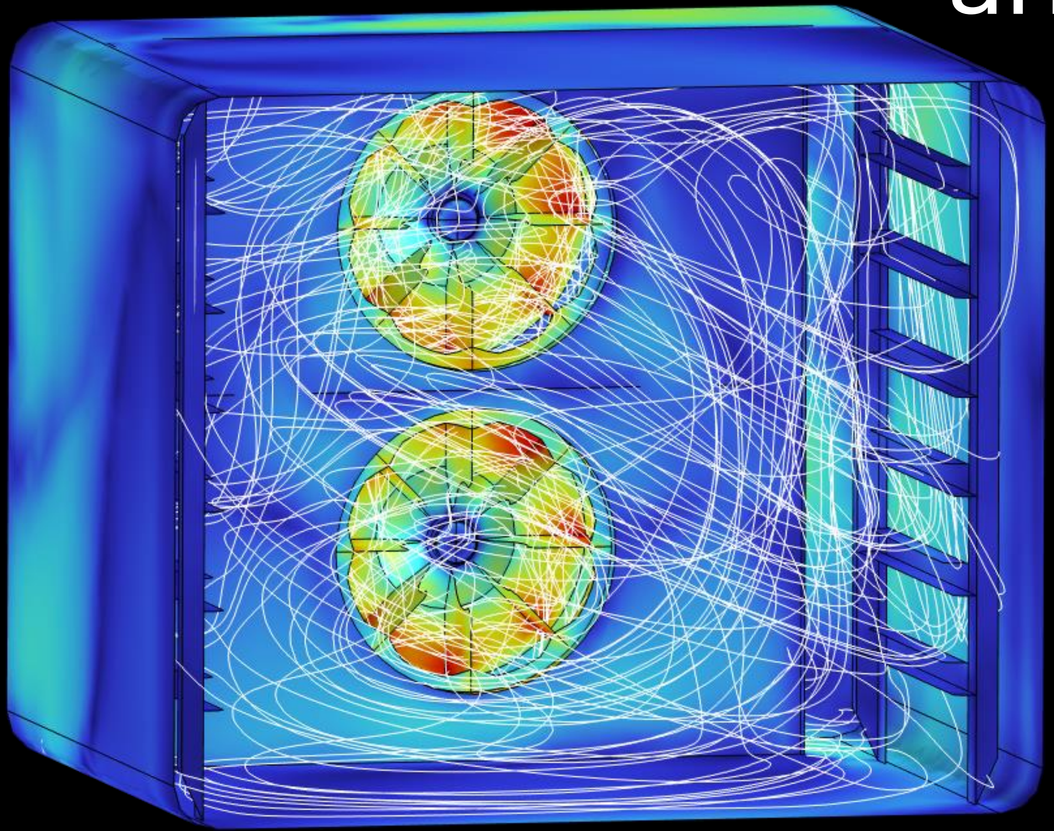
Fluid Dynamic Modeling in Oven Chambers: Balancing Accuracy and Computational Efficiency



Comsol Conference
Florence, October, 2024
Ph.D, Christian Bianchi

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Main goal of the investigation

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- **Reduction of computational complexity** by choosing the best model strategy to simulate the fluid dynamics in a closed oven chamber

- **Optimization of the process workflow** to maximize the efficiency of module usage

Basic Hypothesis

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The classical way to investigate the forced ventilation and thermal distribution in a closed chamber is to simulate the **coupled CFD and HT** problem in the full domain

A simpler, but less accurate way to make the same investigation is to **separate the study of the driving force (fan) from the effect in the remaining chamber.**

How good this accuracy can be?

General concept

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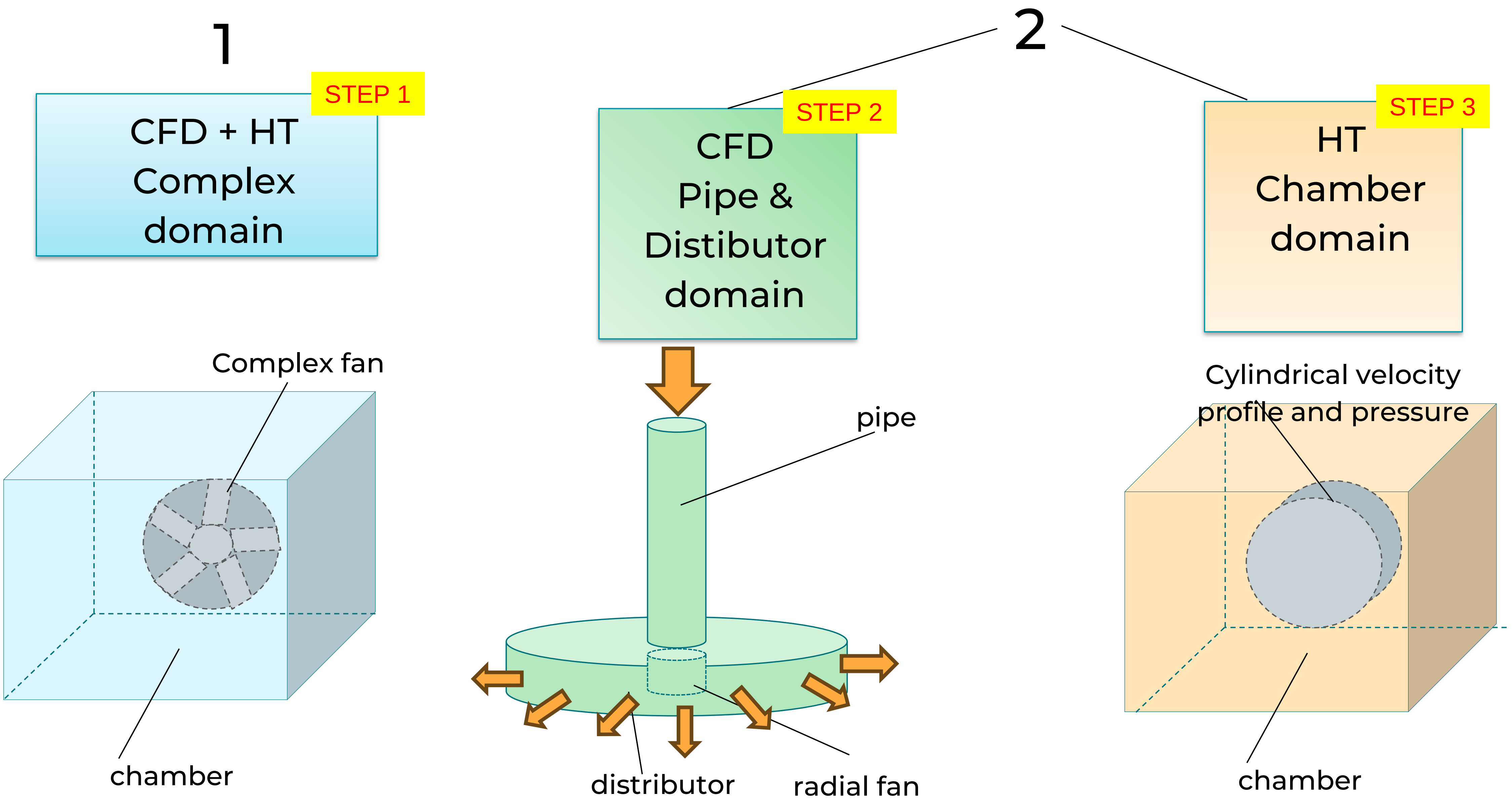


Steps

The analysis is characterized by three steps:

Step 1

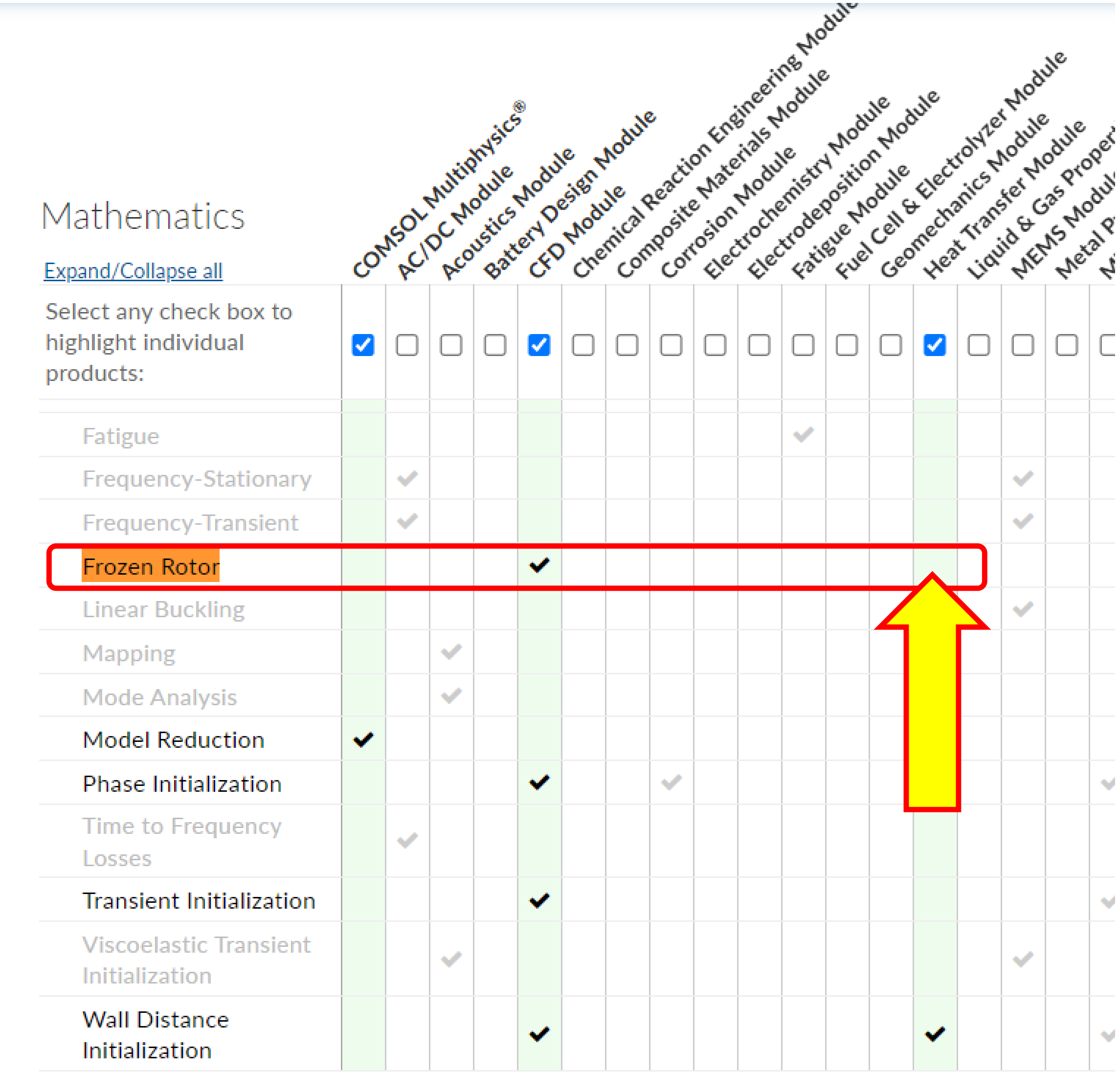
Need of both CFD and HT modules for the entire simulation time over a complex domain

Step 2

Need of only the CFD module for a simplified domain

Step 3

Need of the only HT module for the chamber domain (complexity of the fan is excluded)

