FOSSEE, IIT Bombay
OpenFOAM Case Study Project
April 21, 2024

Analysis of ventilation in a classroom with machine learning

Shiva Sudhan
Department of Mechanical Engineering, IIT Bombay

Abstract

Air residence time is an important parameter which is a measure of the time which air spends in a region before being replaced by fresh air. Monitoring and ensuring optimum values of air residence times in a room is essential to prevent the spread of airborne infectious diseases. The objective of this case study is to perform flow and air residence time simulations and analyse air flow patterns that exist in a classroom environment (Chemical Engineering classroom, IIT Bombay). A machine learning model has been deployed to predict air residence times without running the flow simulations, to save computational time and power. Finally, some improvements in ventilation have been suggested by introducing interventions in the flow domain.

1 Introduction

In modern times, humans are spending more time indoors than ever. Most of the office and educational activities are carried out in closed rooms for long periods of time. These places can become hotspots for spreading of airborne diseases. Therefore, it is essential to design buildings, meeting rooms and classrooms with proper ventilation. Ventilation designers need to optimize some design parameter to ensure air replenishment in such spaces at a pace fast enough to reduce chances of infection when different people cross the same area. One of the parameters used to track this is called the Air Residence Time(ART). [1]

Commonly used ventilation systems in classrooms are air conditioners, exhaust fans, and table fans. The goal of this project is to analyse changes in air flow and air residence time due to the varying location of exhaust fans in a classroom. To achieve this, the computational fluid dynamics (CFD) solvers in OpenFOAM v9 have been used. Running CFD simulations for all possible ventilation configurations of a large room is a very tedious and computationally heavy task. With the rise in machine learning algorithms, complicated systems can be modelled in a very simple manner for fast and accurate results. The application of predicting air quality is an interesting domain to explore. Using ML, fewer CFD simulations can be used to extract results for new and innovative ventilation configurations, saving computational resources.

2 Problem Statement

A classroom in the Chemical Engineering Department, IIT Bombay, is used as a test case. The room is modelled as a cuboidal fluid domain containing air. One wall has a door and two air conditioners. The opposite wall has an exhaust near the corner. A second exhaust is tested for different locations at the same height as the first exhaust on three walls. Air enters the room through the air conditioners, circulates inside the room, and leaves through the exhaust fans. The door is maintained at ambient conditions.

Fig 1 shows the different positions for which the simulation would be run, leading to a total of 24 simulations for the flow field and air residence time. At the end, based on the results, some interventions are introduced in order to minimize the air residence time in specified regions of interest.

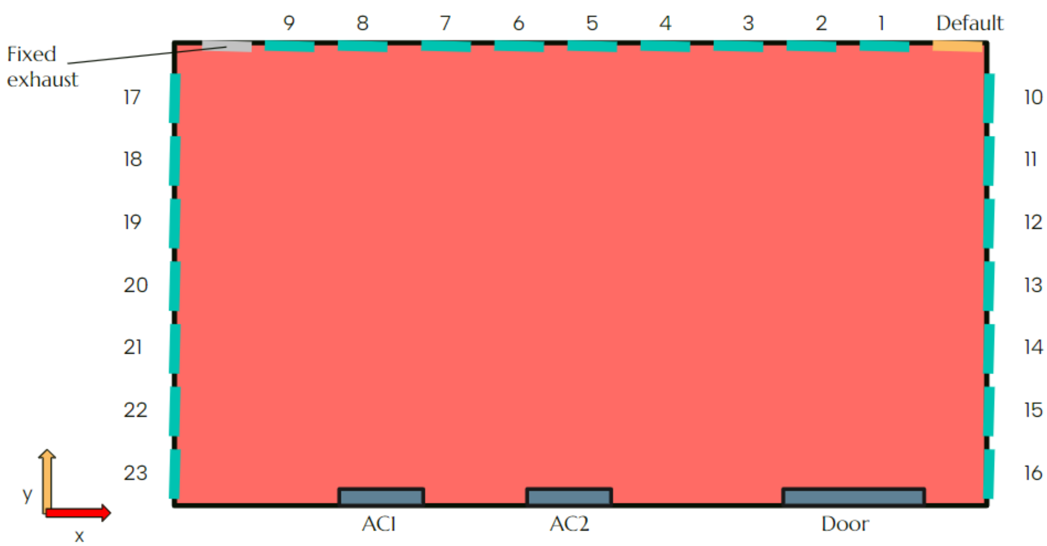

Figure 1: Positions of variable exhaust fan (1-23)

3 Governing Equations and Models

The incompressible Navier-Stokes equations are the governing equations for the flow of air inside the room. The continuity and momentum equations are relevant to this case.

$$\nabla \cdot \vec{V} = 0 \tag{1}$$

$$\rho \frac{\partial \vec{V}}{\partial t} + \rho(\vec{V} \cdot \nabla)\vec{V} = -\nabla p + \mu \nabla^2 \vec{V} \tag{2}$$

To incorporate effects of turbulence, the Reynolds Averaged Navier Stokes equations were used, with the $k - \epsilon$ turbulence model for calculating turbulent viscosity.

