Effect of Air Conditioner on the Ventilation of Nuclear Lab, IIT Bombay

Polipalli Madhusudhanarao
Indian Institute of Technology Bombay

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Abstract

This case study investigates the impact of air conditioning systems on ventilation within a nuclear laboratory environment, specifically at the Indian Institute of Technology Bombay (IIT Bombay). The study aims to assess how air conditioning affects the ventilation rates, air residence time within the laboratory. By examining the existing ventilation systems and introducing air conditioning, the study seeks to provide insights into optimizing environmental conditions for nuclear research while maintaining safety standards, particularly focusing on reducing air residence time.

1 Introduction

Nuclear laboratories demand strict environmental controls to ensure personnel safety and experimental integrity. Ventilation plays a critical role in maintaining air quality and removing contaminants, especially in environments dealing with radioactive materials. However, the introduction of AC systems may alter ventilation dynamics, potentially reducing air residence time in the laboratory. This case study aims to investigate how AC impacts air residence time.

(a) Front view of wall at backside

(b) Front view of wall with door

Figure 1: Nuclear Lab, IIT Bombay

2 Problem Statement

Figure 1 displays images of the Nuclear Lab. We can see the nuclear laboratory at IIT Bombay is equipped with advanced facilities for nuclear physics and materials science research. Ventilation systems are designed to control airflow, remove contaminants, and prevent the spread of radioactive particles. Despite the effective ventilation, there's a growing interest in installing AC systems to improve comfort for personnel. However, the impact of AC on air residence time and overall ventilation efficiency needs examination. We can see the exhaust in the first image, and the door in the second. A CFD analysis was performed for this geometry with operational AC using Ansys 2024 R1. And compare the Air residence time with and without Ac.

3 Methodology to find ART Using AI-ML algorithm:

The methodology involves two main phases tailored to the specific requirements of the nuclear laboratory. Firstly, finding the air residence time of the nuclear lab without AC being installed using Open Foam. But finding the ART using Open-Foam with exhaust takes a lot of computational time. So, we (group of 4 members) decided to find a solution for finding the ART at different co-ordinates by Al-ML algorithm. Initially, computational fluid dynamics simulations were conducted to predict air residence time for various exhaust positions using Open FOAM. An AI-ML model was developed based on these simulations to calculate air residence time.

A total of 16 simulations are done in Open foam for ML training and an additional 4 simulations are done for testing. Based on the ML training and testing, we got the Accuracy of above 90 percent. So, from that we calculate the ART at any co-ordinates in the given plane and in the given range by giving co-ordinates as input.

The range of the Co-ordinates (4.752,0,1.35) to (5.62,4.8,1.35) on the geometry uploaded in the case files. The plane of consideration is 1.35m above the base. The detailed ML matrix of simulations and code files are uploaded in the attached files.

Subsequently, after finding the air residence time of the nuclear lab without AC, an air conditioning system was installed to reduce air residence time. Comparative analysis between exhaust and air conditioning strategies was conducted to assess their effectiveness in achieving the desired ventilation outcomes.

4 Governing Equations and Models

Navier Stokes equations for single phase flows are the governing equations for the fluid flow, and for modeling turbulence, the k-epsilon turbulence model is used. Below are the governing equations for both:

- **Navier-Stokes Equations:**

$$\frac{\partial(\rho v)}{\partial t} + \nabla \cdot (\rho v v) = -\nabla p + \nabla \cdot \tau + \rho g$$

Where:

P is the Pressure

τ is the stress tensor

g is the gravitational acceleration vector

- **The necessary equations used for calculating turbulence are:**

$$k = \frac{3}{2}(U\infty I)^2$$

$$I = 0.16(Re)^{\frac{-1}{8}} \qquad \varepsilon = \frac{0.164\cdot(k)^{1.5}}{0.07\cdot L}$$

Where:

k is turbulent kinetic energy,

I is the turbulent intensity

$\boldsymbol{\varepsilon}$ Turbulent dissipation rate

L is the inlet length

$\boldsymbol{U}\infty$ is a characteristic velocity scale

- **Governing equation for Art-Foam solver:**

$$\frac{\partial(S)}{\partial t} + \nabla \cdot (S) - \nabla^2(S) = Source$$

Where S = air residence time.

