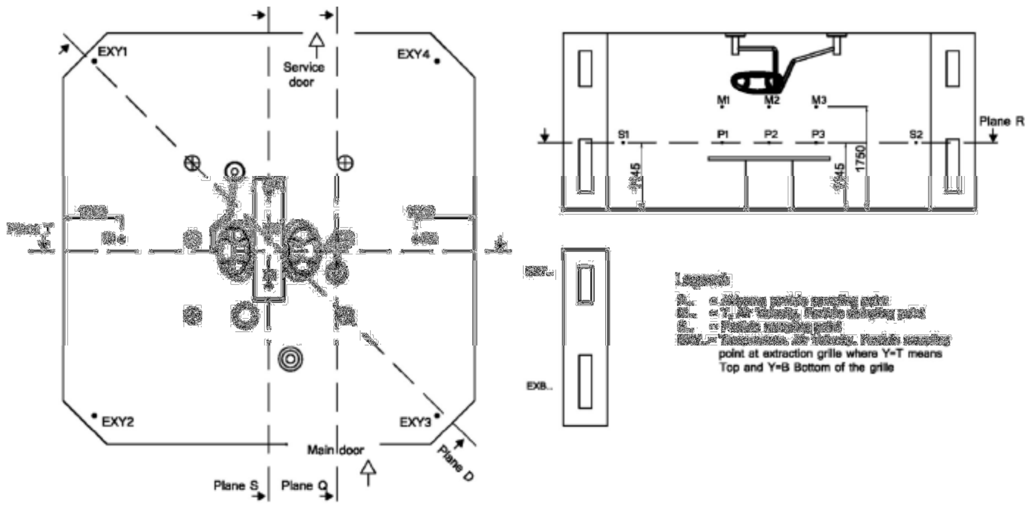


Fig. 10a. Hospital OT setup Romano *et al.*, [15]. (b) Current setup

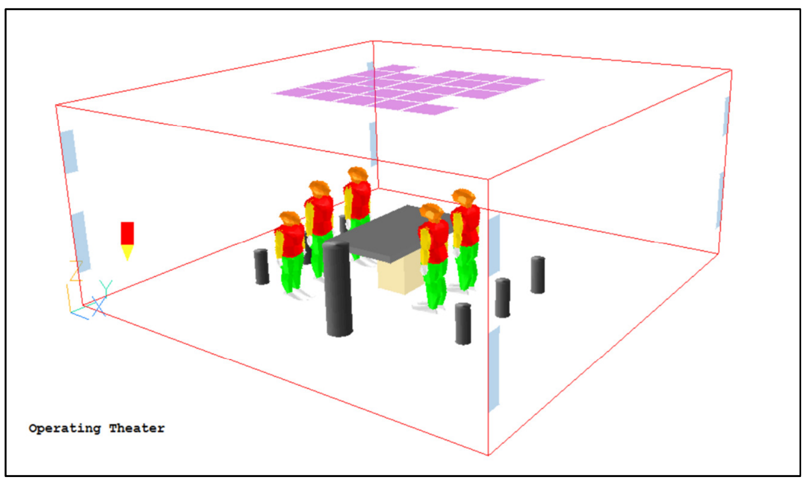


Fig. 11b. Computational setup of hospital OT

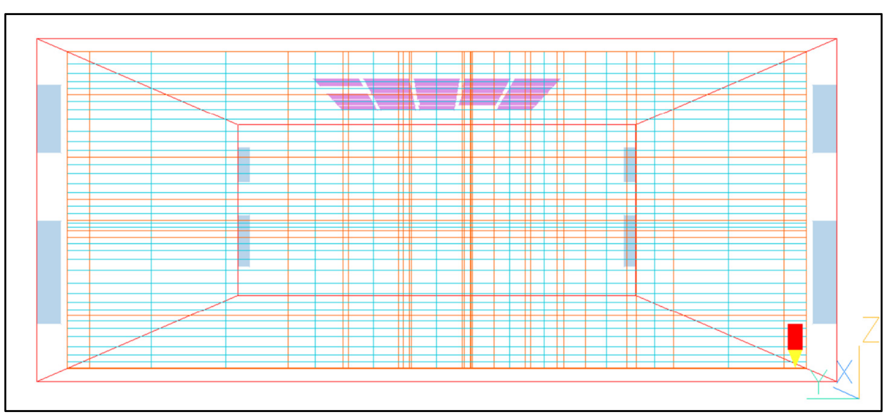


Fig. 12. Low Density Grid

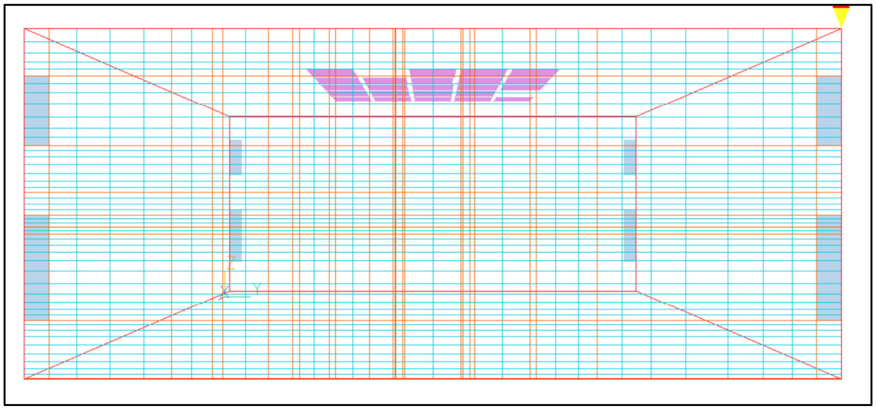


Fig. 13. Medium Density Grid

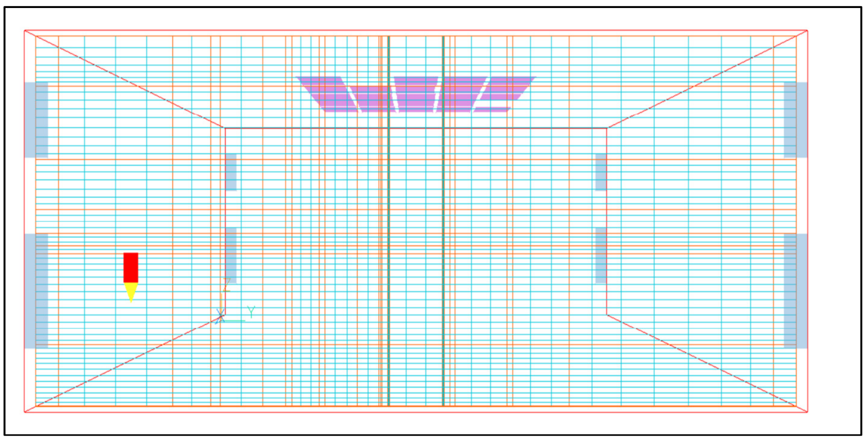
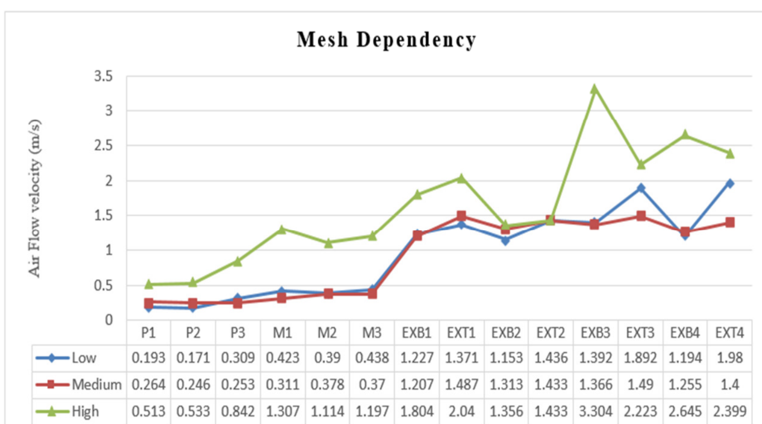


Fig. 14. High Density Grid



	P1	P2	P3	M1	M2	M3	EXB1	EXT1	EXB2	EXT2	EXB3	EXT3	EXB4	EXT4
Low	0.193	0.171	0.309	0.423	0.39	0.438	1.227	1.371	1.153	1.436	1.392	1.892	1.194	1.98
Medium	0.264	0.246	0.253	0.311	0.378	0.37	1.207	1.487	1.313	1.433	1.366	1.49	1.255	1.4
High	0.513	0.533	0.842	1.307	1.114	1.197	1.804	2.04	1.356	1.433	3.304	2.223	2.645	2.399

Fig. 15. Result from different mesh

The results shown in Figure 14 indicate that the low and medium mesh can capture the air flow velocity at different locations accurately, compared to the high mesh density. There is an increase in the flow velocity in case of high density mesh making it unsuitable for the current case.

