# Reviewing and modeling the optimal output velocity of slot linear diffusers to reduce air contamination in the surgical site of operating rooms

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**Summary**
To remove the particles and the environmental contaminations, the hospitals and the health centers need an appropriate air conditioning. Thus, to provide an appropriate design considering all conditions for an air conditioning system will ensure a healthy environment by achieving the thermal comfort for the nurses, doctors, patients and visitors. In the present paper, the outlet airflow through a laminar flow diffuser in order to find the optimal airflow velocity to reduce the air contamination in the surgical site of operating rooms has been studied. The governing equations on the fluid flow including the continuity, momentum, energy equations and species equation have been numerically solved by using the FLUENT software. The results show that the air curtain without any sufficient effect on the laminar airflow cannot properly control it and even it may pull the outlet airflow from this curtain into the laminar airflow and the operating room is turned back into its same conditions when using the vertical laminar airflow. Also, the results show that an air curtain having an optimal velocity of the outlet air greatly influences the reduction of air contamination, maintaining the more desired conditions and a better flow pattern.

***Key words:***
*Laminar flow diffuser, Operating room, Contamination, Air curtain.*

## 1. Introduction

A space with inappropriate and non-standard air conditioning not only causes the lack of comfort but also results in spreading the infection, bacteria and toxins in the surrounding space. Designing an appropriate air conditioning system for the operating room prevents the infections spreading during the surgical operation while all persons inside the operational room (doctors, nurses and patients) are very comfortable. Preventing the patients' infection spreading often is possible by difficult and problematic processes including some different factors. Achieving an acceptable and reliable performance requires the exact control of the various factors. One of the important considerations related to the air conditioning in the hospitals is to treat the patients alongside establishing the humans' comfort conditions. Preventing the virus and bacteria transfer from a space to the other space is the most important problems in the hospitals. Generally, this transfer is through the air flow, patients, employees, visitors and also by the hospital equipment. The air flow is one of the most important factors to transfer the bacteria in the hospitals because the dust particles in the air or aerosols are the appropriate means to transfer the bacteria and increasing the rate of air flow accelerates the effect of bacteria transfer. To prevent absolutely penetrating the outside air into the operating rooms, the relative pressure of this space to its adjacent spaces is always positive. The air of the operating room doesn't return back again inside and is directly discharged towards the outside. That is, the air handling units of the operating rooms don't have any return channels and use 100% fresh air. According to the national and international regulations of the hospitals the air volume of the operating rooms must be replaced by the fresh air for many times in each hour. The operating rooms should be neither very big in which moving is very time-consuming and nor very small in which the equipment are contaminated. A multi-objective operating room by 6*6*3 m for the emergency surgeries and endoscopy is generally suitable. The size of the large operating rooms for the heart surgery or the complex surgeries requiring more equipment's is slightly more than these above mentioned. The walls and the ceiling of the operating room must be rigid, fireproof, waterproof, seamless and sound insulation and washable. In addition to these above mentioned, the floor of the operating rooms must be resistant against the chemical materials. If it is very rigid or very soft, it will cause the fatigue of the operating room's staff. The walls and doors of the operating room must be painted semi-matt and non-glassy colors to prevent eye-strain of the operating room's staff. As much as possible the geometry of the operating room is designed such a way that it has fewer sharp corners to prevent the airflow circulation or dust accumulation in those regions. The air quality in the hospitals due to the presence of different particles like viruses, bacteria and diffused gases including formaldehyde has been always considered by the health care providers of the hospitals. Because of the importance of the air conditioning problem in the operating room, a system must be installed in the

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operating room which directs the stale and contaminated air towards outside and replaced it by the fresh air. This system filters the fresh air entering the operating room from outside. After air purification, these filters reduce the aerosols having dimensions greater than 0.5µm to 1 through 5 per ft3 after filtering the air. In general, the air conditioning of the operating room is designed based on 15- 25 times of air exchange [1]. Generally, the air pressure of these regions is positively remained to prevent the particles transfer from the outside into the room. There is a simple and general method to classify the clean operating rooms i.e. the 209 Federal Standard which is based on the number of existing particles in the volume unit of the room air . In this classification, the operating room is in the 100th class that is the number of the aerosols by diameter of 0.5 µ per ft3of the room space is 100 particles. To design the air conditioning of the operating room the following considerations must be regarded [2, 3]:

-An air conditioning system of the operating room should be cost-effective and is simply installed. It should be simply cleaned and repaired and has a standard sound level.

