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Research Article

Computational Fluid Dynamics Analysis of Fire Risks in COVID-19 Intensive Care Units: Assessing Oxygen Concentration, Ventilation Effectiveness, and Material Flammability in High-Risk Healthcare Environments

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Abstract:
This study examines the threats to fire safety in intensive care units (ICUs) during the COVID-19 pandemic, concentrating on ventilation effectiveness and oxygen concentration. Increased safety precautions are required in light of many deadly fires in intensive care units (ICUs), which were mostly brought on by electrical short circuits and made worse by elevated oxygen levels. Oxygen dispersion and concentration fluctuations were modeled in congested ICU rooms under various ventilation situations using Computational Fluid Dynamics (CFD) techniques. Important studies show that if ventilation systems fail, ICU rooms become high-risk zones in 6–10 minutes, with potentially catastrophic oxygen concentration levels. The study shows that natural ventilation is inadequate in critical care settings for controlling infection risks and oxygen levels. Oxygen distribution is greatly improved by increasing the number of mechanical ventilation points, which lowers fire risk. Furthermore, a number of textiles and polymers become combustible at oxygen concentrations between 24% and 35%, according to an analysis of the Limiting Oxygen Index (LOI) of popular ICU materials. In critical care settings, the study highlights the significance of appropriate ventilation design, reliable power backup systems, and cautious material selection. These results offer vital information for improving ICU fire safety procedures and safeguarding patients and medical staff in environments with high oxygen levels.

Keywords: *Thermal performance, zigzag-winglet, perforated-tape, Nusselt number, Reynolds number*

1. Introduction

A vital part of contemporary healthcare systems, the Intensive Care Unit (ICU) is intended to treat patients with serious, life-threatening diseases or injuries with specialized care. The administration and control of oxygen, a crucial component in the treatment of a wide range of critical illnesses, is central to the operation of intensive care units [1]. The recent COVID-19 epidemic has highlighted the need of oxygen in intensive care units (ICUs) even more, as there has been an unparalleled need for respiratory assistance in these conditions [2] [3]. Oxygen therapy is used in intensive care units (ICUs) for a number of reasons, such as managing different critical illnesses, treating hypoxemia, and providing support for mechanical ventilation [4].

The average amount of oxygen in air that humans breathe in is about 21%. Only around 5% of this oxygen is taken up by haemoglobin in the lungs during respiration, with the other 95% being exhaled [5].

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An occurrence known as oxygen enrichment occurs in intensive care units (ICUs) as a result of this physiological process and the widespread usage of oxygen delivery equipment in these settings.

In intensive care units, oxygen enrichment happens via a variety of methods. It is mostly caused by patients' exhaled breath, which has a higher oxygen concentration than surrounding air, when they get oxygen therapy. The oxygen levels in the environment are also raised by leakage from oxygen delivery tools such masks, nasal cannulas, and ventilators [6]. As a result, certain regions inside an intensive care unit can have considerably higher oxygen concentrations than other places, possibly resulting in zones where oxygen concentrations are higher than those of the surrounding air [7].

Although oxygen is essential for medical treatment, there is a serious safety risk associated with its enrichment in intensive care units. Although oxygen does not ignite on its own, it greatly aids and speeds up the combustion process. Materials that are often thought to be non-flammable or slow-burning in regular air can ignite more readily and burn more strongly in oxygen-enriched atmospheres [8]. This increased danger of fire is especially concerning when it comes to intensive care units (ICUs), as there are a lot of possible sources of ignition there, such as electrical equipment, heating devices, and other medical instruments [9, 10].

A thorough investigation into fire-related accidents in hospitals was carried out by the European Commission Joint Research Centre [11], with a specific emphasis on wards housing COVID-19 patients. According to their research, there is a noticeable rise in the risk of fire when the oxygen content of the surrounding air surpasses 23%. In oxygen-rich intensive care units, this threshold draws attention to the thin line that separates therapeutic requirement from safety concern. Numerous studies have confirmed these findings by identifying oxygen enrichment in intensive care units (ICUs) as a significant factor in fire dangers, highlighting the necessity of strict safety procedures and mitigation techniques [12]–15].

The Limited Oxygen Index (LOI) concept is used to measure the fire risk associated with various materials in oxygen-enriched situations. The lowest oxygen concentration (given as a volume percentage) needed to maintain a material's stable combustion after ignition is known as the limit of ignition (LOI) [16]. This parameter is especially important in intensive care units (ICUs), where a wide variety of materials are present, each with unique flammability properties. Table 1 shows the range of fire risks associated with different components of the ICU environment by presenting the LOI values for several materials usually encountered in ICU environments.

Table 1: A list of different materials and their LOIs utilized in an ICU room

Materials	Minimum LOI	Maximum LOI
PEKK (Polyetherketoneketone)	24	35
PEI (Polyetherimide)	46	47
PSU(Polysulfone)	30	32
PPSU(Polyphenylene Sulfone)	44	44
PEI (Polyetherimide)	46	47
PVC (Polyvinyl chloride)	35	40
Wool	24	25
Polyester	20	23
Acrylic	18	20
Polypropylene	17	18
Cotton	18	21

The difficulties with oxygen enrichment and fire safety are made much more difficult by the intricate design of intensive care units. An example of an intensive care unit (ICU) is shown in Fig 1, where the complex configuration of patient beds, medical equipment, monitoring devices, and support systems is displayed. This intricate arrangement affects not just how oxygen is distributed around the room but also possible routes for fire spread and emergency evacuation plans. The dynamics of oxygen dispersion in an intensive care unit are important for managing fire safety as well as patient care. The geographical and temporal fluctuations in oxygen concentration are caused by various factors, including room geometry, ventilation systems, air currents, and the placement of oxygen supply stations [17].