$$\rho\frac{D}{Dt}(k) = \rho\nabla\cdot(D_k\nabla k) + P - \rho\epsilon \tag{3}$$

Here, k represents the turbulent kinetic energy (TKE), D_k is the effective diffusivity of k and P is the TKE production rate.

$$\rho\frac{D}{Dt}(\epsilon) = \rho\nabla\cdot(D_\epsilon\nabla\epsilon) + \frac{C_1\epsilon}{k}\left(P + C_3\frac{2}{3}k\nabla\cdot\vec{V}\right) - C_2\rho\frac{\epsilon^2}{k} \tag{4}$$

In this equation, ϵ represents the turbulent kinetic energy dissipation rate, D_ϵ is the effective diffusivity of ϵ and C_1, C_2 and C_3 are the model constants.

$$\nu_t = C_\mu\frac{k^2}{\epsilon} \tag{5}$$

The turbulent viscosity is represented by ν_t, and C_μ is a model constant, generally having a value of 0.09.

To solve for the air residence time in the flow field, we first take the general passive scalar transport equation

$$\rho\frac{\partial S}{\partial t} + \rho\frac{\partial u_j S}{\partial x_j} = G \tag{6}$$

We then replace G with ρ, so that S represents the air residence time (ART), the quantity we want to solve for.

$$\frac{\partial S}{\partial t} + \frac{\partial u_j S}{\partial x_j} = 1 \tag{7}$$

4 Simulation Procedure

4.1 Geometry and Mesh

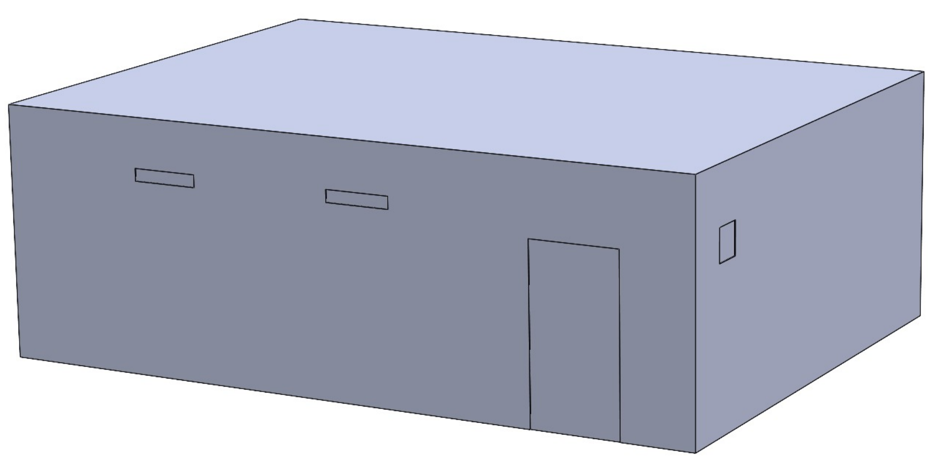

Figure 2: Chemical engineering classroom

The geometry shown above has the following dimensions. All units are in centimetres. A single door is located near the room's corner and 2 air conditioners are fixed on the wall which has the door. One of the exhaust fans' position is fixed on the wall opposite to the door, and the other exhaust fan is moved along the three walls (other than the one containing the air conditioners) of the room.

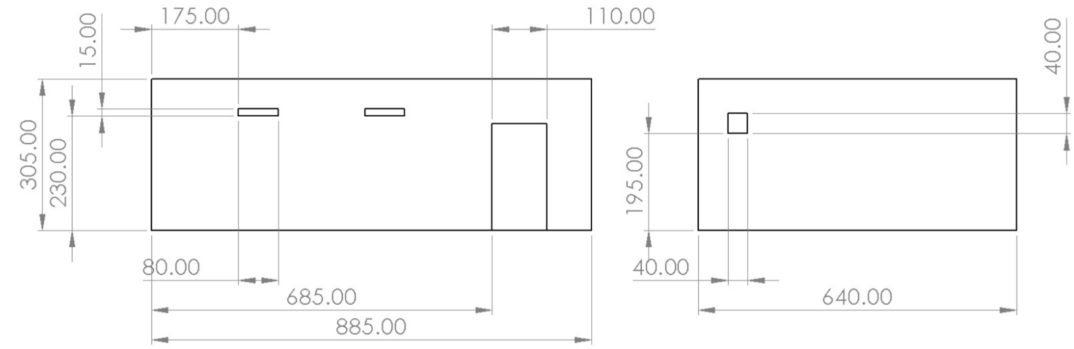

Figure 3: Dimensions of the classroom

The geometry and mesh were created using the blockMesh feature in OpenFOAM 9. The patches for air conditioners, door and exhaust fans were made using the topoSet and createPatch features, by specifying the coordinates and the area of each component. For all 3 directions, 20cm of domain from each wall was refined with a gradient of 10, as the mesh became finer near the external faces. This was done primarily for small y+ values. The rest of the domain had uniform hexahedral meshing. There were 189 cells in the x direction, 140 in the y direction, and 73 in the z direction. A total of 1931580 cells were constructed in the entire domain.