- The appropriate temperature of air conditioning for the operating room are generally between 20 to 40 ºc and the relative humidity of 30 to 60%.

-The air pressure to the peripheral environment of the operating room must be positively kept through entering approximately 15% additional air into the room. This pressure difference must be at least 2.5 Pascal.

- The number of air exchange by hour must be between 15 to 25 times.

-All conditioning systems must have two layers filter such that the efficiency of the first layer filter is more than 30% and that of the second filter is more than 90%.

-To design the air conditioning system of the operating room, 100% fresh air must be used which not only helps reduce the contaminates but also, due to two characteristics of the room's positive pressure and 100% fresh air, increases the room safety against the smoke when firing.

As much as possible the geometry of the room should be designed such that it has less sharp corners to prevent the airflow circulation or accumulating the dust in that place. The air inlet registers into the operating rooms are classified into two grille and diffuser groups. The grille one is placed in the ceiling of the room and the air flow is falling directly down in the form of jet, but in the diffuser one the inlet fresh air before reaching the bed is mixed by the air of the other parts in the room . The research shows that in the operating rooms the best inlet airflow registers is of diffuser kind [4]. According to the No. 44 ANSI / ASHRAE standard provided in 2004, the individuals' breathing zone inside of the room is a zone situated by the hypothetical plates at intervals between 75 through1800 mm from the floor of the room and 600 mm from the side walls of the room. According to the Standard No.55 ANSI / ASHRAE, the space between the floor and ceiling of the room and also the interval of 0.3 m by the room's side walls is called the occupied zone. In general, the individuals' breathing zone could be considered the same as occupied zone. Memarzadeh and Manning [5] in their research as “Reducing the risks of surgery” traced the particles motion through the operating room and determined the particles contamination on the surgical tables and beds. Son et al. [6] (2008) studied the thermal comfort and contaminant removal in the three-dimensional operating room. In this work, the airflow inlet diffusers on the wall and in the various situations were studied. It was concluded that the best place to install the diffusers to reduce contaminants and providing the thermal comfort is in the center of the operating room. Liu et al. in 2009 [7] studied the effect of the horizontal airflow on controlling the infect level in the operating room. They concluded that the particles concentration around the patient's body depends on how the patient has been localized. In the other research, Attia et al. [8] in 2013 studied the effect of door gradually opened on the thermal comfort level for the staff of the operating room where has been equipped with the diffusers. It was specified that opening and closing the entrance door influence the thermal comfort of the staff of the operating room equipped with the trapdoors. The extent of opening the door causes to increase the temperature and humidity in the space. In 2013, Sadrizadeh et al. [9] studied the influence of the number of staff in the operating room on the surgical site infections. They concluded that in an exchange rate of the stationary air with the increase of the staff number, the particles rate is increased. In 2014, Sadrizadeh et al. [10] performed the numerical investigation of vertical and horizontal laminar airflow ventilation in an operating room. They concluded that several different factors including the staff's situation and the equipment’s of the operating room, the rate of airflow exchange and the kind of the surgery could influence selecting the kind of the laminar airflow. Several works have studied to control the contamination rate of the surgical operating room [12,13] but there has been no research about finding the optimal velocity of the outlet airflow from the linear diffusers in order to reducing the contamination of the surgical site operating room. Therefore, in the present study the rate of contamination has been investigated by studying the different outlet velocities from the airflow linear diffusers.