Fig.1. Pictorial view of a typical ICU room.

Comprehending these dynamics is crucial to formulating efficacious approaches to alleviate fire hazards while upholding ideal patient care circumstances. In particular, the oxygen dispersion velocity and patterns play a major role in controlling the risk of fire caused by increased oxygen concentrations. High-velocity flows have the potential to exacerbate fire dangers in particular ICU zones by generating localized pockets of severe oxygen enrichment [18]. On the other hand, properly planned ventilation systems can aid in the more equitable distribution of oxygen, lowering the possibility that hazardous quantities will accumulate in any one location [19]. Utilizing computational fluid dynamics to investigate smoke control systems in hospital emergency scenarios, recent research has placed an increased emphasis on safety and risk management in healthcare facilities [20]. In pediatric emergency rooms, thorough risk studies of healthcare worker safety have been carried out [21]. In order to identify important problems and possible solutions, researchers have investigated fire safety management in public healthcare buildings [22]. There have also been publications that offer insights on the testing and inspection of medical devices, especially those used by children and newborns [23].

Together, these studies demonstrate how crucial it is to implement complete safety strategies in healthcare settings that include environmental hazards, emergency readiness, and the dependability of medical equipment.
A thorough examination into oxygen content and its dispersion characteristics in typical ICU rooms is urgently needed, given the essential significance of these concerns. Such studies can offer insightful analysis and recommendations based on solid data to enhance a number of ICU design and operation-related factors, such as:
1. Ventilation system optimization to provide efficient oxygen distribution and reduce localized enrichment [24].
2. The creation of enhanced safety procedures for the provision of oxygen treatment [25].
3. To reduce the risk of fire, strategically locate heating sources, electrical equipment, and other potential sources of ignition [26].
4. Creating fire suppression systems that are more efficient and suited for situations with more oxygen [27].
5. The use of cutting-edge monitoring equipment to give data on oxygen concentrations in the intensive care unit in real time [28].

This work looks at oxygen dynamics in intensive care units in an effort to address these important safety issues. Our goal is to create a thorough understanding of oxygen behavior in these intricate systems by integrating risk assessment techniques, computational fluid dynamics simulations, and empirical data. The ultimate objective is to help build healthcare facilities that are more robust and safe, which will improve patient safety and the general standard of critical care delivery.

The subsequent segments will expound on our approach to examining oxygen dispersion in intensive care units, showcase our discoveries about concentration trends and related hazards, and deliberate on the consequences of our findings for ICU layout and security measures. Our goal in conducting this research is to close the knowledge gap between theory and practice by offering healthcare.

By analyzing oxygen dynamics in intensive care units, this research seeks to solve these important safety issues. Our objective is to create a thorough comprehension of oxygen behavior in these intricate settings by merging risk assessment techniques, computational fluid dynamics simulations, and empirical data. The ultimate goal is to improve patient safety and the general standard of critical care delivery by helping to build safer, more resilient healthcare facilities.

The subsequent segments will expound on our approach to examining oxygen dispersion in intensive care units, showcase our discoveries about concentration trends and related hazards, and deliberate on the consequences of our findings for ICU layout and security measures. By doing this research, we hope to close the knowledge gap between theory and practice by giving facility administrators and medical practitioners practical advice on how to improve ICU safety without sacrificing patient care.

Our study aims to address this crucial knowledge gap through two primary objectives: firstly, to conduct numerical simulations to determine oxygen concentration patterns in a simplified two-dimensional geometry of a typical ICU room; secondly, to perform numerical simulation studies to understand the impact of various ventilation strategies on oxygen concentration and fire risk in these high-stakes environments. Given the increased oxygen use in ICUs treating COVID-19 patients and the potential for catastrophic outcomes in the event of a fire, this research gap is especially concerning. By accomplishing these goals, we hope to offer evidence-based knowledge that will contribute to improved fire safety procedures in intensive care units (ICUs), ultimately improving the safety of both patients and medical personnel in these oxygen-rich settings.

2. Methodology

2.1. Geometry

The geometry used for the study is a two dimensional plan of an ICU room with 10 beds as shown in Fig 2. The geometry contains 10 beds each having dimensions 2057.40 mm × 914.50 mm. The geometry has two doors each of dimensions 2400 mm × 1200 mm. The room uses ventialtion vents of size 700 mm × 700 mm. In ICU rooms, oxygen masks are generally used to provide patients with oxygen to support breathing . For simplicity in geometry, the mask is modelled in the shape of a vertical ellipse with vertical axis of 115 mm and horizontal axis of 45 mm. All the dimensions conformed with the standard dimensions used in a typical ICU room.

