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PERFORMANCE ANALYSIS OF AIR-CONDITIONING SYSTEMS IN COMMERCIAL BUILDINGS USING CFD SIMULATION

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ABSTRACT

This study investigates the performance of air conditioning systems within a standardized room using Computational Fluid Dynamics (CFD) simulations conducted in ANSYS Fluent. The analysis focuses on three distinct duct placement configurations: a single duct positioned at 4 meters above the floor, two ducts placed on opposite walls, and two ducts placed side-by-side on the ceiling. The primary objective was to evaluate the impact of duct positioning on room temperature distribution and cooling efficiency. Results indicate that the configuration with two ducts positioned on opposite walls achieved the most uniform air distribution and the lowest average room temperature of 20°C, outperforming the other setups. The study highlights the role of strategic duct placement in optimizing thermal comfort and energy efficiency. By leveraging CFD tools, this research provides actionable insights into enhancing HVAC design for residential and commercial spaces.

Keywords: Air Conditioning Systems, Duct Placement Optimization, Computational Fluid Dynamics (CFD), ANSYS Fluent, Thermal Comfort.

I. Introduction

Air conditioning (AC) systems are fundamental in creating comfortable indoor environments, especially with the growing global demand for cooling driven by urbanization, climate change, and technological advancement. These systems control temperature, humidity, and air quality, ensuring optimal conditions for residential, commercial, and industrial settings. The performance of AC systems is influenced by several factors, such as room size, heat load, airflow distribution, insulation, thermostat settings, and regular maintenance. Larger spaces or those with higher heat loads, such as those with more occupants, electronic devices, or significant sunlight exposure, require more cooling capacity. Efficient airflow and well-designed ductwork ensure uniform distribution of conditioned air, avoiding hot or cold spots that can compromise comfort and energy use. Proper insulation also plays a significant role by limiting heat gain or loss, reducing the workload on the AC system as shown in Figure 1.1,

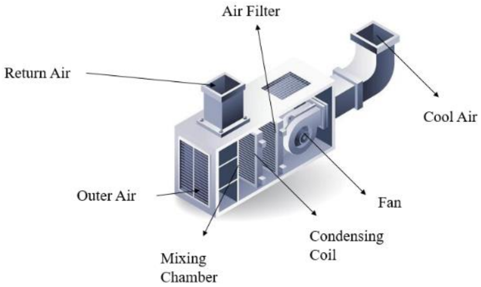


Figure 1.1: Air conditioner

The internal heat gain from occupants, lighting, and equipment, as well as external heat gain through windows, walls, and roofs, are key factors in calculating heat load. Heat load calculation is vital for correctly sizing an AC system, ensuring it is neither oversized nor undersized, both of which can lead to inefficiency and discomfort. Additionally, regular maintenance such as cleaning filters, checking refrigerant levels, and ensuring proper compressor function is essential for maintaining optimal system performance. Neglecting maintenance can reduce cooling efficiency, increase energy consumption, and shorten the lifespan of the system.

AC systems are categorized based on purpose, seasonal use, equipment arrangement, and the type of refrigerants used. Comfort air conditioning systems, commonly found in homes, offices, and schools, focus on providing thermal comfort by regulating temperature, humidity, and air quality. Industrial AC systems, on the other hand, are designed to meet the specific environmental requirements of industrial processes, such as maintaining the proper temperature and humidity for data centres, textile manufacturing, or pharmaceutical production. Seasonal use also influences AC system design; summer systems are focused on cooling spaces, while winter systems are designed for heating. Central air systems, which are typically used in large buildings, condition air centrally and distribute it through ducts to multiple spaces. In contrast, unitary systems, like window units or portable AC units, are compact and typically used for individual rooms or smaller areas.

Energy efficiency is a critical consideration for modern air conditioning systems due to the increasing environmental concerns surrounding energy consumption and rising operational costs. The efficiency of an AC system is often measured by the Coefficient of Performance (COP) and Energy Efficiency Ratio (EER). These metrics measure how much cooling is provided per unit of energy consumed, with a higher COP or EER indicating better efficiency. Proper system design, insulation, and the choice of refrigerant all impact energy use. Oversized or undersized units consume more energy than necessary, and poor insulation forces the AC system to work harder to maintain indoor comfort. Smart thermostats and programmable controls improve efficiency by adjusting cooling based on occupancy, external weather, or time of day, while variable speed drives and inverter-driven compressors further optimize energy consumption by adjusting compressor speeds based on cooling demand.