## 2. General design

Kind of the conventional air conditioning systems in the operating room are as follow:

## 2.1 Turbulent airflow system:

In this system the fresh airflow is entered into the operating room through a channel from the ceiling. This airflow is immediately mixed with the inside airflow and resulting in the dilution and reduction of contamination. If the mixing action is completely done, the primary dust concentration is progressively lost. Performing this project is very comfort and its air distribution system is less complex and its repair and maintenance is very simpler than the other methods. Its disadvantages include establishing turbulence in direction of the air movement and when the air moves into the environment. Because of this phenomenon, this system would not be able to control the airflow distribution transfer patterns in the operating room [11]. One of the other disadvantages of the turbulent airflow system is to provide negative pressure around the diffuser causing all environmental contaminations infiltrate into the fresh inlet air and mix with it and finally this contaminated air diffuses throughout the operating room. Figure 1 demonstrates a general layout of the turbulent air flow distribution inserted in the ceiling of the operating room.

## 2.2 Horizontal laminar airflow system:

To design the laminar airflow systems, the air moves through a straight direction from the inlet to the outlet with the least mixing or turbulence. This kind of clean operating rooms have a more expensive and larger airflow system than the traditional ones and since the discharge of the aerosols in it is relatively fast, it is possible many restrictions and supports provided in the traditional operating rooms are lost and consequently time –saving and the cost-effective operation can compensate the high cost of the equipment. These systems can conduct the air into the operating room horizontally and vertically. Designing by the vertical state is of several advantages than the horizontal one so that in the vertical system the heavy aerosols due to their gravity force move down along with the airflow and help reduce the contamination [11]. Figure 2 shows the schematic of the horizontal laminar airflow distribution.

## 2.3 Vertical laminar airflow system:

The most effective laminar airflow conditioning system is when the laminar airflow diffusers are placed in the throughout ceiling. By using this system, if its inlet diffusers are very large compared with the working area, the less turbulence is established. But in this state a high rate of the air exchange per hour, generally about 50 through 400, is needed. For this reason this system is not generally accepted due to its high energy costs and not to be cost-effective economically. Figure 3 shows a schematic of the airflow distribution in system.

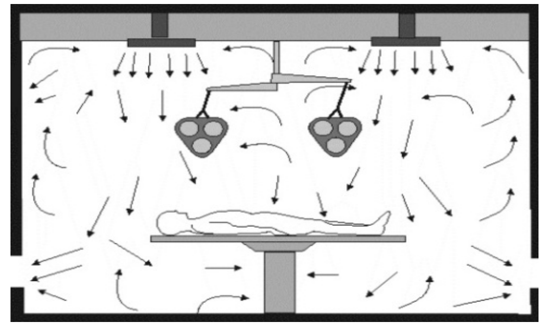


Figure 1- Turbulent airflow distribution system

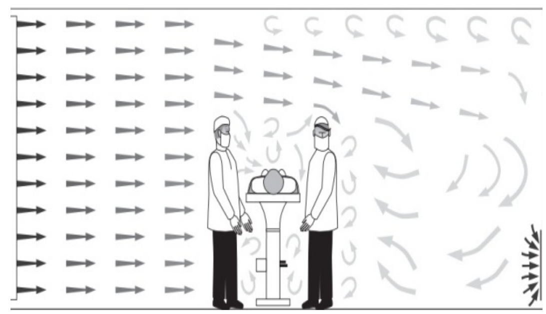


Figure 2-Horizontal Laminar airflow distribution system

Figure 3- Vertical Laminar airflow distribution system (the whole ceiling)

