FOSSEE, IIT Bombay
OpenFOAM Case Study
Project12 April, 2024

Air Residence Time analysis for Nuclear lab in IITB with and without AC

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April 2024

Abstract

Indoor air quality and occupant comfort are paramount considerations in built environments, particularly in spaces equipped with ventilation systems featuring exhaust, inlet, and air conditioning (AC) units. Understanding the air residence time, the average duration air particles remain within a room before being exchanged, is essential for effective ventilation design and pollutant mitigation strategies. This study employs computational fluid dynamics (CFD) techniques to analyses airflow patterns and temperature distributions in a room with one exhaust, one inlet, and two AC units. The simulation process encompasses geometry definition, mesh generation, solver setup, and post-processing analysis. Through meticulous simulation and post-processing, the air residence time is computed by evaluating the volume of the room relative to the total volumetric flow rate of air entering or exiting the space. The findings of this study offer insights into optimizing ventilation strategies, and reducing Air Residence Time.

1 Introduction

This case study delves into the effects of air conditioning (AC) on air residence time in nuclear laboratory environments. Maintaining stringent environmental controls is imperative in these facilities to safeguard personnel and preserve experimental integrity. Ventilation serves as a vital component in upholding air quality and eliminating contaminants, particularly in areas handling radioactive substances. Nevertheless, the installation of AC systems could potentially disrupt ventilation dynamics, leading to a decrease in air residence time within the laboratory.

(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 shows images of the Nuclear Lab which is at IIT Bombay. IIT Bombay is equipped At IIT Bombay, advanced facilities cater to nuclear physics and materials science research, including the Nuclear Lab showcased in Figure 1. The lab's ventilation systems are meticulously designed to regulate airflow, eliminate contaminants, and contain radioactive particles. Despite their efficacy, there's a burgeoning interest in integrating air conditioning (AC) systems to enhance personnel comfort. However, the potential impact of AC on air residence time and overall ventilation efficiency necessitates investigation. Notably, the first image depicts the exhaust system, while the second showcases the lab's entrance. To analyze this, a computational fluid dynamics (CFD) study was conducted using Ansys 2024 R1m, comparing air residence times with and without AC operation.

3. Governing Equations

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:**

$$\partial(\rho v)/\partial t + \nabla\cdot(\rho vv) = -\nabla p + \nabla\cdot\tau + \rho g \quad \text{-----①}$$

Where:

P is the Pressure

τ is the stress tensor

g is the gravitational acceleration vector

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

$$\boldsymbol{k = 3/2\ (U\infty I)}\ \hat{}2 \quad \text{------------------------------------②}$$

$$\boldsymbol{I = 0.16(Re)\hat{}\ (-1/8)} \quad \text{------------------------------------③}$$

$$\boldsymbol{\varepsilon} = (\mathbf{0.164}\cdot(\boldsymbol{k})\hat{}\mathbf{1.5})/(\mathbf{0.07}\cdot \mathrm{L}) \quad \text{---------------------------④}$$

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:**

$$\partial(S)/\partial t + \nabla\cdot(S) - \nabla 2(S) = \text{Source} \quad \text{-----------------------⑤}$$

Where S = air residence time.