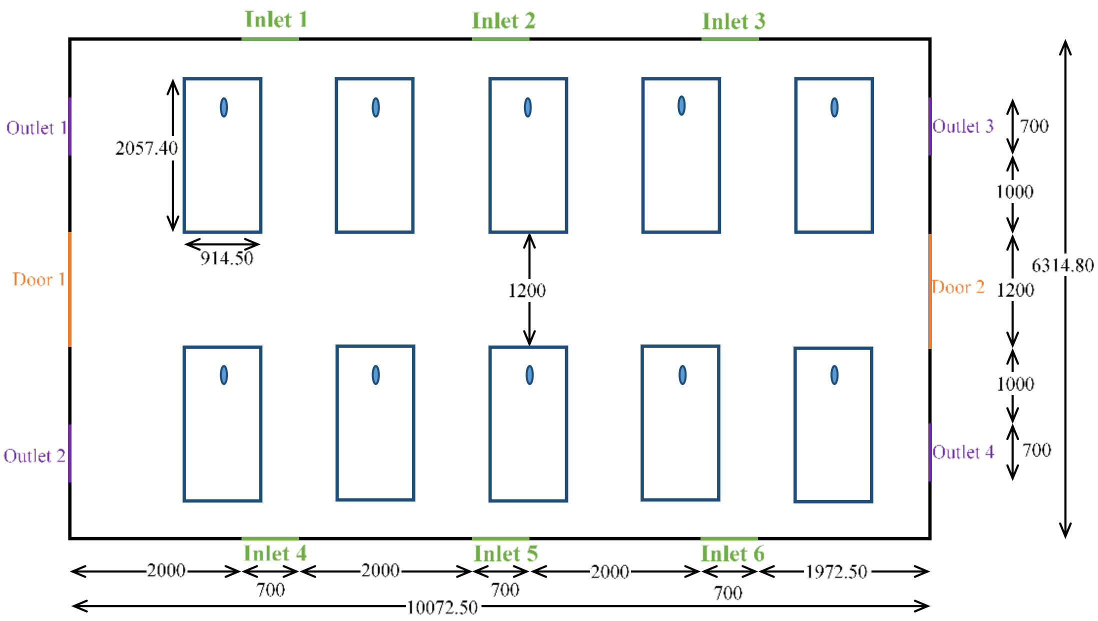


Fig 2. Plan of a typical ICU room.

2.2. Cases under study

The study is focused mainly on 4 Cases

Case 1- The Case ressembles a scenerio where due to power failure all the inlet AC vents (inlet 1, inlet 2, inlet 3, inlet 4, inlet 5 and inlet 6) in the room have stopped working and only all the outlets (outlet 1, outlet 2, outlet 3 and outle 4) are working. The doors (door 1 and door 2) are also closed. The oxygen is leaking from the masks continuously. All the masks are given mass flow inlet boundary conditions with mass flow rate of oxygen calculated on basis of 60 litres/min. This Case simulates worst Case scenerio in an ICU room.

Case 2-This Case models the natural ventilation inside the ICU room with 6 ACH, suggested by Ventilation of health care facilities. ANSI, ASHRAE, ASHE, value which is smaller then standard value. The natural ventilation is taking place from inlet 2, inlet 5, door 1 and door 2. All other inlets and outlets are closed.

Case 3-In this Case, all the inlet AC vents (inlet 1, inlet 2, inlet 3, inlet 4, inlet 5 and inlet 6) and all outlet vents (outlet 1, outlet 2, outlet 3 and outle 4) are open. Both the doors are closed. This simulation aims to study the enhancement of ventilation over Case 2 by using AC vents with the same ACH value of 6 which is less than standard value.

Case 4–This Case is similar to Case 3. However, the value of the ACH is 12 which is in the conformity with WHO standards.

3. Boundary conditions

Various boundary conditions have been used to model the actual scenario of the ICU room are as follows:

3.1 Mass flow inlet

The mass flow rate of air is given as input along with the composition of air i.e. 22% oxygen and 78% nitrogen. The mass flow rate of oxygen is given as input for the mask.

3.2. Calculation of mass flow rate of air

Patients with suspected COVID-19 should be isolated in airborne infection isolation rooms with a minimum ACR (Air Change Rate) of 6 per hour. According to the World Health Organization (WHO) COVID-19 patients should be isolated in well-ventilated negative pressure chambers with a minimum of 12 ACH. The following formula is sued to define ACH-

$$\text{Air change rate per hour} = \frac{(3.6 \times Q)}{Vol.} \quad (1)$$

where,

Q = Volumetric flow rate of air in litres per second (L/s).
Vol. = Volume of the entire ICU room.

