Mini Project Viva Voce

STUDYING THE VENTILATION PATTERNS IN A COVID-19 MULTI-PATIENT WARD USING CFD

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Table of Contents

1. PROBLEM STATEMENT

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Hospitals are required to implement containment strategies to prevent their staff and visitors from spreading the disease, usually through isolation wards.

By studying the natural ventilation patterns inside a hospital ward, we can try to curb the spread of airborne pathogens.

In India, the National Centre for Disease Control (NCDC) publishes guidelines addressing the setting up of isolation wards in hospitals.

We propose to design an isolation ward using FreeCAD in accordance with the NCDC guidelines for COVID 19, and use OpenFOAM to study the ventilation patterns in the room.

2. LITERATURE SURVEY

2.1 General CFD Papers

[1] Application of open-source CFD software to the indoor airflow simulation

Wang, C., Sadrizadeh, S., Holmberg, H., 38th AIVC Conference, **2017**

[2] Thermo-ventilation study by OpenFOAM

Limane, A., Fellouah, H., Galanis, N., *Build. Simul.* 8, **2015**

[3] Natural Ventilation for agriculture buildings

Hong, S., Exadaktylos, V,. Lee, I., Amon, T., Youssef, A., Norton, T., Berckmans, D., *Computers and Electronics in Agriculture*, Volume 138, **2017**

2.1 General CFD Papers

[4] [Comparison of OpenFOAM and ANSYS Fluent]

Welahettige, P., Vaagsaether, K., 9th EUROSIM Conference, **2016**

[5] [OpenFOAM simulation of the natural ventilation system in a university chemical laboratory]

Córdova-Suárez, M., Tene-Salazar, O., Tigre-Ortega, F., et al., E3S Web Conf. Volume 167, **2020**

2.2 Hospital Related Papers

[6] Development of ventilation design strategy for effective removal of pollutant in the isolation room of a hospital

K.W.D. Cheong, S.Y. Phua, *Building and Environment*, Volume 41, Issue 9, **2006**

[7] The ventilation of multiple-bed hospital wards: Review and analysis

Beggs, C., Kerr, K., Noakes, C., Hathway, A., Sleigh, A., *American Journal of Infection Control*, **2008**

[8] Numerical Study of Three Ventilation Strategies in a prefabricated COVID-19 inpatient ward

Juan Ren, Yue Wang, Qibo Liu, Yu Liu, *Building and Environment*, Volume 188, Issue 9, **2007**

3. METHODOLOGY

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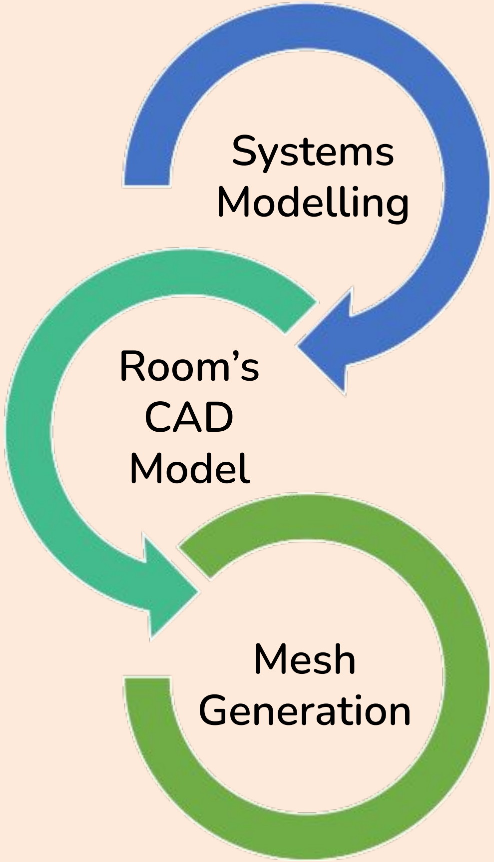
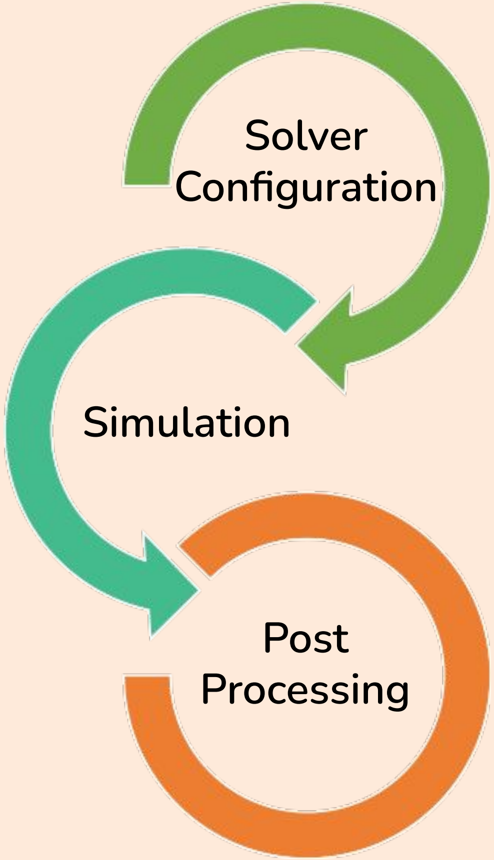


Calculate the size of ventilation ducts for the ward.

Design the room's floor plan according to NCDC guidelines.
Export the model as a STEP file for meshing.

Generate the mesh using Gmsh.

3. METHODOLOGY



Select the Finite Volume solver in OpenFOAM.
Define boundary conditions for the flow field.

Run the OpenFOAM case to simulate the flow field.

Visualize the results in ParaView.

3.1 Main Duct Design

1. IS 659 (1964) safety code for air conditioning states the guidelines for designing an AC system for hospitals.
2. The NCDC guidelines mandate the number of Air Changes Per Hour to be at least 12.

$$ACPH = \frac{60Q}{Volume}$$

$$\Rightarrow 12 = \frac{60Q}{24000}$$

$$\Rightarrow Q = 4800CFM$$

4.1.1 Main Duct Design

IS : 659 - 1964

TABLE 1 MINIMUM FRESH AIR REQUIREMENTS

(*Clauses* 3.2 *and* 3.2.1)

SL No.	APPLICATION	SMOKING	m^3/min PER PERSON Recom-mended	Mini-mum	m^3/min PER m^2 OF FLOOR AREA
(1)	(2)	(3)	(4)	(5)	(6)
i)	Apartments	Some	0.56	0.28	—
ii)	Banking space	Occasional	0.28	0.21	—
iii)	Board rooms	Very heavy	1.40	0.56	—
iv)	Department stores	None	0.21	0.14	0.015
v)	Directors' rooms	Very heavy	1.40	0.84	—
vi)	Drug stores*	Considerable	0.28	0.21	—
vii)	Factories†	None	0.28	0.21	0.03
viii)	Oarages	—	—	—	0.30
ix)	Hospitals:				
	a) Operating rooms (all fresh air)	None			0.60
	b) Private rooms	None	0.84	0.70	0.10
	c) Wards	None	0.56	0.28	—
x)	Hotel rooms	Heavy	0.84	0.70	0.10

IS 659 (1964)

- Ensure that appropriate hand washing facilities and hand-hygiene supplies are available. Stock the sink area with suitable supplies for hand washing, and with alcohol-based hand rub near the point of care and the room door.
- Ensure adequate room ventilation. If room is air-conditioned, ensure 12 air changes/ hour and filtering of exhaust air. A negative pressure in isolation rooms is desirable for patients requiring aerosolization procedures (intubation, suction nebulisation). These rooms may have standalone air-conditioning. These areas should not be a part of the central air-conditioning.
- If air-conditioning is not available negative pressure could also be created through putting up 3-4 exhaust fans driving air out of the room.

NCDC Guidelines

3.1 Main Duct Design

$$Area = \frac{Q}{V}$$

$$A_{max} = \frac{4800}{1000} = 4.8 sqft$$

$$A_{min} = \frac{4800}{1500} = 3.2 sqft$$

Hence, we fix the duct parameters as

- Velocity : 1000 fpm
- Dimensions : 3 ft x 1.6 ft

3.1 Main Duct Design

5.2 Velocity Reduction Method

This method sizes the duct by varying the velocity in the main and branch ducts. The various steps involved are:

a. Select suitable velocities in the main and branch ducts. The table below indicates commonly used velocity limits:

Type of Duct	Comfort Systems Velocity (fpm)	Industrial Systems Velocity (fpm)	High Speed Systems Velocity (fpm)
Main duct	1000 - 1500	1500 - 2400	2000 - 3600
Main branch duct	700 - 1000	1000 - 1600	1200 - 2400
Runout duct	400 - 600	600 - 800	800 - 1000

b. Find the diameters of the main and branch ducts from air flow rates and velocities. The velocity in duct can be expressed as:

$$A = Q / v$$

Where,

- A = duct area (ft^2)
- Q = air flow rate (cfm)
- v = air speed (fpm)

(HVAC - How to Size and Design Ducts)

3.2 Room CAD Model

According to the NCDC,

- At District level, a minimum of 10 bed isolation ward should be established.
- COVID - 19 patients should be housed in single rooms
- If sufficient single rooms are not available, beds could be kept at least 1 metre (3 feet) apart from from other.
- To create a 10 bed facility, a minimum space of 2000 sq feet area clearly segregated from other patient care areas is required.