The type of refrigerant used in an air conditioning system also significantly affects energy efficiency. Modern refrigerants like R32 and R410A are more energy-efficient and have a lower environmental impact compared to older refrigerants such as R22. Regular system maintenance is also key to maintaining efficiency; dirty filters or low refrigerant levels can reduce the system's cooling capacity and increase energy usage. Technological innovations, such as variable-speed compressors and heat recovery systems, have also contributed to greater energy efficiency by allowing systems to better adjust to real-time cooling needs and recover waste heat for use in other processes.

Despite these advancements, air conditioning systems still have a significant environmental impact, primarily due to their high energy consumption and the refrigerants used. In many countries, especially during hot weather, air conditioning systems are responsible for a large proportion of electricity consumption, leading to higher greenhouse gas emissions and contributing to global warming. The use of refrigerants with high Global Warming Potential (GWP) also adds to the environmental burden. In response, international agreements like the Montreal Protocol have phased out ozone-depleting substances like CFCs and HCFCs, but many of the alternative refrigerants, such as HFCs, still have high GWP. As a result, there is growing interest in developing natural refrigerants with low or zero GWP, such as ammonia, carbon dioxide, and hydrocarbons, which do not contribute to ozone depletion or global warming. Additionally, solar-assisted air conditioning systems are becoming a popular solution, integrating solar power to reduce the reliance on grid electricity and further mitigate environmental impact.

As energy efficiency and environmental sustainability become more important, retrofitting and upgrading existing air conditioning systems has become a practical solution for improving performance without replacing the entire system. Energy audits can identify areas where existing systems can be made more efficient, such as upgrading components, sealing ducts, or incorporating renewable energy sources like solar panels. Retrofitting can also extend the lifespan of older systems, making it a cost-effective and sustainable choice for building owners.

2. LITERATURE SURVEY

Pico, P et.al. [1]: The study revealed that improper airflow management and layout design in data centres, such as inadequate separation between hot and cold aisles and poor air distribution, contribute significantly to increased energy consumption and uneven temperature profiles. These inefficiencies also pose risks to hardware safety due to localized overheating. CFD simulations proved to be a valuable tool in detecting these design flaws by providing insights into airflow patterns, temperature distribution, and humidity levels

Kanaan, M. et.al. [2]: The study highlighted that UFAD systems not only improve energy efficiency but also contribute to enhanced occupant comfort by delivering air directly into the occupied zone, where thermal comfort is most critical. The stratification of air in UFAD systems, when properly controlled, reduces energy waste by minimizing unnecessary cooling of unoccupied upper layers in a room. However, the complex interaction between thermal plumes and air jets can lead to unpredictable airflow if not carefully managed, potentially compromising indoor air quality.

Xie, R. et.al [3]: The study showed that ETS is a significant indoor pollutant, with high levels of PM2.5, VOCs, and harmful gases found in environments like prisons, cars, and homes, where ventilation often fails to control exposure. Public spaces are widely studied, but homes also pose serious ETS exposure risks, especially in countries with high smoking rates. Previous research has demonstrated that air conditioners are effective in reducing PM2.5 levels but less effective for VOCs and gaseous pollutants like CO and formaldehyde. The study also noted the potential for nicotine accumulation in the condensate of air conditioners, a concern that has been largely overlooked.

Sun, H. et.al [4]: Researched on particle deposition in HVAC ventilation ducts highlighted the influence of particle size, airflow velocity, and duct design on particle accumulation. Larger particles, generally above 10 μm, tend to settle more readily within ducts due to gravitational effects, particularly on the outer walls of bends and other directional changes, Although higher airflow velocities can impact particle transport, their effect on deposition rates is less pronounced than particle size, with turbulence at duct bends and junctions playing a more significant role

Riaz, M. et.al. [5]: The study results demonstrated that the enhanced air distribution system (S-II) significantly improved thermal comfort inside the tractor cabin. With S-II, the cabin temperature averaged 27.4°C, compared to 30.4°C in the conventional setup (S-I), creating a more comfortable environment for operators. Relative humidity remained consistent in both systems at around 53%, but the temperature difference between the cabin and the outdoor environment was notably higher in S-II, at 11.09°C. This temperature difference met the thermal comfort standards outlined in ISO 14269–2.

Saran, S. et.at. [6]: The review further highlights that some guidelines prioritize specific environmental factors over others based on regional health policies and available resources, leading to uneven implementation across facilities. Additionally, the lack of uniformity in maintenance schedules and equipment standards contributes to varying levels of system efficacy in controlling airborne pathogens.