4 Simulation Procedure

4.1 Geometry and Mesh

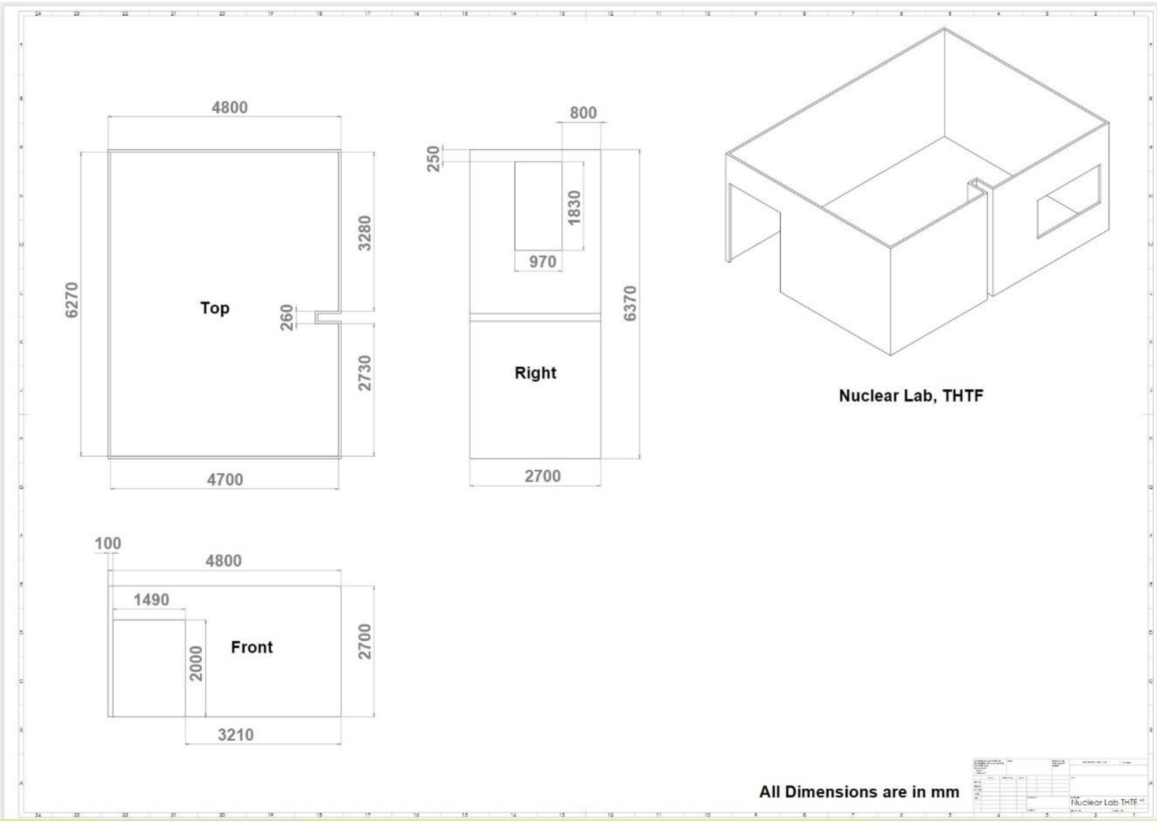


Figure 2: Dimensions of the Nuclear Lab, IIT Bombay

- The geometry for the study was developed using Space Claim modeling software. To evaluate the impact of an air conditioner on room airflow, two different geometries were created: one featuring a single window, and another incorporating two air conditioner.

- 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, and Figure 4 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.

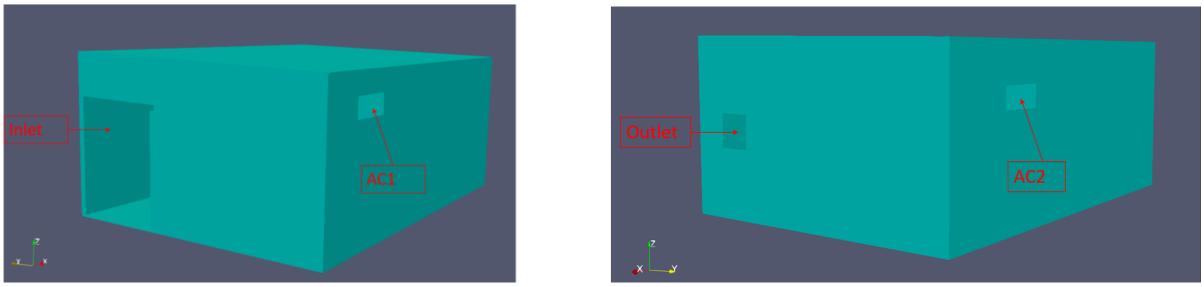


Figure 3: Dimensions of the Nuclear Lab, IIT Bombay

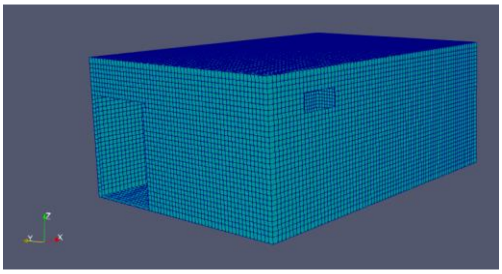


Figure 4: Mesh of the Nuclear Lab, IIT Bombay

4.2 Initial and Boundary Conditions

The initial and boundary conditions are as follows:

- **Velocity:** inlet velocity at door with 0.1667 m/s air flowing inwards; at the outlet, pressure inlet- outlet velocity boundary condition; Ac- pressure inlet- outlet velocity boundary condition with velocity of 2 m/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):** At door inlet turbulent Intensity Kinetic Energy Inlet with Intensity 0.0435 and value 7.98e-05 m2/s2; at ac inlet turbulent Intensity Kinetic

Energy Inlet with Intensity 0.0419 and value 0.0237; at windows zero gradient; at walls kqRWallFunction, Ac- turbulent intensity kinetic energy inlet.

- **Turbulent dissipation rate (ε):** At door inlet turbulent Mixing Length Dissipation Rate with mixing length of 2m and value 8.35e-07 m2/s3; at ac turbulent Mixing Length Dissipation Rate with mixing length of 0.15m and value 0.05699 m2/s3Ac- turbulent mixing length frequency inlet; Ac- turbulent intensity kinetic energy inlet.

For Solving artFoam

- **Velocity:** Steady state velocity calculated by SimpleFoam solver
- **Air residence time:** at ac and door inlet fixed value 0s; at windows and walls zeroGradient boundary condition.

4.3 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- ε 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.

5 Results and Discussions

- Our primary aim was to conduct a comparison solely with the exhaust case study. As previously stated, the earlier study examined multiple scenarios. Specifically, contour plots of velocity streamlines were generated and analyzed at heights of 1.35 m and 0.2 m from the floor. These specific heights were chosen as they are of particular interest to us, aligning with our objective of assessing re-circulation and stagnation of air particles within the nuclear lab across different planes.
- The results of velocity streamlines for the two cases of 1.35m and 0.2m heights are displayed in Figure5. Case1, which had both inlet and exhaust open, has the highest number of recirculation zones and very poor ventilation. In case 2, an open door and exhaust, and an operating one Ac at the top right corner, on the exhaust side wall and another AC diagonally opposite to it.

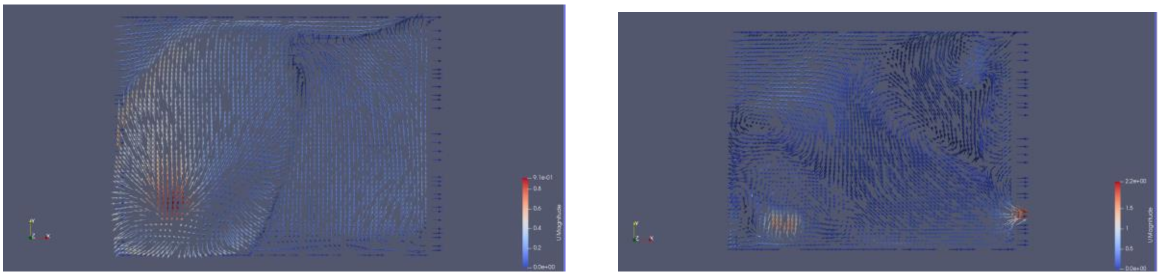
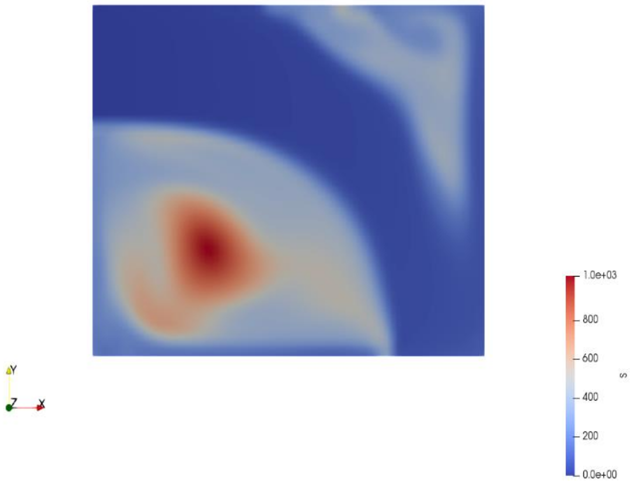