5 Simulation Procedure

5.1 Geometry and Mesh

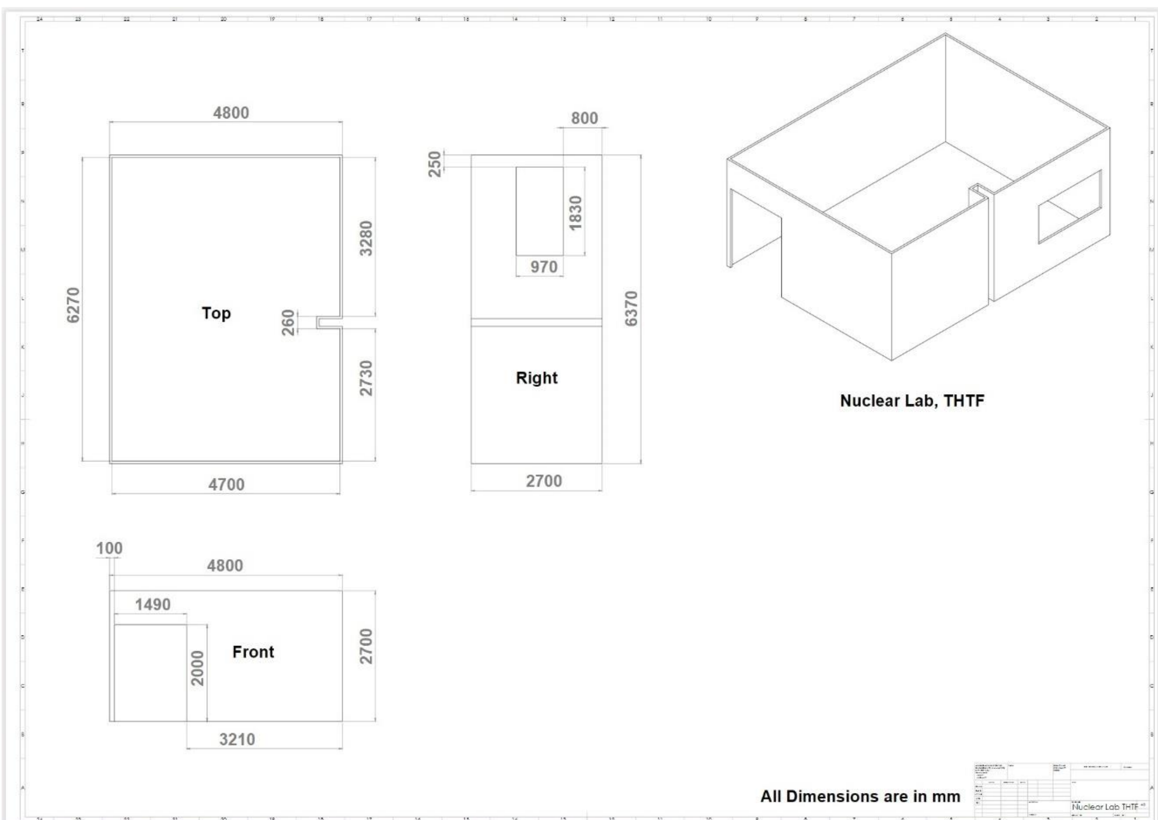
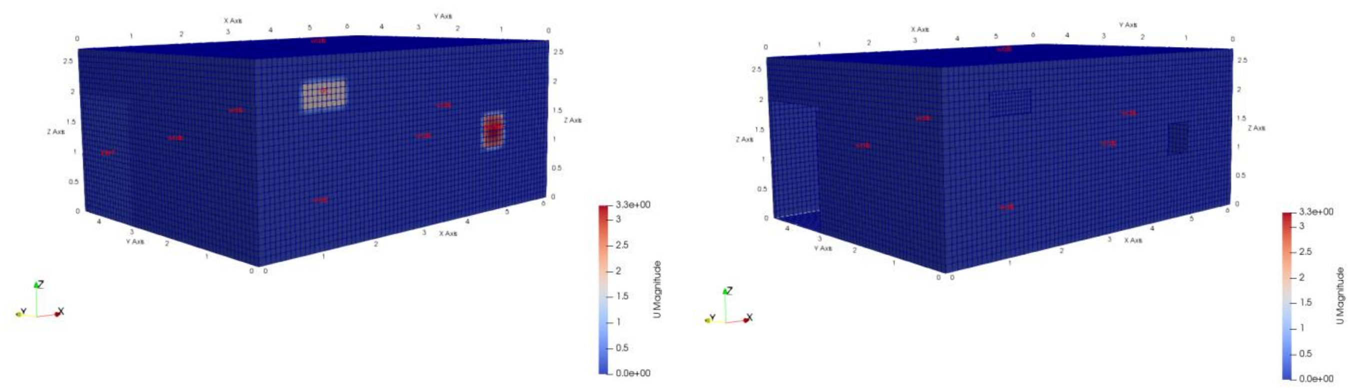