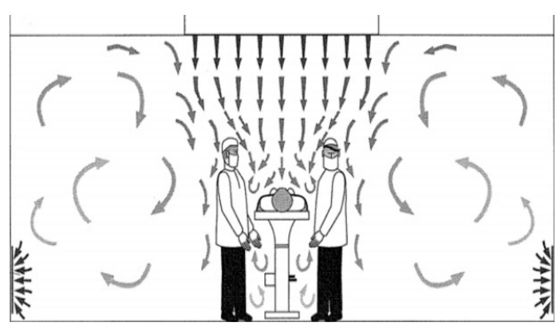


Figure 4-Vertical laminar airflow distribution system

The defect of the previous system can be corrected by reducing the level of laminar airflow and restricting it to the critical region, i.e. around of the surgical bed (table). The environments of the operating rooms need the air exchange rates of 20 times per hour. Of course, sometimes the higher rates of the air exchange for the operating rooms using the high risk surgical operations including the orthopedic surgery, brain and bone, some organ transplant and heart surgeries are considered. In the operating rooms the floor outlet diffusers are never been used because their cleaning is very hard and almost impractical and therefore they are unsafe. The velocity of the laminar airflow system is highly depends on the air temperature. Generally, the round-trip temperature difference for cooling is 7ºc. Therefore, in the time of cooling because the cold air is denser, it will be accelerated under influence of the mass. The acceleration rate of the air is a function of the mass and potential energy. Whatever the round air is more and cooler than the environment temperature it will be accelerated in the space by a higher velocity. It has been confirmed that the airflows with the high velocity in the operating room are harmful. It has been demonstrated that using the systems with the high velocity results in increasing the infection rate and has many adverse impacts on the surgical wounds. It seems that this problem is the result of using the laminar airflow with the high velocity. Because, firstly to approach the airflow from the low velocities to this acceleration level, it must be mixed. Secondly, in the high velocities the airflow will be no much longer with the low induction. In the velocities higher than 0.46 m/s, using a laminar airflow diffuser almost will not be different from the similar velocities in the traditional ceiling diffusers. Establishing the positive pressure in the operating room requires the outlet air from the space is almost 15% lower than the inlet air. In practice, if the outlet air is less than the inlet air, some air must be recirculated in the space. This recirculating air is a contaminated air and therefore it accumulates the aerosols in itself. These particles are immediately exposed to the high speed air and can induce inside it. One of the other problems related to the high speed air is to erode and separate the micro- flakes from the skin without any coverage of the surgical team. The high velocities can help this erosion and result in placing these particles directly on the surgical wounds. Additionally, the high velocity of the lower temperature trip air, due to the effect of the evaporate cooling; can cause hypothermia in the patient. Consequently, the laminar airflow systems, without using the air curtain, are rarely used in the operating rooms. They have a low efficiency in terms of removing the environmental contamination and in this airflow the fresh air is simply mixed with the environmental contaminated air. Figure 4 shows a general layout from this system.

## 2.4 Vertical laminar airflow system along with the air curtain:

The higher amounts of the airflow mean the higher mass of the cold air, higher potential energy and higher airflow velocity to exit the diffuser. For the larger operating rooms such as the surgical site of operating room, orthopedic and heart surgeries, finding a way to provide a better laminar airflow behavior is very important. The complex or expensive systems are not good solutions for these mentioned operating rooms. Therefore, the designers seek the other ways out to make the laminar airflow more predictable and approach it to the optimal airflow meaning “one transition and then exhaust”, of course with a fewer cost and complexity. One of these new methods which have relatively been successful is to use the air curtain. This system includes the number of the laminar airflow diffusers with a low velocity which are on top of the surgical bed and have been surrounded by the linear diffusers with a higher velocity. Considering the experiments performed on this system, the laminar airflow pattern is usually obtained by the velocity of 0.35 to 0.55 m/s. The linear diffusers placed on the ceiling must be at least at intervals of 0.9m from the surgical bed such that the surgical team and the equipment can easily move without causing to become turbulent the laminar airflow. Using the air curtain in this system has several functions but its major function is that it functions as a permanent discharge valve and causes the laminar airflow has a better behavior. In such situation, the outlet air from the laminar airflow diffusers in the middle of the operating room not only moves down but also it is forced to extend towards outside. This reduces the recirculating regions containing the breathless air which collecting the pathogenic particles (Dilution control). The air curtain also prevents turbulence the laminar airflow and its acceleration and it guarantees the slow and downward airflow surrounding whole sterile region. The air curtain help draw and turn away the bio-aerosols from the surgical team and consequently that air curtain prevents the contamination transport from the other sites into the sterile region. Figure 5 shows a schematic of the airflow distribution in the laminar airflow system along with the air curtain. Also, the figure 6 shows the layout of the laminar airflow diffusers and the air curtain in an operating room.