Table 1
Comparison of velocity at various locations

	P1	P2	P3	M1	M2	M3	EXB1	EXT1	EXB2	EXT2	EXB3	EXT3	EXB4	EXT4
Experimental	0.28	0.25	0.22	0.35	0.39	0.4	1.19	1.46	1.22	1.45	1.19	1.5	1.19	1.4
Numerical	0.25	0.2	0.28	0.32	0.36	0.35	1.32	1.3	1.32	1.31	1.32	1.3	1.32	1.3
Simulation	0.264	0.246	0.253	0.311	0.378	0.37	1.207	1.487	1.313	1.433	1.366	1.49	1.255	1.4

Table 1 clearly shows the results of Experimental observation agree with the current simulation results, Figure 15 depicts the same. It can be noticed that the trend of experiment is like that of the current simulation whereas the previous numerical results did not capture the variation in velocity at different locations.

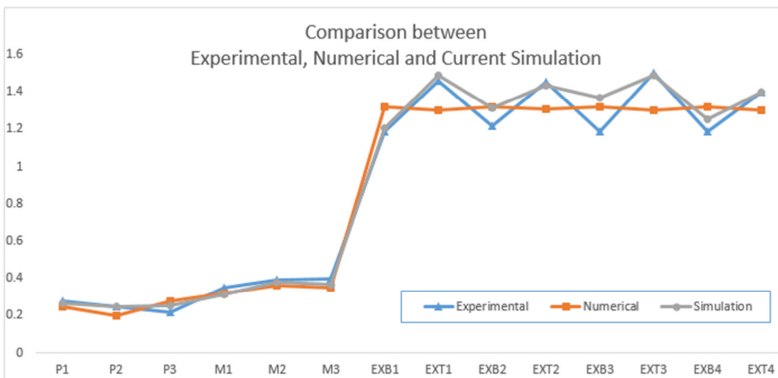


Fig. 16. Comparison between Experimental, Numerical Romano *et al*., [15] and current simulation

3. Boundary Conditions and Setup

The current Operation Theatre (OT) setup includes a patient on the operating table and two staff. The room is equipped with two health monitoring systems, which have three display screens. The major heat and light source in the room is the overhead primary and secondary lamp. The room is pressurized with a positive pressure of 15pa. The positive pressure inside the room enhances the air exchange inside the room.

The room has various heat sources such as the patient, staff, electrical equipment, computer screens, Primary light and secondary light. The total heat output inside the OT is as shown in Table 2.

In the current simulations we have not considered the contaminants, as the main objective of this work is to determine the airflow pattern and its effectiveness in cooling the OT.

Table 2
Total Heat inside the OT

Object	Heat output	Total
Staff	100W x 2	200W
Patient	100W x 1	100W
Computers	100 Wx 2	200W
Display Screens	50W x 2	100W
Main light	1500W	1500W
Secondary light	1000W	1000W
	Total Heat output	3100W

4. Results and Discussions

As each case has different setup, the results of velocity distribution and temperature distribution are discussed for that particular case. The objective is to determine the most suitable setup for thermal comfort and utilize that setup to conduct studies for contaminant removal.

4.1 Horizontal airflow

Case 1: Two inlets and two outlets

Figures 16 (a), (b) and (c) show the front, side and top view of the OT. This three dimensional flow inside the OT environment will give a clear picture of velocity distribution. The velocity distribution pattern clearly shows that in this setup that the air enters and exits the room. The velocity of the air is unevenly distributed. The velocity of $1ms^{-1}$ which is the inlet velocity can only be seen near the inlet zone as shown in Figure 16 (a).

Figure 17 (b) and (c) clearly show that the velocity in the central region is very low due to the location of the inlet vent. The improved design is shown in the next cases.

As the cool air is unevenly distributed, it results in the uneven temperature distribution too. The Figure 17 (a) shows the inlet temperature at 20℃ but it is not effectively reducing the temperature in the central region where the primary and secondary heat source are present Figures 17 (b) and (c).

This setup clearly is not suitable for further consideration as the temperature and velocity distribution pattern show its ineffectiveness. One of the major drawbacks can be noticed in Figure 16 (b), the recirculation zones present in the central region, and this traps the heat. It will also be a major hurdle in contamination removal.

Case 2: Two inlets and four outlets

Extra addition of two outlets in this case reduces the recirculation zone on the left-hand side as demonstrated in Figures 18 (a) and (b). Figure 18 (c) clearly shows that the velocity distribution in the central zone is very low. Thus we need to consider further modification, in order to enhance the even distribution of air inside the OT.