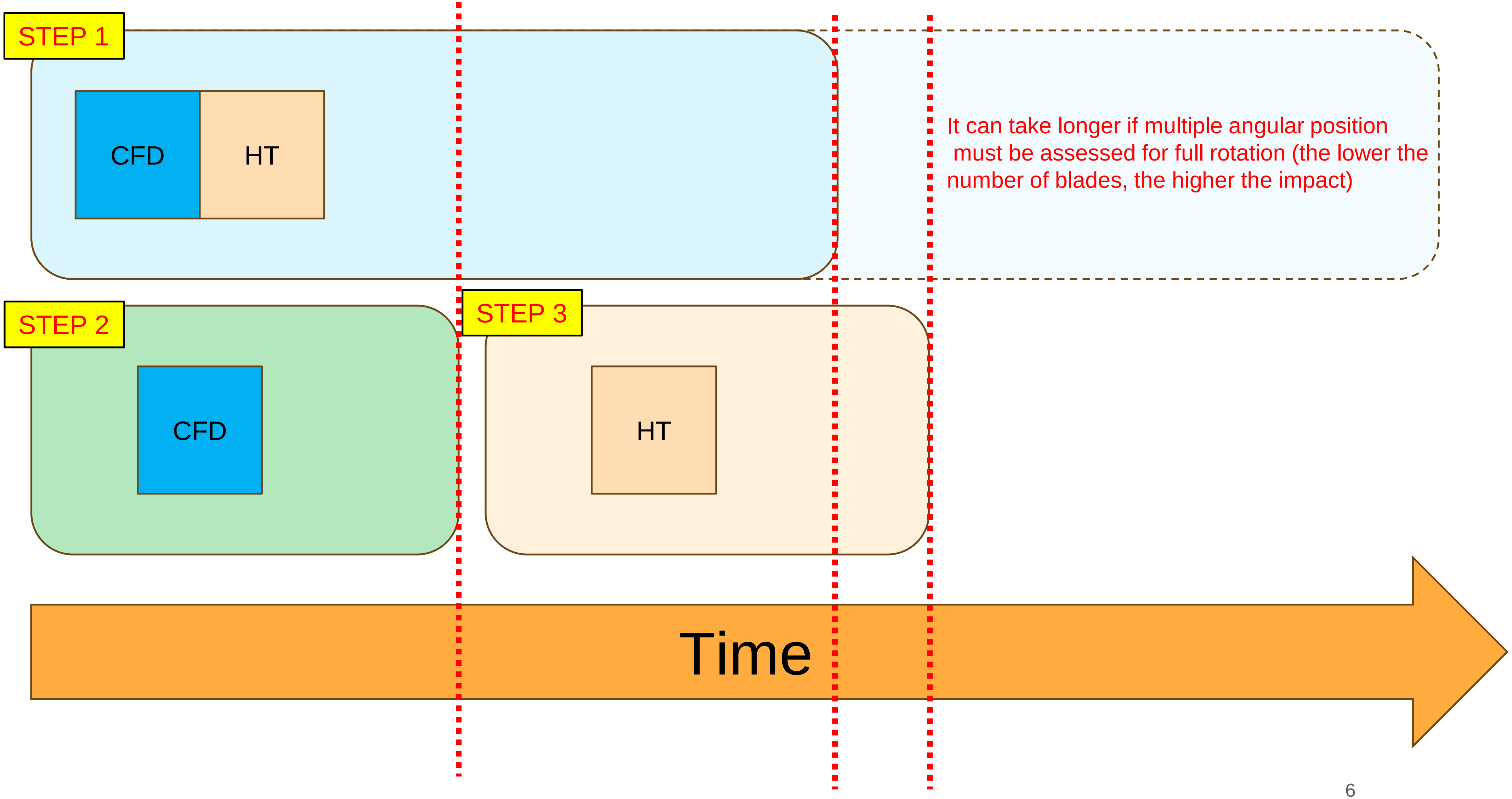


Mathematics

Expand/Collapse all

	COMSOL Multiphysics®	AC/DC Module	Acoustics Module	Battery Design Module	CFD Module	Chemical Reaction Engineering Module	Composite Materials Module	Corrosion Module	Electrochemistry Module	Electrodeposition Module	Fatigue Module	Fuel Cell & Electrolyzer Module	Geomechanics Module	Heat Transfer Module	Liquid & Gas Proper	MEMS Modul	Metal P	M
Select any check box to highlight individual products:	☑	☐	☐	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐
Fatigue											✓							
Frequency-Stationary		✓														✓		
Frequency-Transient		✓														✓		
Frozen Rotor					✓													
Linear Buckling																✓		
Mapping			✓															
Mode Analysis			✓															
Model Reduction	✓																	
Phase Initialization					✓			✓										✓
Time to Frequency Losses		✓																
Transient Initialization					✓													✓
Viscoelastic Transient Initialization			✓													✓		
Wall Distance Initialization					✓									✓				✓

Module usage and timing



Step 1 – Model characteristics

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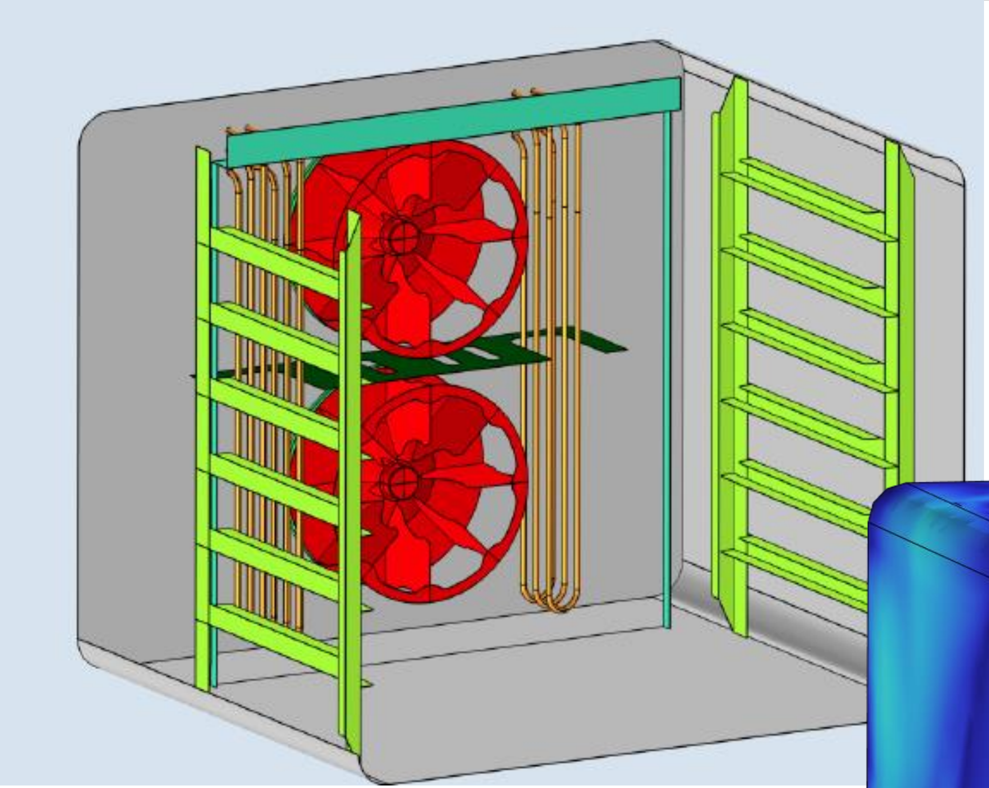
physics setting

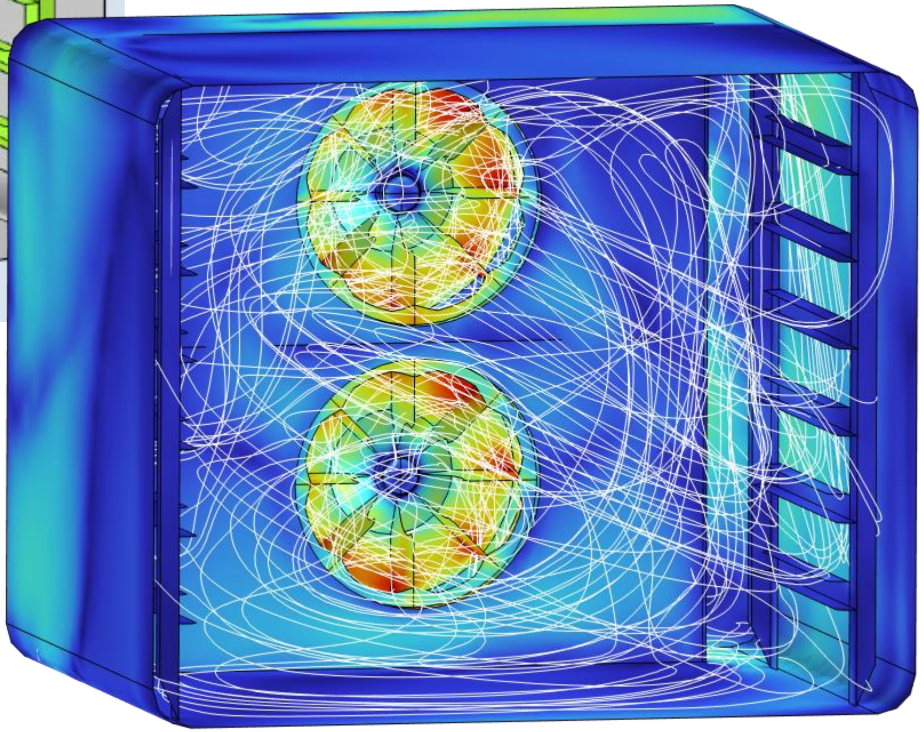
- Turbulent Flow, k-ε *(spf)*
  - Fluid Properties 1
  - Initial Values 1
  - Wall 1
  - Gravity 1
  - Interior Wall 1
  - Interior Wall - Fan
  - Pressure Point Constraint 1
- Heat Transfer in Fluids *(ht)*
  - Fluid 1
  - Initial Values 1
  - Thermal Insulation 1
  - Temperature 1
  - Heat Flux 1
- Multiphysics
  - Nonisothermal Flow 1 *(nitf1)*



Two frozen rotors are defined

Gravity is also included

Pressure reference is set at one corner



Temperature is set at the resistors surface (500 degC), thermal dissipation can occur at the door

