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Assessing the Impact of Air Conditioning Systems on Aerosol Dispersion within Intensive Care Units

Evaluarea impactului sistemelor de aer condiționat asupra dispersiei aerosolilor în cadrul Unităților de Terapie Intensivă

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Abstract. *This comprehensive study investigates the influence of air conditioning (AC) systems on aerosol dispersion within Intensive Care Units (ICUs), emphasizing the critical context of patient cough events. This research uses advanced Computational Fluid Dynamics (CFD) simulations to analyze airflow patterns, aerosol behavior, and potential exposure risks within ICU settings, offering valuable insights for healthcare facility design and infection control protocols.*

Keywords: Aerosol Dispersion, ICU Airflow Patterns, CFD Simulation.

1. Introduction

The propagation of aerosols within healthcare settings, especially Intensive Care Units (ICUs), is a critical concern for infection control and patient safety. In these environments, the minute particles suspended in the air can travel considerable distances, carrying potentially infectious agents. The management of aerosol dispersion is thus integral to reducing the risk of nosocomial infections [1].

Aerosols in ICUs originate from various sources, including medical procedures, equipment, and, significantly, the respiratory activities of patients, such as coughing or

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sneezing. When a patient coughs, a complex mixture of particles of varying sizes is expelled, creating a potential pathway for transmitting pathogens like viruses and bacteria. The behavior and fate of these particles in the ICU atmosphere depend on several interrelated factors influenced by the air conditioning (AC) systems:

Air Velocity and Flow Patterns: AC systems dictate air movement within a room, influencing how aerosols travel and settle. High air velocity can carry particles over longer distances. Still, strategic airflow design can enhance the removal of these particles by directing them toward filtration systems or out of the room [1].

Temperature: The temperature affects air buoyancy, creating convection currents that can influence aerosol movement. Warmer air rises, potentially carrying aerosols upward, while cooler air descends. By controlling room temperature, AC systems can impact these currents and thus the vertical distribution of aerosols.

Humidity: Humidity levels can alter aerosol dynamics by affecting particle evaporation and size. Higher humidity can slow the evaporation of the moisture in aerosols, maintaining their size or causing them to grow by coalescence, which might impact their deposition rate and transport distance. AC systems that control humidity can thus influence these dynamics [2].

Room Geometry and Air Distribution: The physical layout of an ICU, including the placement of beds, equipment, and the location of air supply and exhaust points, interacts with the AC system to create unique airflow patterns. These patterns can either contribute to the effective dispersion and removal of aerosols or lead to areas of stagnant air where particles accumulate.

Given these complexities, the role of AC systems in modulating aerosol dispersion is pivotal. Effective AC system design and operation in ICUs should aim to achieve optimal air exchange rates, remove contaminants efficiently, and maintain comfortable and safe environmental conditions for patients and healthcare workers. This necessitates a multidisciplinary approach, incorporating insights from engineering, infection control, and healthcare operations to design AC systems that can respond to the dynamic conditions of ICU environments and minimize airborne transmission risks.

2. Material and method

Room Configuration and Simulation Setup.

To accurately assess the impact of air conditioning systems on aerosol dispersion, a detailed and realistic representation of the ICU room is essential. The room configuration setup in the simulation model would include:

Dimensions: The exact length, width, and height of the ICU room need to be specified. These dimensions are crucial as they influence air movement and particle distribution patterns within the space (Fig. 1) [5].

Bed Placement: The location of patient beds affects the source points of aerosol generation and determines the critical areas where air quality needs to be meticulously controlled. The placement should reflect typical ICU layouts to ensure the simulation's

relevance to real-world settings.
Air Inlets and Outlets: The positions of vents, air returns, and any other openings that facilitate air exchange are mapped out in detail. The effectiveness of aerosol removal is significantly influenced by how air circulates, which is dictated by the location of these inlets and outlets (Fig.1).