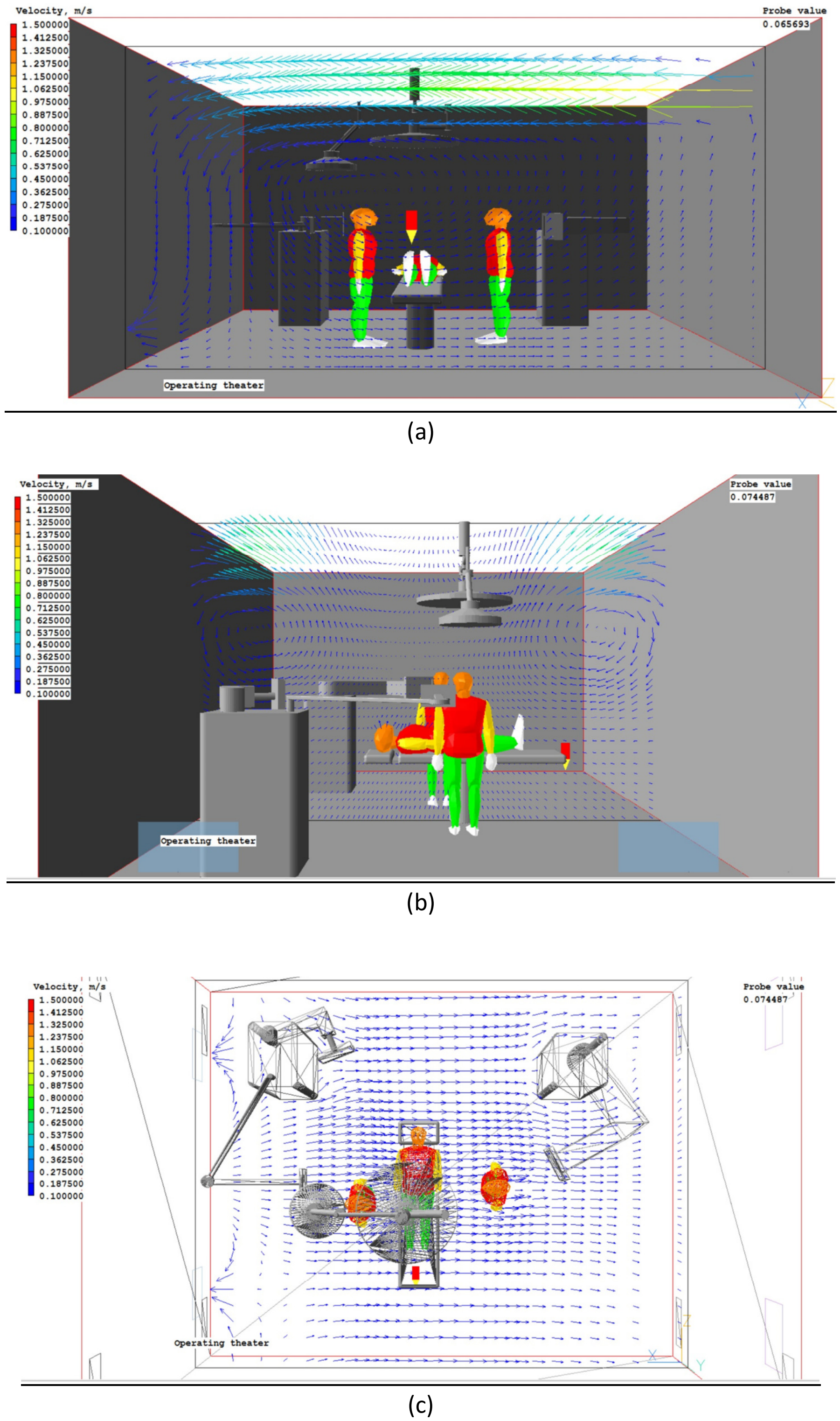
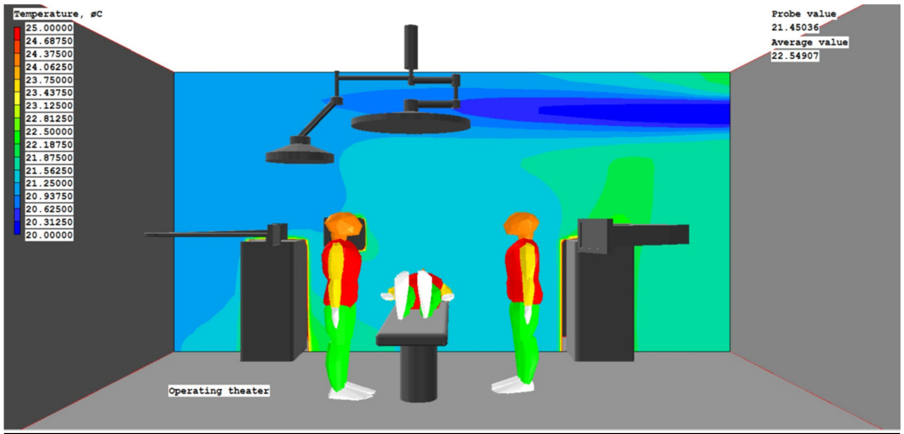
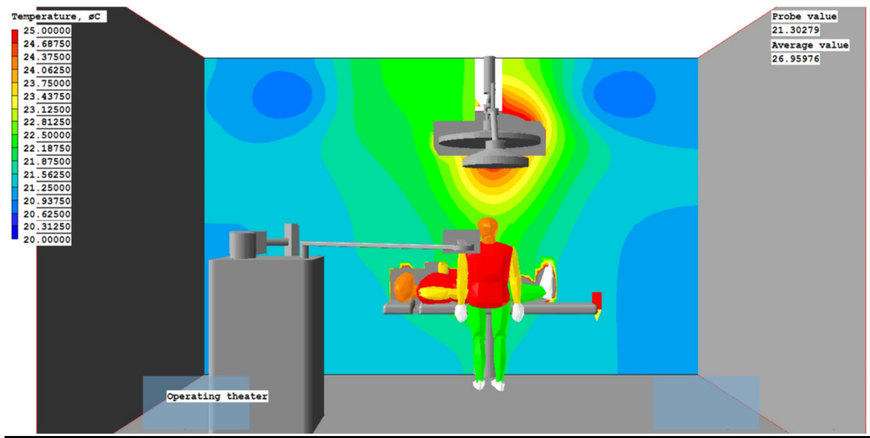


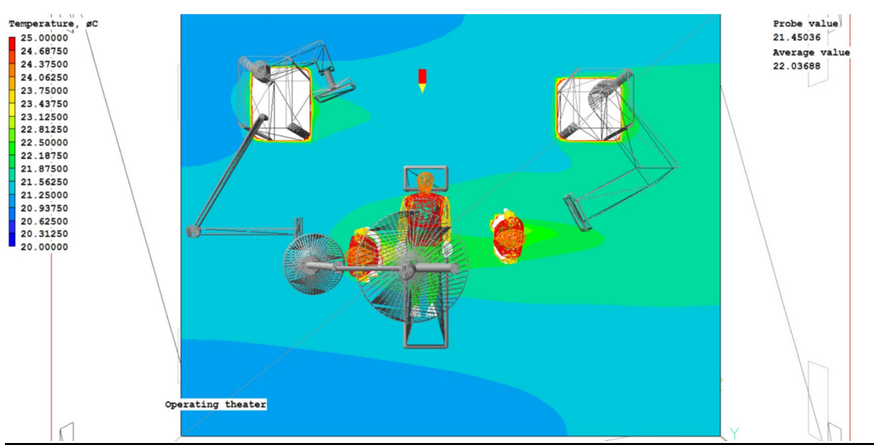
Fig. 18. Flow velocity vector see from various angles



(a)



(b)



(c)