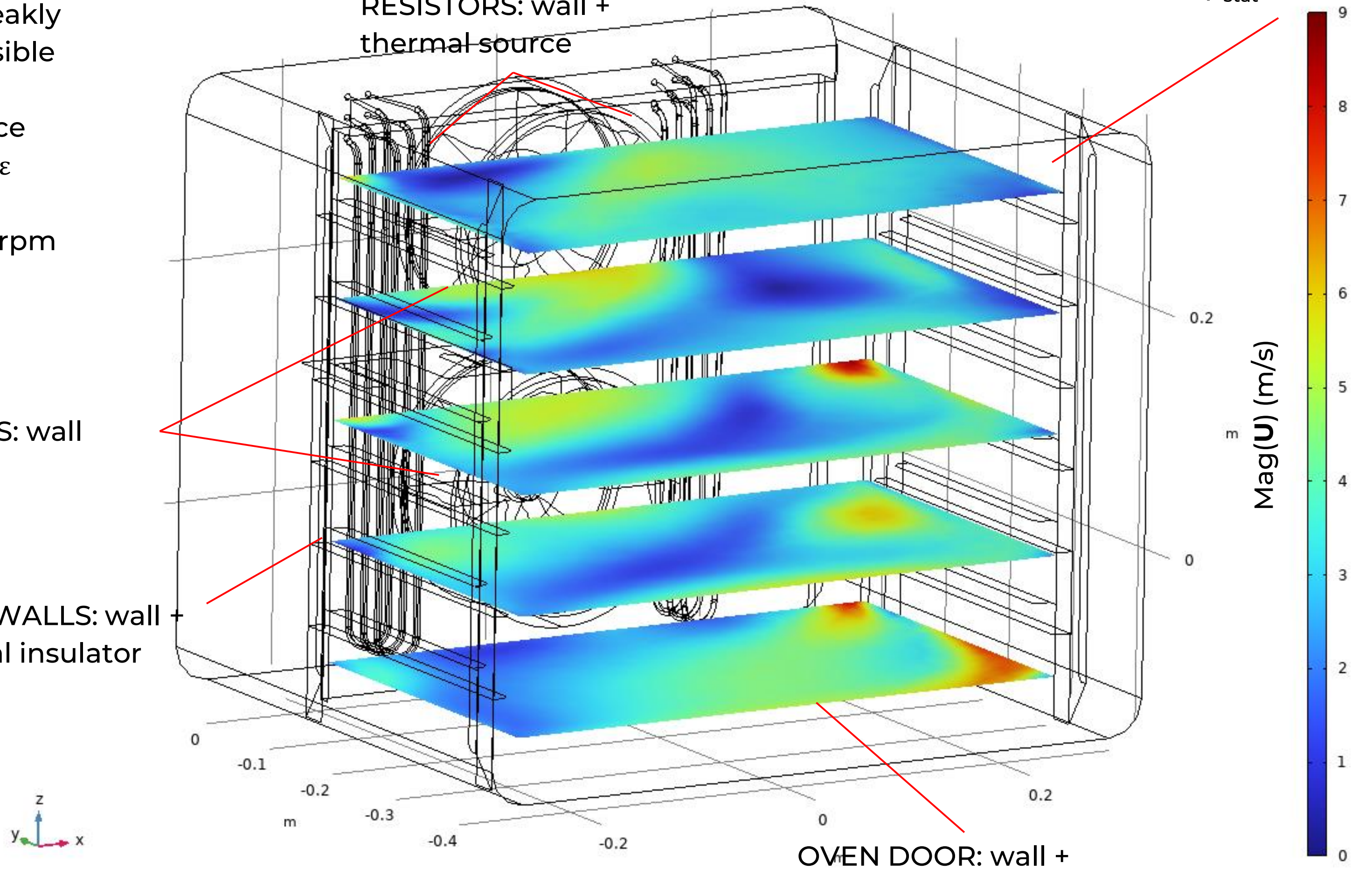
Results - Step 1 – Full oven simulation

Full domain with fan, carter, resistors and cavity

Fluido weakly compressible

Turbolence model: k-ε

ω = 2000 rpm



Step 2 – Model characteristics

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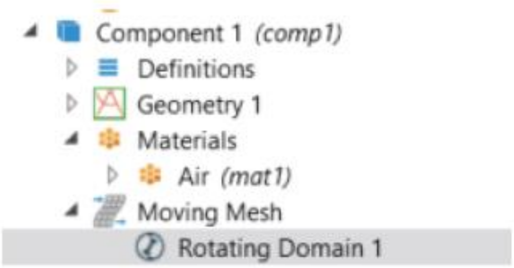
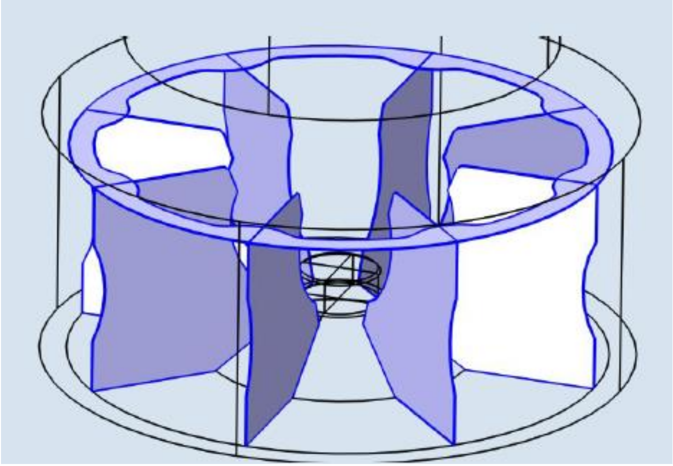
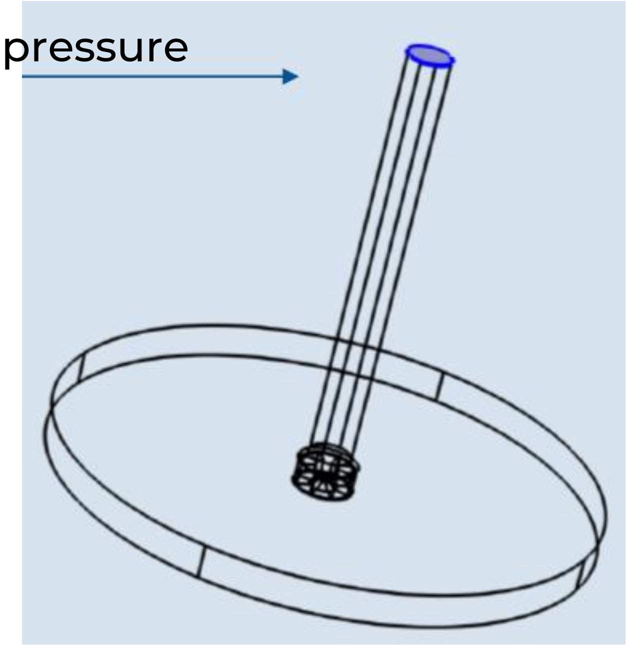
Domain setting



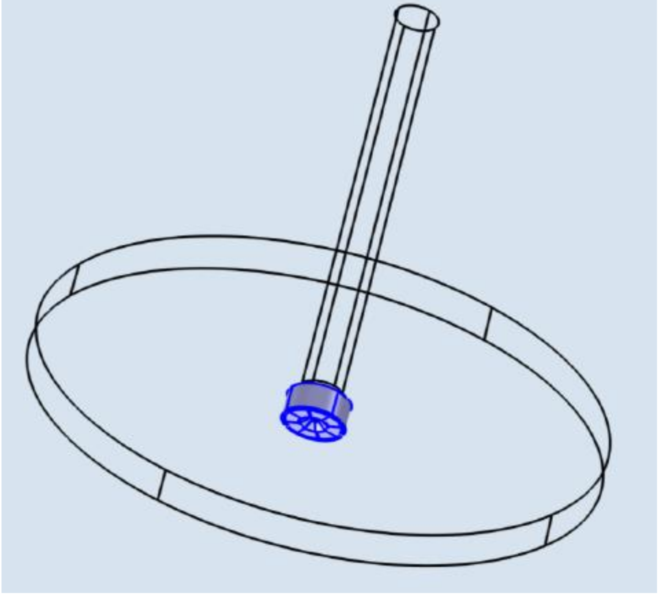


Thin faces used to define the fan geometry

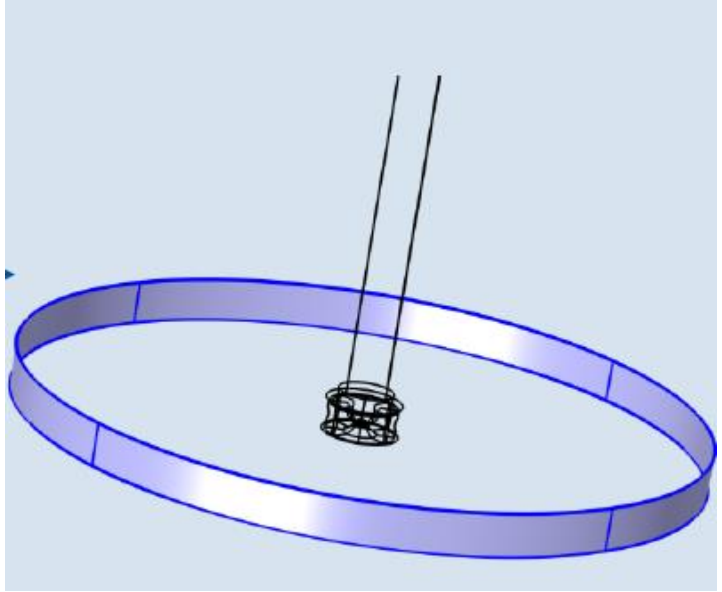
Inlet pressure



Frozen rotor



Outlet pressure



Step 2 – simplified domain

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Condotto di aspirazione + outlet indefinito.