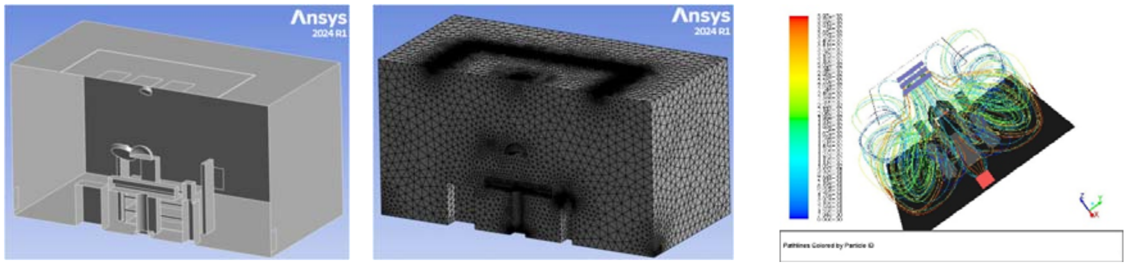
Specifications of the AC System: Critical parameters include:

Air Change Rates: This is the rate at which the air within the ICU is replaced with fresh or filtered air, typically measured in changes per hour (ACH). Higher ACH values are associated with more effective dilution of airborne contaminants.
Filtration Efficiency: The quality of air filters within the AC system, often quantified by the Minimum Efficiency Reporting Value (MERV) or High-Efficiency Particulate Air (HEPA) standards, which indicate their ability to trap particles of specific sizes.
Airflow Patterns: The direction and speed of air being circulated by the AC system, which should ideally promote the dispersal of clean air and the evacuation of potentially contaminated air.

CFD Simulation Approach

The CFD simulation translates the physical scenario into a computational model, allowing for the analysis of airflow and aerosol dynamics under various conditions:
Boundary Conditions: These are the set conditions at the simulation's edges, such as walls, windows, and doors, which could affect airflow. For instance, walls are typically treated as no-slip boundaries, meaning the air velocity at the wall is zero, reflecting the physical reality (Fig. 1) [3].
Mesh Generation: This step involves dividing the room into discrete, small volumes or cells, which the simulation uses to solve the governing equations of fluid flow. A finer mesh can provide more detailed results but requires more computational power. Key areas, like around the patient's bed or near air inlets and outlets, might be assigned finer meshes for enhanced accuracy (Fig. 1) [3].
Solver Settings: These settings determine how the simulation calculates the flow field and particle trajectories. They include time step size, convergence criteria, and the choice of turbulence and particle dispersion models.
Aerosol Generation Modeling: This component simulates the generation of aerosols due to a patient coughing. It includes:
Droplet Sizes: Aerosols are modeled in a range of sizes to reflect the diversity generated by coughing. Smaller aerosols (<5 microns) can remain airborne for extended periods, while larger droplets settle more rapidly [4].
Emission Rates: The rate at which particles are introduced into the air, which can be based on empirical data from studies of cough aerosols [3].

By carefully setting up the room configuration and the CFD simulation parameters, researchers can create a sophisticated model that provides valuable insights into how AC systems influence aerosol dispersion in ICUs, informing strategies to minimize infection risks.



a) b) c)

Fig. 1. a) Geometry; b), c) Mesh and air lines dispersion

3. Results

3.1 Airflow Patterns

Visualization and Analysis: Utilizing CFD simulation outputs, airflow within the ICU can be visualized through vector fields or streamlines, which illustrate the direction and speed of air movement. This visualization helps identify how air travels around the room, interacts with obstacles like furniture or medical equipment, and impacts aerosol transport (Fig. 2) [3].

Zones of High and Low Air Exchange: Through the analysis, specific areas within the ICU can be pinpointed where air exchange is either particularly efficient or insufficient. High air exchange zones are typically near air inlets or in the direct path of strong airflow, whereas low exchange zones are often in corners or behind obstructions where air movement is minimal [3].