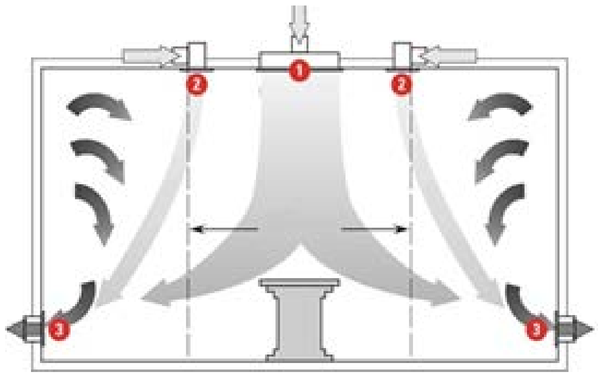


Figure 5- The vertical laminar airflow distribution system with the air curtain

Figure 6- The layout of vertical laminar airflow system with the air curtain

For the prolonged surgeries, surgery of the sensitive body areas (e.g. chest or cranium) and for the patients with weak immune system, the airborne infections are considered very large threat. For these kinds of surgeries the use of the air curtain systems providing an extra protection is advised.

## 3. Materials and methods

The governing equations on the movement of a viscous incompressible fluid in the turbulent state are expressed by the averaged Navier-Stokes equations namely Reynolds (RANS). The governing equations are as follows:

Continuity equation:

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x}(\rho\overline{u})+\frac{\partial}{\partial y}(\rho\overline{v})+\frac{\partial}{\partial z}(\rho\overline{w})=0 \quad (1)$$

Momentum equation:

$$\frac{\partial}{\partial t}(\rho u_j)+\nabla.(\rho u_j\vec{V})=-\frac{\partial p}{\partial x_j}+\nabla.(\mu\nabla u_j)+\frac{1}{3}\frac{\partial}{\partial x_i}(\mu\nabla.\vec{V}) + \frac{\partial}{\partial x}(-\rho\overline{u'u'_j})+\frac{\partial}{\partial y}(-\rho\overline{u'_j v'})+\frac{\partial}{\partial z}(-\rho\overline{u'_j w'})+\rho g_j \quad (2)$$

In the momentum conservation equations, the oscillating values as the new unknowns and by the name of turbulent Reynolds stresses enter the equations which must be determined by using the turbulent models.

Energy equation:

$$\frac{\partial}{\partial t}(\rho\overline{T})+\nabla.(\rho c_p\overline{vT})=\nabla.(\mathrm{k}\nabla.\overline{T})+\frac{\partial}{\partial x}(-\rho\overline{u'T'}) +\frac{\partial}{\partial y}(-\rho\overline{v'T'})+\frac{\partial}{\partial z}(-p\overline{w'T'})+S_T \quad (3)$$

In the energy equation as well as in the turbulent flow the new terms as the turbulent fluxes are appeared which must be determined by the turbulent models.

Species equation (concentration):

$$\frac{\partial}{\partial t}(\rho\overline{C})+\nabla.(\rho c_p\overline{vC})=\nabla.(\mathrm{k}\nabla.\overline{C})+\frac{\partial}{\partial x}(-\rho\overline{u'C'}) +\frac{\partial}{\partial y}(-\rho\overline{v'C'})+\frac{\partial}{\partial z}(-p\overline{w'C'})+S_c \quad (4)$$

In the species equation as well as in the turbulent airflow the new terms as the turbulent concentration fluxes appear which must be determined by the turbulent models. In the turbulent airflows, the shear stress includes two terms and in addition to the shear stress resulting from the flow average component, the other shear stress resulting from the velocity oscillating components is established which is known as Reynolds stresses and is shown in the form of an equation as follows:

$$-p\overline{u'_i u'_j}=\mu_t\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)-\frac{2}{3}(\delta_{ij}\rho k) \quad (5)$$

In the above equations $\mu_t$ is the eddy viscosity or turbulence viscosity which in contrast to the molecular viscosity, it is not the liquid property type but it is the function of the flow properties and its turbulence of which values for the different liquids and points are different. Kronecker Delta is used to functionalize the definition of the eddy viscosity. The turbulence kinetic energy in the mass unit $(k)$ is expressed as follows:

$$k=\frac{1}{2}\left(\overline{u'_i}^2+\overline{u'_j}^2+\overline{u'_k}^2\right) \quad (6)$$

$$\delta_{ij}=\begin{cases}1 & i=j\\ 0 & i\neq j\end{cases} \quad (7)$$

The turbulent thermal fluxes in the turbulence equations can be modeled according to the following relationship:

$$-\rho\overline{u'_i T'}=\left(\frac{\mu_t}{\sigma_t}\right)\frac{\partial\overline{T}}{\partial x_i} \quad (8)$$