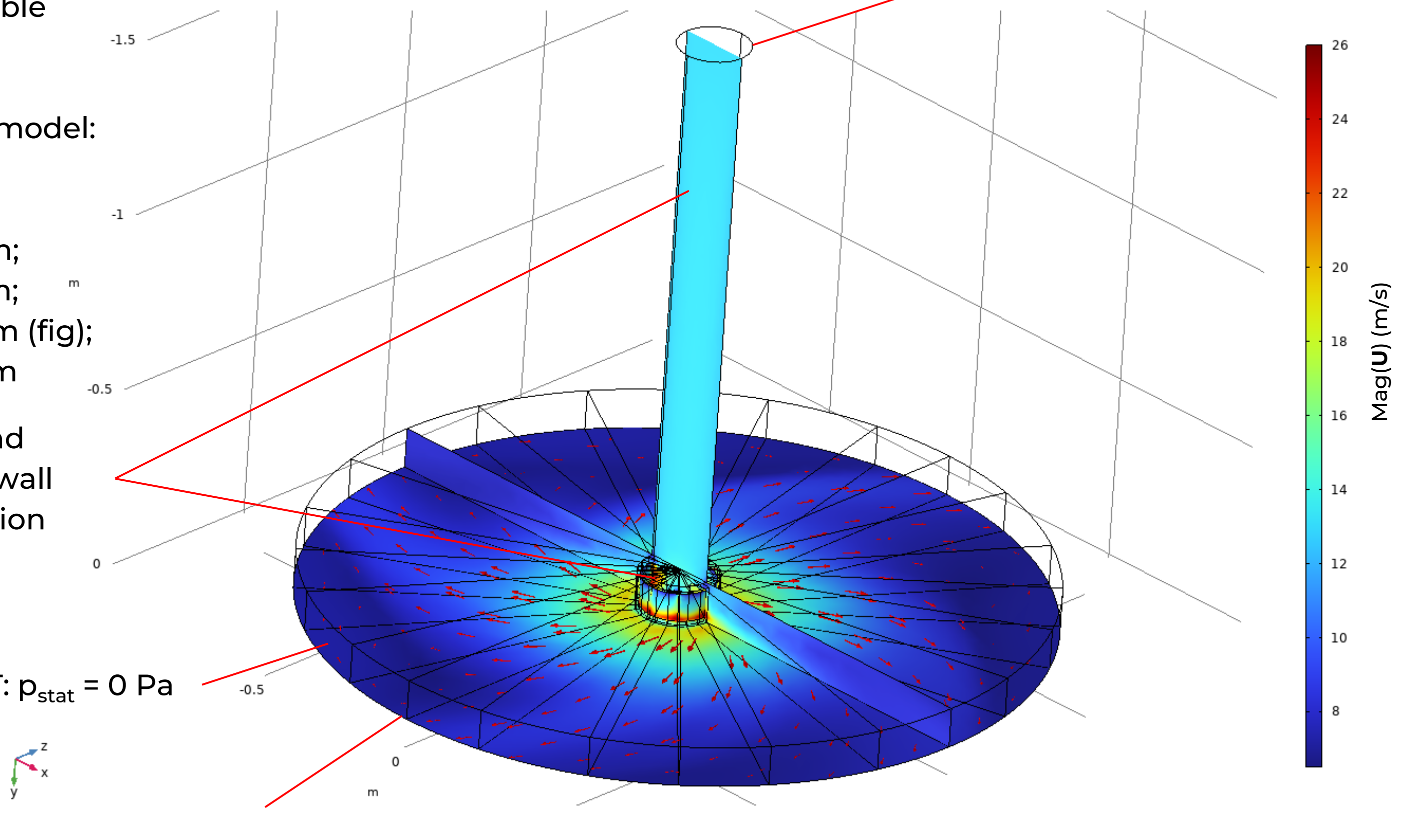
INLET: p_{totale} = 0 Pa

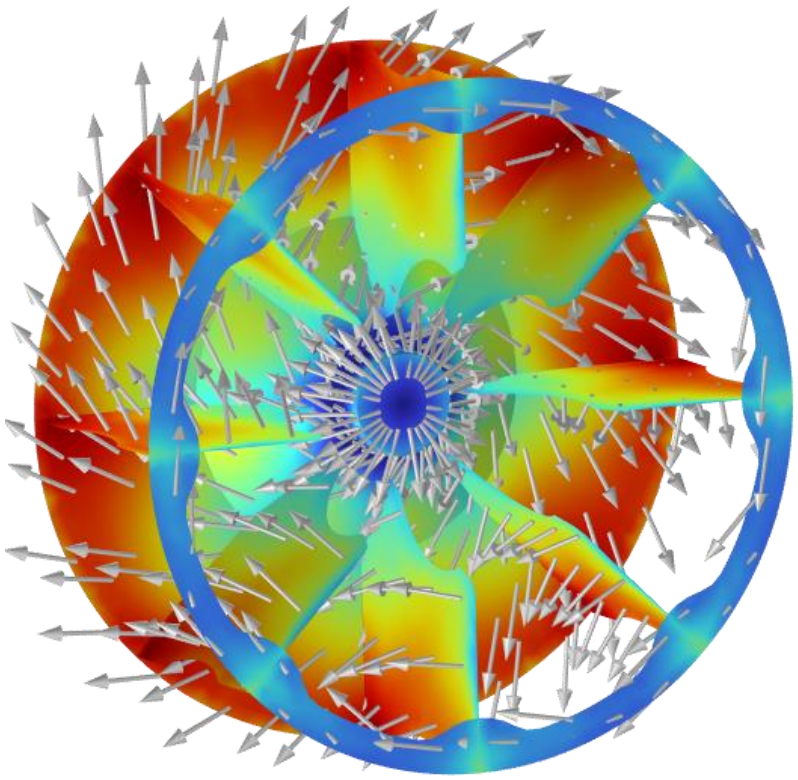
Incompressible fluid

Turbolence model: k-ε

ω = 1000 rpm;
1600 rpm;
2000 rpm (fig);
2600 rpm

Fan and walls: wall condition





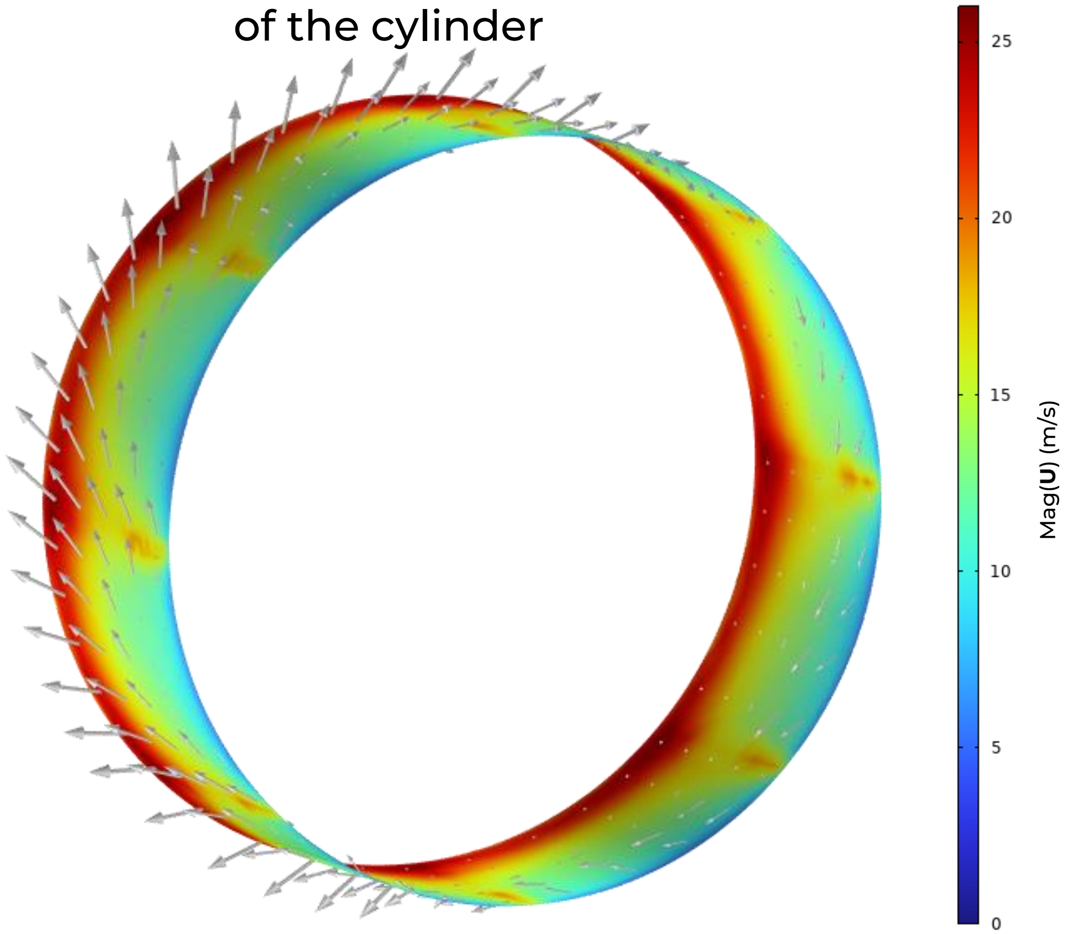
OUTLET: p_{stat} = 0 Pa

OUTLET_WALL: wall

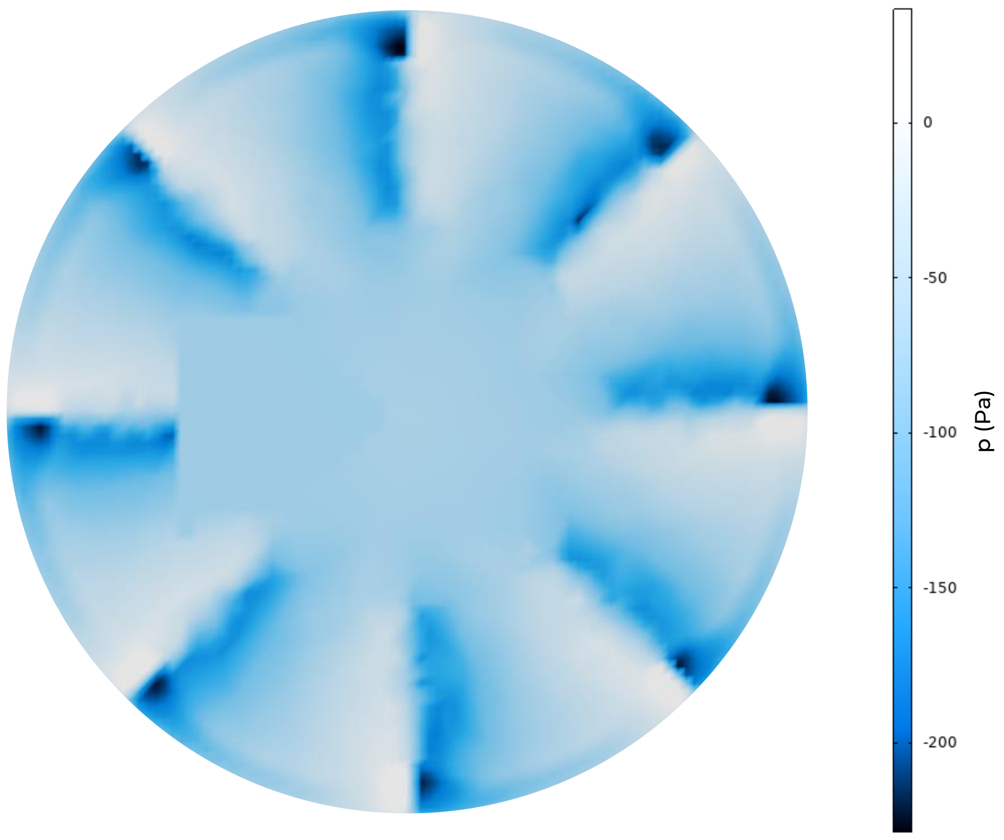
*OUTLET (free flow) and OUTLET_WALL (stopped flow) are considered in the same ratio as in the real oven, given to the following value A_{outlet} / A_{outlet_wall} = 0,6470

Step 2 – Output quantities

Vector velocity profile around external surface of the cylinder



Static pressure at the suction section of the fan



These two output profiles of step 1 are the input for step 3

Step 2 – Experimental validation

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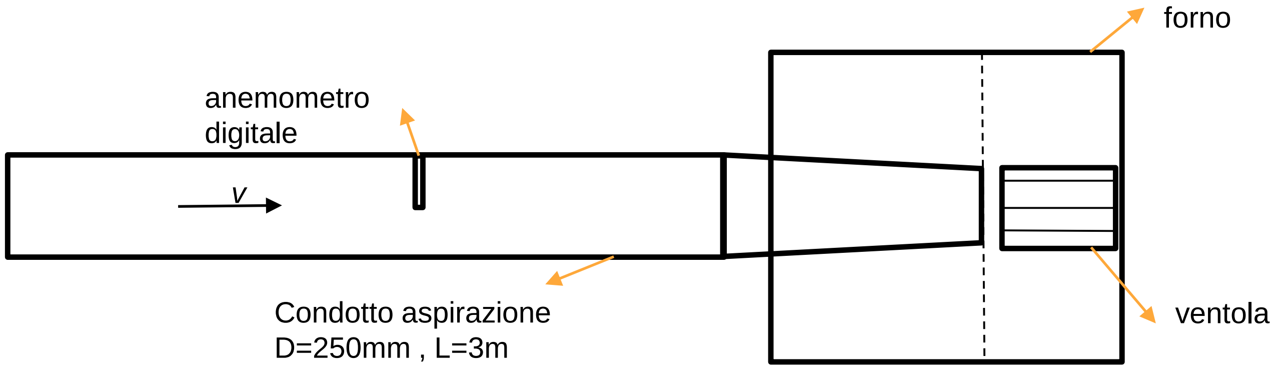
The door of the oven was open to let the insertion of the pipe. The pipe was placed in front of the fan. A digital anemometer was used to measure the volumetric flow rate.