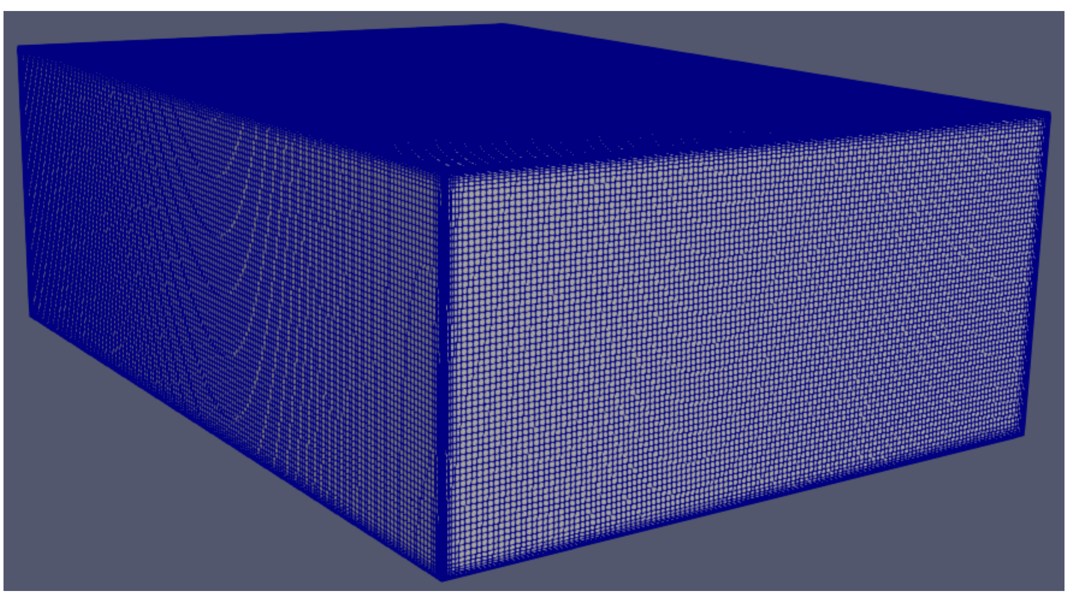

Figure 4: Mesh

Table 1: Overview of meshing parameters

Mesh Metric	Value
Max aspect ratio	10.21738153
Max skewness	1.451977157e-12
Max non-orthogonality	0