The turbulent concentration fluxes in the turbulence equations can be modeled as follows:

$$-\rho\overline{u_i' C'} = \left(\frac{\mu_t}{\sigma_t}\right)\frac{\partial \overline{C}}{\partial x_i} \quad (9)$$

In order to solving the turbulent flow field based on the continuity and Reynolds equations, it is necessary the Reynolds stresses in the equations are modeled on a certain method. In this case, in the three-dimensional flow state despite four equations (one continuity and three momentum equations), four unknowns of the airflow field including the velocities in the directions of x, y, z and the pressure are determined. The turbulence models are used to express the Reynolds stresses and the turbulent thermal fluxes or in other words to close the above equations system.

In the present study, an operating room with square-shape 6*6 and 3.15 m height has been considered. Also, to remove the dead points the corners have been built in the form of chamfer. In the present research, the Gambit software has been used to simulate the geometry of the operating room. Since the equipment and the surgical bed are generally placed in the middle of the operating room and the room has been considered in square – shaped and also to speed up the problem- solving in the short-time, it can be simulated a half of the room and symmetrized the solution to the symmetry line. Furthermore, in this simulation one doctor, two nurses, one patient, anesthesia device, monitor and two surgical lights were considered. All equipment and the people inside the operating room are modeled given to the real dimensions. Also, the 3-D schematic picture of the operating room is observed in the figure 7.

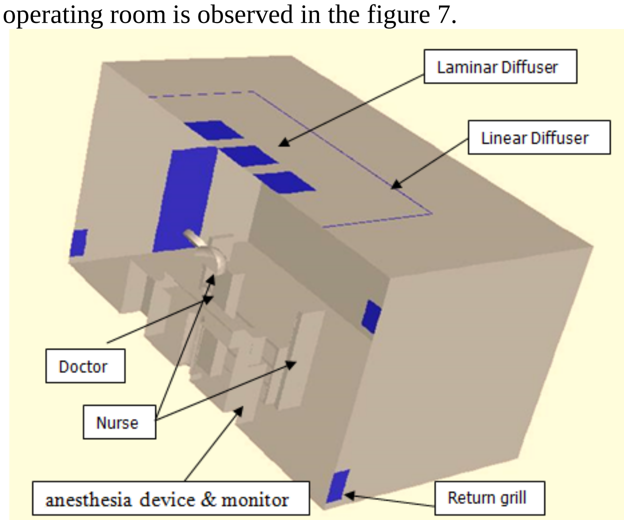



Figure7: Schematic of the simulated model

In order to modeling the operating room and obtaining the type and dimensions of the inlet and outlet diffusers, firstly the total inlet air volume needed should be obtained. Given the standards of American Air Conditioning Engineers Organization, the rate of 25 times of the air exchange per hour is considered for the operating room. The readers for more information about dimension calculation of inlet and outlet diffusers can refer to Ref. [13].

## 4. Results and discussion

The influence of the air curtain on air distribution in operating room without considering the contaminants [12] and with considering the contaminants [13] have been investigated by the authors of the present article. The difference of the present work with the previous researches is related to finding the optimum outlet velocity from the laminar airflow diffuser to minimize the contamination rate in the surgical environment. Figure 8 shows the contamination distribution on the central plate of the operating room. As shown in the figure 8, the most contamination intensity is observed in the outside of the operating room. This pollution resulting from an external source moves towards the surgical site in where is directed towards the outlet by the air curtain. Since the vertical airflow in the operating room has generally an unpredictable behavior and resulting in the flows which don't meet the optimum sterile conditions, the air curtain system sterilizes the vertical airflow and approaches it the ideal situation. As a physical boundary, the air curtain prevents entering the contaminants into the sterile surgical site. These contaminations resulting from the surgical site are directed towards the outside by the doctor and nurse through the laminar airflow. As shown in the figure 8, the contamination rate on the patient is very lower than the mean contamination rate [13].