Rpm	ṁ experimental (kg/s)	ṁ simulation (kg/s)	shift (%)
1000	0,163	0,153	6,22
1600	0,248	0,247	0,25
2000	0,302	0,311	2,65

Velocity and pressure **U** e p – Average over a full rotation step 2 (output)/ step 3 (input)

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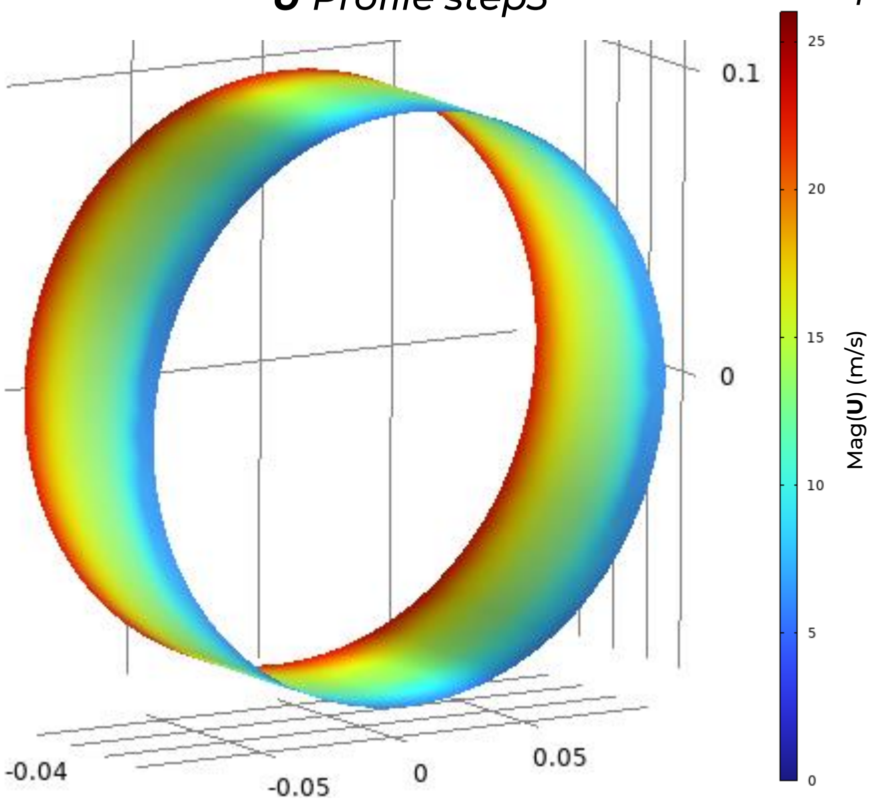
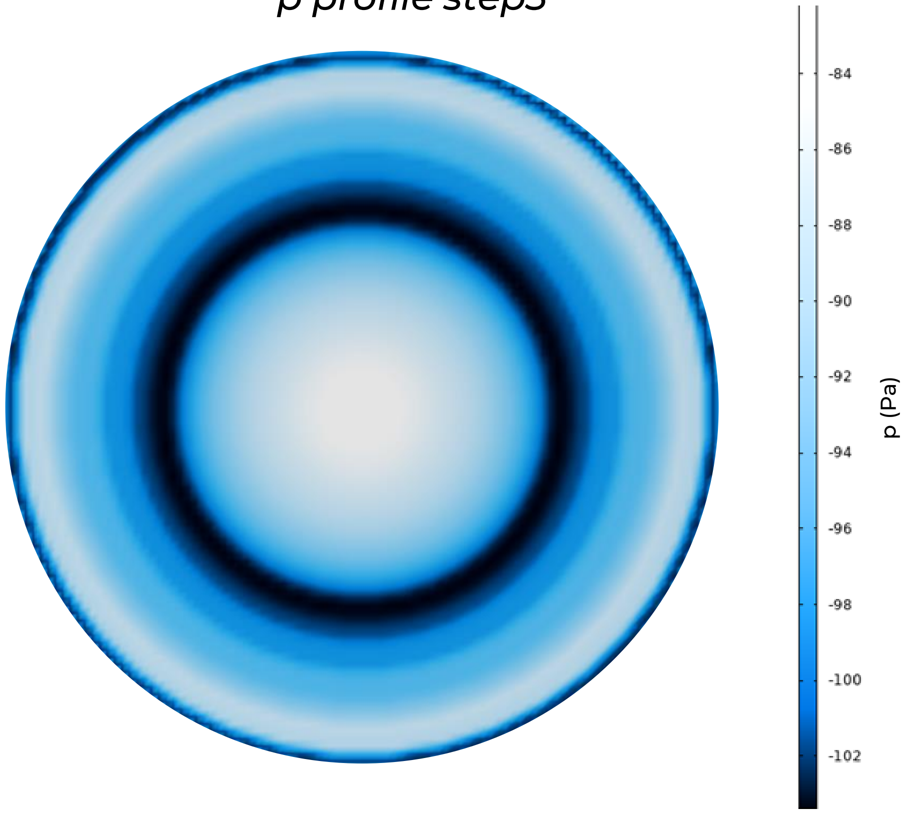
Since the frozen rotor captures a snapshot of a specific angular position of the fan, another velocity and pressure profile has been considered by averaging all the quantities along the rotation axis

***U** Profile step3”*



+

p profile step3”



Step 3 – Model characteristics

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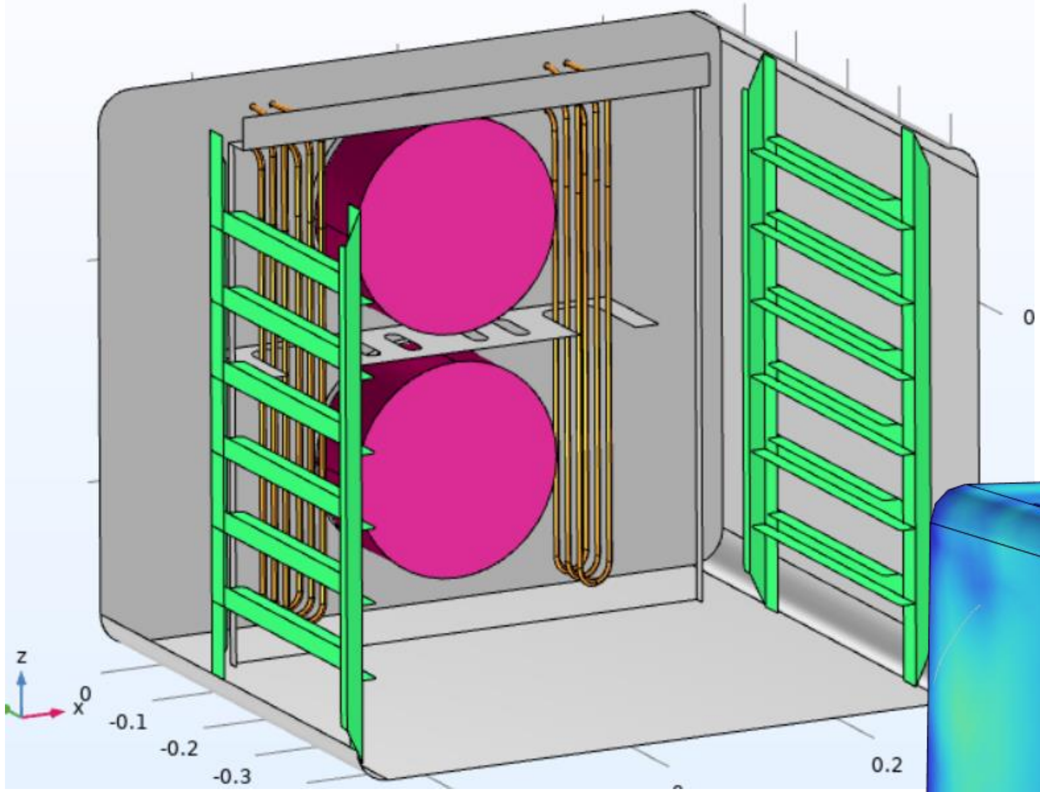
physics setting

- Fluid Properties 1 *{fp1}*
- Initial Values 1 *{init1}*
- Wall 1 *{wallbc1}*
- Gravity 1 *{grav1}*
- Interior Wall 1 *{iwbc1}*
- Inlet 1 *{inl1}*
- Inlet 2 *{inl3}*
- Outlet 1 *{out1}*
- Outlet 2 *{out2}*

Heat Transfer in Fluids 2 *(ht2) {ht2}*

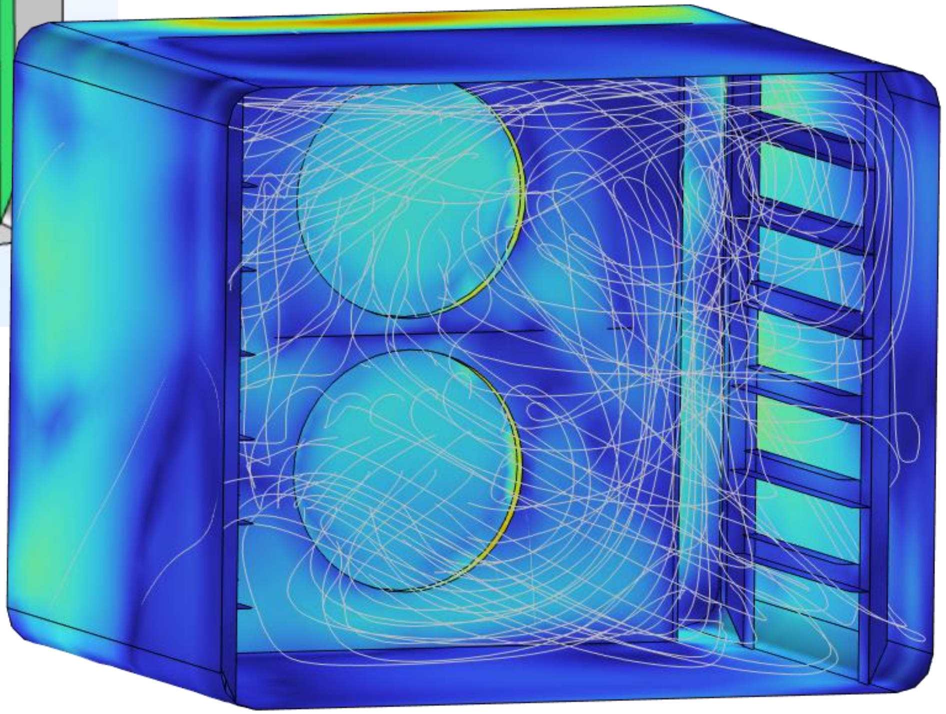
- Fluid 1 *{fluid1}*
- Initial Values 1 *{init1}*
- Thermal Insulation 1 *{ins1}*
- Temperature 1 *{temp1}*
- Heat Flux 1 *{hf1}*



Velocity profile and pressure at the suction are imported

Gravity is also included

Pressure reference is set at one corner



Temperature is set at the resistors surface (500 degC), thermal dissipation can occur at the door

Results - Step 3 – Simplified simulation Averaged over full rotation

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Forno 0611 privato degli elementi superflui e delle ventole, profili mediati.