This fragmentation not only affects infection control but also complicates staff training and compliance, as personnel must adapt to different HVAC protocols depending on the ICU setting

Qiao, H et.al [7]: The results indicate that both vane angle and airflow mode have a significant effect on the pull-down time required to cool a room to the desired temperature. Adjusting these factors can lead to variations in cooling efficiency, with certain configurations promoting faster temperature drops. Furthermore, the study highlights the limitations of the well-mixed assumption in building energy simulations; CFD modeling, which accounts for non-uniform airflow and temperature variations, demonstrated more accurate predictions compared to traditional BES models.

Asim, N. et.al [8]: The study emphasizes the growing importance of designing HVAC systems that are both sustainable and energy-efficient, highlighting the critical impact of the design phase in new constructions and the need for strategic retrofitting in existing buildings. Retrofitting is crucial, as it provides an opportunity to upgrade the large number of outdated systems still in use, allowing for improved energy efficiency, reduced environmental impact, and better health outcomes.

Alif, M. N. et al. [9]: The research highlighted the importance of proper duct design and material choice in mitigating energy losses associated with long duct runs. Common design methods, such as equal friction, velocity reduction, and static regain, play a pivotal role in achieving energy efficiency, with the static regain method often demonstrating superior performance due to its ability to recover pressure and maintain high velocity at outlets. The integration of Computational Fluid Dynamics (CFD) has emerged as a powerful tool for optimizing duct designs, revealing areas of pressure drop and airflow inefficiencies that traditional manual calculations may overlook

Rahman, M. et al. [10]: The research underscored the necessity of designing HVAC systems for large venues with a comprehensive understanding of multiple influencing factors, including air temperature, velocity, and relative humidity. These parameters significantly affect human comfort, and adhering to guidelines set by the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) is crucial for maintaining acceptable ranges that ensure comfort throughout different seasons. The study highlights the increasing use of computational tools like ANSYS-Fluent in HVAC performance analysis, enabling detailed simulations of airflow, temperature distribution, and humidity levels in enclosed environments

Ryan Kennett, et.al [11]: The findings highlight that the extended-duct air delivery system substantially enhances air distribution in high-bay buildings, achieving uniform airflow that effectively reduces temperature stratification across vertical zones. By strategically placing ducts, the system maintains consistent temperatures from floor to ceiling, addressing common comfort challenges in large, open spaces. Optimized airflow patterns not only support temperature control but also reduce the need for continuous, high-intensity HVAC operation, leading to potential energy savings of 10-20%. The controlled air velocity minimizes drafts, preventing discomfort and creating a stable indoor environment suitable for occupants and equipment.

Pushpak Doiphode, et.al [12]: The study revealed that wind speed and direction significantly affect the performance of split air conditioning systems. Higher wind speeds, especially when perpendicular to the outdoor unit, reduce the heat exchange efficiency by disrupting airflow, which leads to less effective cooling. When wind flows directly against the airflow of the outdoor unit's fan, the cooling capacity is compromised due to heat accumulation around the condenser. Additionally, unfavourable wind conditions caused the system to consume more energy, as it worked harder to maintain the desired indoor temperature.

Jing Xu, et.al [13]: The study revealed that each air-conditioning system offers distinct advantages and limitations in terms of thermal comfort. Centralized HVAC systems provide stable temperature control across large spaces but can lead to drafts and slightly uneven airflow in certain zones. Split air conditioning systems offer personalized comfort for individual rooms but struggle with humidity control and may cause temperature fluctuations when cycling on and off. VRF systems demonstrated the best performance in maintaining consistent temperature and humidity levels, allowing precise control of individual zones with minimal noise and air disturbance, making it ideal for thermal comfort in mixed-use or zoned areas

Pushpak Doiphode et.al [14]: The study found that high-speed winds greatly influence the thermo-flow performance of split air conditioning systems, particularly by disrupting the airflow around the outdoor unit. Winds blowing perpendicular to the outdoor unit caused a reduction in cooling capacity, as the airflow was diverted and heat dissipation was hindered. In adverse wind conditions, the compressor's operational load increased, resulting in higher energy consumption and decreased efficiency.

Hariharan. C et.al [15]: The CFD analysis revealed that optimized airflow pathways and vent placements in the HVAC system significantly enhanced energy efficiency and thermal comfort. Properly directing airflow to the rear of the cabin helped to achieve uniform temperature distribution, reducing the load on the HVAC system and leading to improved fuel efficiency. The study found that the redesigned HVAC system could achieve energy savings of up to 15% compared to standard configurations by minimizing temperature gradients and reducing the required cooling or heating load. Improved air circulation also reduced the time needed to reach the desired cabin temperature, which enhanced passenger comfort and contributed to overall energy savings.