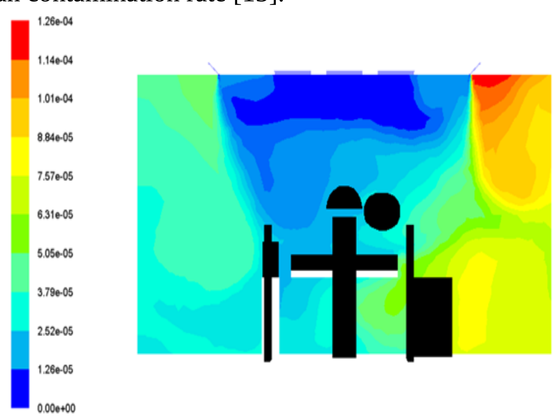



Figure 8- Contamination contour

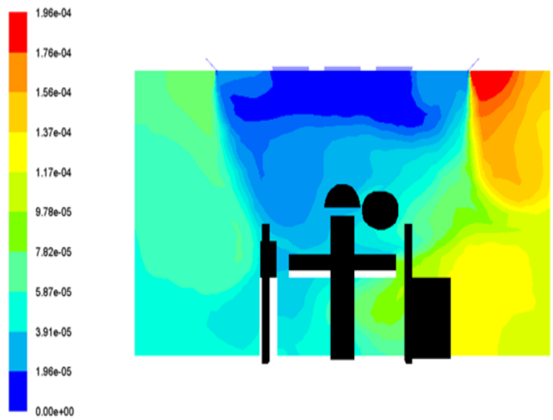



Figure 9- Humidity contour

(Laminar diffuser velocity equal to 2.5 m/s and linear diffuser velocity equal to 0.25 m/s)

In the figure 9, the humidity contour has been drawn in the operating room space and its center. The major humidity in surgical region results from the doctor and nurse's body. It has been considered that the other humidity results from opening the door of the operating room suddenly. The doctor and nurse's bodies are exposed to the transpiration due to activity and this transpiration reaches the patient's body and this humidity rate is minimized by the laminar flow which is distributed from the ceiling of the room by the laminar diffusers. The humidity resulting from the entrance door is constrained by the air curtain. Indeed, the air curtain prevents reaching the humidity of the external diffused air into the surgical site [13].

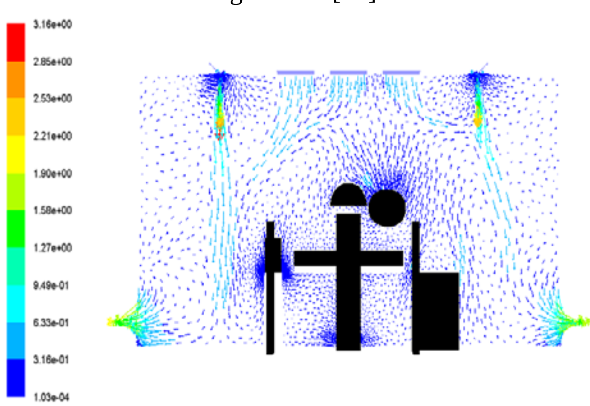
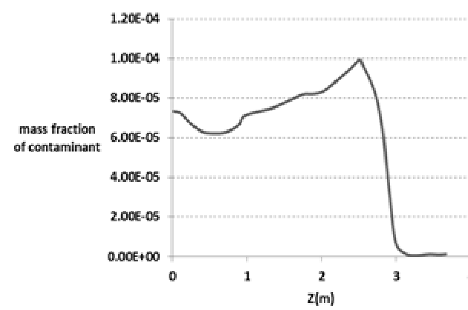


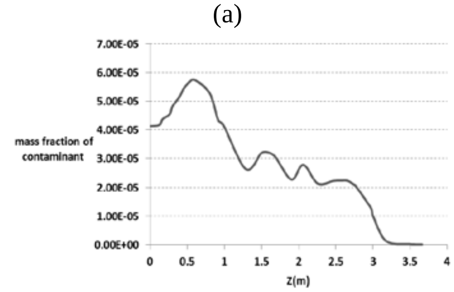

Figure 10-velocity vector

Figure 10 shows the velocity vectors in the operating room. As shown in the above figure, there is the most velocity in the regions near the air curtain and outlet diffusers. The velocity vectors reach the surgical bed with a desired velocity due to the existence of the air curtain such that there is a laminar zone in this region. The air curtain acts as a diffuser and it causes the laminar airflow both moves down and extends towards the outside. It also prevents the laminar airflow turbulence. In the figure 11 the contamination diagram in the operating room to the height from the room floor for 4 different velocities has been drawn.