weakly compressible fluid

Turbolence model: k-ε

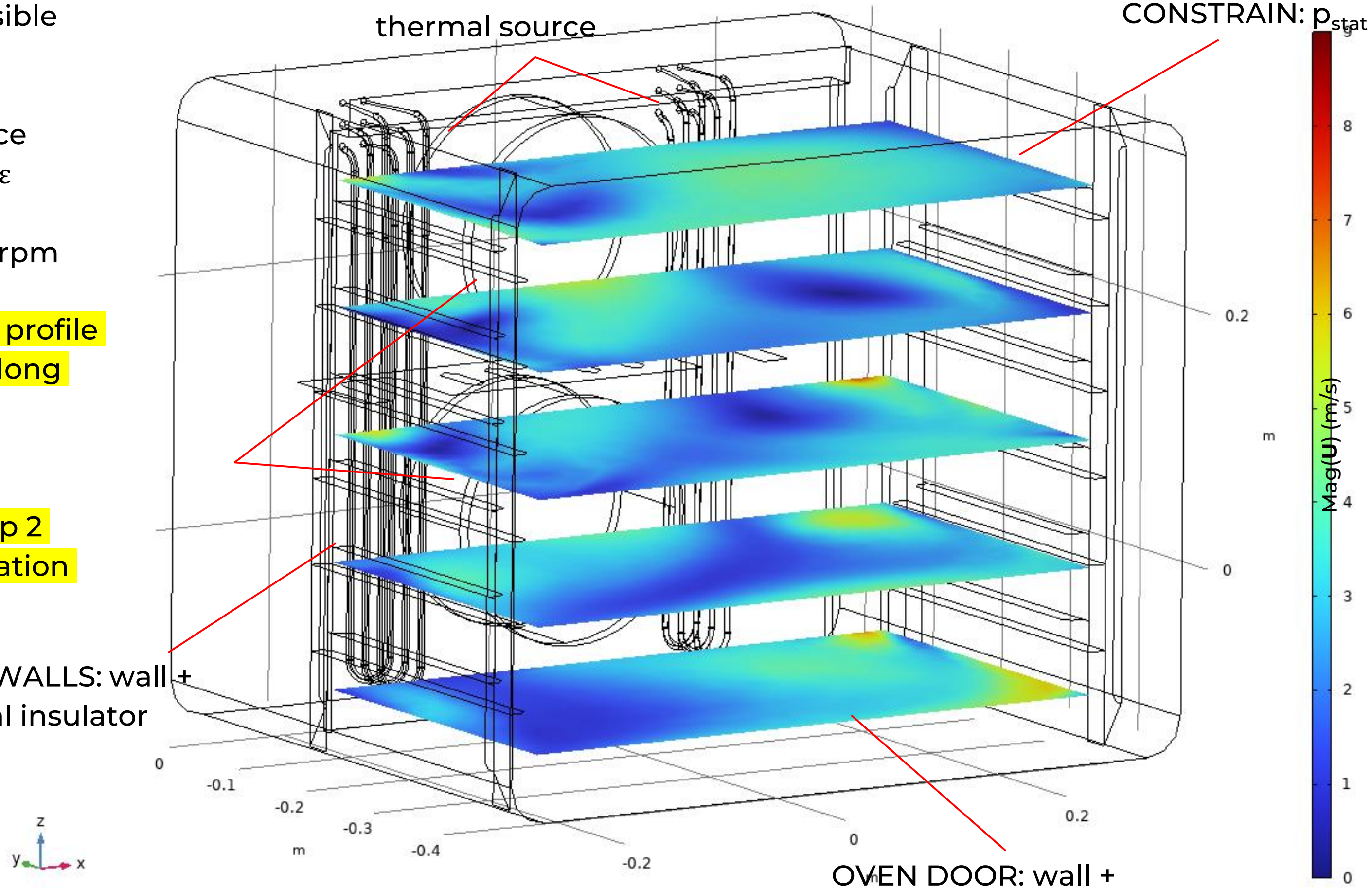
ω = 2000 rpm

CYLINDRICAL FAN: inlet (**U** profile from step 2 with average along the rotation axis)

FAN FACES:
outlet (profile p_{stat} from step 2 with average along the rotation axis)

RESISTORS: wall + thermal source

PRESSURE POINT CONSTRAIN: p_{stat} = 0 Pa



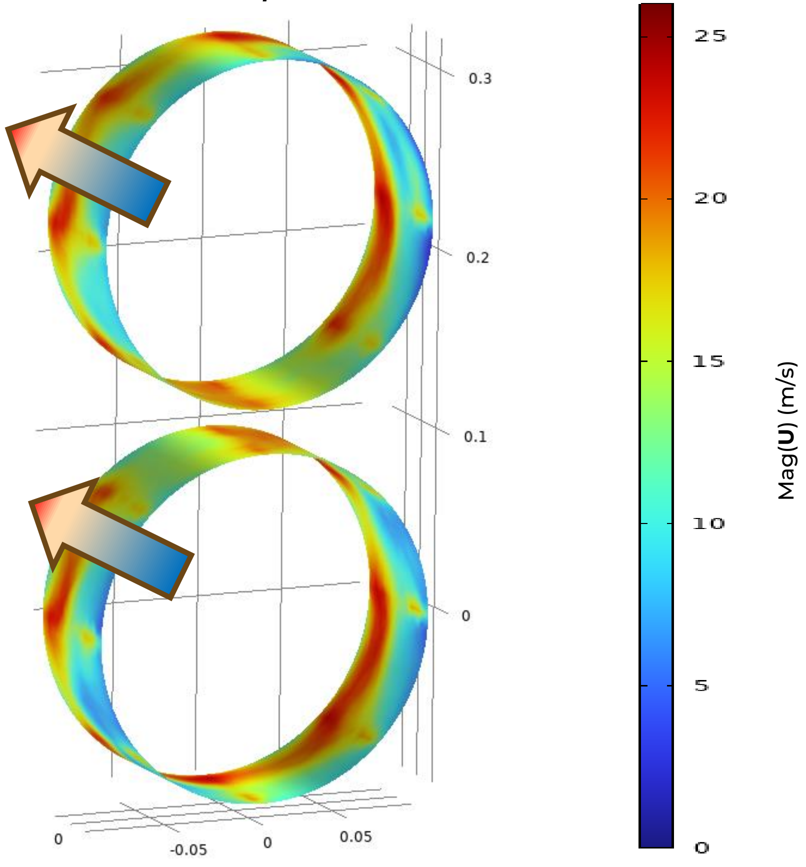
OVEN WALLS: wall + thermal insulator

OVEN DOOR: wall + thermal dissipation

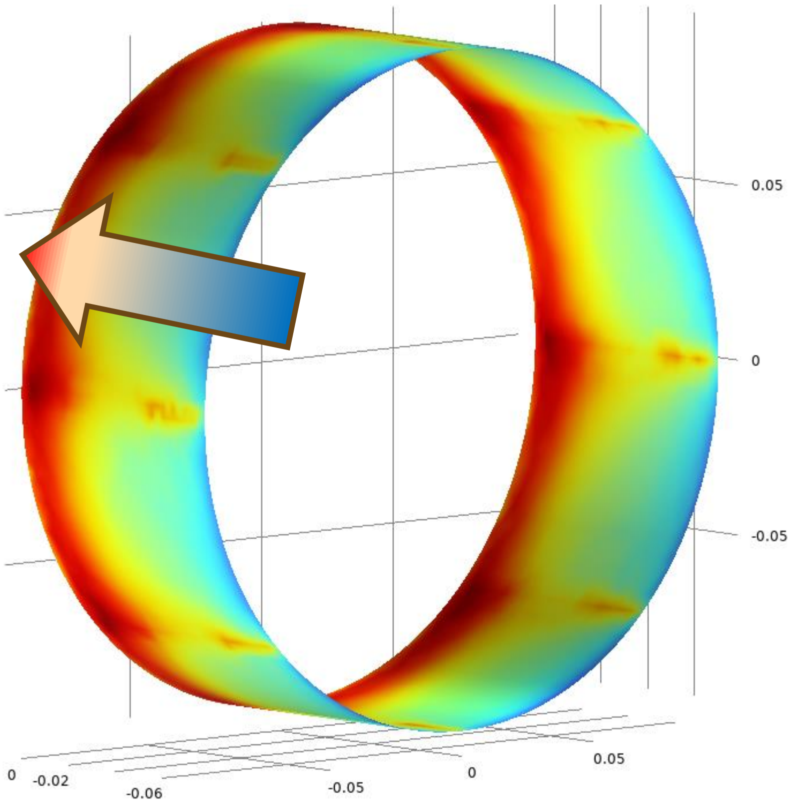
Results – Velocity profile – step1 vs step2

We can compare the results in terms of magnitude of field velocity along the lateral surface of the cylinder that defines the frozen rotor domain

Step 1



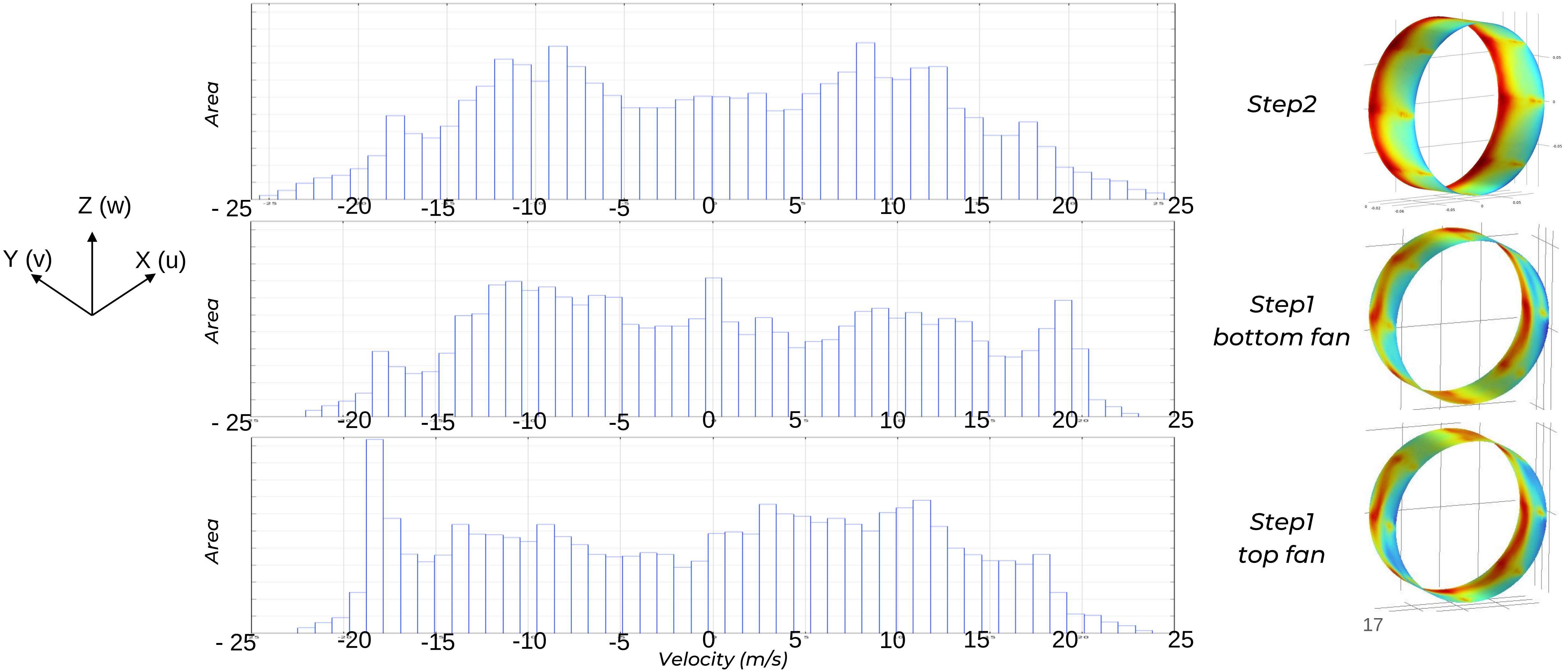
Step 2 (output) /Step 3 (input)



Velocity gradient toward the bottom of the fan is captured by both the models.