Yin Hua1 et.al [16]: The CFD simulations revealed uneven airflow patterns in the metro station, leading to stagnant air in some areas and excessive drafts in others, with significant temperature variations in high passenger density zones. Temperature gradients indicated that some locations exceeded comfort levels while others were too cool, suggesting a need for targeted adjustments. The analysis showed that the current air-conditioning system operated inefficiently, with energy consumption much higher than necessary, particularly during peak passenger volumes. Testing different configurations, such as variable air volume systems, demonstrated potential for energy savings while maintaining comfort.

Ashish Mogra et.al [17]: The CFD analyses revealed several critical insights regarding airflow and temperature distribution in the classroom. It identified significant imbalances in airflow, with certain areas experiencing stagnant air while others had excessive drafts. Temperature variations were notable, with specific zones being overcooled and others remaining uncomfortably warm. Through simulations, optimized air-conditioning placements resulted in a more uniform temperature distribution across the classroom. Additionally, energy consumption was reduced when implementing the recommended placement strategies, demonstrating the potential for increased efficiency alongside enhanced comfort levels for students.

Mohammed Juma et.al [18]: The simulation analysis revealed significant insights regarding the airflow dynamics and thermal conditions within the commercial kitchen. Various air-conditioning placements led to noticeable differences in airflow patterns, with some configurations resulting in stagnant air zones and others causing uncomfortable drafts. The study found that certain placements improved temperature uniformity, significantly reducing hotspots near cooking equipment. Moreover, the optimized air-conditioning configurations contributed to better air circulation, enhancing overall ventilation. Energy consumption was also evaluated, revealing that strategically positioned units could decrease operational costs while maintaining an effective cooling environment for kitchen staff.

NurAlif et.al [19]: The CFD analysis revealed critical insights regarding airflow dynamics and temperature distribution throughout the shopping mall. Various duct configurations demonstrated differing levels of efficiency, with some designs causing airflow stagnation in certain areas while others facilitated better circulation. The study highlighted significant temperature variations, with some zones experiencing excessive cooling and others remaining warm. By optimizing duct sizes and layouts, the analysis improved airflow uniformity and reduced thermal discomfort. Furthermore, energy consumption was assessed, indicating that well-designed duct systems could lower operationally costs by enhancing cooling efficiency.

M Rahman et.al [20]: The CFD analysis provided valuable insights into the airflow dynamics and thermal conditions within the amphitheatre. It revealed that certain areas experienced inadequate air circulation, leading to hot spots and discomfort for both the audience and performers. The analysis highlighted the importance of strategically placed air supply and return vents to improve airflow uniformity. Temperature variations were significantly reduced when optimal configurations were implemented, promoting a more comfortable environment.

K. Ratna Kumari et.al [21]: The analysis revealed significant insights regarding airflow dynamics and thermal comfort throughout the office building. Various design configurations were tested, highlighting areas of inefficient airflow and temperature imbalances. The findings indicated that certain layouts resulted in hot spots near equipment and inadequate cooling in perimeter areas. By optimizing duct sizes and locations, airflow uniformity improved, reducing discomfort among occupants. Additionally, the proposed design showed a potential decrease in energy consumption of approximately 15-20%, emphasizing the importance of thoughtful planning and efficient system design.

Haofu Chen et.al [22]: The investigation revealed that both air supply speed and temperature significantly influence thermal comfort levels and energy use. Higher air supply speeds improved overall airflow distribution and reduced temperature stratification; however, they could lead to discomfort if the temperatures were not appropriately calibrated. Conversely, lower air speeds often resulted in localized hot spots and uneven cooling. The study identified an optimal range for both parameters that enhanced occupant comfort while minimizing energy consumption. This range was associated with improved air mixing and reduced reliance on additional cooling sources. The study identified an optimal range of approximately 0.5 to 1.0 m/s for air supply speed and temperatures between 20°C and 22°C, which maximized occupant comfort.

Obula Reddy Kummitha et.al [23]: The CFD simulations revealed that wind direction significantly impacts airflow patterns around the building. For winds approaching from the north, a notable increase in ventilation was observed through the building's north-facing windows, while southern winds created stagnant zones on the leeward side. Winds from the east and west resulted in complex flow patterns, with significant turbulence near corners. Overall, the analysis indicated that optimizing window placement and architectural features can enhance natural ventilation and mitigate adverse airflow conditions.