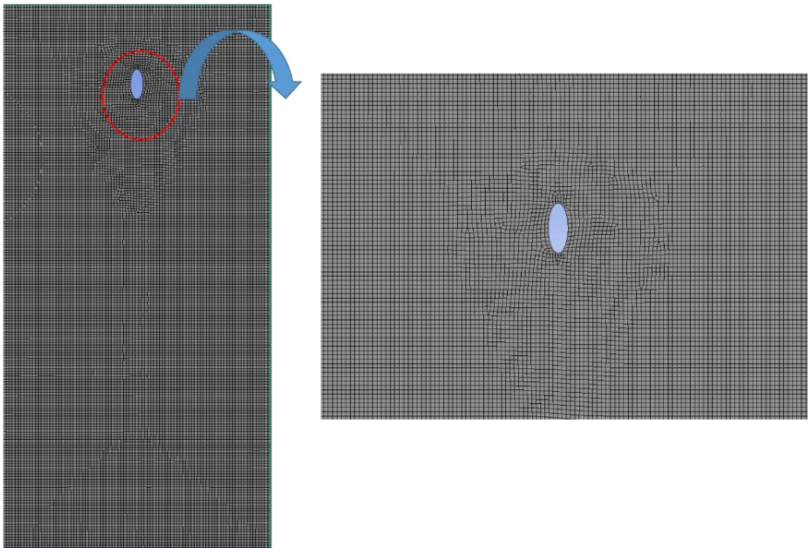
Using standard value of ACH as 12 for the taken geometry for 3 meters ceiling height, the value of mass flow rate of air is 0.78 kg/s.

3.3 Flow rate of exhaled oxygen from the patient

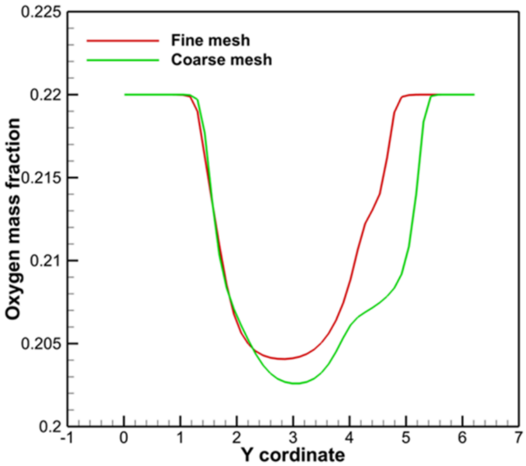
For severe patients, oxygen inflow rates as high as 80 litres/min. Some critical patients were also administered oxygen flow rates up to 200 litres/min. (60 litres of oxygen per minute: How doctors are treating Covid patients without ventilators. The New Indian Express). By considering these facts, the flow rate of exhaled oxygen is taken as 60 litres/min. A no slip wall boundary condition was specified for the patient and bed. In order to reduce complexity, equipments were not considered in the study.

4. Mesh independency study

To ensure precise and trustworthy results, a mesh independence study was carried out with Ansys Meshing. The geometry of the rectangular ICU room was composed of uniform, square-shaped pieces. A fine mesh with 637,063 nodes (10 mm element size) and a coarser mesh (20 mm element size) were the two mesh densities that were examined. As seen in Fig 3, special attention was paid to fine-tuning the mesh in the vicinity of the mask area. Mesh-independent solutions were found for the 10 mm mesh size after comparing simulation results for important factors like oxygen concentration and velocity profiles. As a result, this mesh density was chosen to balance computational efficiency and result accuracy in the ensuing simulations.



(a)



(b)

Fig.3. (a) Mesh used in the present work, (b) Mesh independency on oxygen mass fraction.

5. Fluent setup

For the simulation, solver was pressure-based and transient to study variation of properties with respect to time. K-epsilon viscous model with realizable and standard wall settings is used. The simulation involves two species i.e. air and oxygen hence species transport model is used. In the solution methods, coupled scheme is used for pressure velocity coupling. In spatial discretization, gradient is set at least square cell based and transient formulation is set to second order implicit. The convergence criteria for all residuals is set to 10^{-6}.

6. Result and discussion

6.1. The Base simulation

The mass proportions of nitrogen and oxygen in the atmosphere are 77% and 23%, respectively. Before starting simulations for every scenario, it is essential to make sure that the initial circumstances inside the intensive care unit match the atmospheric conditions. This was accomplished by running a base simulation with all input and output vents operating for ten minutes. While outlet vents were given pressure outlet conditions, inlet vents were given mass flow rate boundary conditions. Twelve was the constant air change rate (ACH). Following the base simulation, the oxygen mass percentage was found to be consistent with atmospheric conditions, ranging from 0.21 to 0.23 in every area of the room.

6.2. Oxygen mass fraction

This section compares the oxygen mass fraction inside ICU room for all Cases after 2, 4, 6, 8 and 10 minutes.

6.2.1 After 2 minutes

For all the Cases, increased concentrations of oxygen can be seen in regions near the mask (27-29%). The oxygen mass fraction after 2 min is depicted in Fig.4. In Case 1 due to absence of ventilation, leaked oxygen is not dispersed. In Cases 2, 3 and 4 dispersion of oxygen is more due to ventilation by outlet vents. Oxygen levels inside the room are at safe levels after 2 minutes for all the Cases except the regions near the mask.

6.2.2. After 4 minutes

In Case 1, the oxygen mass fraction in the entire region of the ICU room is increased in the range of 27 to 29% due to lack of proper ventilation. In such a scenario, materials like fabrics, plastics and medical equipment having LOI more than 23% are vulnerable to catch fire. Fig.5 shows the oxygen mass fraction after 4 minutes. The Case 2 where the natural ventilation is taking place only from inlet 2, inlet 5, door 1 and door 2, the oxygen concentration is increased up to 27% at some localized spaces like near the mask and bed.