Figure 2: Dimensions of the Nuclear Lab, IIT Bombay

The geometry was prepared using the exact dimensions of the room, as shown in Figure 2. Ansys 2024 R1 was used in generating the geometry of the room, door, exhaust and Air Conditioner. The dimensionsof the Ac were those of a standard commercial 2 Ton Ac which is suitable for the dimensions of the room.The final geometry is displayed in Figure 3, where the Ac region is clearly visible.

Ansys was used to construct a fine mesh, with 124465 elements and the element size is 0.089m. Expansion ratios were kept as unity in all directions. The Air Conditioner was designed with the dimensions of 80cmX30cm with the velocity of 1.8m/s pumping into the room.



a. Internal mesh of the nuclear room b. block-mesh of the nuclear lab

Figure 3: Dimensions of the Nuclear Lab, IIT Bombay

5.2 Initial and Boundary Conditions

The initial and boundary conditions are as follows:

- **Velocity:** inlet- velocity inlet with 2 m/s air flowing inwards; outlet- pressure inlet-outlet velocity boundary condition; Ac- pressure inlet- outlet velocity boundary condition with velocity of 1.8m/s; walls- no slip boundary condition.

- **Pressure:** inlet- fixed pressure flux with 0 gradient and 0 value; outlet- pressure outlet with value 0; Ac- fixed pressure flux with 0 gradient and 0 value; walls- fixed pressure flux with 0 gradient and 0 value.

- **Turbulent Kinetic Energy (k):** inlet- turbulent intensity kinetic energy inlet; outlet- zero gradient; Ac- turbulent intensity kinetic energy inlet; walls- kqr wall function.
- **Turbulent dissipation rate ($\boldsymbol{\varepsilon}$):** inlet- turbulent mixing length frequency inlet; outlet- zero gradient; Ac- turbulent mixing length frequency inlet; walls- epsilon wall function.

5.3 Solver

The main interest is in studying the steady state behavior of air and checking for any re-circulation or stagnation zones that may be present and calculating the Air residence time. For that we want to have a solver that can perform steady state, turbulent simulations. For this, we use the simple Foam solver. Simple Foam is a steady-state solver for incompressible, turbulent flow problems. It solves the Reynolds-averaged Navier-Stokes (RANS) equations coupled with turbulence modeling to simulate fluid flow phenomena.

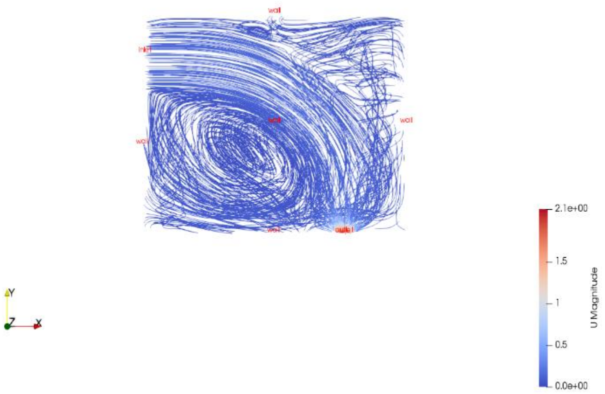
We use k- $\boldsymbol{\varepsilon}$ model for turbulence, to ensure that we get accurate solutions both close to the wall as well as within the domain. The values are calculated taking into account the standard y+ values of 201 and the characteristic length of 2m. We keep an end time of 4000s, with delta-t of 1s.

For calculating the Air residence time, we developed a solver called art-Foam as there is no default solver available for calculating ART in the open-foam. In this we used ‘S’ variable for indicating ART. The velocity file required is taken from the end time step of the simple-foam simulation. The art-Foam is simulated for the end time of 2000 seconds with delta-t of 0.01s.