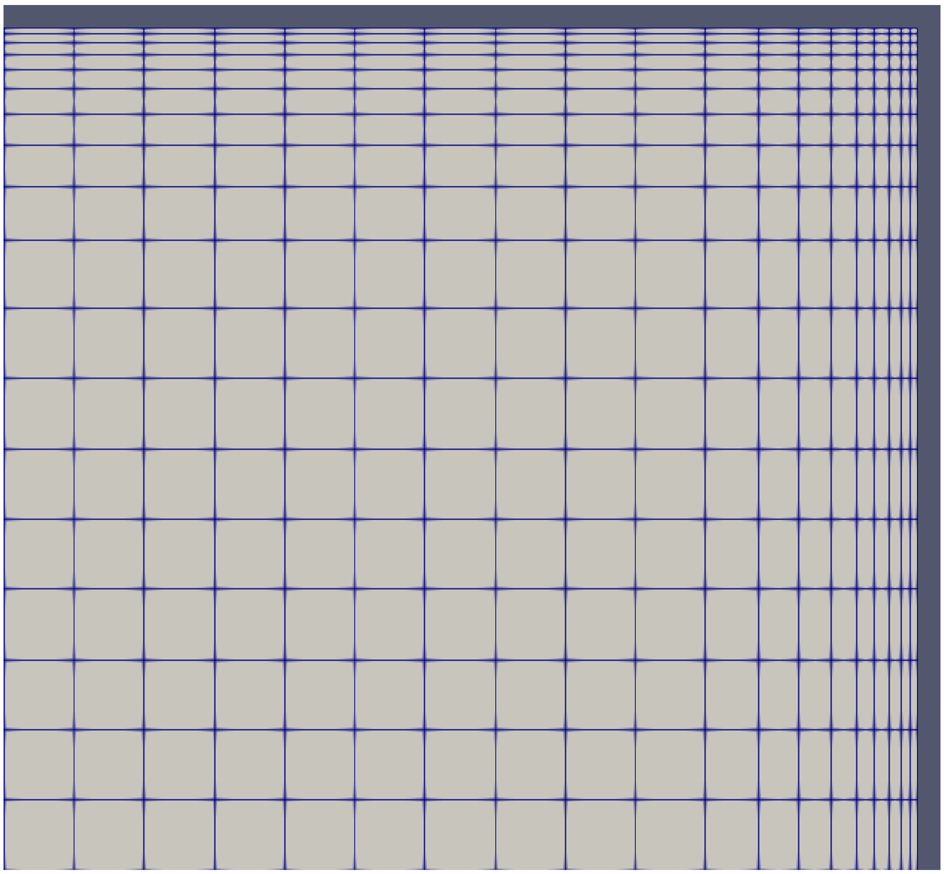

Figure 5: Grading in the mesh

The domain was divided into four blocks using topoSet. A shell 30cm thick from all 6 faces was formed, hereafter referred to as the outer zone. The rest of the domain was divided into three blocks which were sliced horizontally from the remaining block. These will be referred to as the lower inner zone, middle inner zone and upper inner zone. These zones were 60 cm high, 25 cm high and 60 cm high, respectively. The domain that interests us the most is the inner middle zone. This zone is at least 30cm (approximately 1 foot) away from all the walls and ranges from 90cm to 115cm in height, which is a good representation of the sitting height of a human being. The quality of air in this zone would affect any person who is sitting in the room the most. The outer zone was isolated as it would generally have high air residence times and affect the volume averaged values of the other zones. The upper and lower zones would also have high air residence times in the presence of interventions like fans and desks, so further analysis into this classroom may require the air residence time values in those zones. Furthermore, data from these zones help to train the machine learning model, as shown later.

4.2 Initial and Boundary Conditions

The classroom is assumed to be having ambient air conditions, with the AC blowing in air and the exhaust fans acting as outlets. Air in deficit or excess is compensated for by the presence of the door. All inputs of numerical values were uniformly distributed over the inlet/outlet patches. The internal field of the domain was initialised with initial values of U, p, k and ϵ.

Table 2: All initial and boundary conditions of the simulation

	U	p	k	ϵ	ν_t	S (ART)
ACs	2m/s inlet @ 60º with vertical	Fixed flux pressure	Inlet value 0.015	Inlet value 2.95e-3	Calculated value 6.83e-3	Fixed value zero
Door	Pressure Inlet Outlet Velocity	Total pressure 101325 Pa	Inlet outlet	Inlet outlet	Calculated value	Fixed value zero
Exhaust fans	2m/s outlet	Fixed flux pressure	Inlet value 0.015	Inlet value 5.91e-3	Calculated value 3.43e-3	Zero gradient
Walls	No slip	Fixed flux pressure	Wall function	Wall function	Wall function	Zero gradient
Internal field	Uniform 0	Uniform 101325 Pa	Uniform 3.37e-5	Uniform 1.17e-5	Uniform 8.74e-4	Uniform 0

The values used in boundary and initial conditions of Turbulent kinetic energy (k), Turbulent dissipation rate (ϵ), and Turbulent viscosity (ν_t) were obtained through calculations shown below. The calculations were verified using an online calculator. [2]

$$k = \frac{3}{2}(U_\infty I)^2 \tag{8}$$

where U_∞ is the free stream velocity, taken to be exhaust outlet velocity (2 m/s) and AC air velocity (2 m/s) for exhaust and AC, respectively. I is the turbulence intensity, taken to be 5% (standard value).

$$\epsilon = \frac{C_\mu k^{1.5}}{0.07L} \tag{9}$$

where C_μ is a k-ϵ model parameter, typically given as 0.09, k is the turbulent kinetic energy calculated above, and L is the characteristic length. L is taken as the larger length of the corresponding entity, for example, height of the door. Turbulent viscosity was calculated as per equation (5).

4.3 Solver

The simpleFoam solver was initially used to obtain the steady-state flow field in the room. The fluid flow equations are solved using the existing SIMPLE algorithm (Semi-Implicit Method for Pressure-Linked Equations), with the temporal term set with a steady state condition. The $k-\epsilon$ turbulence model was used to model turbulence in the flow. The simulation was run for a total of 15,000 time steps until a suitable convergence of the residuals was reached.

The inbuilt OpenFOAM solver was modified to develop a custom solver (artFoam) for air residence time. The equation 7 was discretized using finite volume method functions and used as the governing equation. The in-house artFoam solver was then used, with the velocity field solution as input, to calculate the air residence time values throughout the domain.

The age function, an inbuilt OpenFOAM function, was used to calculate the ART immediately after each simulation to verify the values of the artFoam solver. Based on the results, the limited-Linear scheme was used as the divergence scheme for the artFoam solver, particularly to eliminate the presence of negative values of ART in some parts of the domain.

5 Results and Discussions

The 24 simulations mentioned were run and flow fields and air residence times were obtained. The extensive tabulated results for all zones (outer, inner upper, inner middle and inner bottom) can be found in the following linked spreadsheet: Tabulated Results

The crucial areas prone to spread of infection are near human sitting and standing heights. In this regard, our 'inner middle' zone is of most interest, since it covers the region from 0.9m to 2.15m from the floor. The 'inner' zones exclude a 0.3m (around a foot) distance from all walls (and floor), which generally have a high ART value but are not of much significance, being outside regions of human occupancy.