Xiaochen Liu et.al [24]: The study shows that air-conditioning systems significantly impact buoyancy-driven air infiltration in large spaces like railway stations. Specific AC configurations—such as airflow direction and intensity—can either reduce or increase infiltration, affecting energy efficiency and comfort. In winter, infiltration rates rise due to larger indoor-outdoor temperature differences, requiring tailored AC settings to maintain stable conditions. Effective AC management reduces heating and cooling demands by limiting uncontrolled infiltration, thus improving energy efficiency. Additionally, controlling infiltration benefits indoor air quality, particularly in polluted urban areas, supporting a healthier environment. Optimized AC configurations enhance both energy savings and indoor comfort year-round.

Jaafar Saleem et.al [25]: The study finds that integrating DEC with AC systems in high-temperature climates can substantially reduce energy consumption. By pre-cooling the intake air, DEC lowers the temperature before it reaches the AC unit, reducing the cooling load on the compressor and enhancing system efficiency. The findings show energy savings of up to 20-30% under optimal conditions, with the effectiveness varying based on humidity levels-higher humidity reduces the cooling potential of DEC. Additionally, the system provides more stable indoor temperatures, enhancing comfort and potentially extending the lifespan of AC units due to reduced operational strain.

3.METHODOLOGY

We present and analyse the results obtained from the Computational Fluid Dynamics (CFD) simulations conducted using ANSYS Fluent 2022 R2, which were aimed at optimizing the performance of air conditioning systems within the context of an internal combustion engine environment. The primary objective of these simulations is to provide a detailed understanding of the fluid flow and thermal behaviour within the combustion chamber and to evaluate how different design configurations influence air distribution, temperature gradients, and overall system efficiency.

Geometry Creation:

The ANSYS Design Modeler acts as an interface for handling geometry in ANSYS analyses. Specifically designed for the creation and preparation of geometries used in simulations, it provides the tools necessary for configuring models to accurately reflect the relevant physics, without extraneous details. Including unnecessary details in a simulation can increase solver run times significantly, so it’s often beneficial to streamline the model, which can reduce the total simulation time by hours or even days.

Figure 3.1 show the geometry created for an air-conditioned room model, including duct regions. The features of the Design Modeler and the outline tree display the components of the air-conditioned room with specific dimensions.

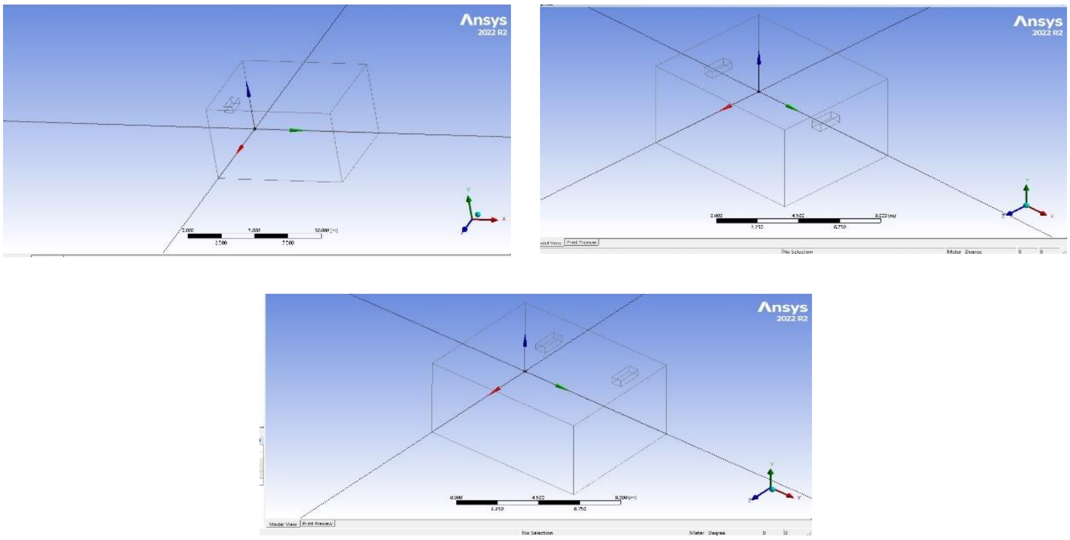


Figure 3.1: Geometry of Rooms with A. C. Duct

Mesh Generation:

Meshing, or discretization, is a critical step in Computational Fluid Dynamics (CFD) simulations, involving the division of the computational domain into smaller, manageable elements or "mesh." This step transforms complex, continuous equations governing fluid flow, such as the Navier-Stokes equations, into discrete algebraic approximations. Since analytical solutions to these equations only exist for idealized flows, numerical methods are necessary for solving real-world fluid problems.