Fig. 19. (a) Front, (b) side and (c) top view of temperature distribution

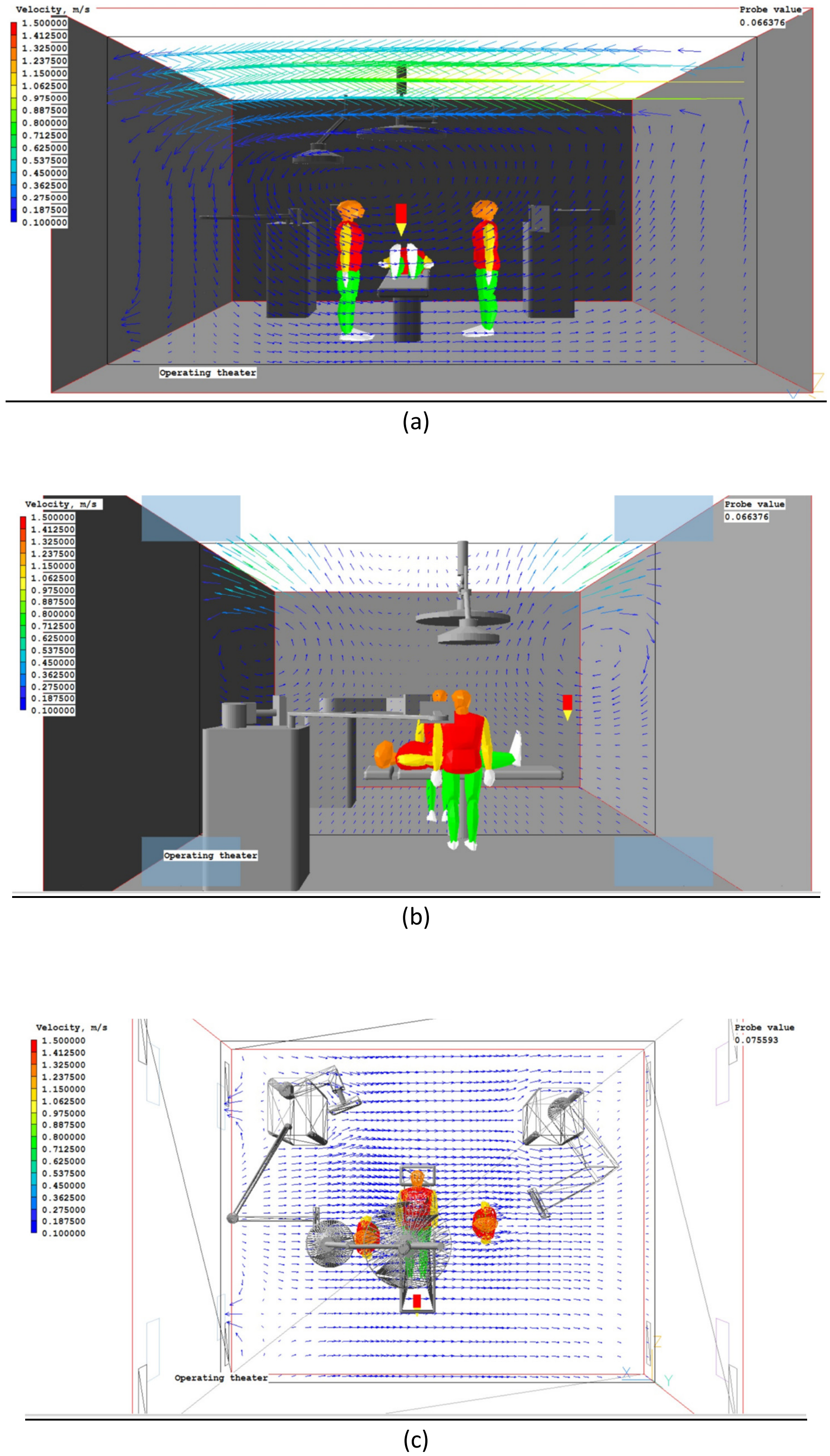


Fig. 20. (a) Front, (b) side and (c) top view of velocity distribution

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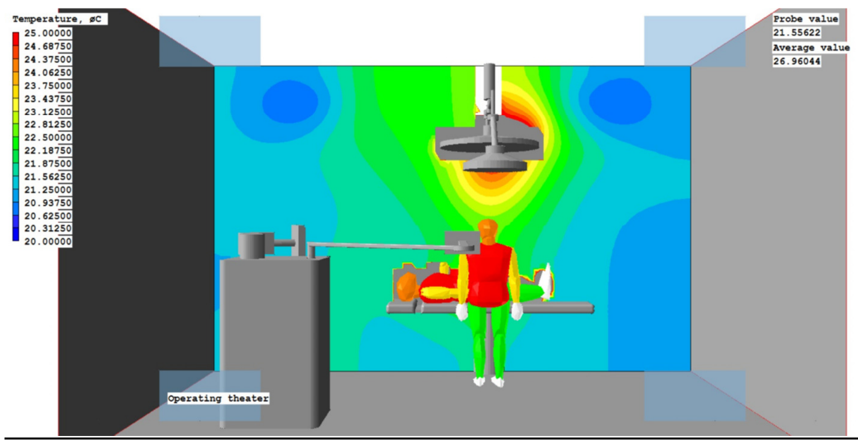
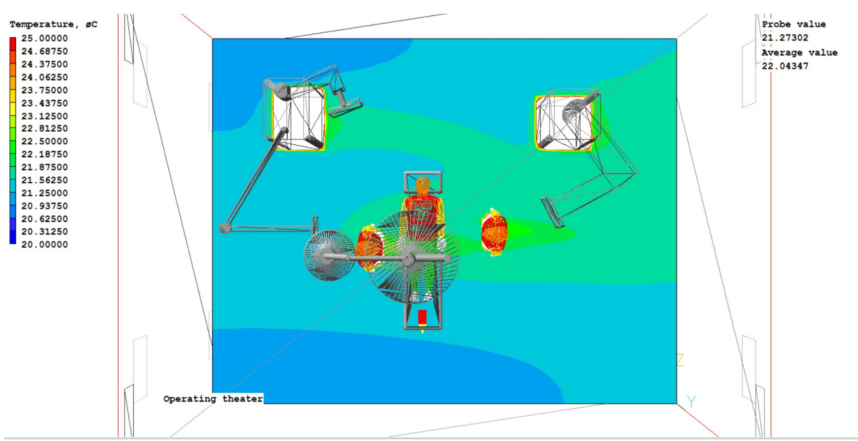
The temperature distribution as shown in Figure 19 (a), (b) and (c) is quite similar to the one observed in Figure 17 (a), (b) and (c). There is no drastic change in the temperature in between case 2 and case1.

(a)



(b)

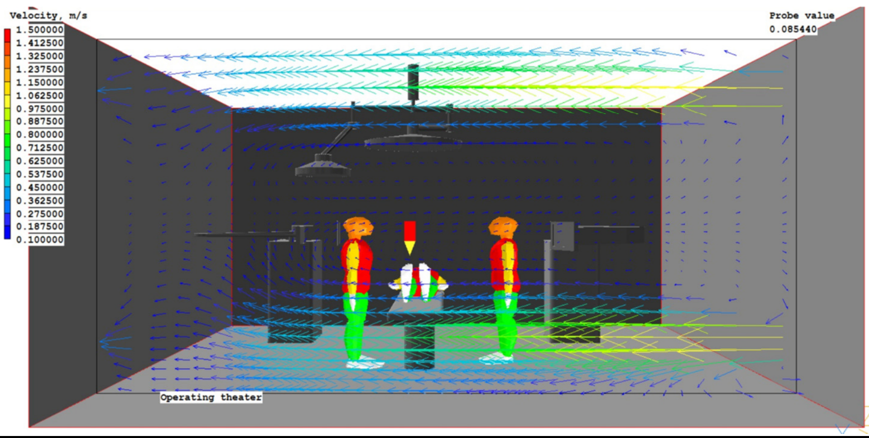


(c)

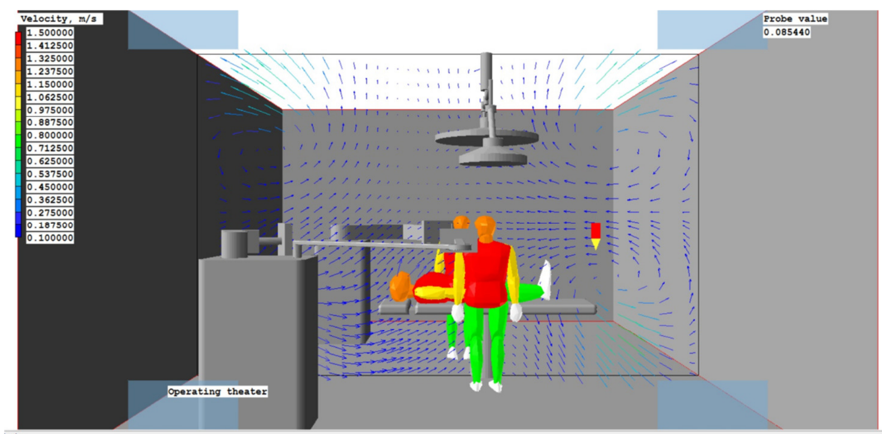
Fig. 21. (a) Front, (b) side and (c) top view of temperature distribution

Case 3: Four inlets and four outlet

This case shows significant improvement in both in case of velocity and temperature distribution. The addition of two inlets at the bottom changes the scenario.