In Case 3, where all the inlet AC vents (inlet 1, inlet 2, inlet 3, inlet 4, inlet 5 and inlet 6) and all outlet vents (outlet 1, outlet 2, outlet 3 and outlet 4) are open with ACH value of 6. This results in better dispersion of oxygen from the ICU room compared to the Case 2. The oxygen concentration in regions near the mask is 27% or more, but in the rest of the regions of the ICU room concentration is 25% or less. The best dispersion of oxygen takes place in Case 4, which is similar to Case 3 except the ACH value is 12. The oxygen mass fraction in the entire room is 24% or less, except the regions that are very close to the mask. After 4 minutes, Case 1 and Case 2 are prone to fire risk.

6.2.3 After 6 minutes

After 6 minutes, oxygen rich environment is created in entire region of the ICU room for Case1 where the oxygen mass fractions are 29% or more. The oxygen mass fraction for all four cases after 6 minutes is depicted in Fig. 6. In this oxygen rich environment, any source of ignition can lead to fire hazard. In Case 2 the dispersion of the oxygen enhances in the corridor due to inflow of fresh air from inlet 2 and inlet 5 and probable pressure build up inside the ICU room compare to conditions for the same case after 4 minutes. In rest of the regions the oxygen concentration is almost similar as seen after 4 minutes. For Case 3, after 6 minutes, the oxygen mass fraction in most regions of ICU room is slightly higher than the mass fraction after 4 minutes. After 6 minutes the conditions inside the ICU room are almost similar to conditions after 4 minutes for Case 4. After 6 minutes Case 1, Case 2, Case 3 are prone to fire risk.

6.2.4 After 8 minutes

Oxygen mass fraction is continuously rising with time for Case 1. The oxygen mass fraction after 8 minutes is represented in Fig.7. After 8 minutes oxygen mass fraction is more than 31% in the entire ICU room. In this oxygen rich environment, apart from fabrics, many plastics like PEEK, PSU and PVC sustain combustion. For Case 2, Case 3 and Case 4 apart from flow pattern there is no noticeable change in the mass fraction of the oxygen from the mass fraction after 6 minutes. After 8 minutes Case 1, Case 2 and Case 3 are prone to fire risk.

6.2.5. After 10 minutes

For Case 1 oxygen mass fraction is keep on rising and reaches up to 32% or more. The oxygen mass fraction after 10 minutes is represented in Fig.8. This scenario is highly dangerous from the fire safety point of view. In Case 2 the oxygen mass fraction is higher at bottom right corner near door 1, while for rest of regions it is similar to as observed after 8 minutes. For Case 3 and Case 4 apart from flow pattern there is no noticeable change in the mass fraction of the oxygen from the mass fraction after 8 minutes. After 10 minutes Case 1, Case 2 and Case 3 are prone to fire risk.