Figure 3.2, shows the mesh created for the geometries of above figures including duct regions. The features of the mesh display the meshed components of the air-conditioned room with specific dimensions.

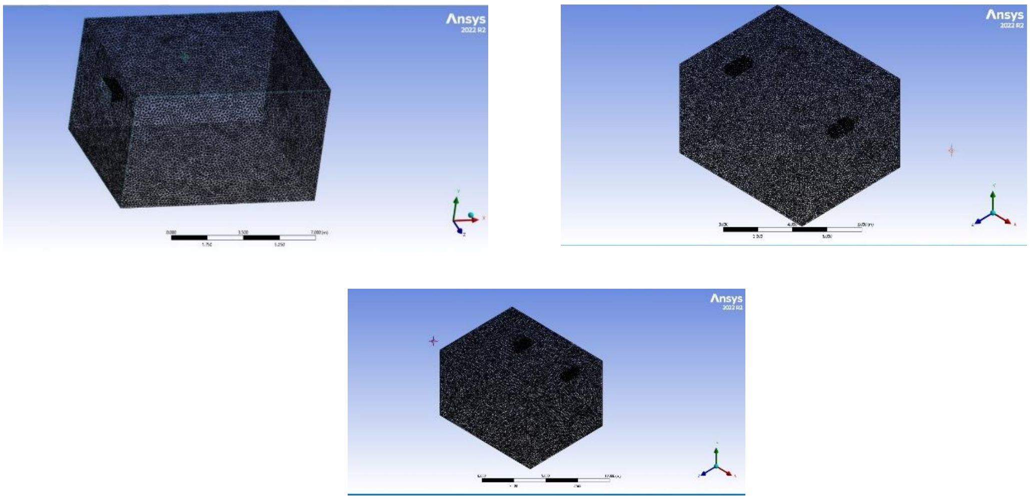


Figure 3.2: Mesh of Rooms with A. C. Duct

Parameters Considered for Simulation Results

Temperature: Examines the temperature distribution across the 3D plane, showing how heat is distributed within the domain.

Thermal Conductivity: Measures the ability of the material to conduct heat, expressed as the ratio of the heat flow rate to the temperature gradient.

Heat Transfer Coefficient: Defines the rate of heat transfer between the surface and the fluid around it, depending on factors like fluid velocity and material properties.

Velocity: Describes the speed and direction of fluid flow within the domain, influencing heat and mass transfer in the system.

Designing an Air-Conditioned Room in ANSYS

Table 3.1: Dimensions of Rooms and Ducts

CASE	DESCRIPTION	DIMENSIONS OF ROOM	DIMENSIONS OF DUCT	DUCT LOCATION	AIR VELOCITY
1	Singe AC Duct	6m×8m×10m	0.5 m x 1.5 m x 0.65 m	AC duct is located at 4 meters from base	2m/s
2	Double AC Duct one below other	6m×8m×10m	0.5 m x 1.5 m x 0.65 m (each)	Both AC Duct place in opposite each other in room wall	2m/s
3	Double AC Duct In front of each other	6m×8m×10m	0.5 m x 1.5 m x 0.65 m (each)	Both AC Dust place in front of each other in room wall	2m/s

Computer simulations provide valuable insights into ventilation efficiency, smoke movement, natural airflow, and thermal comfort early in the design process. In this study, CFD simulations were conducted in ANSYS Fluent to analyze forced ventilation within an air-conditioned room, focusing on the impact of air duct placement on thermal comfort.

The simulations used a consistent room size of 6 m x 8 m x 10 m and a target room temperature of approximately 27°C, slightly above the ideal comfort level. This higher temperature was observed due to airflow stagnation zones at the rear of the room, where circulation was limited. Three different configurations of duct placements were analyzed to understand how these variations affect overall comfort and airflow. Throughout the analysis, the air velocity was set to 2 m/s.

4.RESULTS AND DISCUSSION

In this study, we analyzed three different air conditioning duct placements to determine the most efficient setup for cooling a room. Case 1 involved a single duct placed 4 meters above the floor, which resulted in uneven cooling with concentrated airflow near the duct and inadequate cooling in areas farther away, leading to temperature imbalances and potential energy inefficiency. Case 2, which featured two ducts placed on opposite sides of the room, achieved the best results. This configuration provided the most uniform air distribution and the lowest room temperature, ensuring balanced cooling throughout the space and improving overall efficiency. In Case 3, two ducts were positioned side by side on the ceiling, 4 meters apart. While this improved air distribution compared to Case 1, it was less effective than Case 2, as the ducts' proximity caused air to concentrate in the middle, leaving outer areas cooler. Overall, the dual-opposing duct arrangement in Case 2 was the most efficient, delivering consistent cooling, reducing temperature variations, and promoting energy-efficient airflow in larger rooms.