3.2 Room CAD Model

B. Setting up isolation facility/ward

An isolation facility aims to control the airflow in the room so that the number of airborne infectious particles is reduced to a level that ensures cross-infection of other people within a healthcare facility is highly unlikely.

- At State level, a minimum of **50** bed isolation ward should be established.
- At District level, a minimum of **10** bed isolation ward should be established.
  - Post signages on the door indicating that the space is an isolation area.
  - Remove all non-essential furniture and ensure that the remaining furniture is easy to clean, and does not conceal or retain dirt or moisture within or around it.
  - COVID-19 patients should be housed in single rooms.
  - However, if sufficient single rooms are not available, beds could be put with a spatial separation of at least 1 meter (3 feet) from one another.
  - To create a 10 bed facility, a minimum space of 2000 sq. feet area clearly segregated from other patientcare areas is required.
  - Preferably the isolation ward should have a separate entry/exit and should not be co-located with post-surgical wards/dialysis unit/SNCU/labour room etc.
  - It should be in a segregated area which is not frequented by outsiders.
  - The access to isolation ward should be through dedicated lift/guarded stairs.

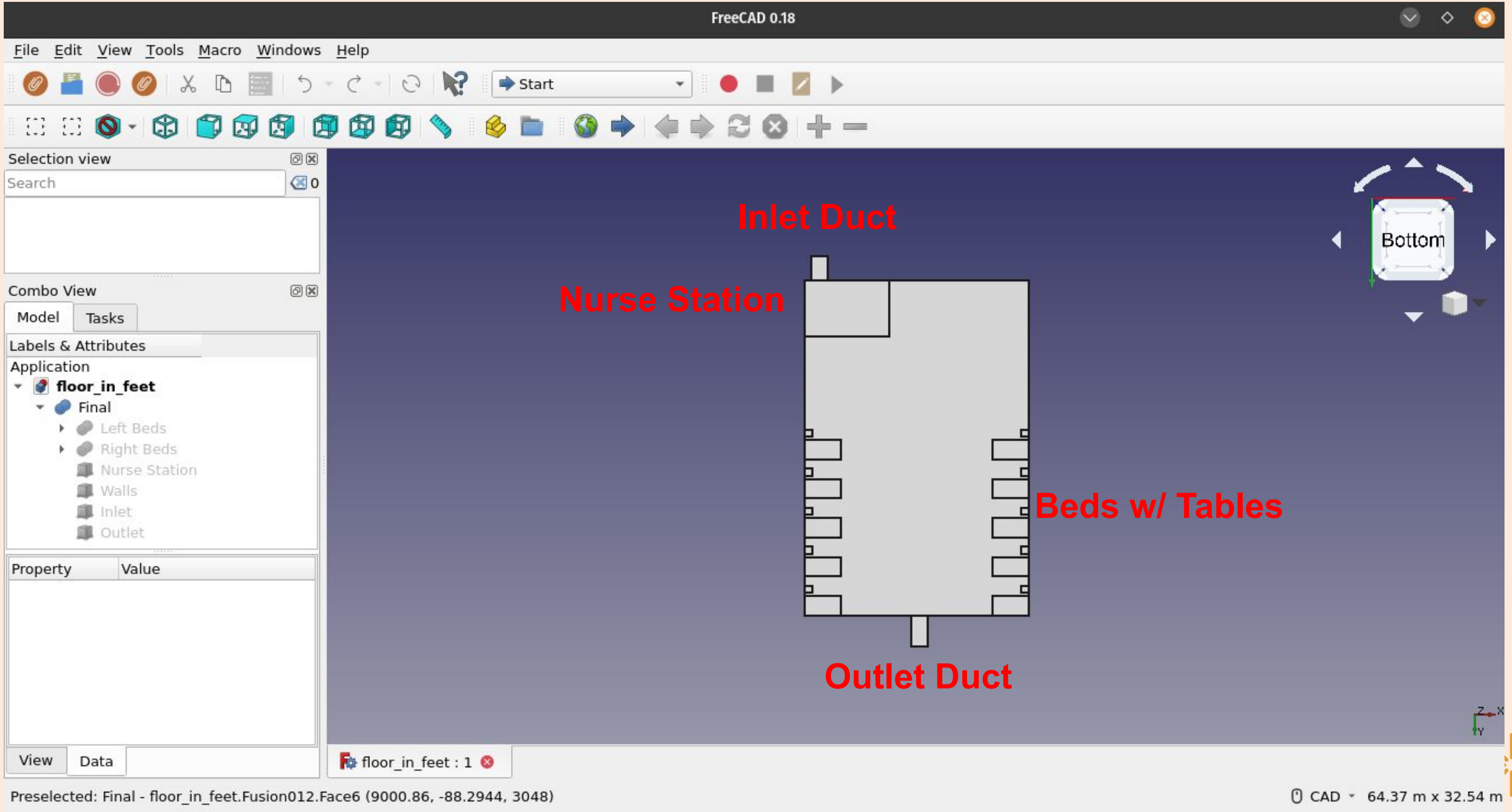
NCDC Guidelines for the handling of the COVID 19 pandemic

3.2 Room CAD Model

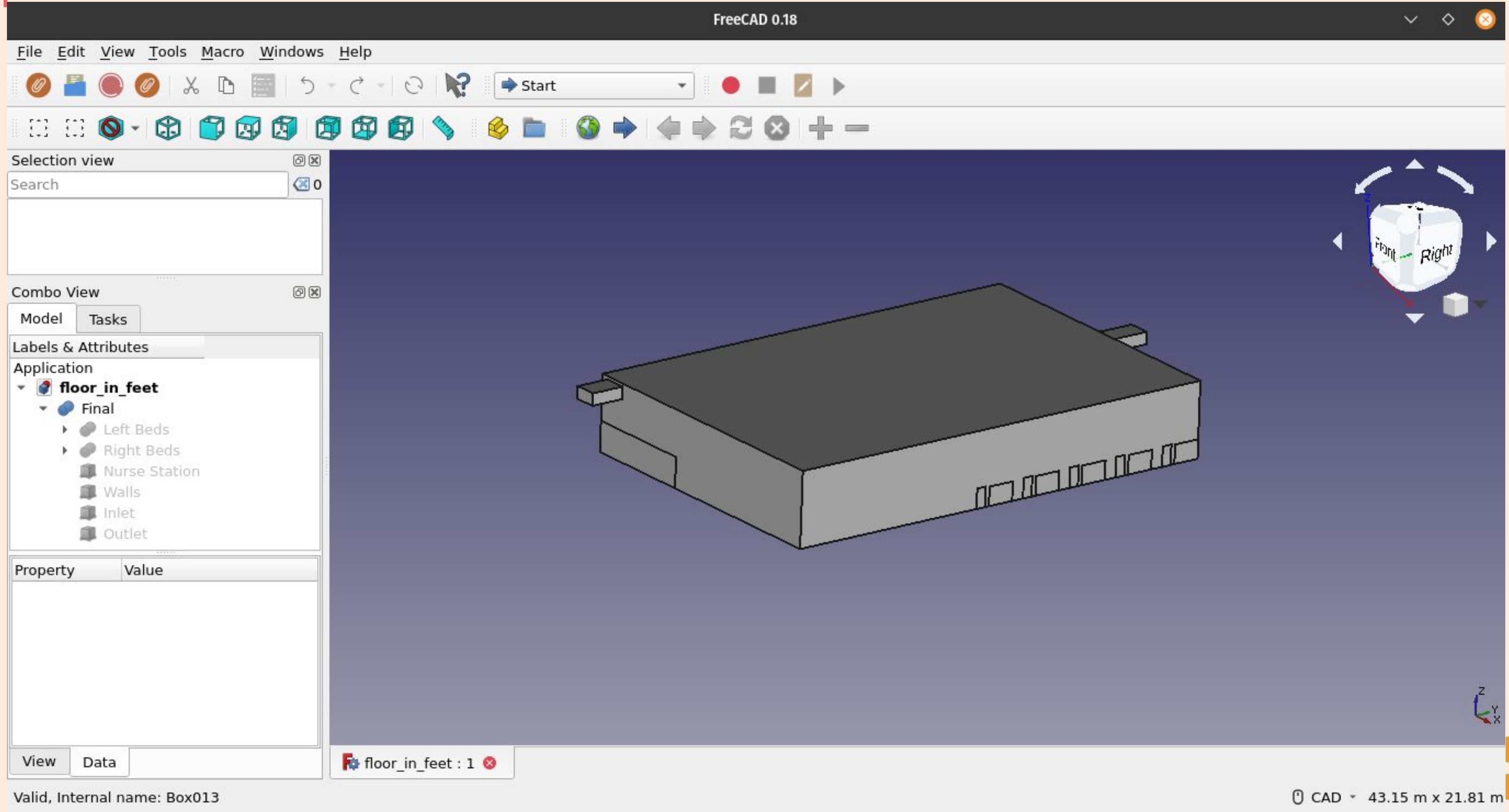
Our Dimensions:

- Room : 60 ft x 40 ft x 10 ft
- Patient Bed : 6.5 ft x 3.5 ft x 2.5 ft
- Patient Bedside Table : 1.3 ft x 1.3 ft x 2.62 ft
- Nurse Station : 15 ft x 10 ft x 4 ft
- Ventilation Duct : 3 ft x 8 ft x 1.6 ft

3.2 Room CAD Model



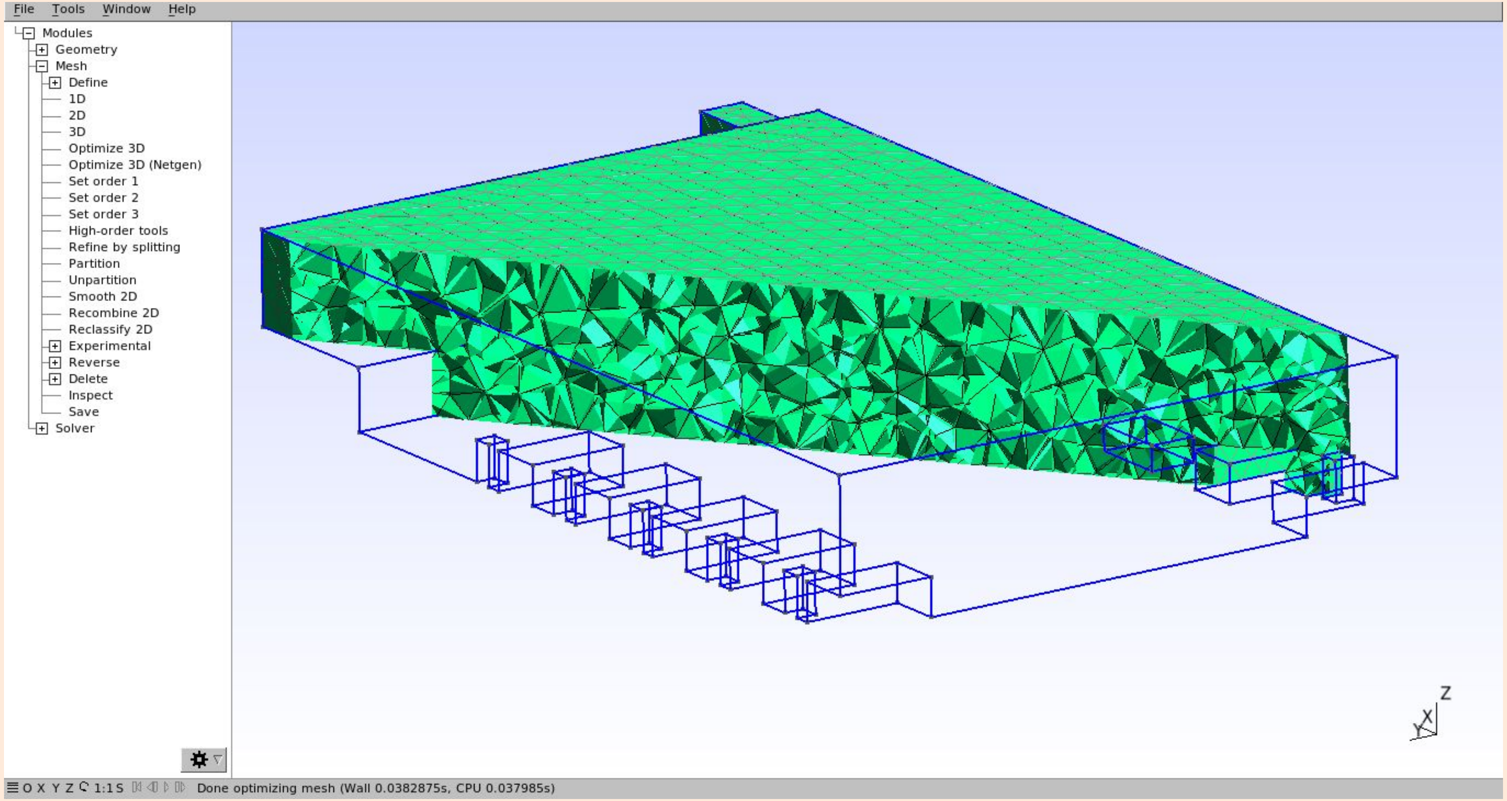
3.2 Room CAD Model



3.3 Mesh Generation

- First, we export the STEP file from FreeCAD. Then, we import it into Gmsh and prepare it for OpenFOAM.
- We generated a quad mesh from our model initially, but shifted to hex mesh later.

3.3 Mesh Generation



4. Case Setup

4.1 Properties and Assumptions

Properties :

- Kinematic viscosity = $1.6 * 10^{-6}$ m^2/s
- Room Temperature = 20° C
- Density = 1.204 kg / m^3

Assumptions :

- Incompressible, unsteady, laminar flow
- Air behaves as an ideal gas

4.2 Boundary Conditions

SURFACE	BOUNDARY CONDITIONS	
	Velocity (m/s)	Kinematic Pressure (m^2/s^2)
Main inlet	(-5.186, 0, 0)	Zero Gradient
Branch inlet	(0, 0, -5.186)	Zero Gradient
Main outlet	Zero Gradient	Uniform 0
Branch outlet	Zero Gradient	Uniform 0
Walls	No Slip	Zero Gradient
Surfaces	No Slip	Zero Gradient

4.3 Equations

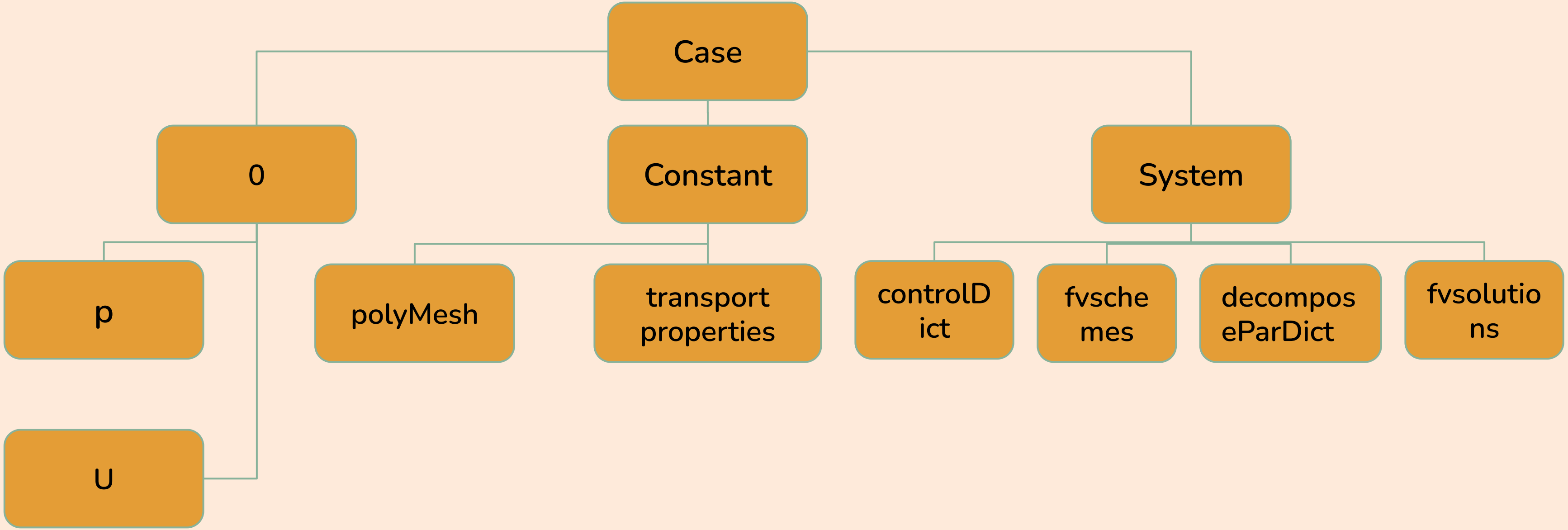
Continuity equation :

$$\frac{\partial \rho}{\partial t} + \overrightarrow{\nabla} \cdot (\rho \overrightarrow{u}) = 0$$