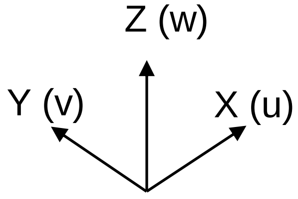
Profilo velocità – step1 vs step2

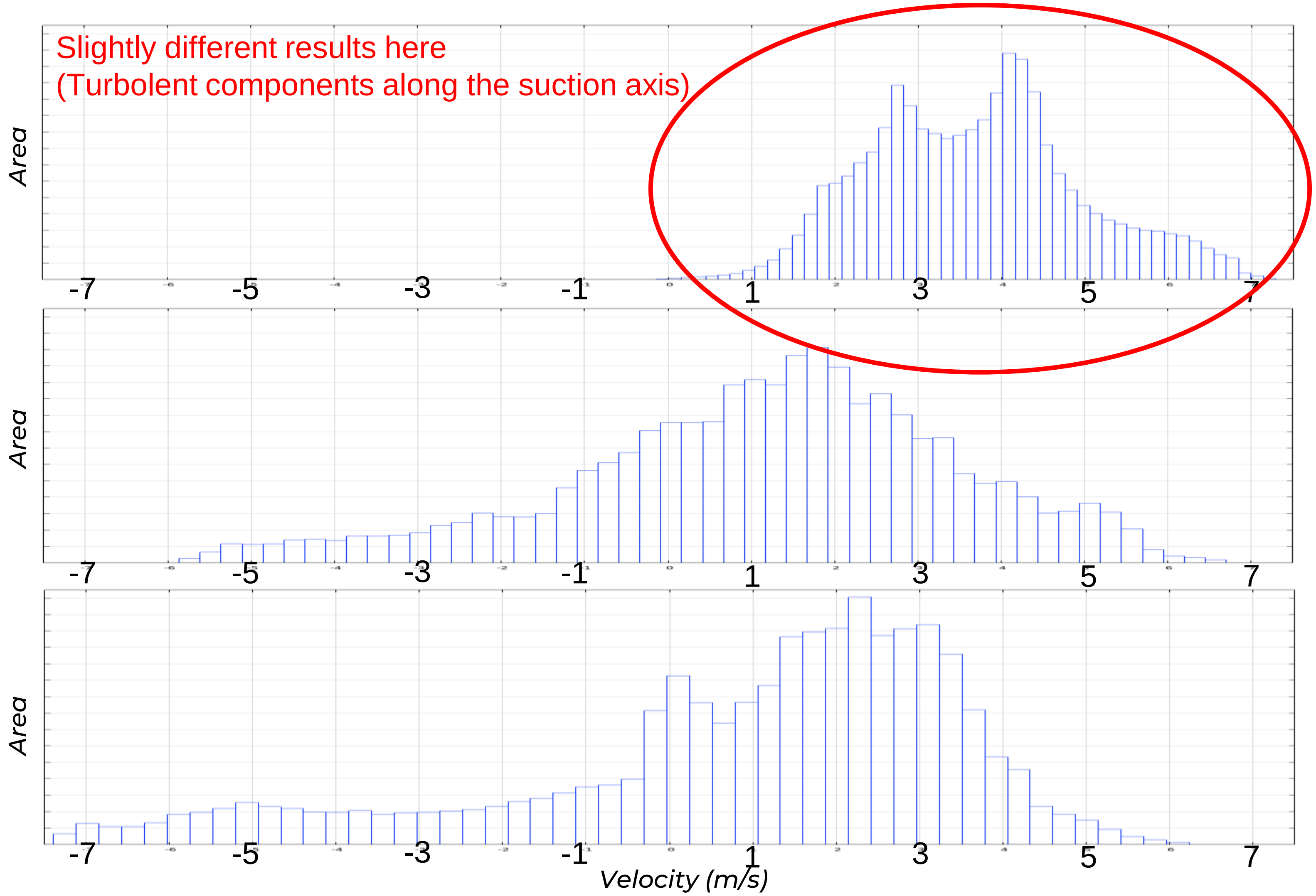
Component u (m/s) along the external cylinder of the fan



Profilo velocità – step1 vs step2

Component v (m/s) along the external cylinder of the fan

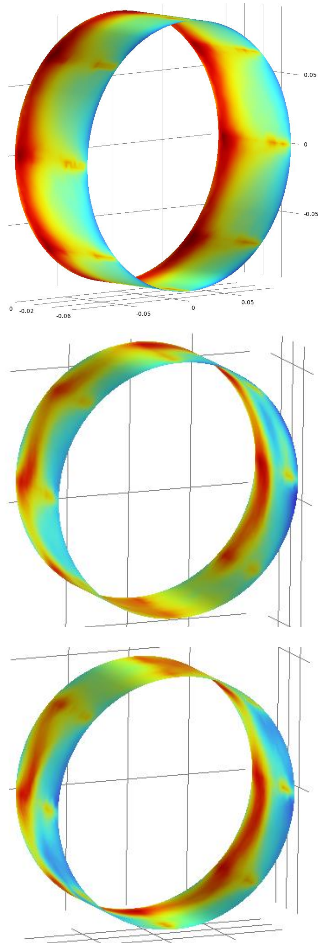




Step 2

Step 1
bottom fan

Step 1
top fan



Profilo velocità – step1 vs step2

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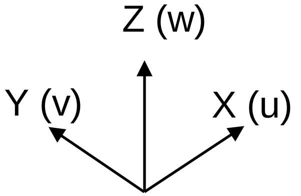
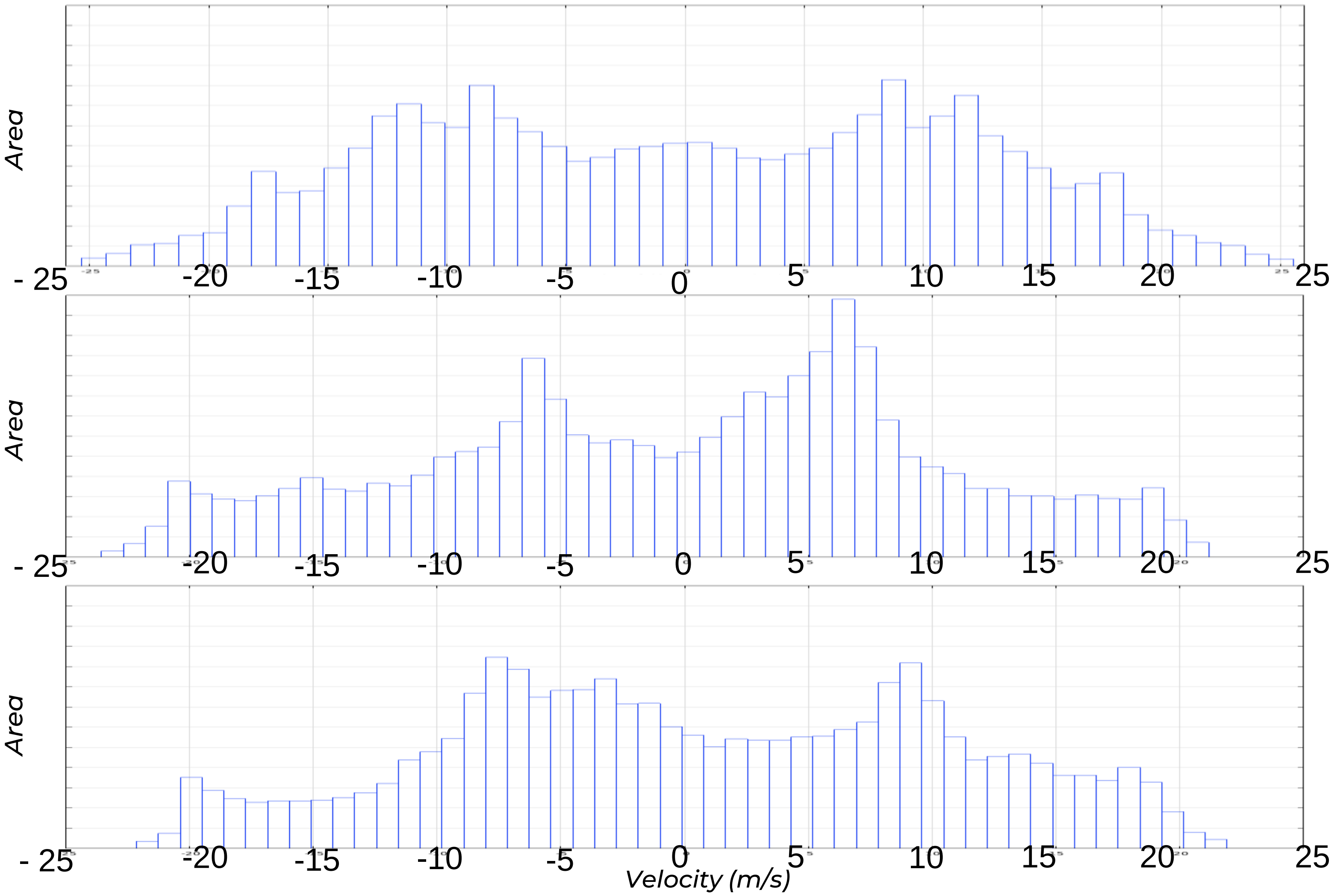
Componente w (m/s) lungo il cilindro circoscritto alla ventola.

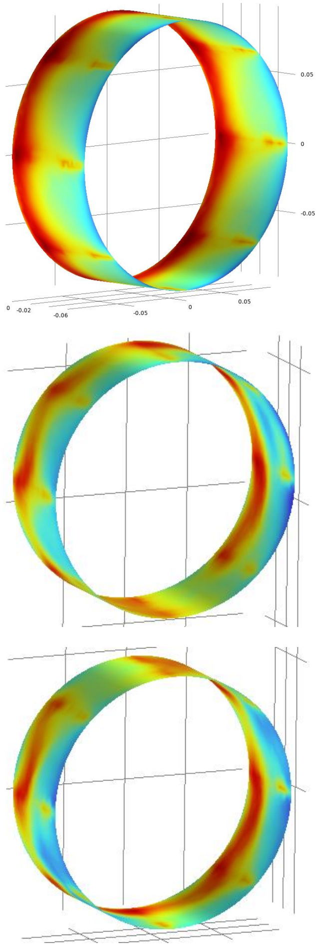




Step 2

Step 1
bottom fan

Step 1
top fan



General overview – step1 vs step3

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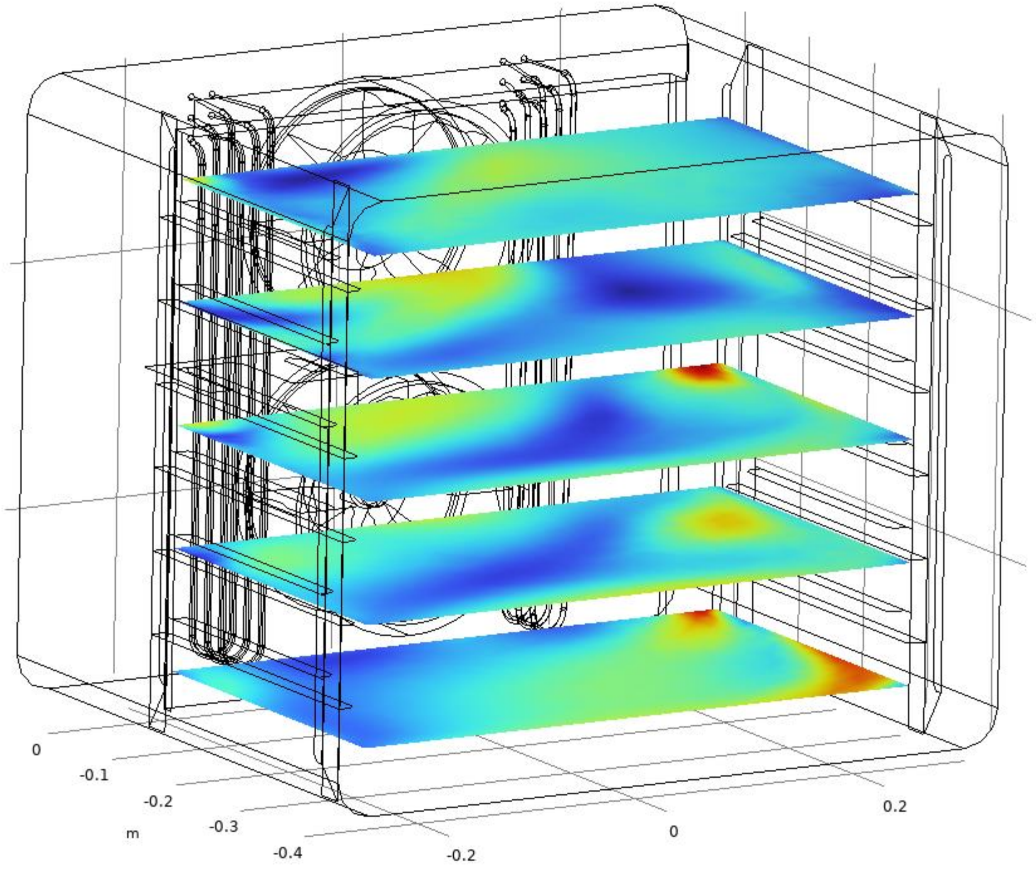
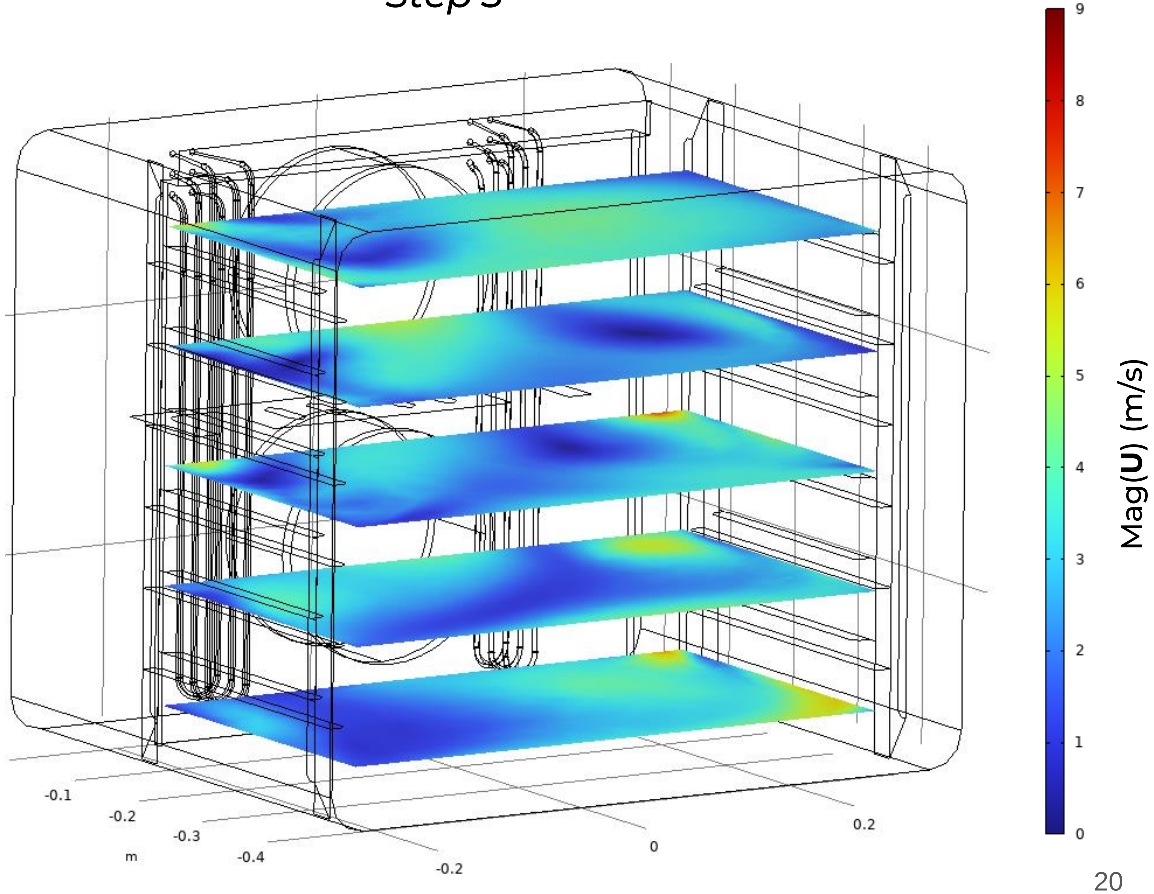
Velocity magnitude over different tray level positions