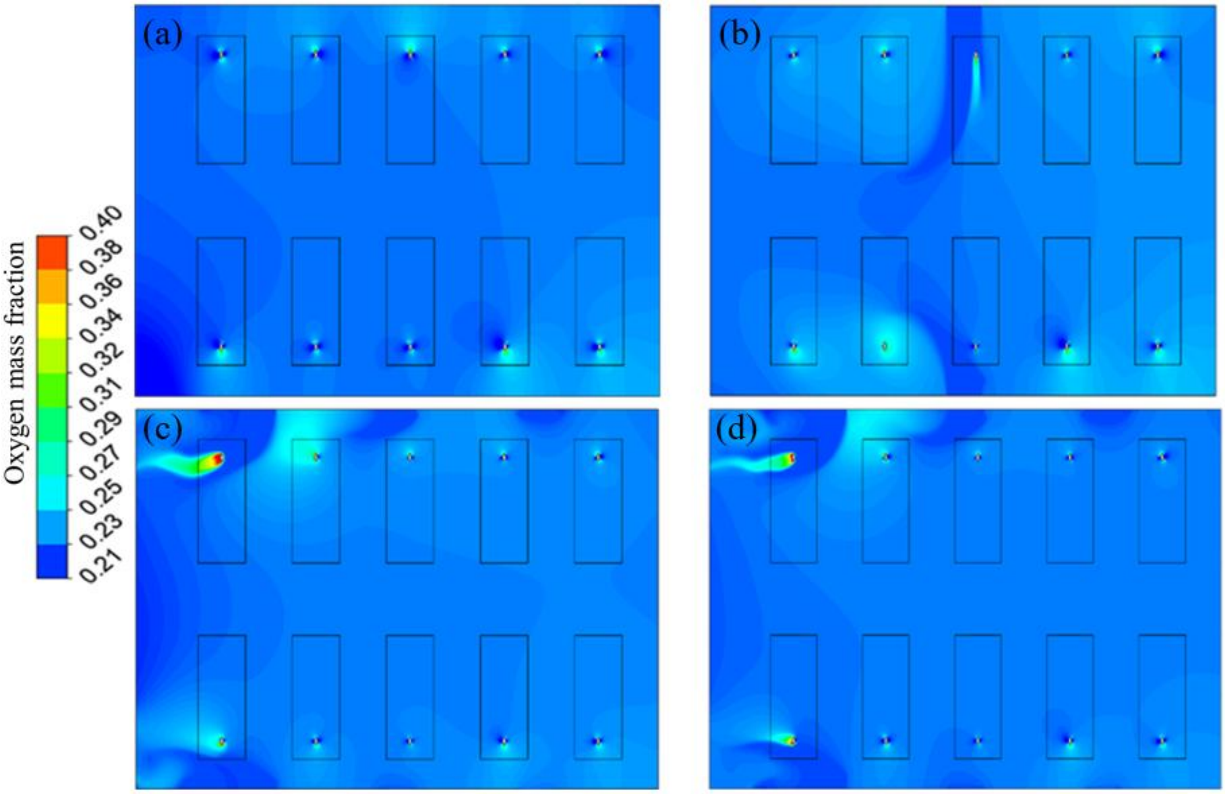


Fig 4. Oxygen mass fraction after 2 minutes: (a) Case 1, (b) Case 2, (c) Case 3, (d) Case 4.

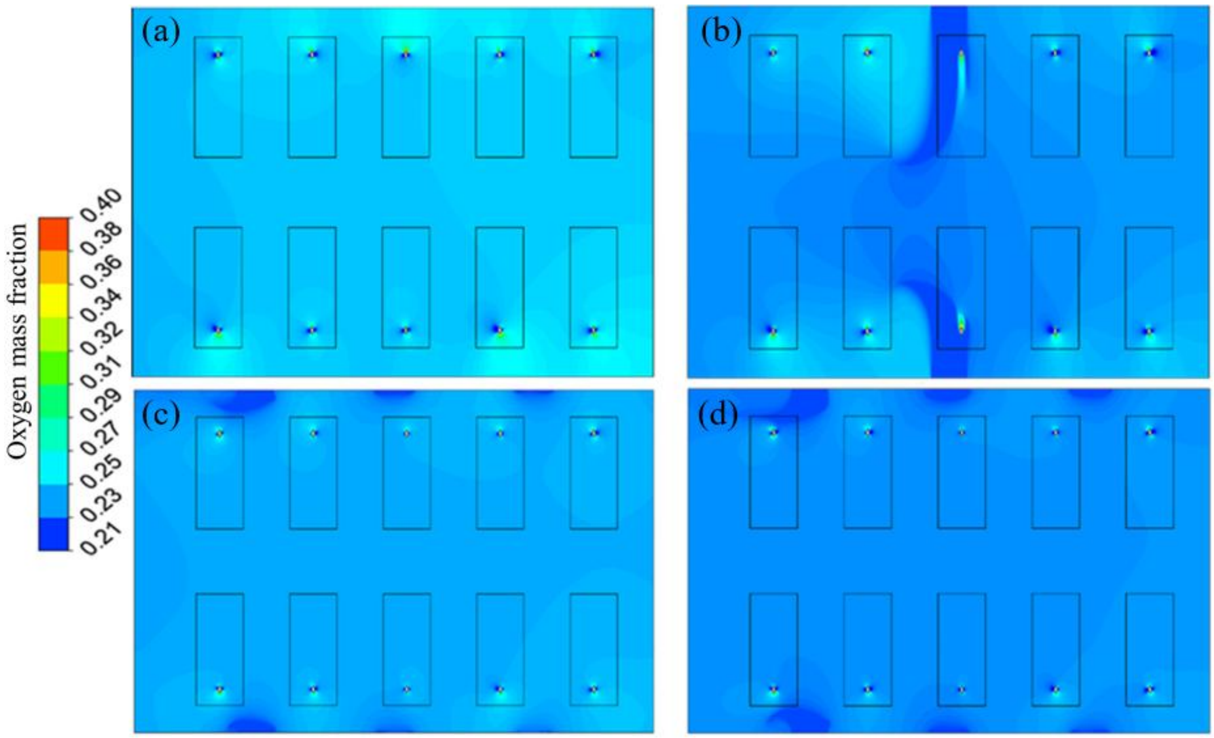


Fig 5. Oxygen mass fraction after 4 minutes: (a) Case 1, (b) Case 2, (c) Case 3, (d) Case 4.