Navier-Stokes equation :

$$\rho[\frac{\partial \overrightarrow{v}}{\partial t} + \overrightarrow{v} \cdot \overrightarrow{\nabla v}] = -\overrightarrow{\nabla p} + \overrightarrow{\nabla} \cdot \overline{\overline{\tau}} + \rho \overrightarrow{f}$$

4.4 Configuration



5. Simulation Results

5.1 Cases We're Discussing

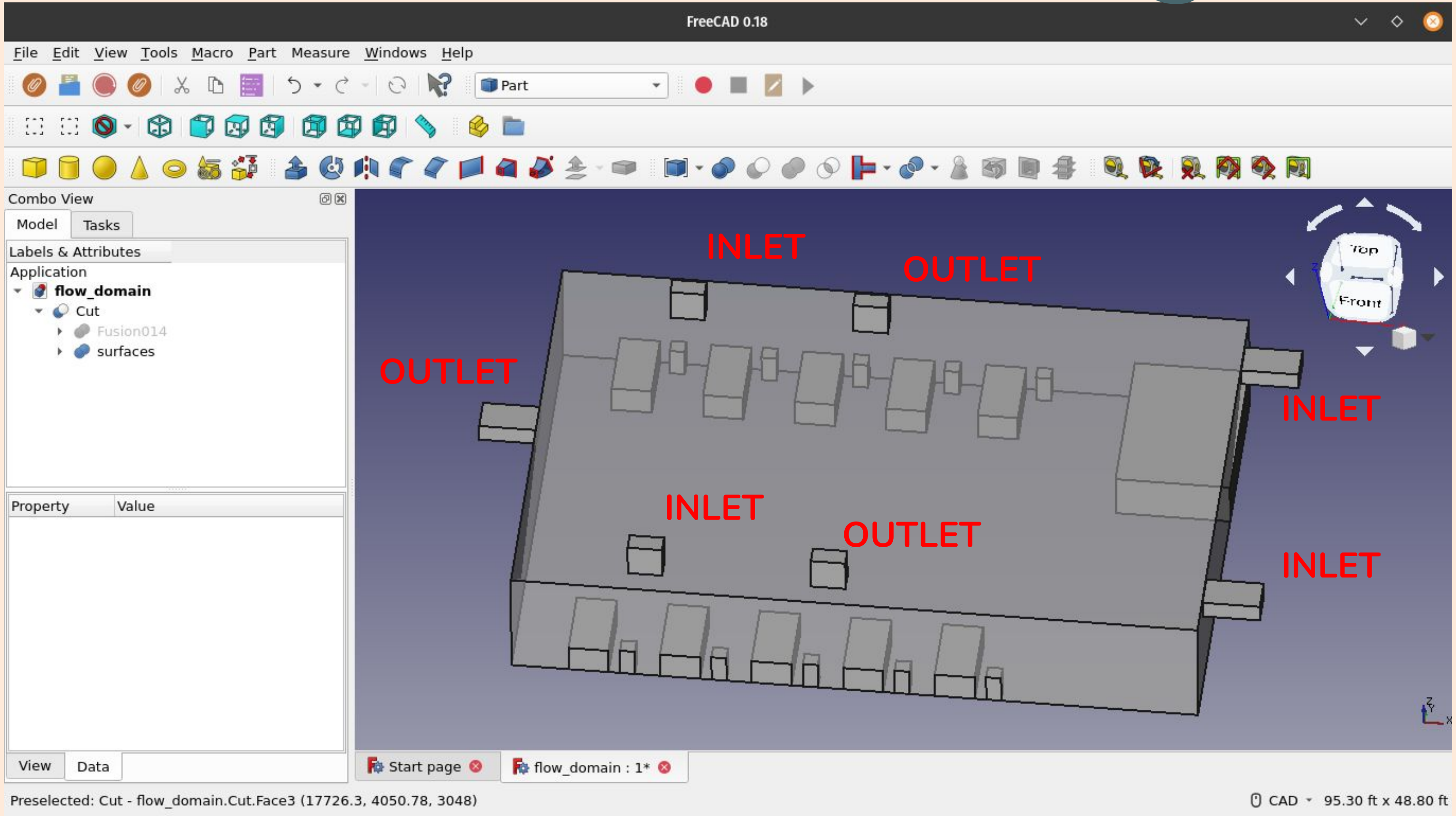
3_wall_4_ceiling

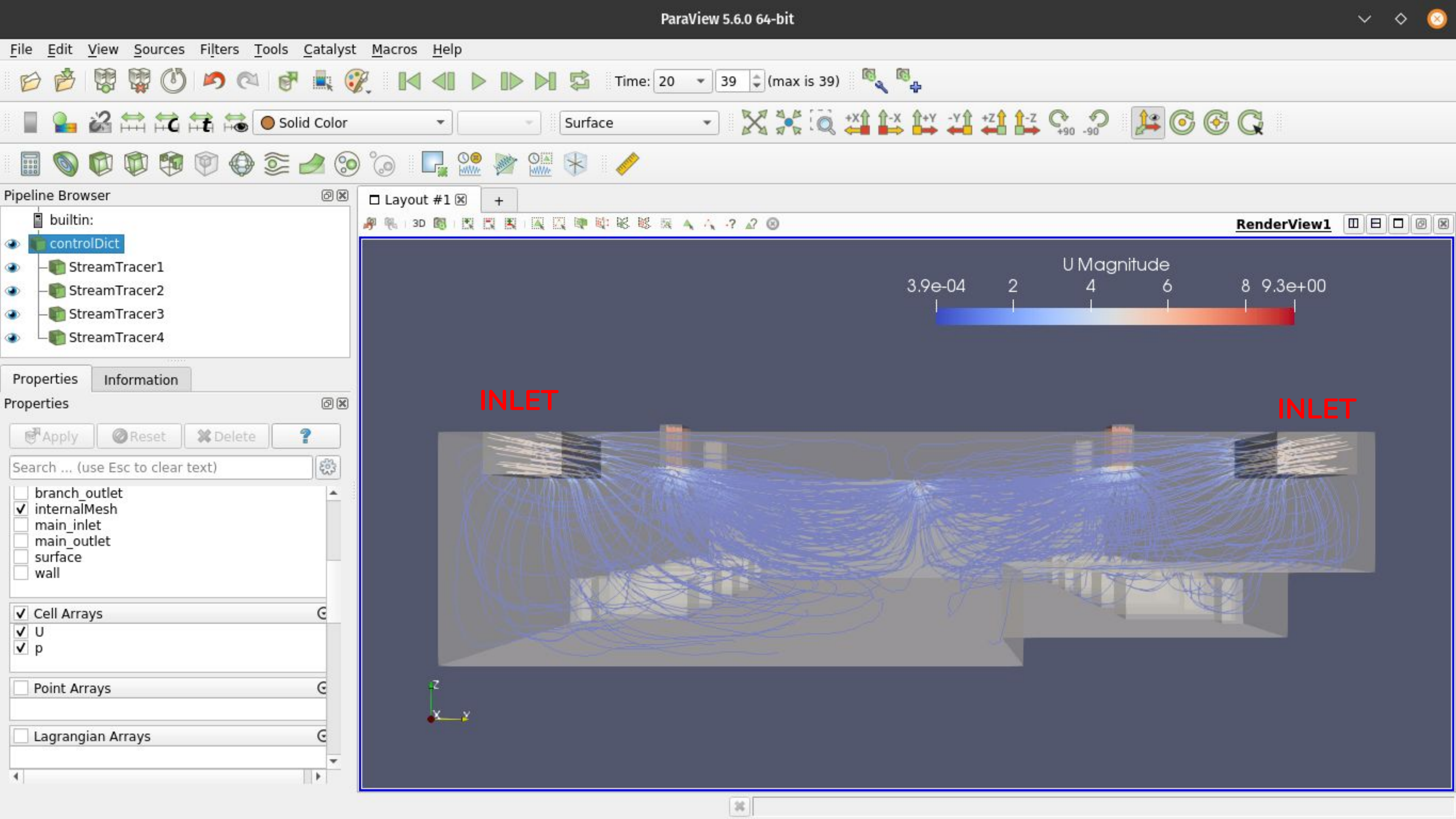
- Installed two wall mounted inlets, while also removing one of the ceiling mounted inlets in an attempt to improve flow near nurse station.