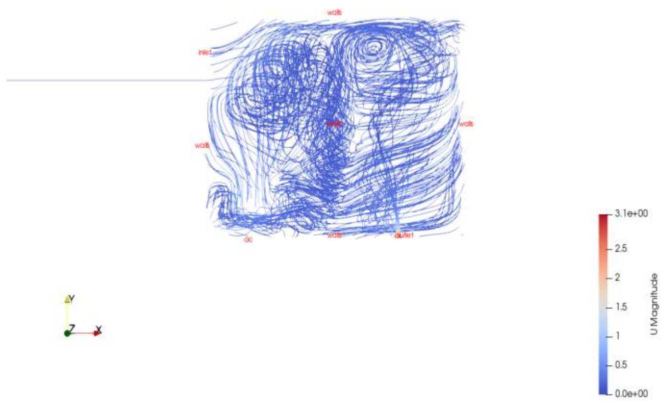
6 Results and Discussions

Our primary objective was to have a comparison with the only exhaust case study. As mentioned already, the previous study performed the analysis for various cases. The contour plots of velocity streamlines for 1.35 m height and 0.4 m height from the floor were generated and analyzed. These were our heights of interest since our intention is to check for re-circulation and stagnation in the context of air particles in the nuclear lab at various planes.

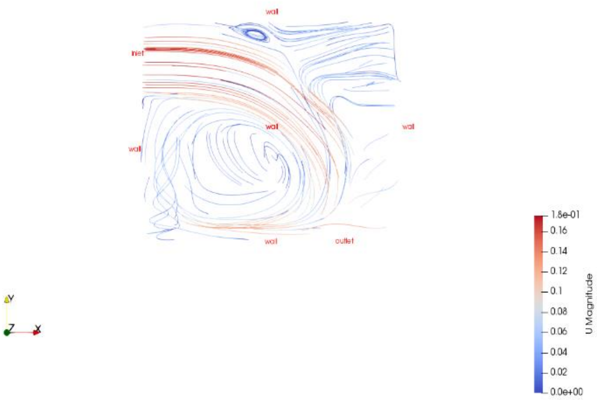
The results of velocity streamlines for the two cases of 1.35m and 0.4m heights are displayed in Figure5. Case1, which had both inlet and exhaust open, has the highest number of recirculation zones and very poor ventilation. Case 2 is the best case with an open door and exhaust, and an operating Ac at the top right corner, on the exhaust side wall.



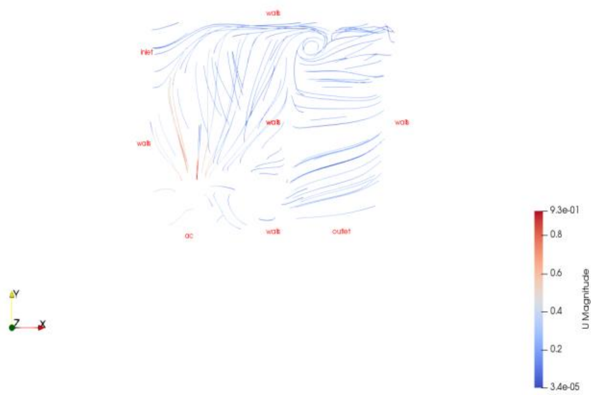
a. Velocity streamline contour at 1.35m



b. Velocity streamline contour at 1.35m



c. Velocity streamline contour at 0.4m



d. Velocity streamline contour at 0.4m

Figure 5: Velocity streamline contours at 1.5m and 0.4m heights both cases

Case	Door	Exhaust	AC
1	Open	Open	Off
2	Open	Open	On

We observe that there is a large recirculation zone with almost stagnant air is present in the right corner of the room in the first images both figure5 and figure7. This is caused due to a lack of an outlet for air to escape. Another small recirculation zone is present in the back left corner in both the images. Apart from this, the rest of the room does not have stagnant air, and a direct pathway exists for air to freely flow out of the room through either the door or the exhaust. Comparing directly with the previous study, we can draw the following inferences:

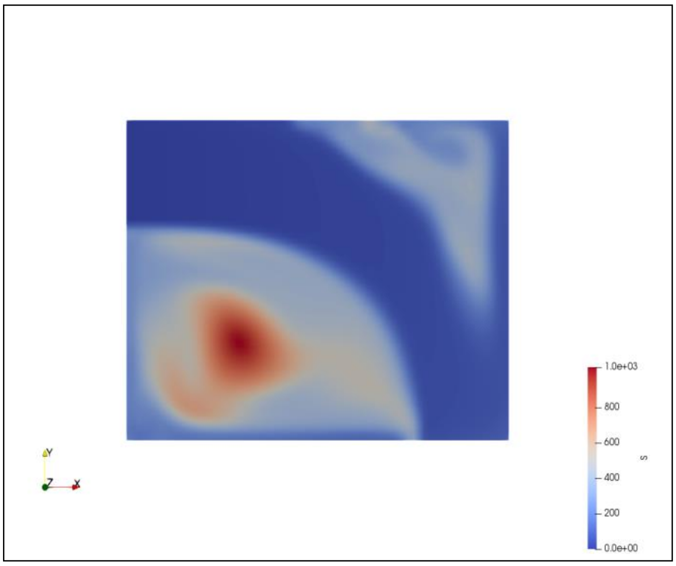
- Significantly the best results are observed in the second case as the formed recirculation is broke down.
- This is because the AC present on the wall close to the corner eliminate the recirculation zone present in that corner.

Air residence time for the both cases are shown in figure6. Case 1, which had both inlet and exhaust open, has the highest number of recirculation zones and high Air Residence Time (ART). Case 2 is the best case with open door and exhaust, and an operating Ac at the top right corner, on the exhaust side wall with less Air Residence Time (ART).

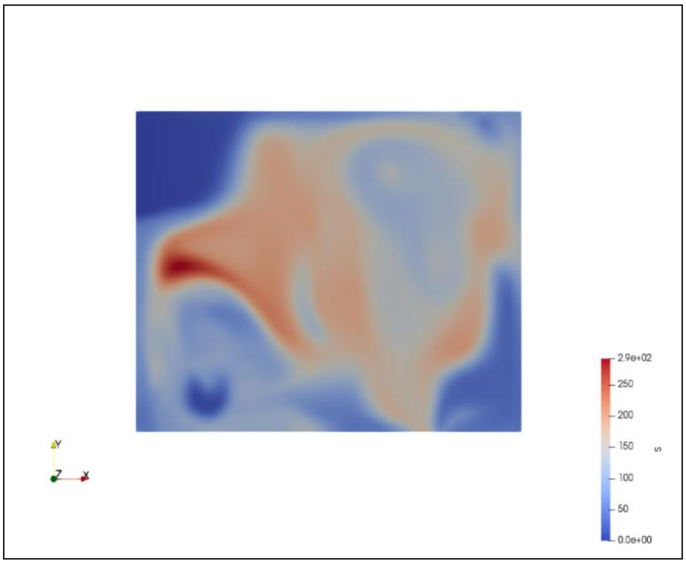
From the figure6, we observed that the Air residence time for the case 1 at 1.35m height is 1000 seconds where for the case 2 it is 290 seconds. The ART drops significantly because of installing AC in the room which breaks the re circulation formed in the case1. Similarly, the ART at 0.4m height of case 1 is 970 seconds whereas for the case 2 it is 220 seconds.

Air Changes per Hour for the both the cases are also calculated and the values are 22 for case1 and 41 for case2. Which indicates that the total air in the room is 22 times replaced with new air in each hour in case1 and similarly 41 times in case2. Which decreases the air stagnation time in the nuclear lab and increases the ventilation.

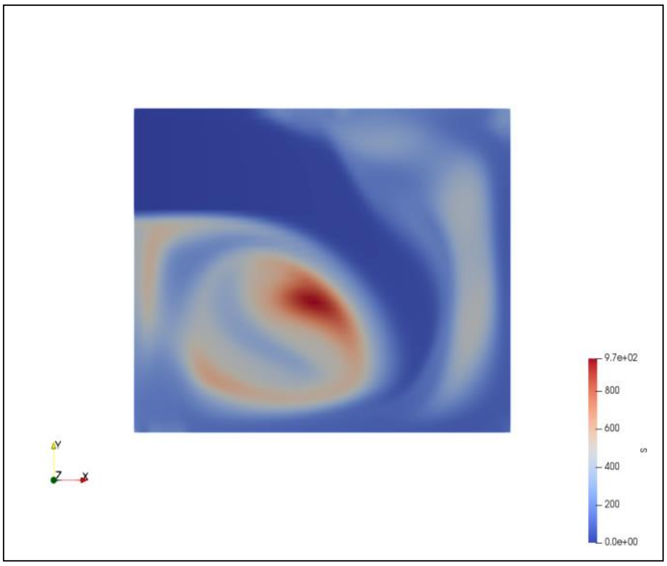
The Air residence time(S) contours for both cases at different heights are shown in figure 6. And velocity contours for the both the cases at different heights are shown in figure 7.