Figure 5: Velocity Vectors at 0.2 m and 1.35 m height for the Two AC Condition

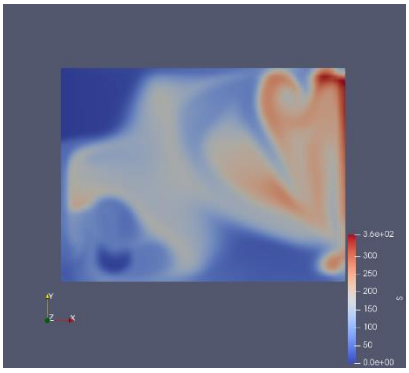
- Upon observation, a sizable recirculation zone with stagnant air is evident in the right corner of the room, attributed to the absence of an outlet for air escape. Additionally, a smaller recirculation zone is noticeable in the back left corner in both images. However, the remainder of the room exhibits no stagnant air, with a clear pathway for air to exit through either the door or the exhaust. Comparing directly with the previous study, we draw the following conclusions:
- Notably, the second case yields significantly superior results as it effectively disrupts the formed recirculation.
- This improvement is attributed to the presence of air conditioning units positioned strategically to eliminate the recirculation zone in the respective corner.
- The air residence time for both cases is depicted in Figure 6. In Case 1, featuring both inlet and exhaust openings, numerous recirculation zones and prolonged Air

Residence Time (ART) are observed. Conversely, Case 2, with an open door and exhaust, along with operational AC units strategically placed, exhibits reduced ART.

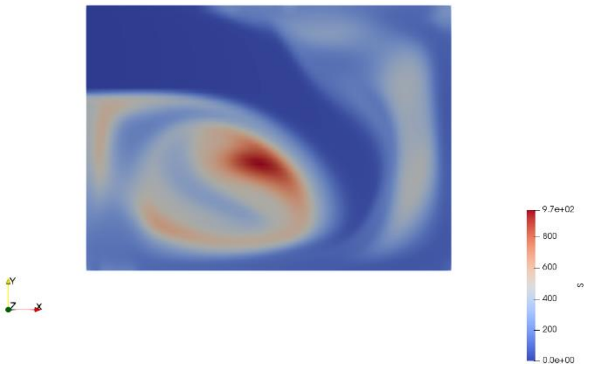
- Further analysis of Figure 6 reveals that at a height of 1.35m, the Air residence time is 1000 seconds for Case 1, contrasting with 320 seconds for Case 2. The significant decrease in ART in Case 2 is attributed to the installation of AC units, effectively disrupting the recirculation observed in Case 1.
- Additionally, Air Changes per Hour (ACH) for both cases are calculated, resulting in values of 22 for Case 1 and 42 for Case 2. These values indicate that the total air in the room is replaced 22 times and 42 times per hour, respectively, highlighting a reduction in air stagnation time in the nuclear lab and an enhancement in ventilation.