3_wall_5_ceiling

- Added an extra outlet vent to the previous case to see what effect it would have on the flow.

5.2 3_wall_4_ceiling

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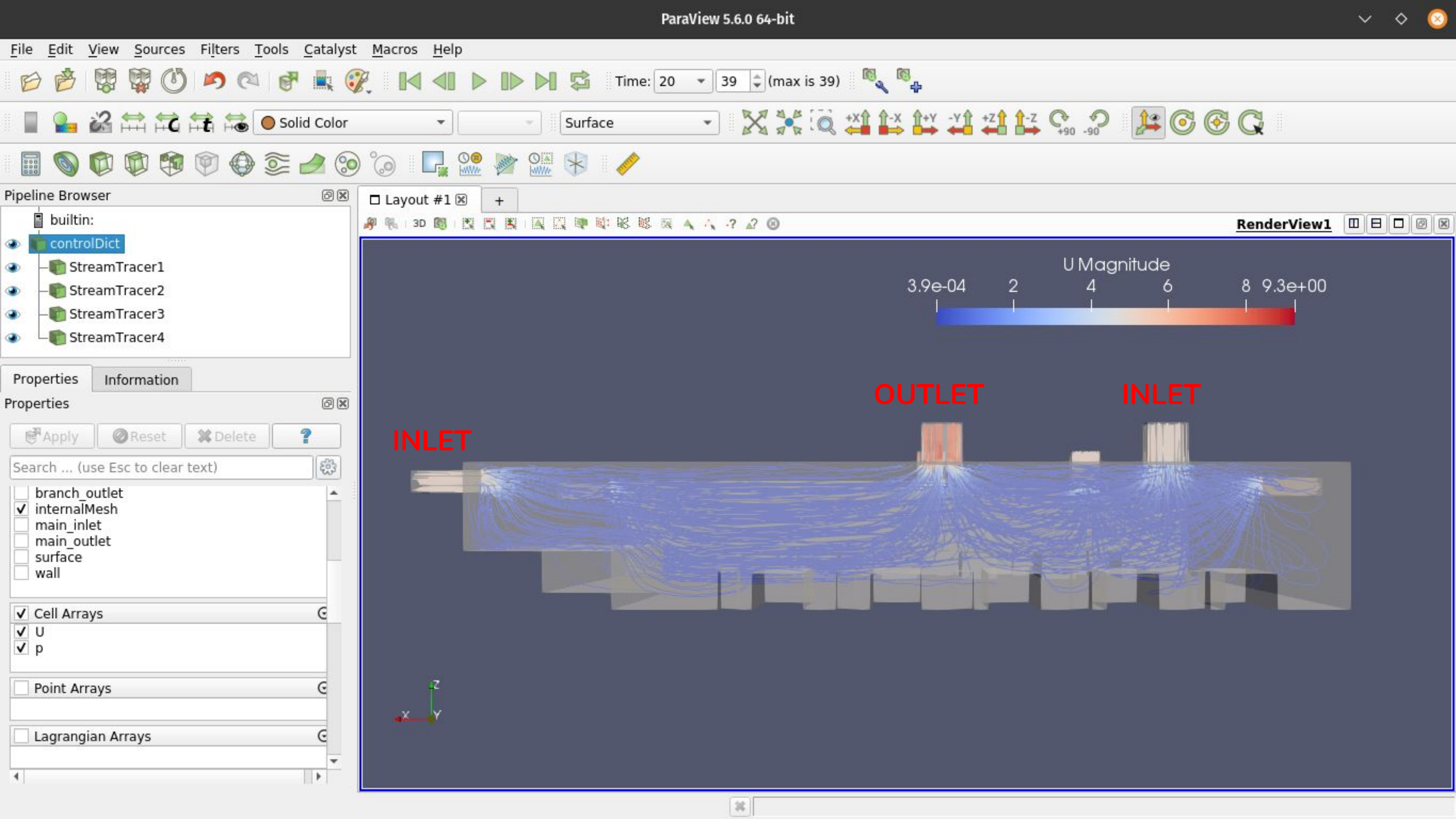

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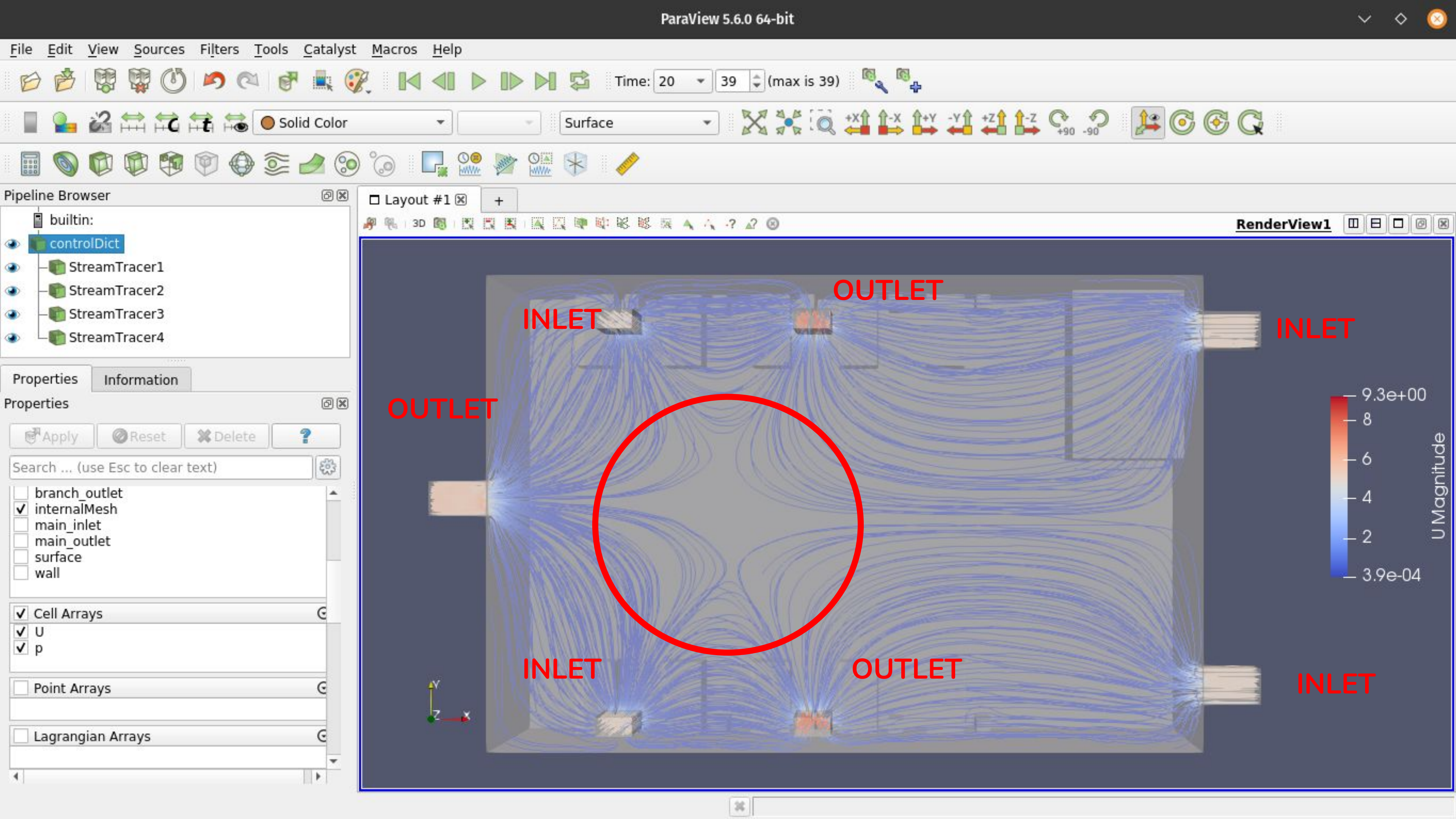
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5.2 3_wall_4_ceiling