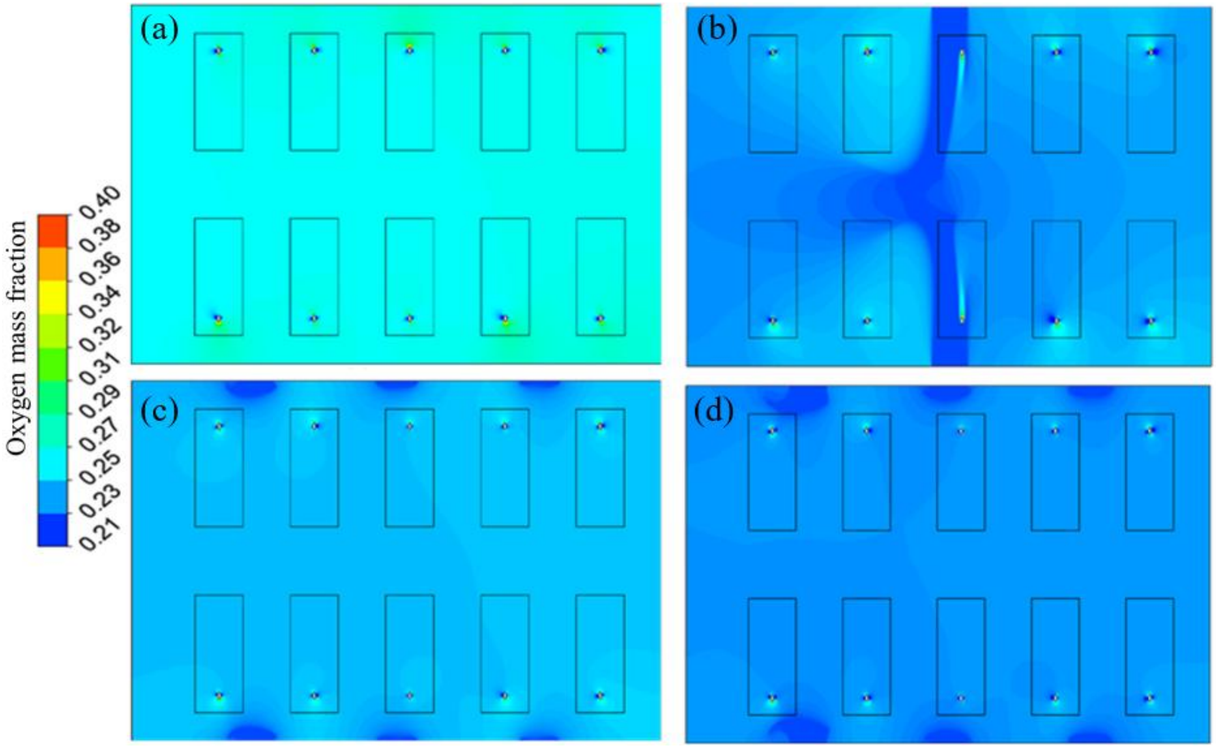


Fig 6. Oxygen mass fraction after 6 minutes*:* (a) Case 1, (b) Case 2, (c) Case 3, (d) Case 4.

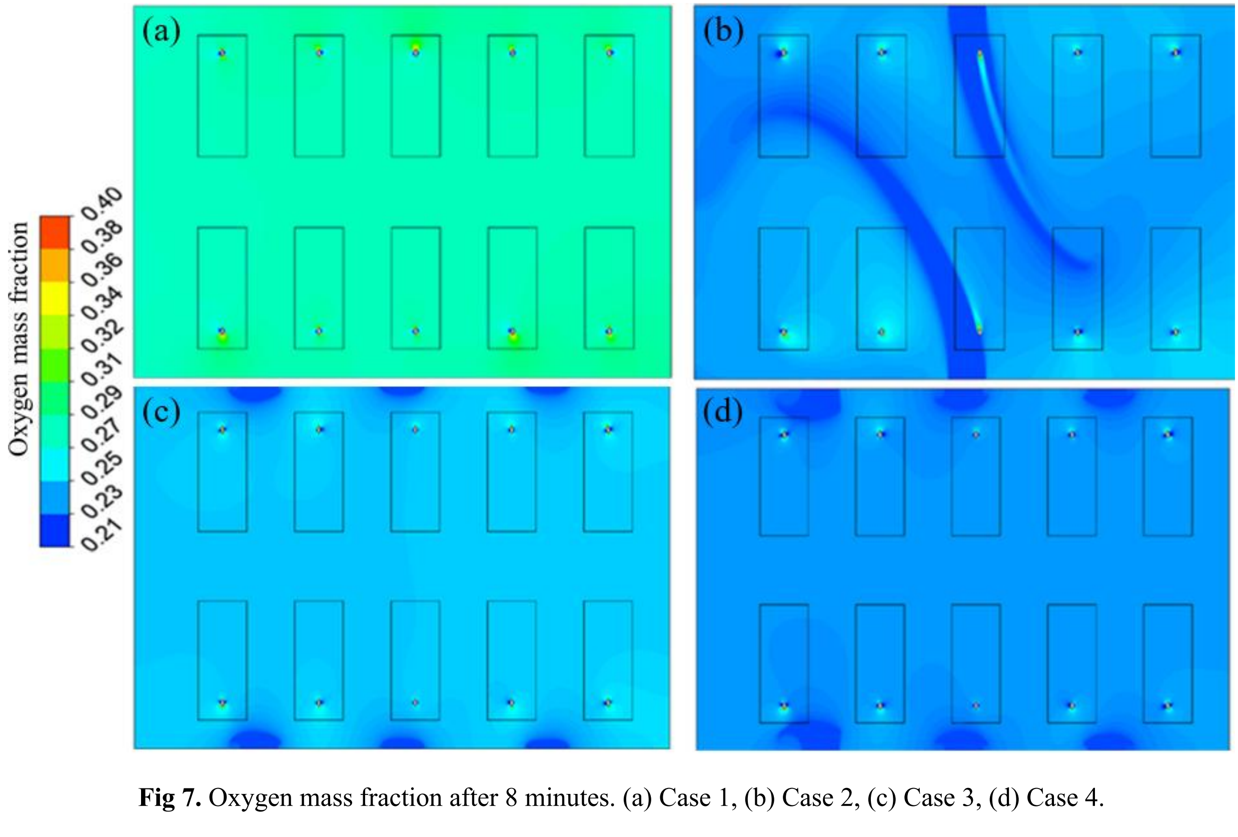


Fig 7. Oxygen mass fraction after 8 minutes. (a) Case 1, (b) Case 2, (c) Case 3, (d) Case 4.