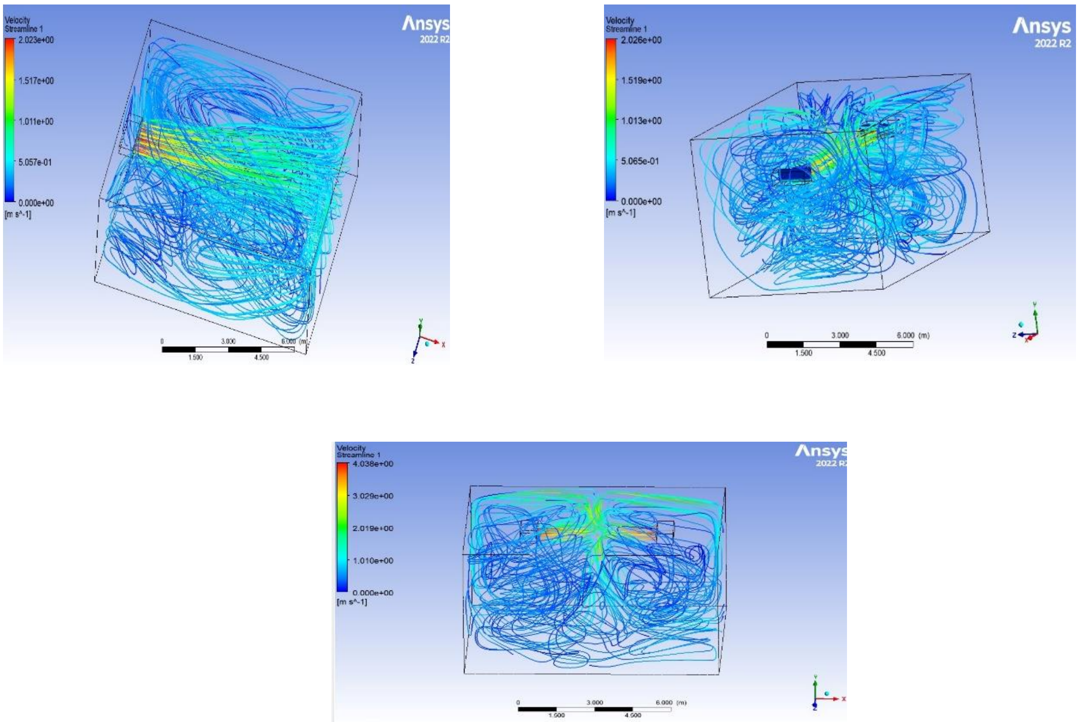
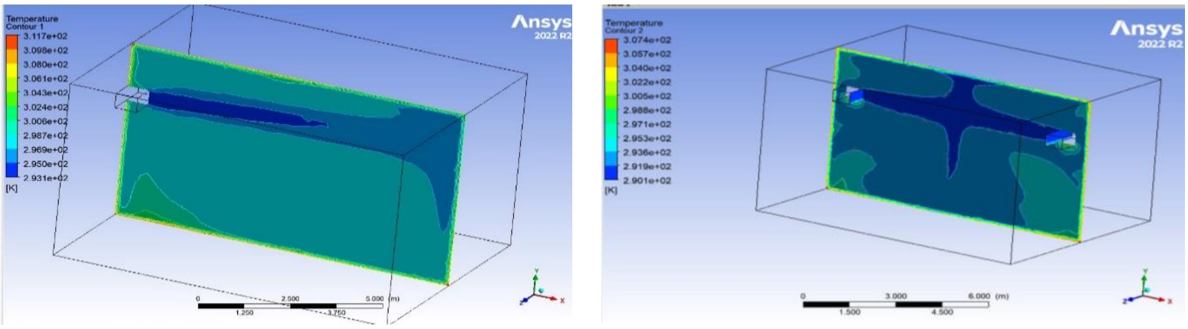