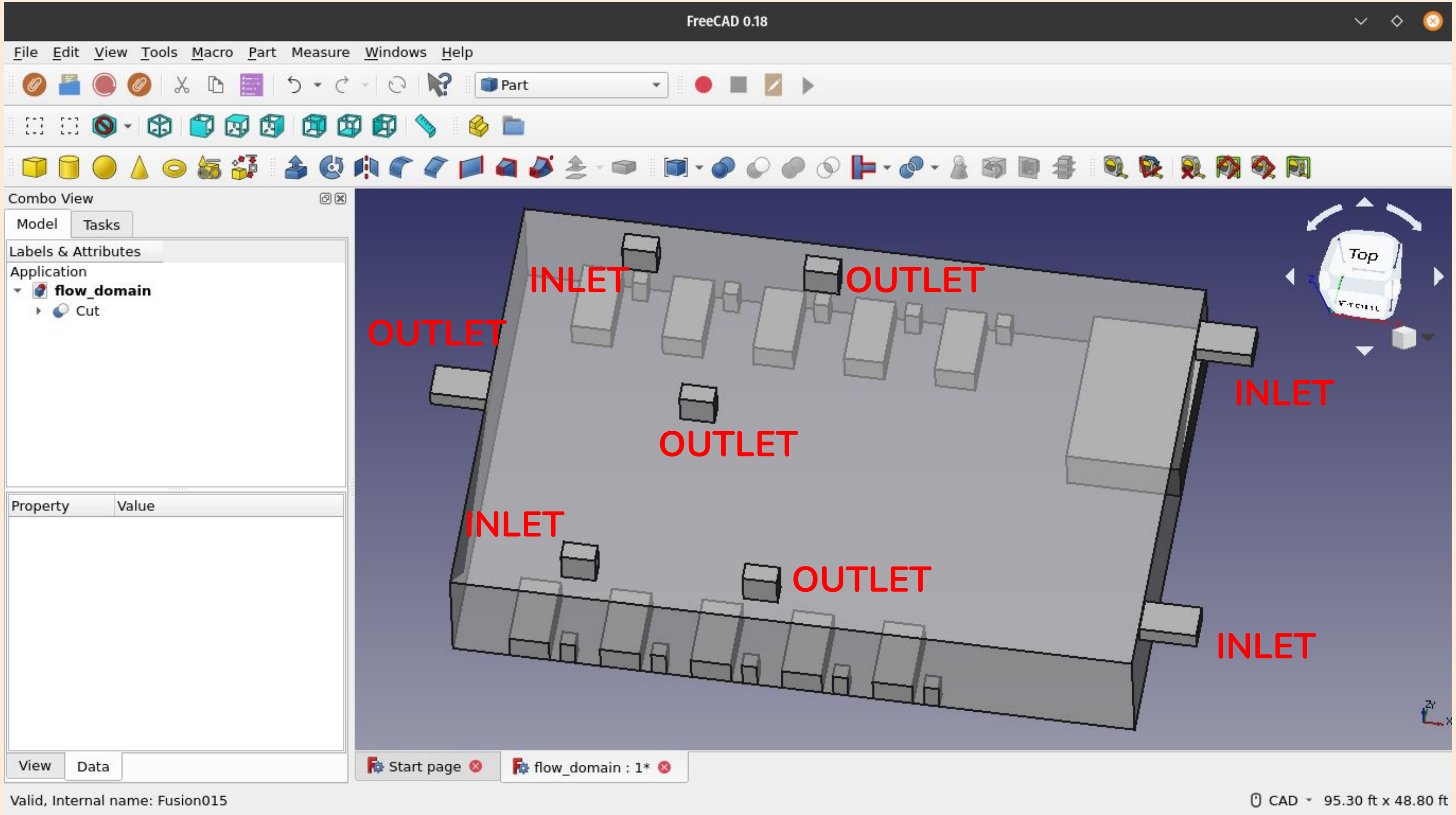
Key Takeaways:

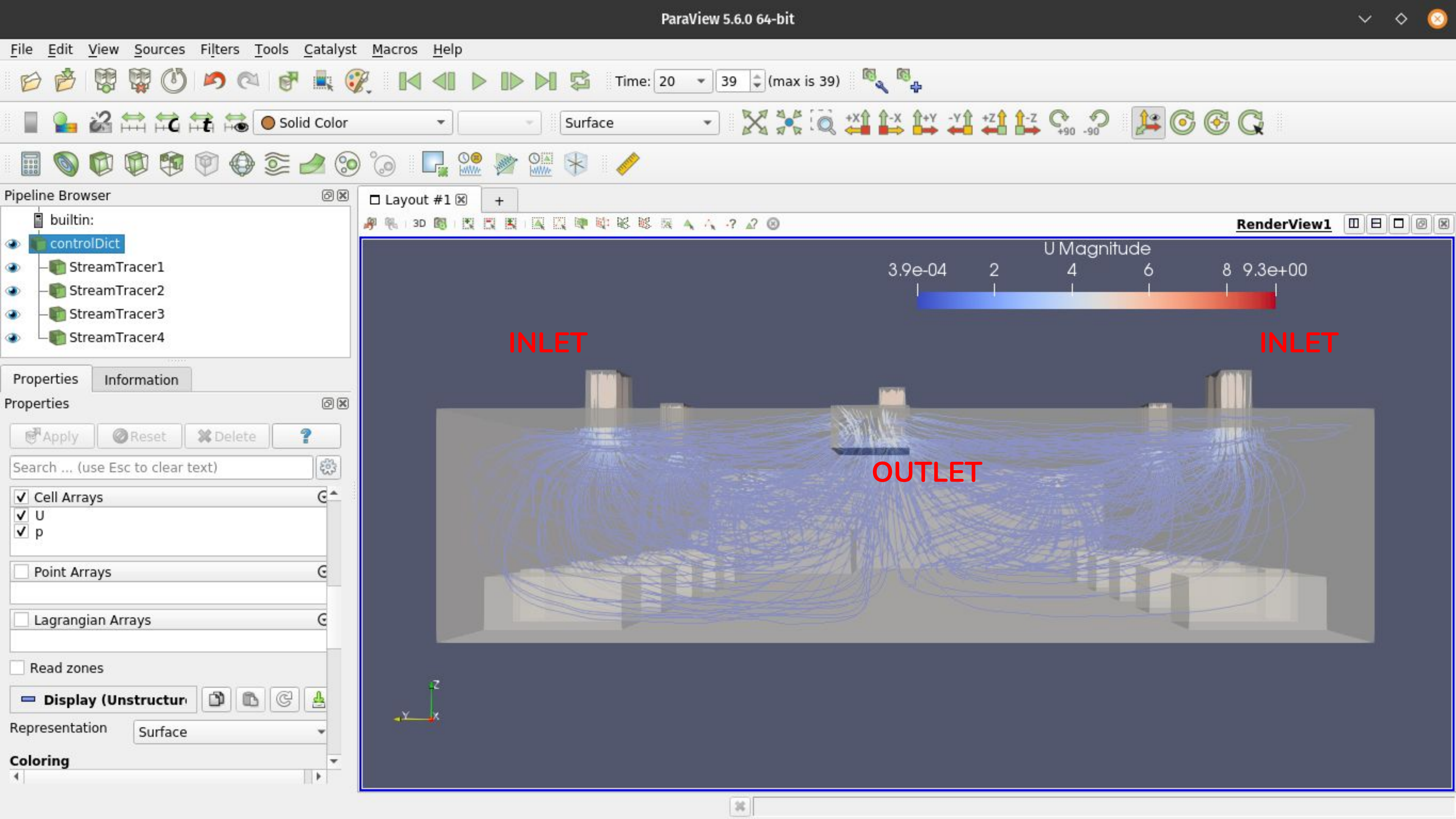
- The nurse station receives good airflow.
- There is a large volume in the middle of the room, which needs proper ventilation.

Next step:

- Try adding ceiling-mounted outlet in the middle.