(a)



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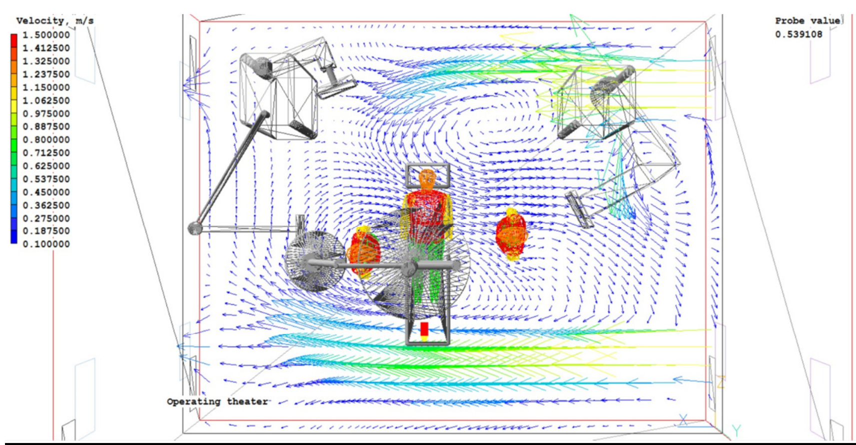
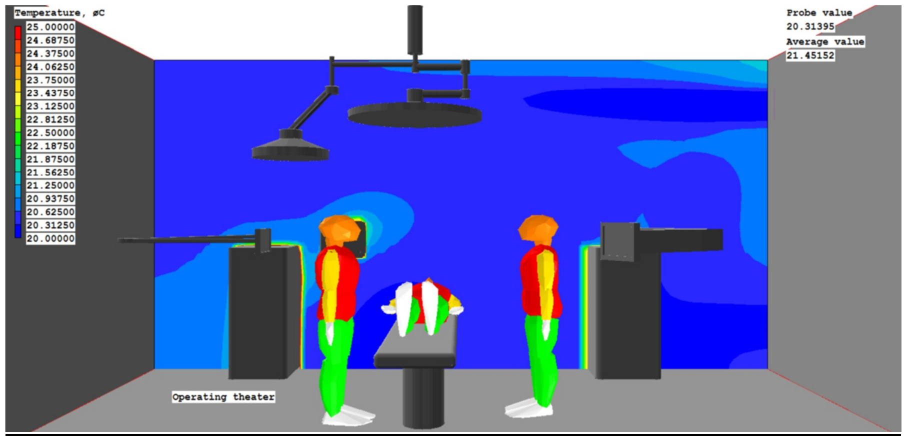


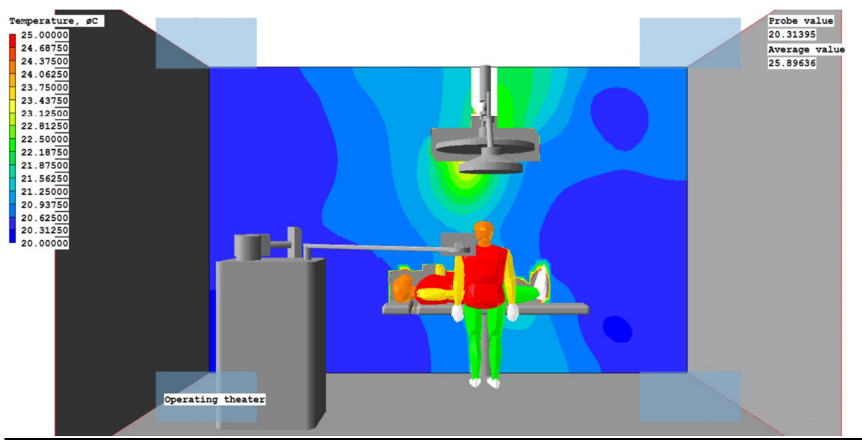
(c)

Fig. 22. (a) Front, (b) side and (c) top view of velocity distribution

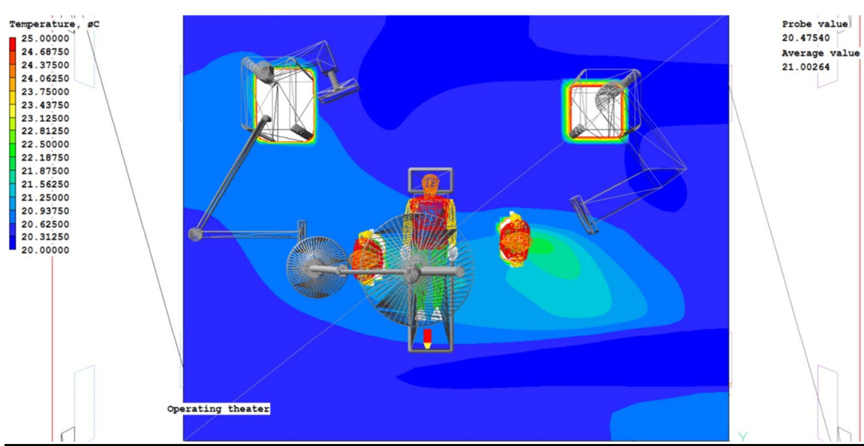
As two inlets are added at the bottom of the right-side wall, this increases the airflow movement, as shown in Figure 20 (a), (b) and (c). The airflow movement is throughout the room which was not noticed in case 1 and case2. The recirculation in the central zone is also quite reduced.



(a)



(b)



(c)

Fig. 23. (a) Front, (b) side and (c) top view of temperature distribution

Temperature is effectively controlled in the OT, this setup cools the room better than case 1 and case2. The Figure 21 (a) (b) and (c) clearly show that temperature is at the 20℃. The central zone of interest also shows less heat transfer from the primary lamp to the operating table Figure 16 (c).

The only drawback noticed is the formation of a new recirculation area, due to the presence of equipment in the path of the airflow, as seen Figure 20 (c). This phenomenon was not seen in case 1 and case 2. The turbulence created will result in improper removal of contamination.

Case 4: Central ceiling inlet and eight outlets

The velocity distribution Figures 22 (a), (b) and (c) show that the air entering from the vertical inlet, clearly distributes more evenly throughout the OT compared to horizontal inlet. The major recirculation zone is in the central region Figure 22 (b) due to the presence of the primary and secondary light source.

Recirculation and low velocity flow is also noticed across the OT. Thus this case shows it is not feasible in effective contamination removal, even if it offers effective airflow distribution.

This case showed the effectiveness of vertical cooling over horizontal. The temperature distribution is quite even throughout the OT. The Figures 23 (a) (b) and (c) show that the room is at our desired temperature. The heat from the light sources is completely removed as it is directly below the inlet vent. The impinging cool air extracts the heat from the room and the zone of interest, i.e. the operating table, patient and staff is at the room temperature.

Case 5: Entire ceiling inlet and eight outlets

This case provides cooling through the entire ceiling. This case provided by far the possible solution in case of velocity distribution and temperature control in the OT. The velocity distribution plots Figure 24 (a) (b) and (c) show the effectiveness of implementing full ceiling inlet. There is no reduction in the airflow velocity throughout the room. The central region where recirculation was observed in case 4 Figure 22 (b) is reduced to a minimum Figure 24 (b).

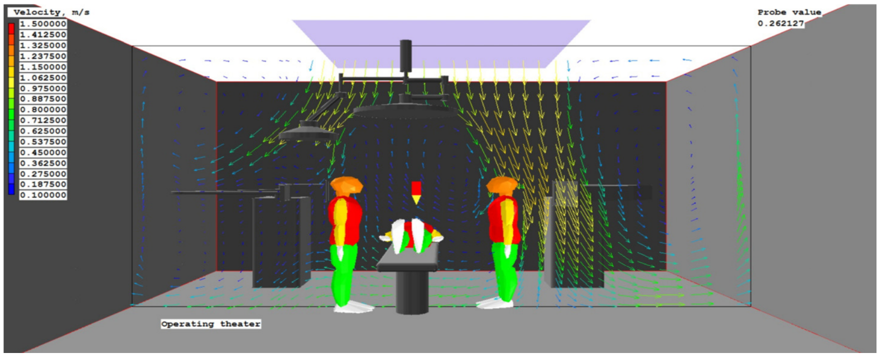
Figure 24 (c) shows the increase in the exit velocity which will effectively help in more Air changes per hour and contamination removal.

Figure 25 (a), (b) and (c) show that the temperature removal is effective in this case too similar to case 4. Thus both the cases are effective in reducing the temperature, but the major advantage noticed in the current case is the velocity distribution which gives it a higher advantage.