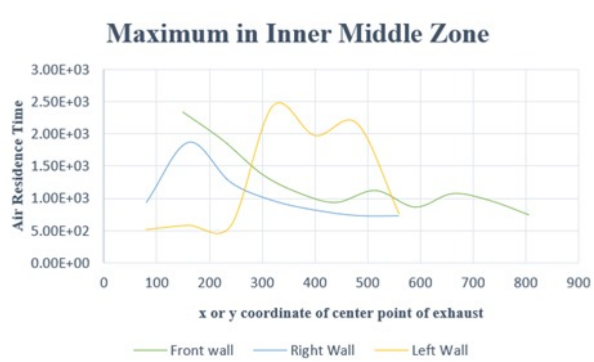

Figure 6: Max ART variation for the three walls

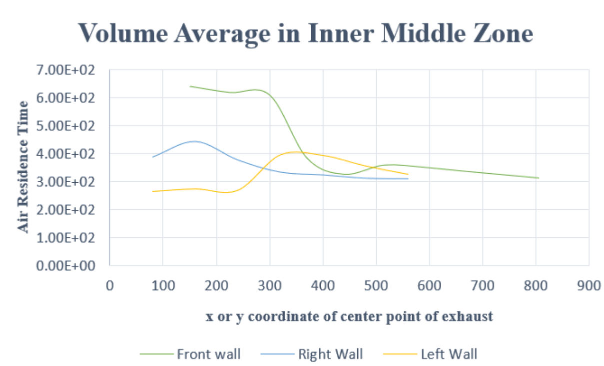

Figure 7: Volume average ART variation for the three walls

Two quantities are used for analysis: maximum ART and volume averaged ART. The plots for ART vs coordinate of exhaust fan on each of the 3 walls is shown above.

Based on these two quantities, the best cases for each wall are default case, case 10 and case 23. The results of these cases are summarised in the table below. Case 20 and Case 9 turned out to be the worst case scenarios, and their results are tabulated as well, showing the impact and relevance of exhaust fan placement on ART.

Case	Max ART	Volume average ART
Default case	744s	313s
Case 10	731s	308s
Case 23	510s	264s
Case 20	2431s	396s
Case 9	2334s	640s

Table 3: Comparison of ART for inner middle zone for various zones of interest

The flow streamlines for the best case (case 23) and worst case (case 9) are shown below.