5.3 3_wall_5_ceiling

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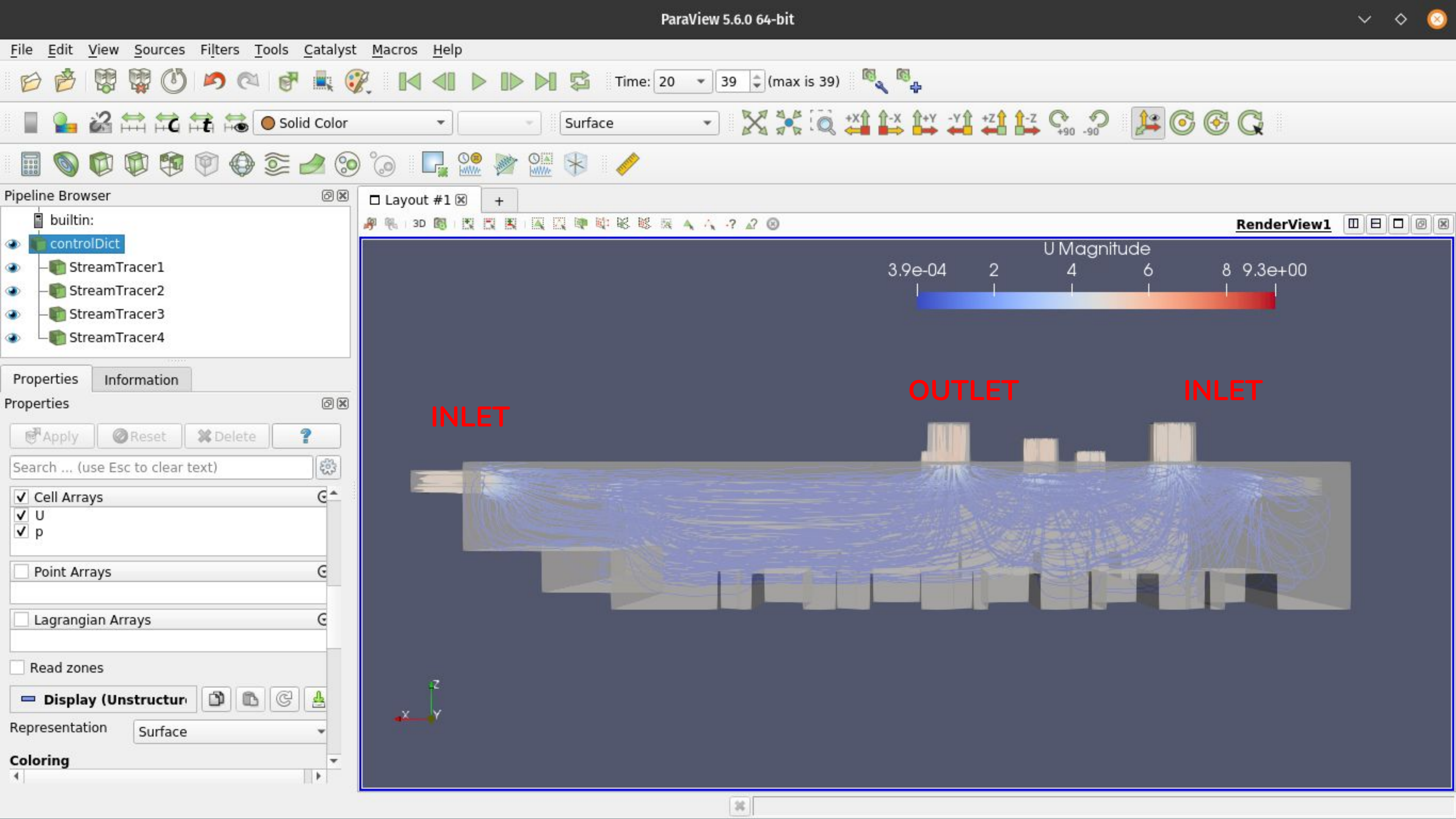
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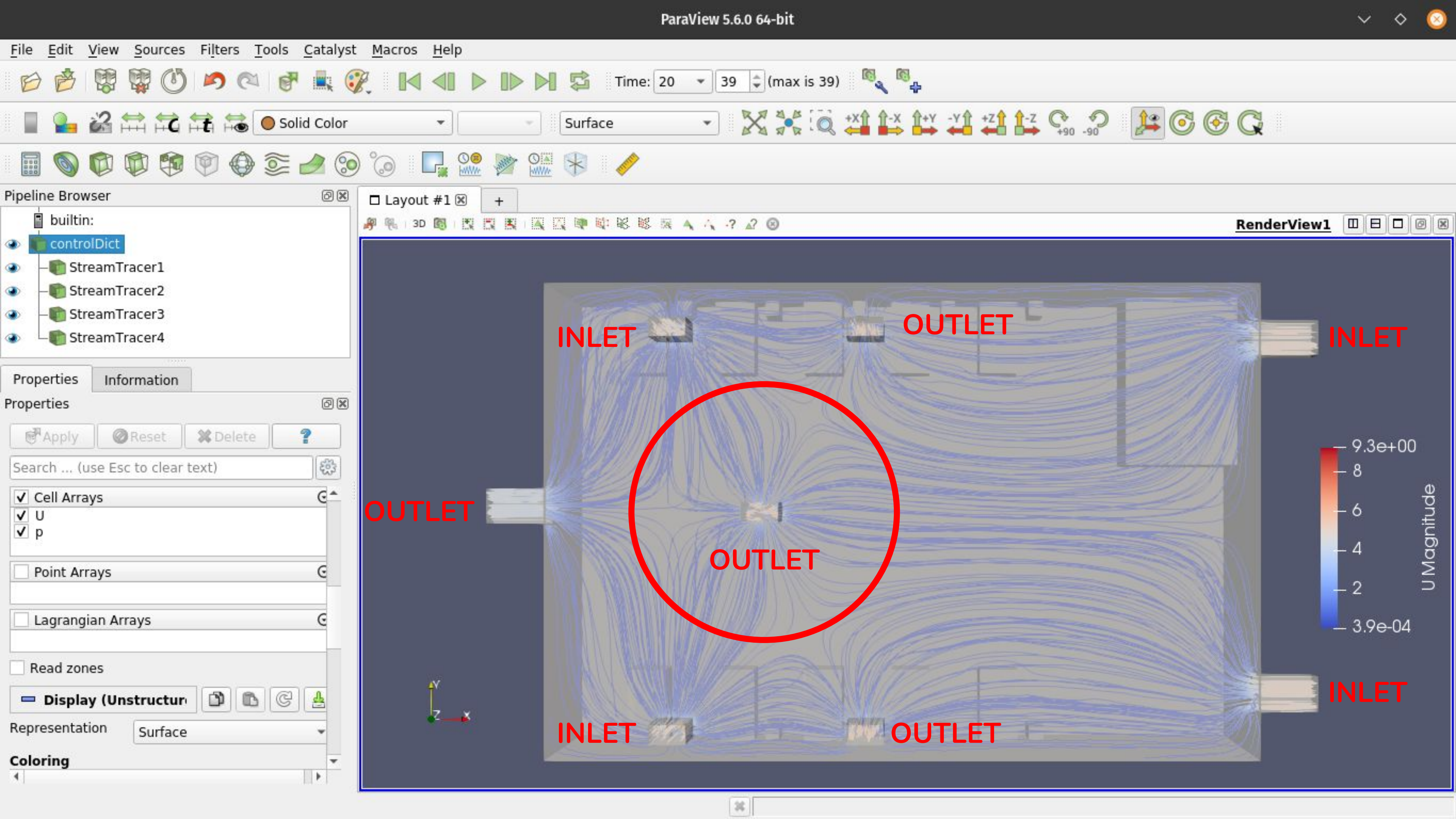
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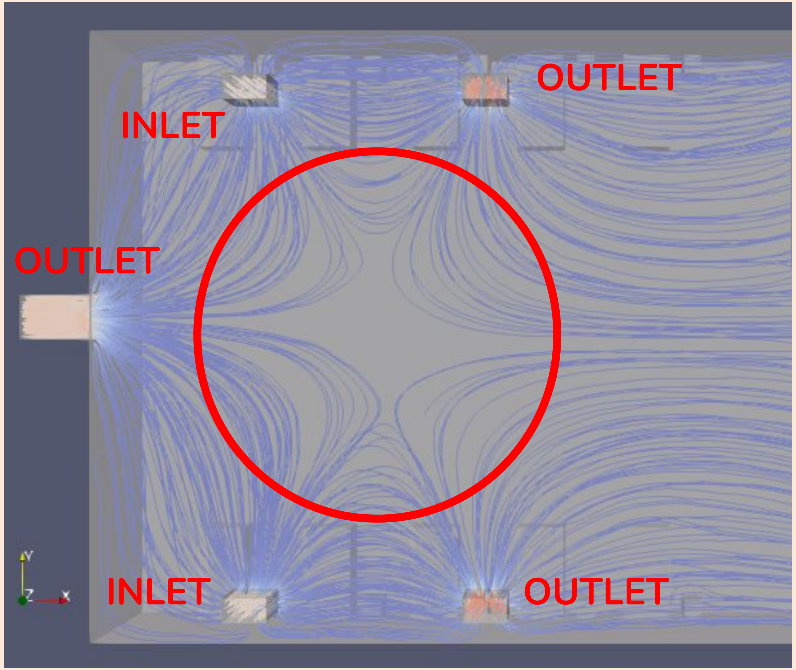
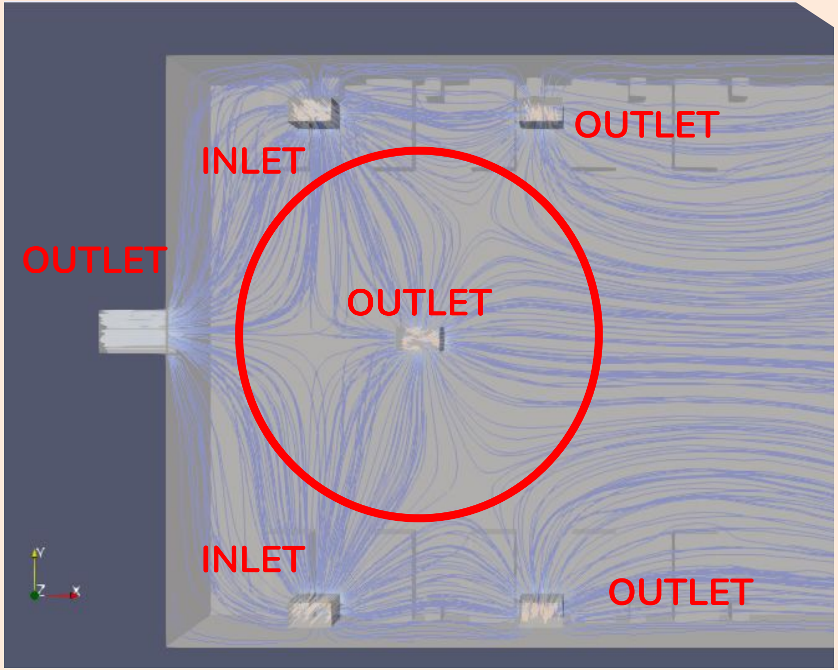
Comparison