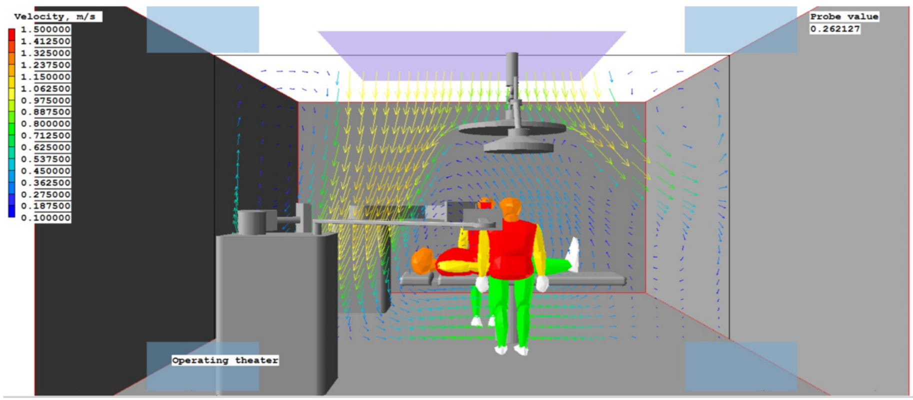
Case 6: Entire ceiling inlet and entire Floor outlet

Figure 26 (a), (b) and (c) show the velocity distribution in case 6. The air is evenly distributed throughout the OT. The airflow is affected initially similar to case 4 and case 5 due to presence of the two lamps. In this case the concept of bottom outlet is implemented. The air at the outlet is sucked from the bottom, their by preventing any chance of recirculation and removing contamination effectively.

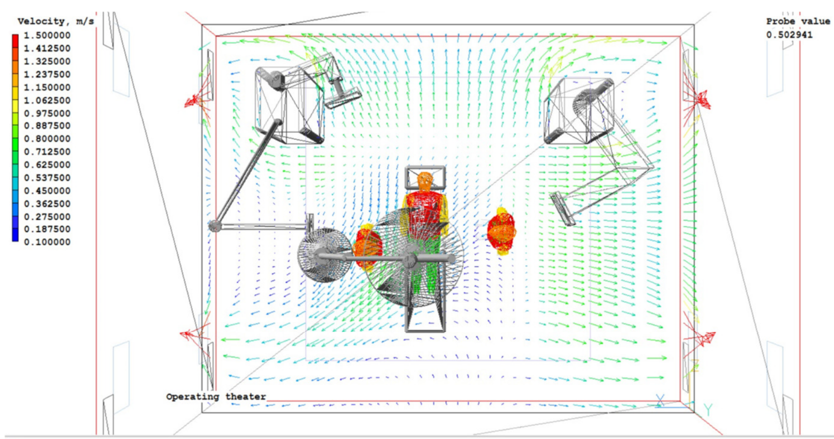
The temperature distribution plot 27 (a) (b) and (c) shows, the cooling in this case also to be effective. There is a slight rise in the temperature in the central region, this can be attributed to the movement of the air as the room is positively pressurised and the outlet is located at the bottom, the air from the inlet to outlet travels faster thus doesn’t get enough time to dissipate the heat.



(a)



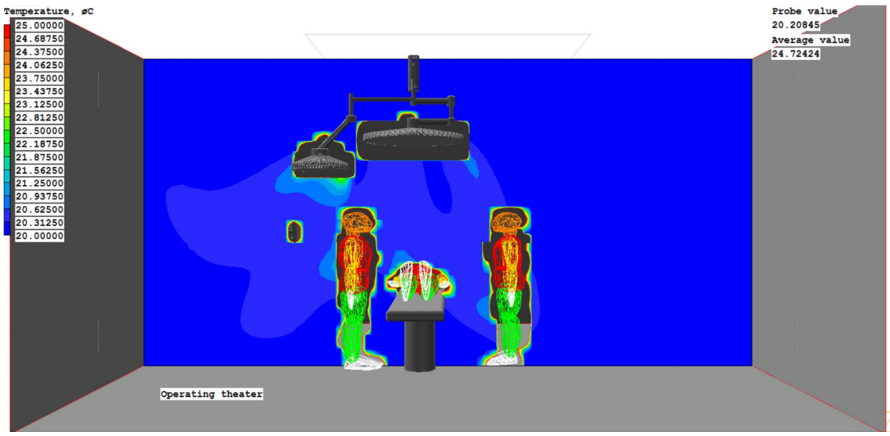
(b)



(c)

Fig. 24. (a) Front, (b) side and (c) top view of velocity distribution

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences
Volume 44, Issue 1 (2018) 99-122



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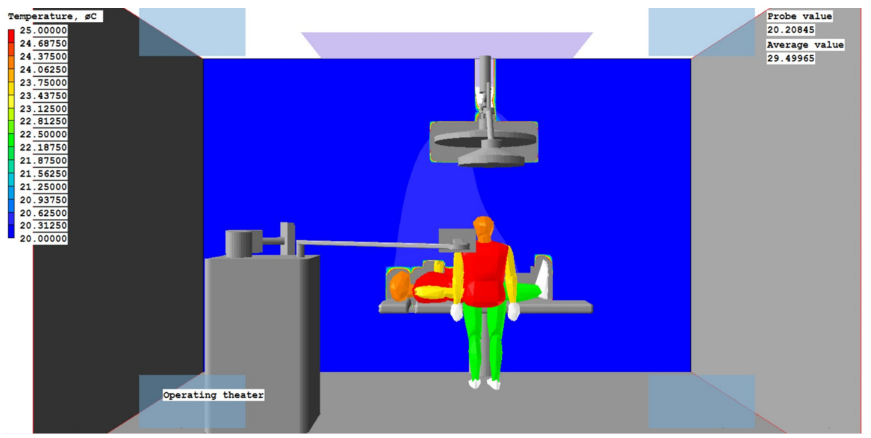

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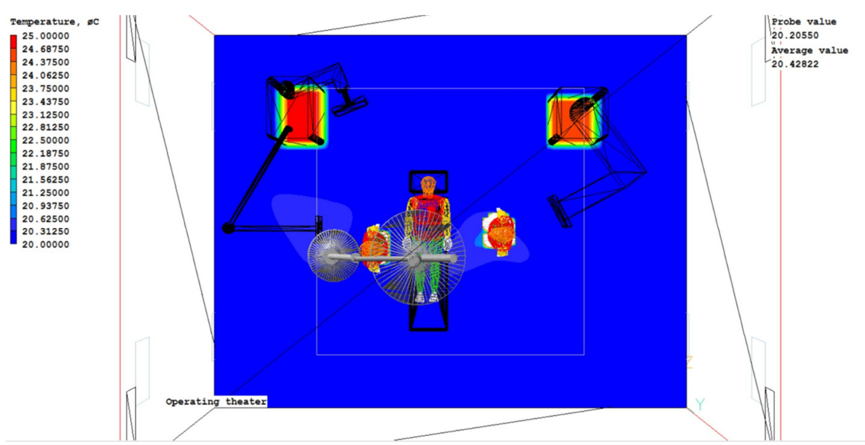


(c)