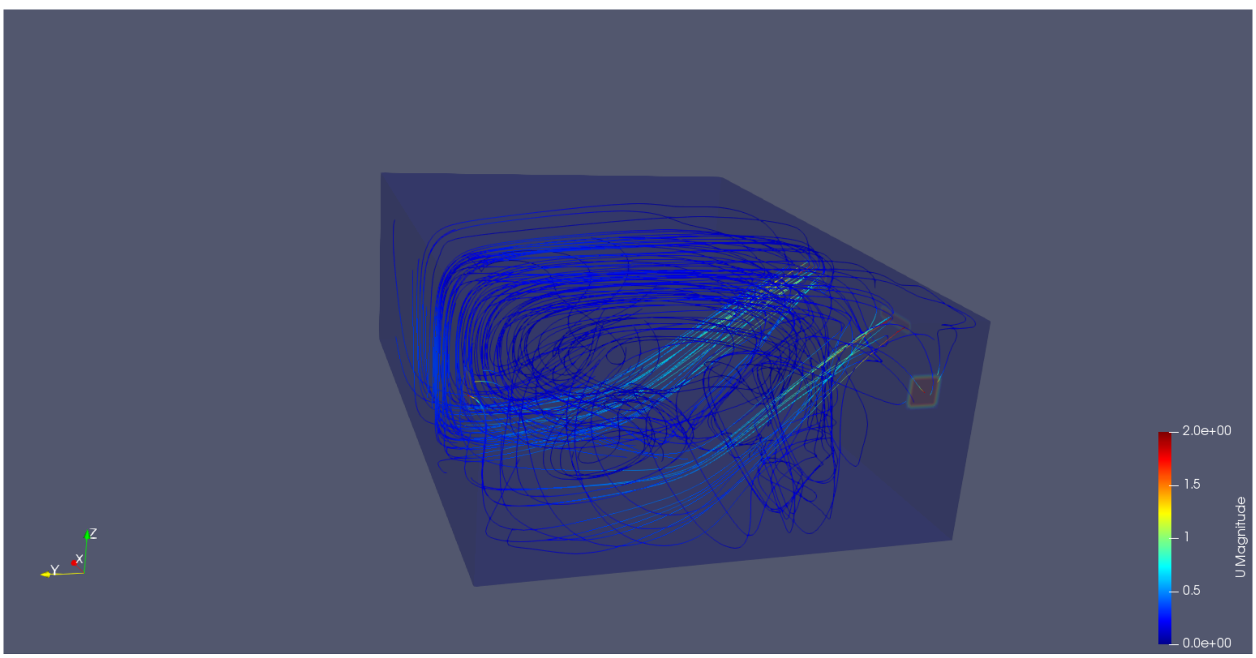

Figure 8: Velocity streamlines for case 23

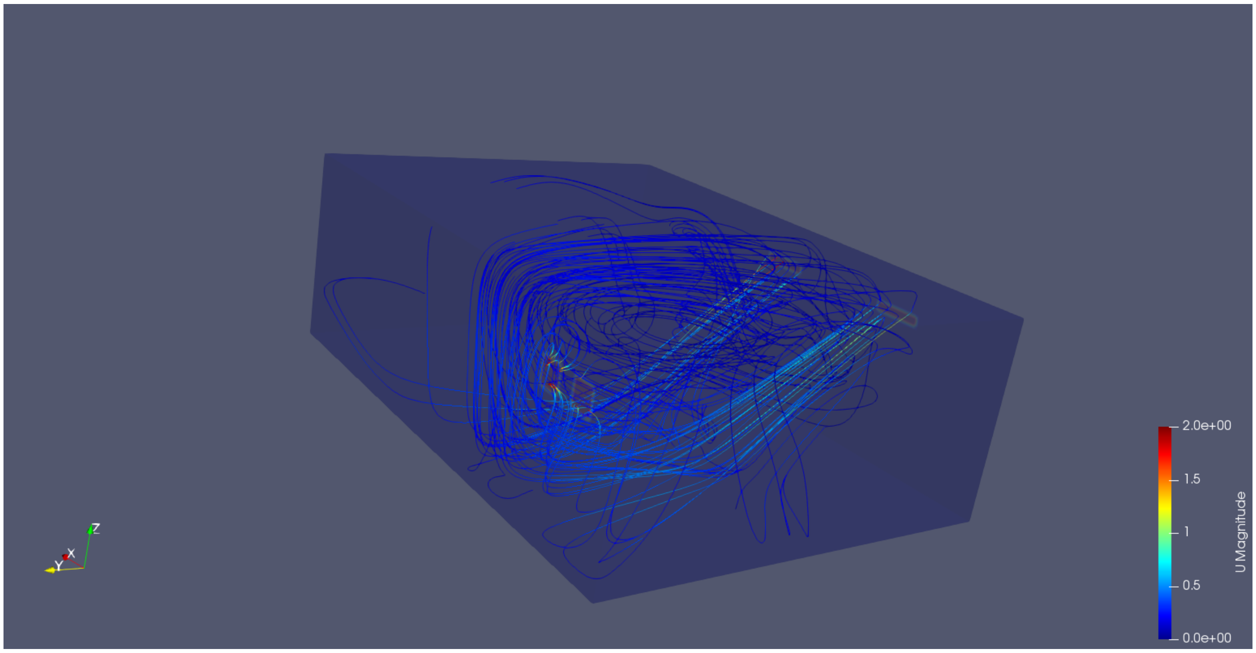

Figure 9: Velocity streamlines for case 9

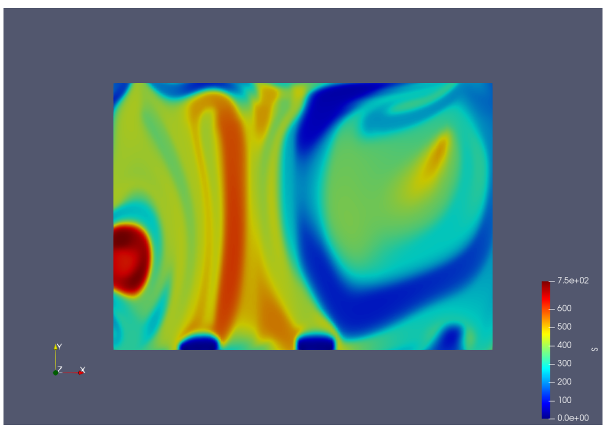

Figure 10: ART contour for Default case

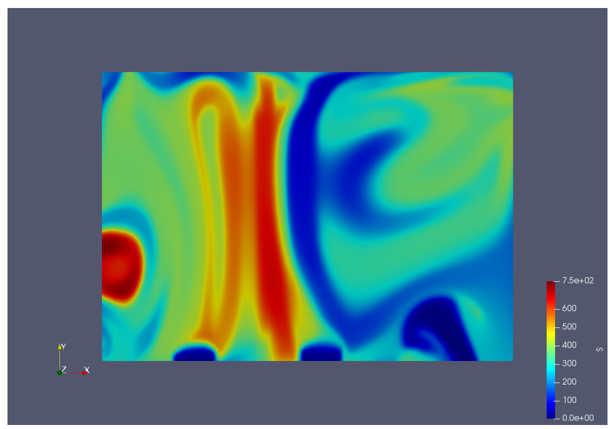

Figure 11: ART contour for Case 10

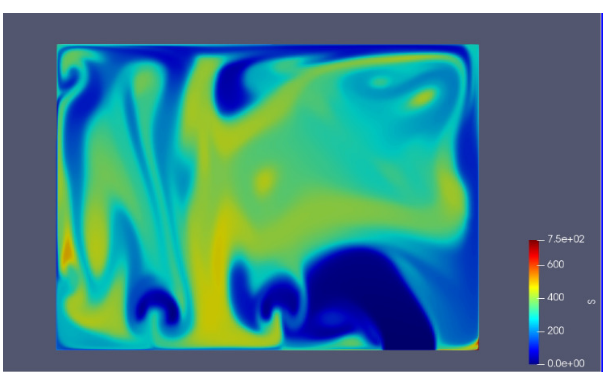

Figure 12: ART contour for Case 23

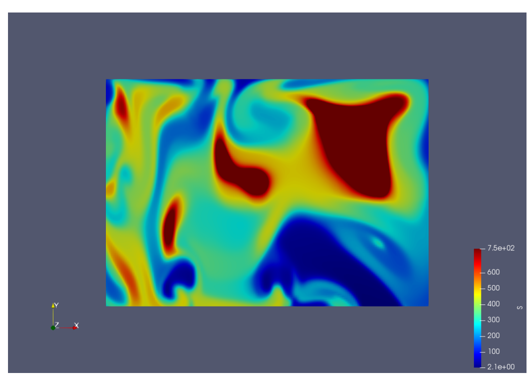

Figure 13: ART contour for Case 20

The ART contours at 1.7m height (around human standing height) are shown above. The scale in all contours is 0 (blue) to 750 (red).