Impact of AC Settings: The configuration of the AC system—including fan speeds, vent locations, and directional controls—plays a significant role in shaping these airflow patterns. By adjusting these settings, the distribution of air can be altered to reduce the occurrence of stagnant air pockets or recirculation zones that might harbor higher concentrations of aerosols.

3.2 Aerosol Dispersion and Concentration

Trajectories and Dispersion Patterns: The CFD simulations can track aerosol particles of various sizes as they are emitted in a coughing event, showing how they disperse throughout the room. These trajectories reveal the influence of airflow patterns on particle movement and highlight potential paths of exposure. [Fig. 2]

Concentration Distributions: Over time, the simulations can aggregate aerosol concentrations across the room, illustrating how particles accumulate or diminish in different areas. These concentration maps can pinpoint high-risk zones where aerosols linger, posing greater risks to patients and healthcare workers.

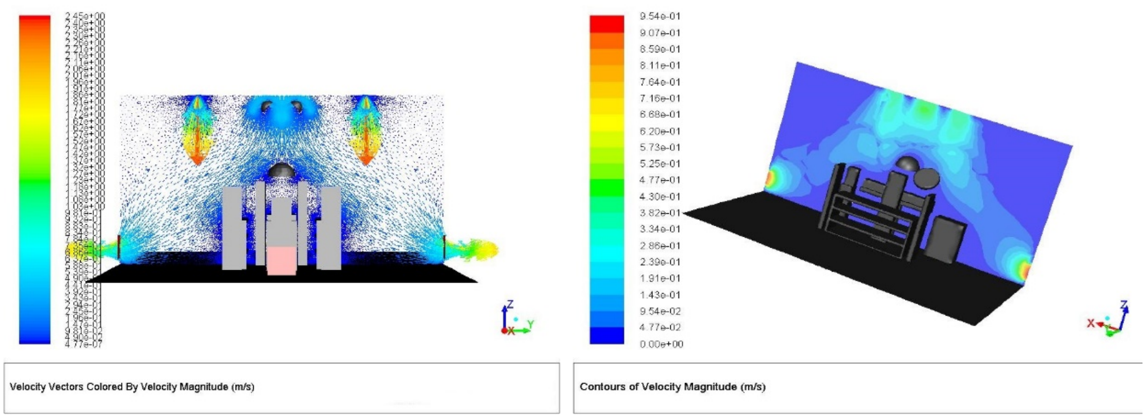
3.3 Impact of AC System Variations

Comparative Analysis: By simulating various AC configurations, the study can evaluate how changes in system design or settings influence aerosol dispersion. For example, increasing the air change rate may show a significant reduction in aerosol concentrations, or altering vent positions might disperse concentrations more evenly [3].

Mitigating Aerosol Accumulation: The effectiveness of each AC configuration in reducing aerosol accumulation provides critical insights. For instance, configurations that enhance vertical airflow may prove effective in removing aerosols from the breathing zone, while others might better prevent aerosol spread between adjacent beds.

Optimization Recommendations: Based on the comparative analysis, specific recommendations can be formulated for AC system settings that optimize particle dilution and removal. These may include guidelines on ideal air change rates, filter specifications, and airflow patterns that should be targeted in ICU design and operation to enhance air quality and minimize infection transmission risks.

By comprehensively analyzing these factors, healthcare facilities can develop informed strategies to leverage AC systems as proactive tools in infection control, ultimately enhancing patient and staff safety within ICUs.



a) b)

Fig. 2. a), b) Contours of Velocity

4 Discussion

Interpretation of CFD results in the context of infection control, emphasizing the importance of strategic AC system design and operation.

Consideration of practical implications for ICU management, including potential adjustments to AC settings during outbreaks.

Limitations of the study, such as assumptions in aerosol generation and behavior, and suggestions for future research.

5 Conclusion

This study underscores the critical role of AC systems in influencing aerosol dispersion within ICUs, highlighting the necessity for evidence-based HVAC design and operation approaches to enhance patient and staff safety. The research provides actionable insights into optimizing air circulation and aerosol mitigation strategies in critical care settings through detailed CFD analysis.

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