Fig. 25. (a) Front, (b) side and (c) top view of temperature distribution

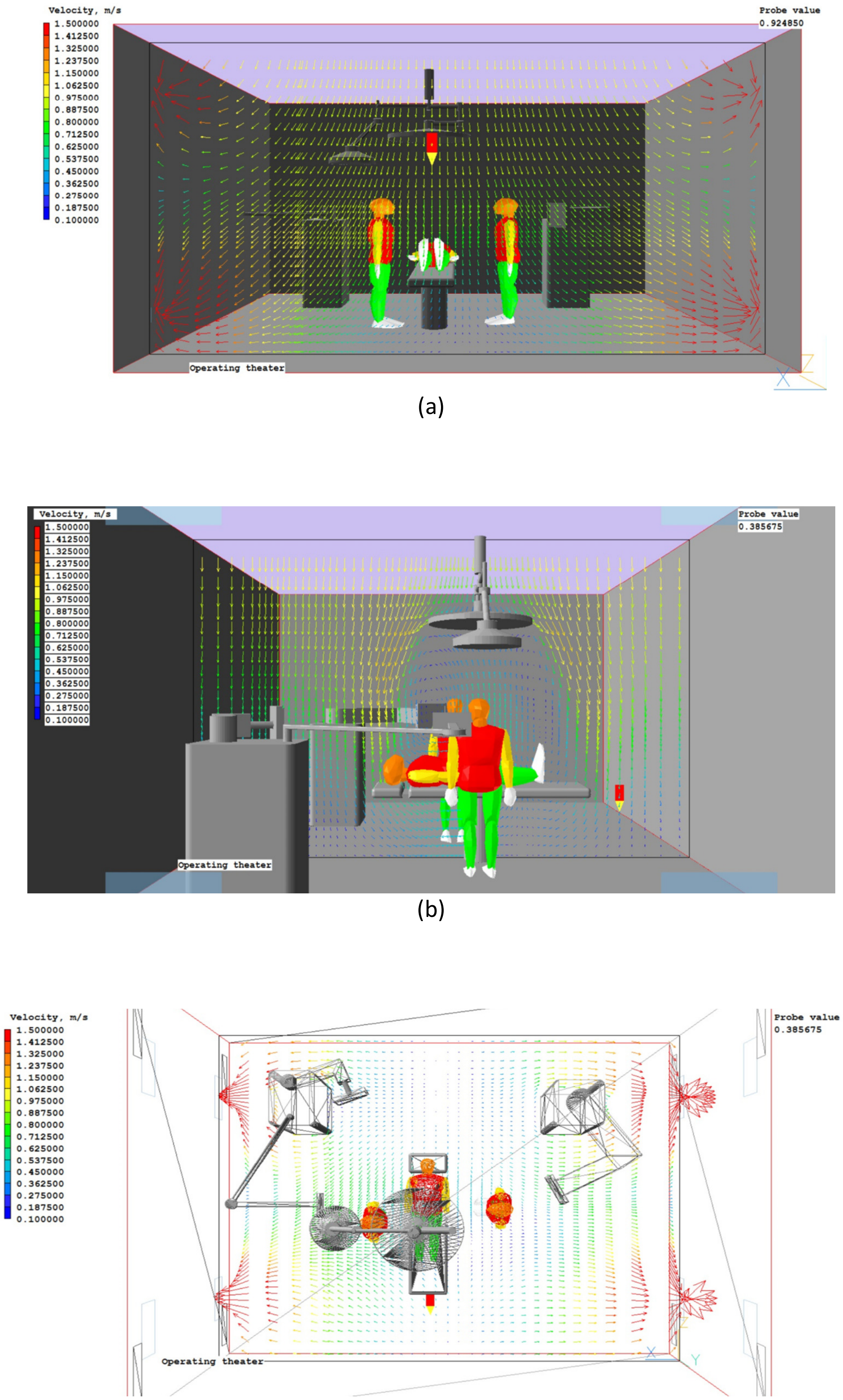
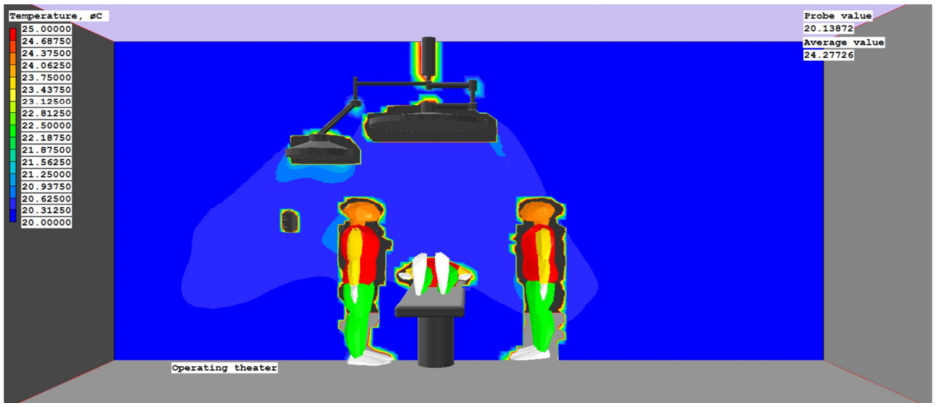


Fig. 26. (a) Front, (b) side and (c) top view of velocity distribution



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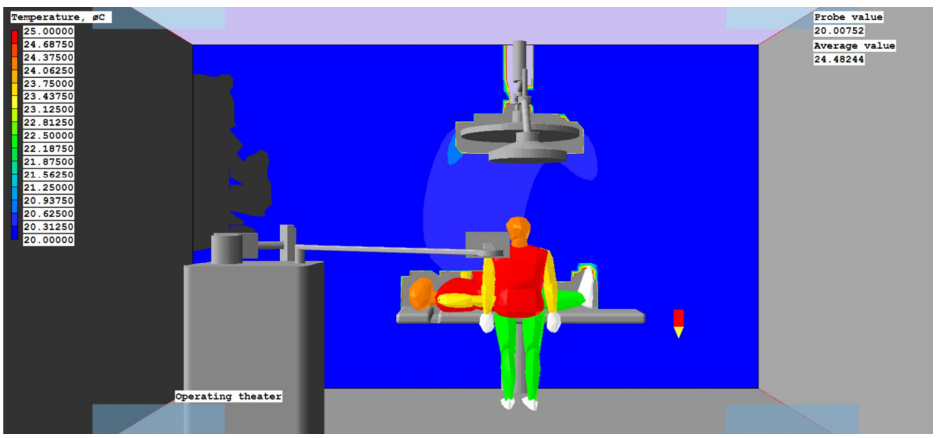

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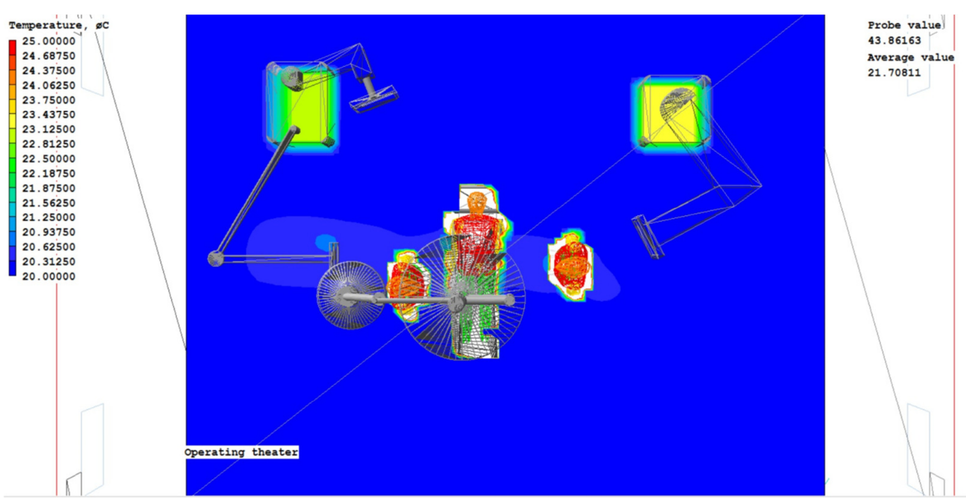
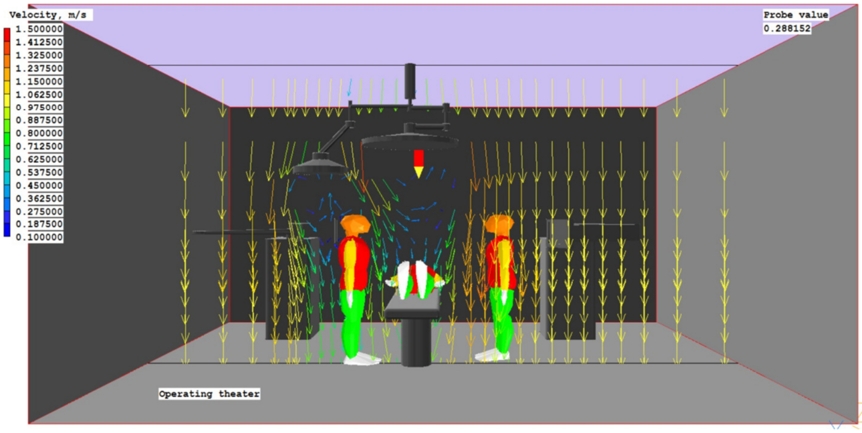
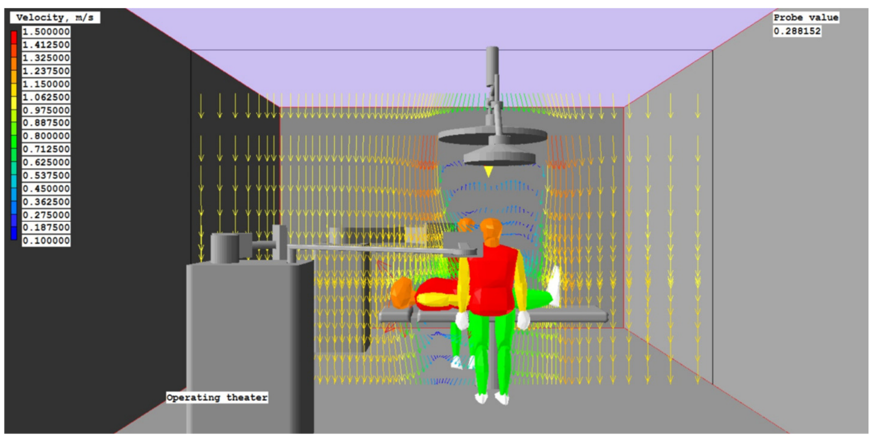