As seen in the contours, there is a recirculation zone (red) on the left-hand side of the room. In case 23, moving the exhaust fan near that recirculation zone helps to break the zone down and reduces ART. In case 20, which has the highest maximum ART, we see that although the exhaust fan is placed on the same wall as that in case 20, which has the lowest max ART, the placement of the exhaust fan affects the ventilation. In case 23, the exhaust fan 'pulls' the stream from AC towards itself, causing dead zones (very low flow) in the opposite corner of the room. In case 20, the exhaust fan manages to dissipate the recirculation in that corner of the room without affecting the AC flow much.

The y+ values obtained for case 23 are shown below:

	Min y+	Max y+	Average y+
Ceiling	0.00127	6.19	2.17
Floor	0.00036	12.22	3.14
Side Walls	0.00036	41.54	2.11

Table 4: y+ values for Case 23

6 Machine Learning

After performing more than 24 CFD simulations, machine learning algorithms were used to track patterns in the maximum and volume-averaged air residence time values of the room for the different positions of the variable exhaust fan.

Initially, the x and y coordinates of the centre of the variable exhaust fan were used as input to the model, and the air residence time in various zones was set as target variables. The machine learning algorithm was run in four zones, i.e. the outer zone, inner upper zone, inner middle zone, and the inner bottom zone for both the maximum value of air residence time and the volume averaged value of the air residence time in that zone. Thus, the model had to be run eight times to find out the prediction accuracies. Additional features were generated using polynomial features transformation from the Python library scikit-learn, to improve performance of the training algorithm. The data was then scaled appropriately and the scikit-learn linear regressor model was used to train and test the data. Approximately 75% of the data was used for training and the remaining 25% for testing. However, the lack of sufficient amount of data caused large mean absolute percentage errors of around 60% during testing for almost all the zones.

To tackle this issue, data of each of the three walls where the exhaust fan was present was first isolated, after which the machine learning algorithm was run separately for each wall, taking only one input variable (x or y coordinate) and one target variable (air residence time). Simple linear regression was effective, as this improved accuracy, and the mean absolute percentage errors in all eight columns (one column corresponds to either maximum or volume averaged residence time for a particular zone) decreased to around 20%, except for some columns, but this can also be explained by the lack of data, as no particular trend could be seen.

In conclusion, the machine learning algorithm performed well when a simple linear regressor model was used on a single variable and single output case. This is because simple models often require fewer data to train and identify trends, even if they are not the most accurate. More complex models like artificial neural networks and convolutional neural networks could have been used to predict the air residence time if there were sufficient data for training. The model can also be reverse trained so that an input ART gives the x and y coordinates of the exhaust fan. This can be useful when trying to find fan positions for a room.

7 Ventilation improvement strategy

In order to improve the ventilation in the room, the best case among the 24 cases was picked up (case 23) and interventions were tested out to improve the ART in the room.

The ventilation solutions which were tried are:

- Placement of an additional air conditioner on the wall opposite to the door
- Placement of an additional air conditioner on the wall adjacent to the door
- Addition of an exhaust fan on the wall adjacent to the door and an air conditioner on the wall opposite to the door.
- Addition of an air conditioner on the wall adjacent to the door and an air conditioner on the wall opposite to the door.

Among these four cases, the last case showed promising results for reduction of ART in the room. The two additional air conditioners were given the velocity boundary condition of 2m/s, similar to the other two air conditioners, but the air was thrown inside the room at an angle of 75 degrees with the vertical, slightly higher than the original case. Other boundary conditions were the same. A reduction in the volume averaged ART was observed because of the presence of the two air conditioners. The flow from the air conditioners help in breaking the recirculation zone on the top right side of the room as shown in Figure 15, hence improving the ventilation.

Case	Max ART	Volume averaged ART
Case 23	510s	264s
Case 23 with two ACs	603s	222s

Table 5: Changes in ART for inner middle zone using two air conditioners

It can be seen that even though the volume averaged value of ART reduced, the maximum value of ART in the inner middle zone increased. This could have been caused by the formation of smaller recirculation zones on the breakup of the larger recirculation zones, leading to local values of high ART, even though the overall ventilation was improved.