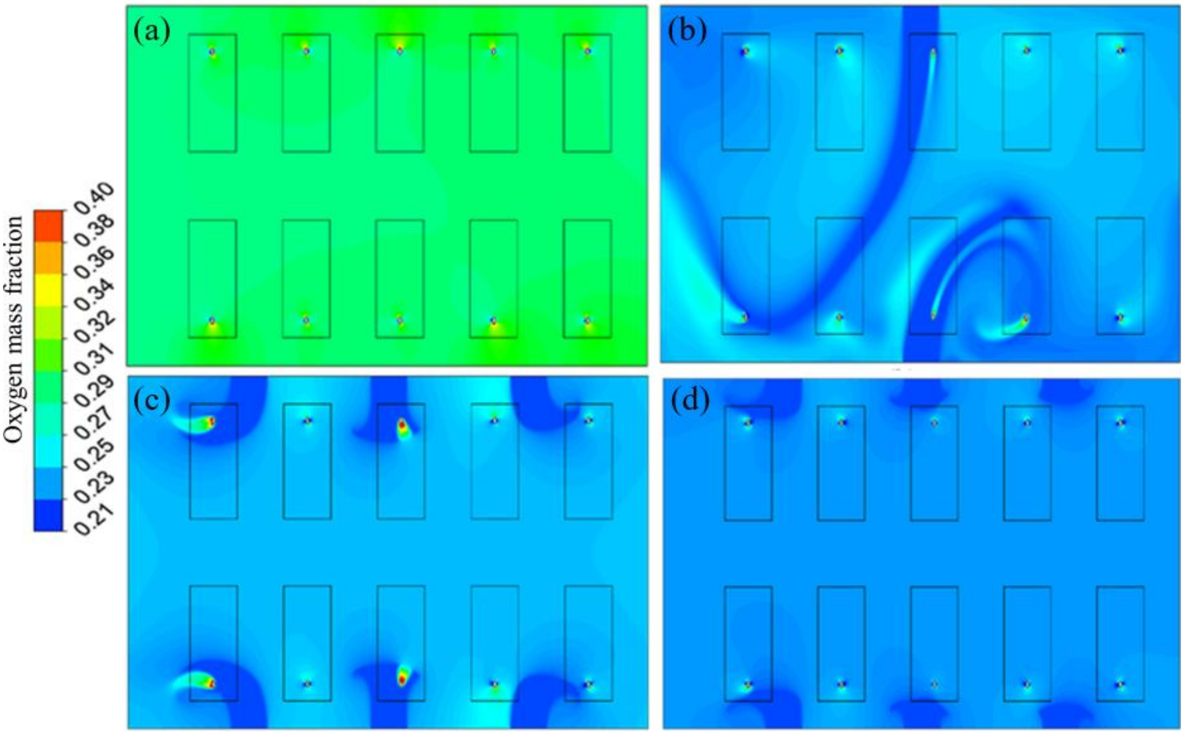


Fig 8. Oxygen mass fraction after 10 minutes. (a) Case 1, (b) Case 2, (c) Case 3, (d) Case 4.

7. Conclusions

a. The oxygen mass fraction increases and reaches to more than 35% in the most of the parts of the ICU room with time due to no ventilation condition for the Case 1. In relation to fire safety, it becomes important to always have a backup of power.
b. Case 2 turns prone to fire risk before 2 minutes because of poor ventilation design.
c. The ventilation design in Case 3 is better than the Case 2 because air is coming inside the ICU room from 6 inlet vents and exiting from 4 outlet vents, still the ICU room turns prone to fire risk before 2 minutes because the value of air change rate is 6, which is less.
d. The ventilation design for Case 4 is similar to Case 3. However, the ICU room is much lesser prone to fire risk even after 10 minutes because the value of air change rate is 12.

8. Future work prospects

Future research in this field will focus on a number of important areas to improve our knowledge of fire hazards in intensive care units. In order to gather vital information, a thorough survey of ICU rooms from different hospitals will be carried out. This survey will gather details about the ventilation system, the number and kind of beds, the kind and material of furniture, the dimensions of the room, and the oxygen flow rates to patients. The design of an experimental prototype intensive care unit room will be influenced by this data. Oxygen flow rates will be kept constant in this controlled environment to replicate real ICU circumstances, and gas analyzers will be used to measure the temperature and concentration of oxygen at different points. To evaluate any fire threats, these measurements will be compared to the Limiting Oxygen Index (LOI) of the various materials in the room. ANSYS software will be used to carry out 3D numerical simulations in order to confirm and expand upon these experimental results. The initial goal of the proposed work will be achieved by using these models, if confirmed, to optimize ventilation settings within the ICU room. This multifaceted method will offer important insights for enhancing fire safety in oxygen-enriched intensive care unit environments by integrating real-world data collection, experimental testing, and sophisticated numerical modeling. In order to gain a more thorough understanding of airflow behavior, future research will concentrate on performing 3D simulations to capture the whole flow dynamics, validating findings through experimental measurements, and comparing 2D and 3D results.

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