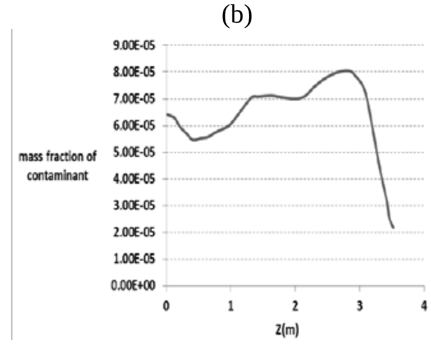
In the Table 1 the contamination on the patient's bed $(z = 1m)$ by the different velocities has been evaluated. As shown in this table, the least contamination level is related to the linear diffuser by the velocity of 1.5 m/s. The velocity of the outlet airflow influences significantly reduce contamination and maintain the more desired conditions and a better flow pattern. In the case of designing improperly the air curtain the velocity increases more than needed and such an air curtain will suck the laminar very slow. This is obviously observed in the velocity vector contour. An air curtain without any sufficient influence on the laminar cannot properly control it. Even the outlet flow from the air curtain may be drawn into the lamina flow. The results show that the air curtain with an optimum velocity in the outlet can greatly influence reduces pollution in different height of operating room.



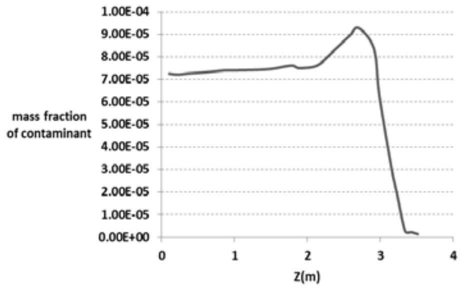

(a)




(b)




(c)




(d)

Figure 11-The variation of contamination with height of the operating room (z) when the values of the air velocity are a) without the air curtain b) 1.5 c) 2.5 and d) 3.5 m/s .

Table 1. Comparing the contamination on the patient's bed in the different velocities

| Linear diffuser velocity (m/s) | Laminar diffuser velocity (m/s) | Contamination concentration on the surgical bed (z = 1m) |
|---|---|---|
| Without air curtain | 0.25 | 10-5×7 |
| 1.5 | 0.25 | 10-5×4.1 |
| 2.5 | 0.25 | 10-5×6.2 |
| 3.5 | 0.25 | 10-5×7.1 |

## 5. Conclusion

In the present research, the simulation of the laminar airflow system associated with the air curtain in order to air conditioning of the operating room has been performed to determine the system behavior and compare its performance with the system without the air curtain. Since the vertical laminar airflow in the operating room may have no predictable behavior and results in some airflows in the room which don’t provide the optimal sterile conditions, the air curtain system will optimize the vertical laminar airflow and will approach it more the ideal situation. The results of analysis by Fluent software showed that the air curtain as a physical boundary in addition to prevent entering the contaminants into the surgical sterile zone, also operates as a discharge diffuser and causes the laminar airflow moves both towards down and outwards. This characteristic of the air curtain results in reducing the recycling area in the operating room and prevents the laminar airflow turbulence. In case of designing incorrectly air curtain, in this system the velocity is highly increased and such air curtain will draw the laminar airflow very fast. Such a system may draw out whole laminar airflow before reaching the surgical table level. The air curtain without any sufficient effects on the laminar airflow cannot properly control it. Even the outlet airflow from this curtain may be drawn into the laminar airflow and turns the room into the same conditions when using the vertical laminar airflow. The results show that the air curtain with an optimal velocity of the outlet airflow can greatly influence the reduction of contamination, maintain the more optimal conditions and a better flow pattern.

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