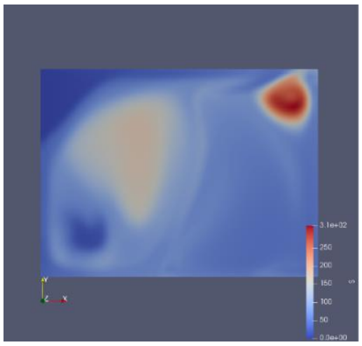
a. S contour at 1.35m height of case 1



b. S contour at 1.35m height of case 2



c. S contour at 0.2m height of case 1



d. S contour at 0.2m height of case 2

Figure 6: S contour comparison for the case 1 and case 2 at different heights

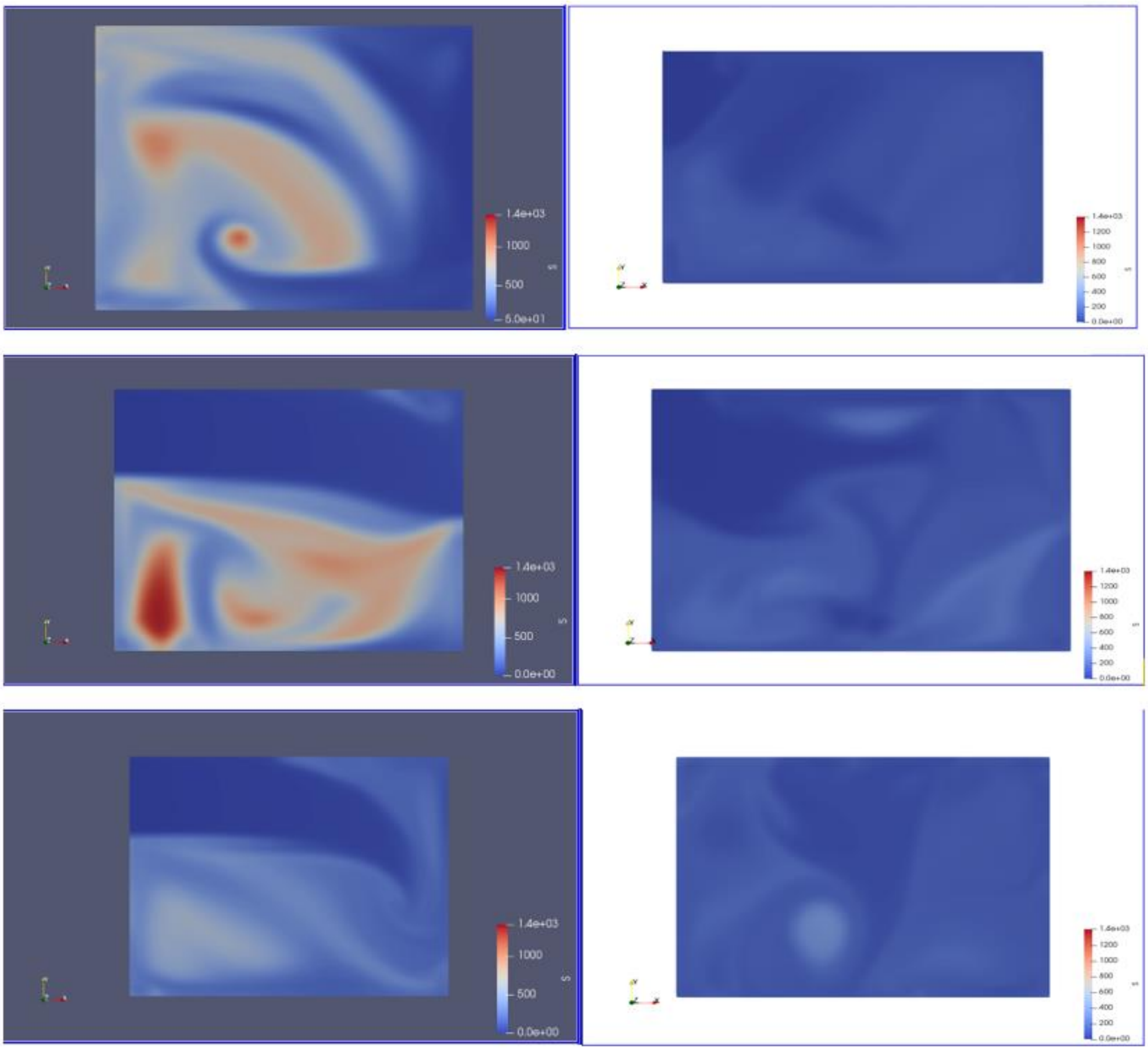


Figure 7: ART contours for case 1 i.e. without AC and Case 2 i.e. with AC at 0.2m, 1.35m, 2.4m height

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 Fluids (Vol. 32, Issue 4, p. 043303). AIP Publishing.

[3] Ventilation Analysis of Nuclear Lab, IIT Bombay for Open-Foam Documentation.