3_wall_4_ceiling



3_wall_5_ceiling

5.3 3_wall_5_ceiling

Key Takeaways:

- Adding the ceiling mounted outlet in the middle significantly improves the airflow.
- The number of inlets and outlets is perfectly balanced.

Next steps:

- Try replacing a wall mounted inlet with a ceiling mounted inlet, to see effect on airflow.

6. Other Simulations

S. No.	Case Name	Link
1	1_inlet_1_outlet	Link
2	3_branch_one_main_pair	Link
3	2_branch_pair_no_main	Link
4	2_branch_pair_shifted	Link
5	3_branch_1_main_shifted_bed	Link
6	3_branch_shifted_bed_shifted_main_one_out	Link
7	3_branch_shifted_bed_shifted_main	Link
8	2_wall_6_ceiling	Link
9	3_branch_pair_shifted	Link
10	3_branch_pair_1_outlet_shifted	Link

7. Next Steps

- Attempt to model turbulent airflow.
- Discuss our findings with microbiologists or hospital officials, and get their inputs.
- Share our code online in the open source domain (Link).

QUESTIONS?

8.1 References

S. No	TOPIC	DESCRIPTION
1	Application of open-source CFD software to the indoor airflow simulation	This paper gives a general idea of the importance of CFD in predicting the environment conditions inside a room. In this project, they have used OpenFoam to simulate indoor airflow and heat transfer.
2	Thermo-ventilation study by OpenFOAM	In this project, they have used Openfoam to carry out a thermo ventilation study of airflow in a heated rectangular cavity. They have used the concept of "air age" to quantify air quality and two other indexes to quantify thermal comfort.
3	Natural Ventilation for agriculture buildings	Here, they have used Openfoam to simulate natural ventilation for agriculture buildings. This paper mainly compares the experimental and numerical results and the accuracy when the number of meshes are changed.
4	Optimisation of Hospital Room by means of CFD for more efficient ventilation	This paper takes a 2 bed hospital room, and explores the effectiveness of partitioning sections like walls and curtains on the ventilation.

8.1 References

S. No	TOPIC	DESCRIPTION
5	The ventilation of multiple-bed hospital wards: Review and analysis	This paper reviews the ventilation guidelines established by the US and UK by designing a compliant room and running analytical CFD simulations with bioaerosol particles.
6	Comparison of OpenFOAM and ANSYS Fluent	This paper compares the performance of OpenFOAM and Ansys Fluent on meshes generated using Ansys. When using an Ansys-generated mesh, OpenFOAM tends to not perform as well as Ansys, but that is to be expected due to ecosystem integrations.
7	OpenFOAM simulation of the natural ventilation system in a university chemical laboratory	Using Laminar and Turbulent solvers, they attempt to model and study the flow patterns of a chemistry lab's natural ventilation and HVAC systems to ensure it is compliant with the UNE 171330-2 standard.
8	Dynamic airflow simulation within an isolation room	They make use of Ansys Fluent to investigate the effects of a moving person and the opening and closing of a sliding door on an isolation room's air flow.
9	Development of ventilation design strategy for effective removal of pollutant in the isolation room of a hospital	This paper investigates the airflow and pollutant distribution patterns in a "negative pressure" isolation room by means of objective measurement and computational fluid dynamics (CFD) modeling based on three ventilation strategies.

8.1 References

S. No	TOPIC	DESCRIPTION
10	Numerical Study of Three Ventilation Strategies in a prefabricated COVID-19 inpatient ward	This paper looks at three ventilation strategies in a prefabricated COVID-19 double-patient ward. Pollutants are modelled as particles with different diameters by the Eulerian–Lagrangian model.
11	Role of ventilation in airborne transmission of infectious agents in the built environment – a multidisciplinary systematic review	This review paper stresses that despite strong and sufficient evidence to demonstrate the association between ventilation, air movements in buildings and the transmission/spread of infectious diseases, there is insufficient data to specify and quantify the minimum ventilation requirements in hospitals, schools, offices, homes and isolation rooms in relation to spread of infectious diseases via the airborne route.
12	Virions and respiratory droplets in air: Diffusion, drift, and contact with the epithelium	Describes the behavior of virions and virion-carrying droplets in air with emphasis on various regimes of diffusion, drift, and evaporation, and estimate the rates of all these steps under virologically relevant conditions.
13	A physicist view of COVID-19 airborne infection through convective airflow in indoor spaces	Provides a concise overview of airborne germ transmission as seen from a physics perspective. Also discusses whether coronavirus aerosols can travel far from the immediate neighborhood and get airborne with the convective currents developed within confined spaces.

8.2 Other References

S. No	TOPIC	DESCRIPTION
1	NCDC Guidelines for Setting up Isolation Facility/Ward	List of guidelines recommended by the NCDC to combat COVID-19
2	BIS 659 (1964) : Safety Code for Air Conditioning	BIS safety code guidelines for setting up an AC system
3	HVAC - How to Size and Design Ducts	Course notes on HVAC system design approved by CED engineering.
4	Open Source Engineering Software recommended by Harvard	An OSS stack suggested by the Harvard School of Engineering and Applied Sciences using FreeCAD, Gmsh, OpenFOAM and Paraview
5	From design to mesh generation using FreeCAD and GMSH	Tutorial on exporting a FreeCAD model and generating its corresponding mesh using Gmsh
6	Water Filling Tank Example	A case walkthrough for filling a tank with water through FreeCAD, OpenFOAM and ParaView.
7	Triangular mesh vs Quad mesh	ResearchGate discussion thread comparing the tri and quad meshes
8	Hospital Bed Dimensions	Website where you can buy hospital beds and tables

8.2 Other References

S. No	TOPIC	DESCRIPTION
9	EPA recommendations for air purification	Discussion about HEPA filters and CADR ratings
10	What is a HEPA filter? | US EPA	An article describing the performance of HEPA filters
11	Using UV to kill Covid 19 airborne particles in the UK	A preliminary scientific report examining using UV rays to purify air
12	STL vs STEP article	An article which explains the benefits of using STEP over STL
13	Parallel Computing with OpenFOAM	A tutorial explaining case setup for parallel processing using OpenFOAM
14	ParaView plot streamlines	A video tutorial walking through the procedure for plotting streamlines in ParaView
15	OpenFOAM course material	A collection of lecture notes explaining how OpenFOAM works and how to set up cases.
16	How to write Allrun and Allclean scripts	YouTube tutorials explaining how to automate running and cleaning cases
17	Piso Algorithm Explanation	A mathematical explanation of how the PISO algorithm is used to solve fluid flow problems
18	K-Epsilon model explanation	A YouTube tutorial explaining the K-e model for turbulence

THANK YOU!