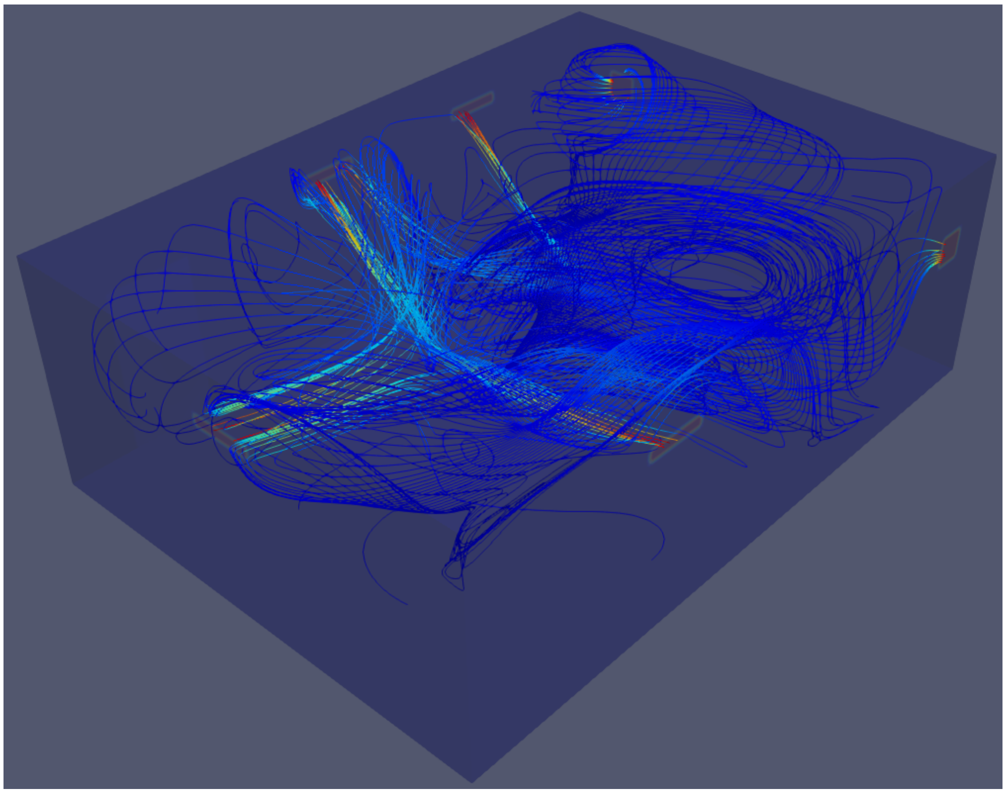

Figure 14: Velocity streamlines inside the room

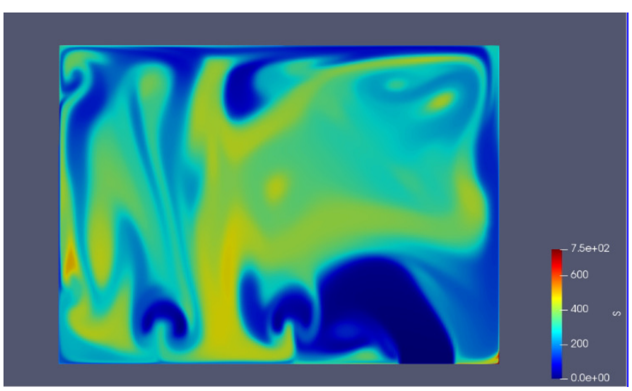

Figure 15: ART contour for Case 23

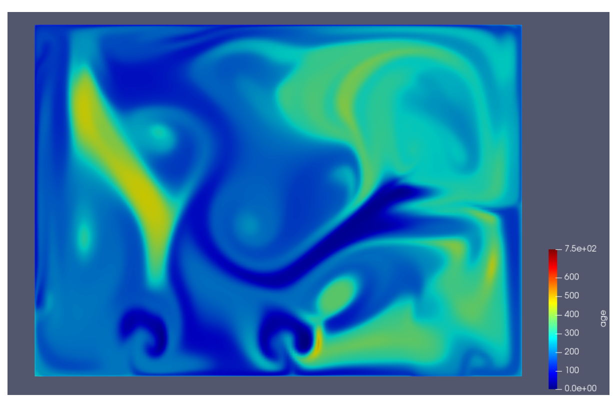

Figure 16: ART contour for Case 23 with air conditioners

It can be seen in Figure 16 that the two additional air conditioners have broken the recirculation zone, leading to generation of smaller recirculation zones and a reduction in overall air residence time.

8 Conclusions

The flow and ventilation analysis of a classroom in Chemical Engineering Department at IIT Bombay was carried out. The air residence time for various locations of an exhaust fan was obtained via OpenFOAM CFD simulations, and an optimum position of the exhaust fan was found out. A machine learning model was trained on the data set obtained from CFD in order to be able to directly predict the air residence time for a given exhaust fan position, in order to eliminate the high computational time and power required for the flow and air residence time calculations. Two additional air conditioners were proposed as interventions in the room to further reduce ART, and the simulation results validate the efficacy of this strategy by demonstrating a noticeable decrease in ART values.

References

[1] Sinha, K., Yadav, M. S., Verma, U., Murallidharan, J. S., & Kumar, V. (2021, November 1). *Effect of recirculation zones on the ventilation of a public washroom*, Physics of Fluids `https://doi.org/10.1063/5.0064337`

[2] Fluid-Mechanics-101.(2021). *Calculators and tools* `https://www.fluidmechanics101.com/pages/tools.html` (accessed: 10.04.2024).