(c)

Fig. 27. (a) Front, (b) side and (c) top view of temperature distribution



(a)



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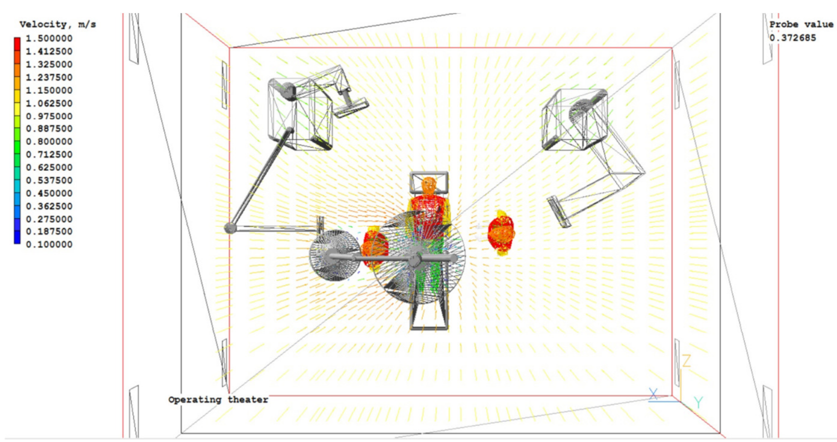

(c)

Fig. 28. (a) Front, (b) side and (c) top view of velocity distribution

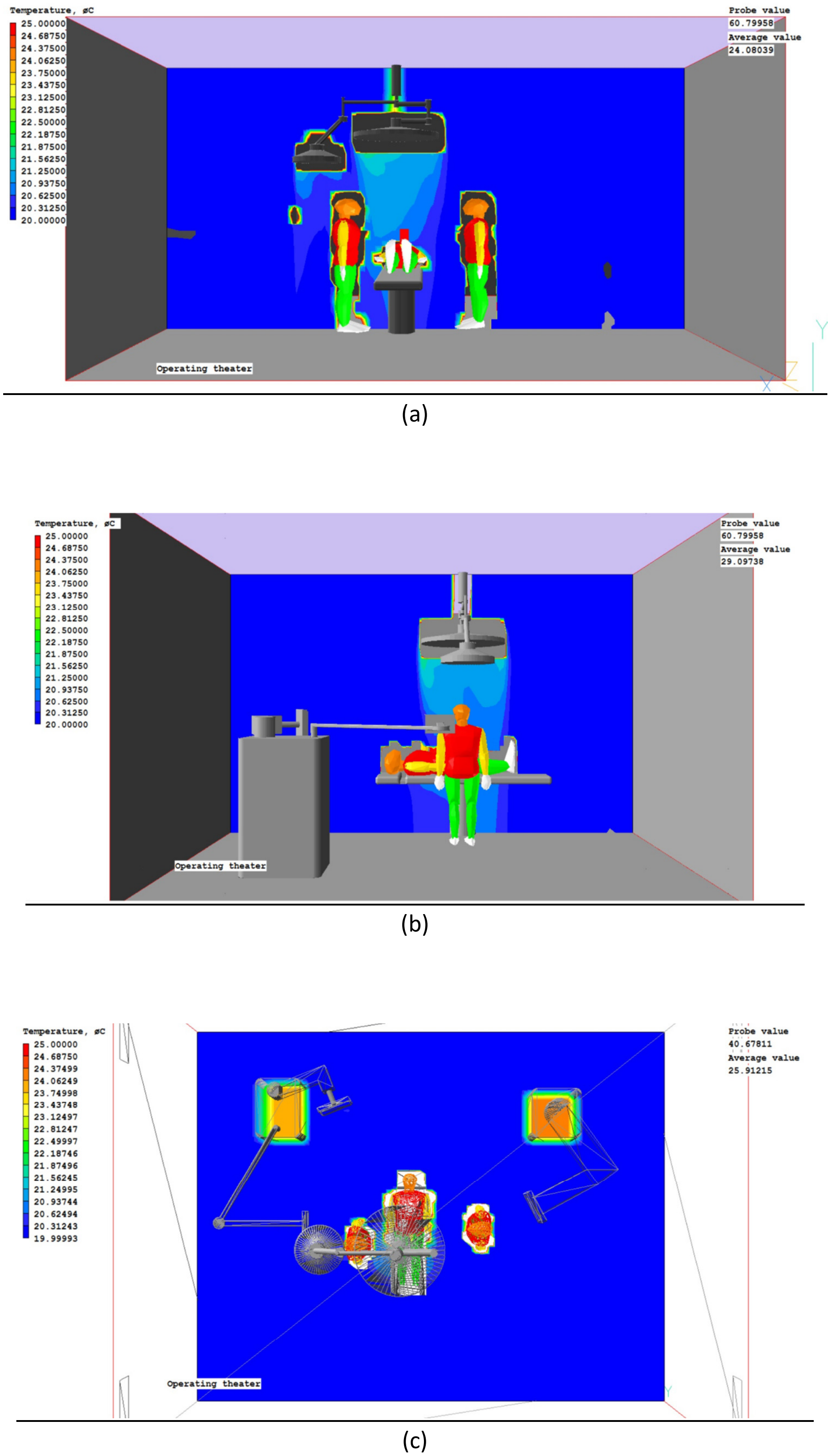

Fig. 29. (a) Front, (b) side and (c) top view of temperature distribution

5. Conclusions

The six cases studied in the current work highlight the working and application of horizontal and vertical Inlets.

Horizontal Inlet

- Case 1 and case2 results showed that both the cases were ineffective in cooling the room. They were also ineffective in reducing the OT temperature, the presence of recirculation zones was most prominent and this might trap the contamination inside the OT.
- Case 3 performance was better compared to case 1 and case2. The effect of adding two inlets at the bottom showed enhanced flow inside OT. The temperature in the zone of the interest was also reduced significantly.
- The major advantage of all the three-horizontal inlet setup is that the airflow is not blocked by the primary and secondary light sources.

Vertical Inlet

Generally vertical inlet cases outperform the horizontal inlet cases, both in terms of velocity and temperature distribution inside the OT.

- Case 4 and case 6 showed better performance than all the horizontal inlet cases. The room was effectively cooled in both the cases, the only drawback was the presence of recirculation zone in case 4. Also Slight increase in temperature in the central region for case 6 was noticed.
- Case 5 is the best case scenario from our study, it effectively maintain the room temperature, reducing the recirculation zones and good velocity distribution throughout the room. This case will be used for further analysis, to effectively track the contamination removal inside OT.

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