Figure4.1: Streamline of Air flow in Rooms



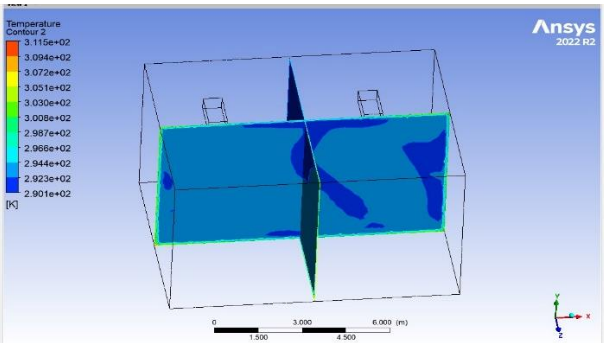


Figure4.2: Temperature variations in Rooms

The figures above illustrate the variations in room temperatures and the effects of air circulation based on different AC duct placements. This study examines three room configurations, each with AC ducts positioned in distinct locations. In each case, the same mass flow rate is used, with ducts divided into two sections, each delivering half the mass flow rate. By comparing the temperature results from all three configurations, we can determine the optimal setup. Additionally, the table provides a comparative analysis of the three cases, highlighting the impact of different duct positions on room temperature distribution and air circulation effectiveness.

Table 4.1: Comparison of temperature Results with all three cases of AC Room

Case	Temperature of Room (°C)
1	25
2	20
3	21

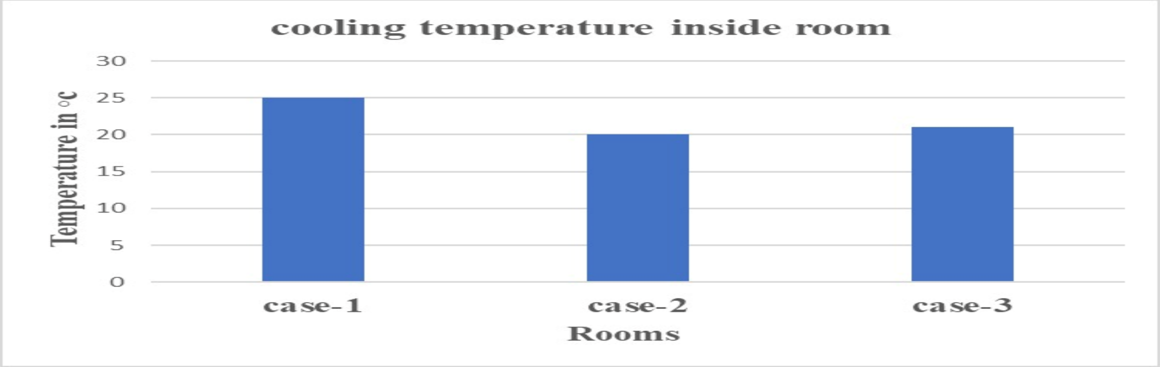


Figure 4.3: Comparison of Temperature between All Room with different duct locations

Based on the study, it is concluded that Room 1, with a single duct setup, achieved a minimum cooling temperature of 25°C. In Room 2, where two ducts were positioned opposite each other, a minimum temperature of 20°C was observed at the center of the room, indicating highly effective cooling. In Room 3, two ducts were also used, with the total mass flow rate kept constant, resulting in a minimum temperature of 21°C. From this analysis, it is evident that Case 3, with a double-duct arrangement and consistent mass flow rate, provides the most efficient setup for rapid cooling within a shorter time frame.

5. CONCLUSION

In the present work, an extensive data analysis was conducted to assess the cooling performance of various AC duct placements using three distinct duct configurations within rooms of identical dimensions. The aim was to optimize the most effective cooling method by comparing results across these configurations. While previous studies have explored air conditioning setups in rooms, this study leverages 3D finite element modeling and computational fluid dynamics (CFD) analysis with ANSYS Fluent to understand how duct positioning affects temperature distribution.

The modeling, meshing, preprocessing, and analysis were performed using ANSYS V14.0. Based on the study findings, Case 1 resulted in a minimum room temperature of 25°C. In Case 2, where two ducts were positioned opposite each other, the temperature was further reduced to a minimum of 20°C at the room's center, indicating the most effective cooling in terms of temperature reduction. Case 3, which also used a double-duct configuration with a consistent mass flow rate, achieved a minimum temperature of 21°C.

In summary, Case 2 proved to be the most effective arrangement, as it achieved the lowest room temperature, thereby maximizing cooling performance. This configuration provided uniform cooling across the room at a reduced temperature, highlighting it as the optimal setup for efficient air conditioning. Figure provides a comparative visualization of temperatures in Room 1, Room 2, and Room 3, confirming these findings and demonstrating the advantages of the double-duct, opposite-facing arrangement in achieving lower and more evenly distributed room temperatures.

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