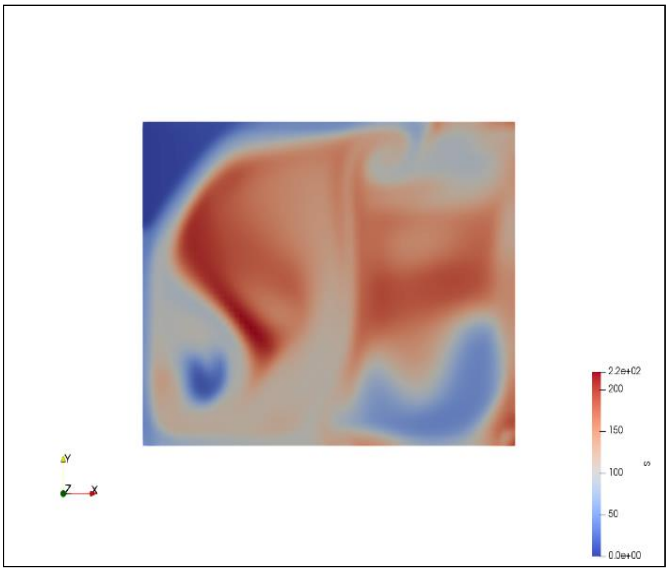
a. S contour at 1.35m height of case 1



b. S contour at 1.35m height of case 2



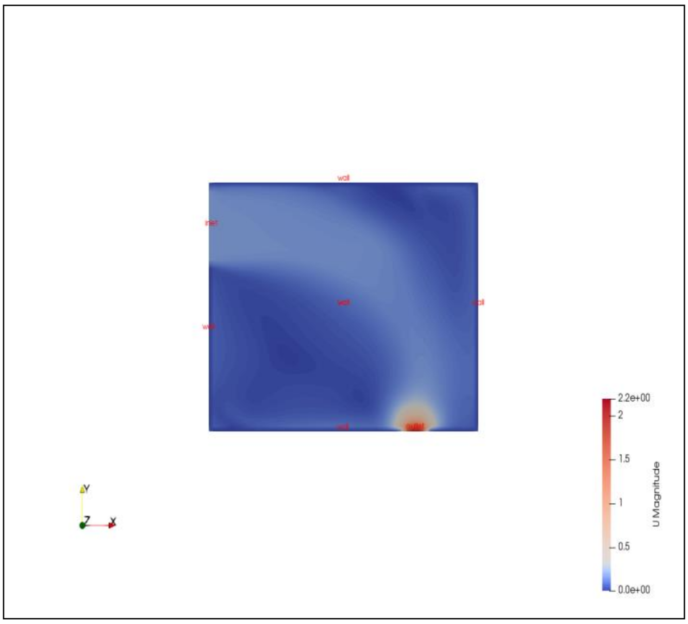
c. S contour at 0.4m height of case 1



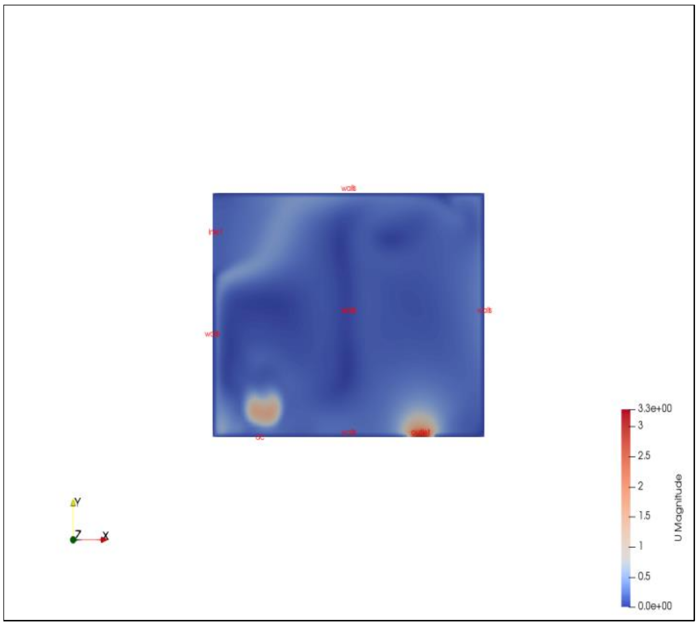
d. S contour at 0.4m height of case 2

Figure 6: Air Residence Time contours at 1.5m and 0.4m heights for both cases

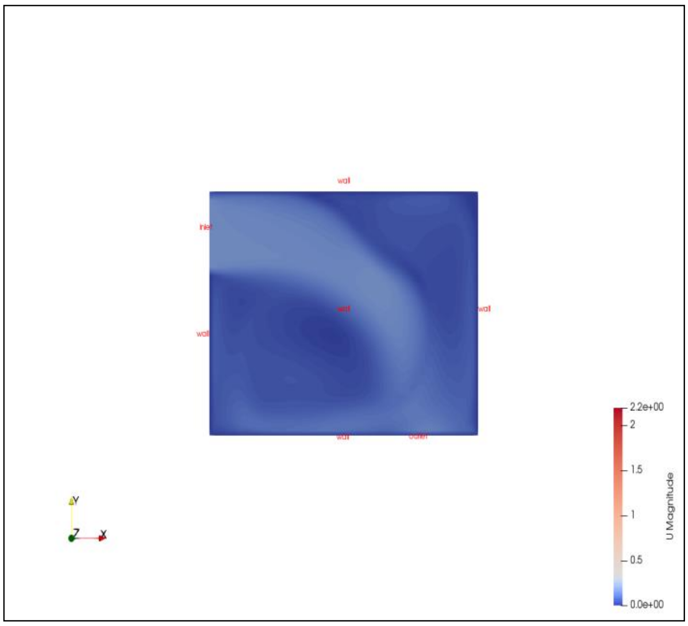
Case	Height(m)	ART value(S)
1	1.35	1000
1	0.4	970
2	1.35	290
2	0.4	220



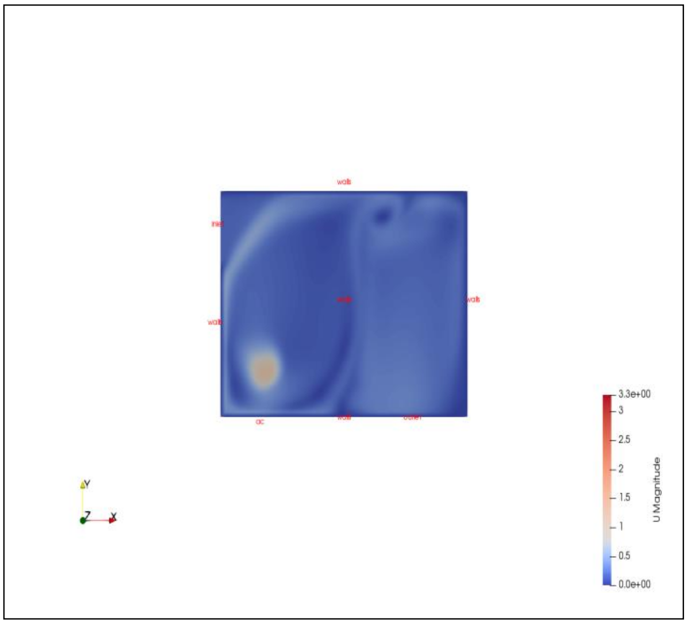
a. Velocity contour at 1.35m(Case 1)



b. Velocity contours at 1.35m(Case 2)



c. Velocity contours at 0.4m(Case 1)



d. Velocity contours at 0.4m(Case 2)

Figure 7: Simulation Results at 1.5m and 0.4m heights from the base

In summary, the results of the simulation proved that the usage of AC would solve a large number of issues present in the ventilation in the room (Case 1) at both the heights, particularly in terms of reducing the Air Residence Time.

References:

[1] Wilcox, D. C. (1998). Turbulence modeling for CFD. La Canada, Calif: DCW Industries.
[2] Nguyen, V.-B., Do, Q.-V., & Pham, V.-S. (2020). An Open-FOAM solver for multiphase and turbulent flow. In Physics of sFluids (Vol. 32, Issue 4, p. 043303). AIP Publishing.
[3] Ventilation Analysis of Nuclear Lab, IIT Bombay for Open-Foam Documentation.