Step 1



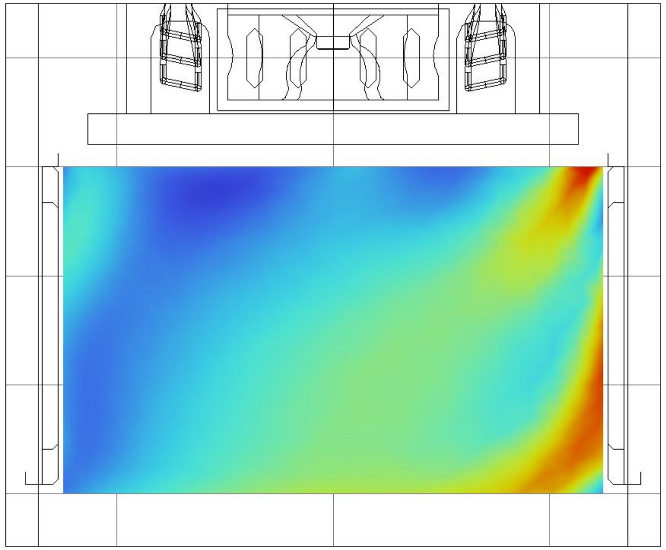
Step 3

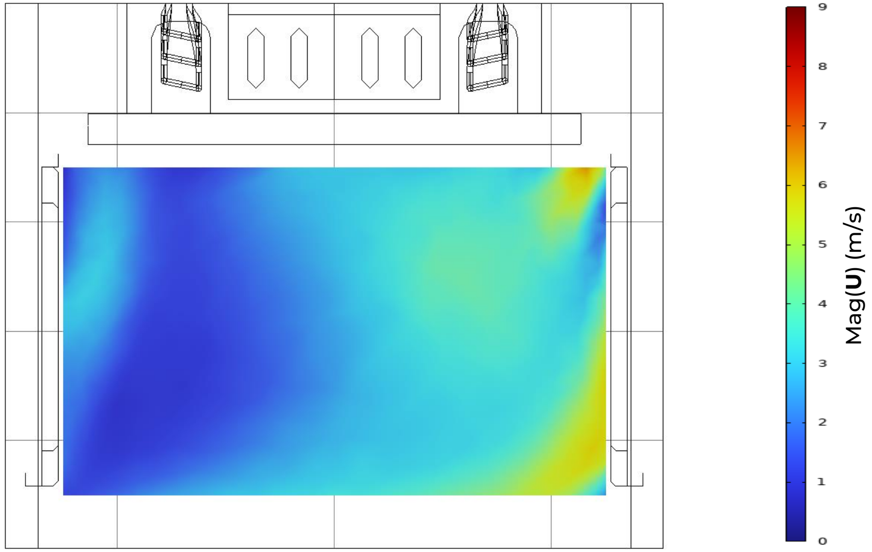


Results Tray 1 position – step 1 vs step 3

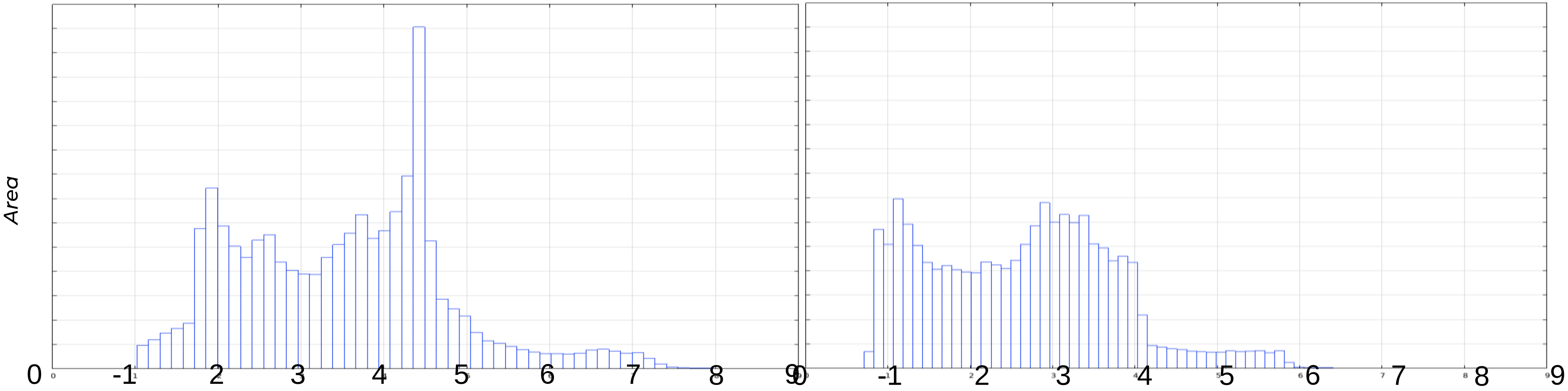
Step 1 | *Step 3*

Mag(**U**) hystogram at h = 0,1 m from the bottom.





Velocity (m/s)



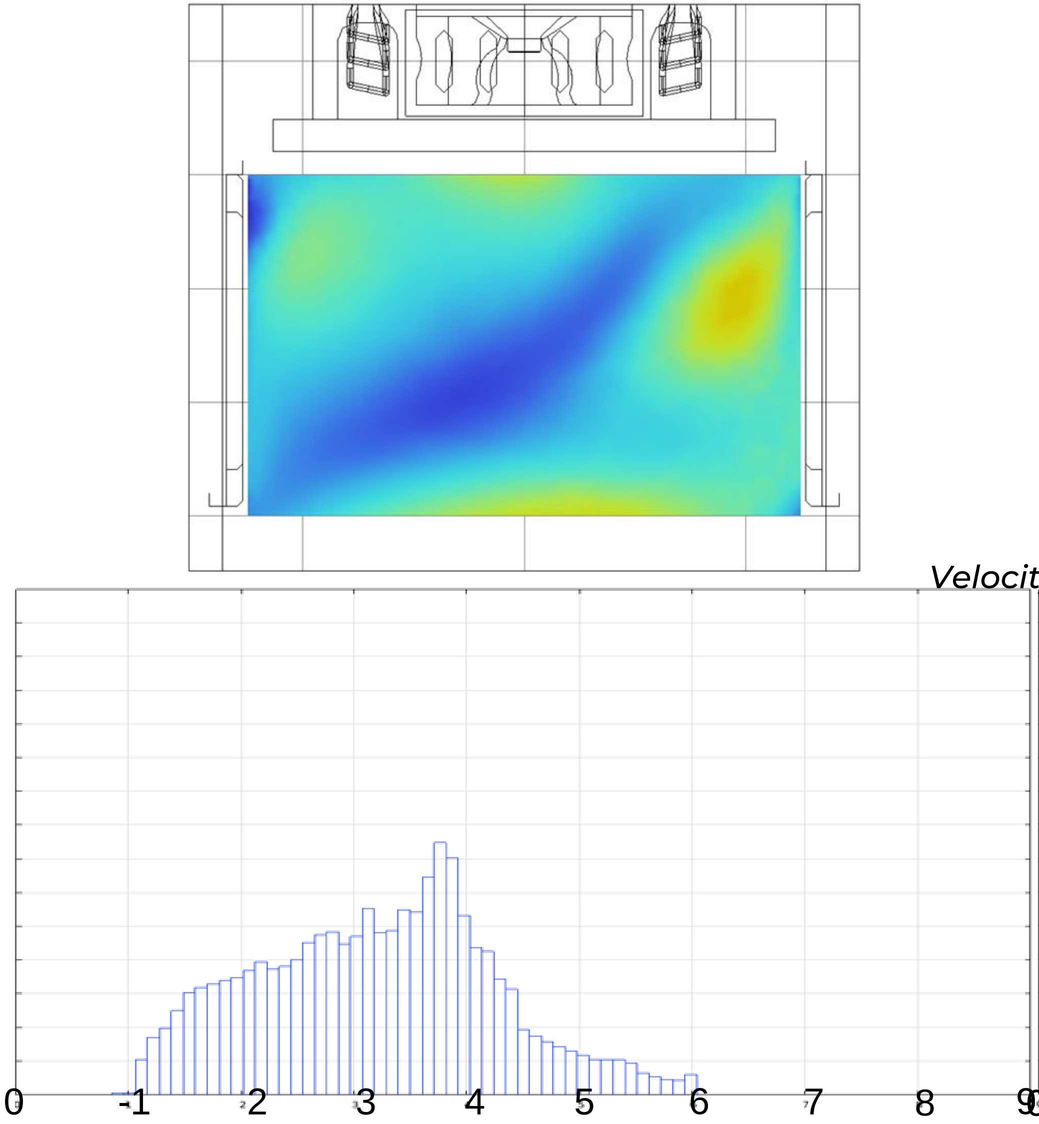
Results Tray 2 position – step 1 vs step 3

INVENTIVE SIMPLIFICATION

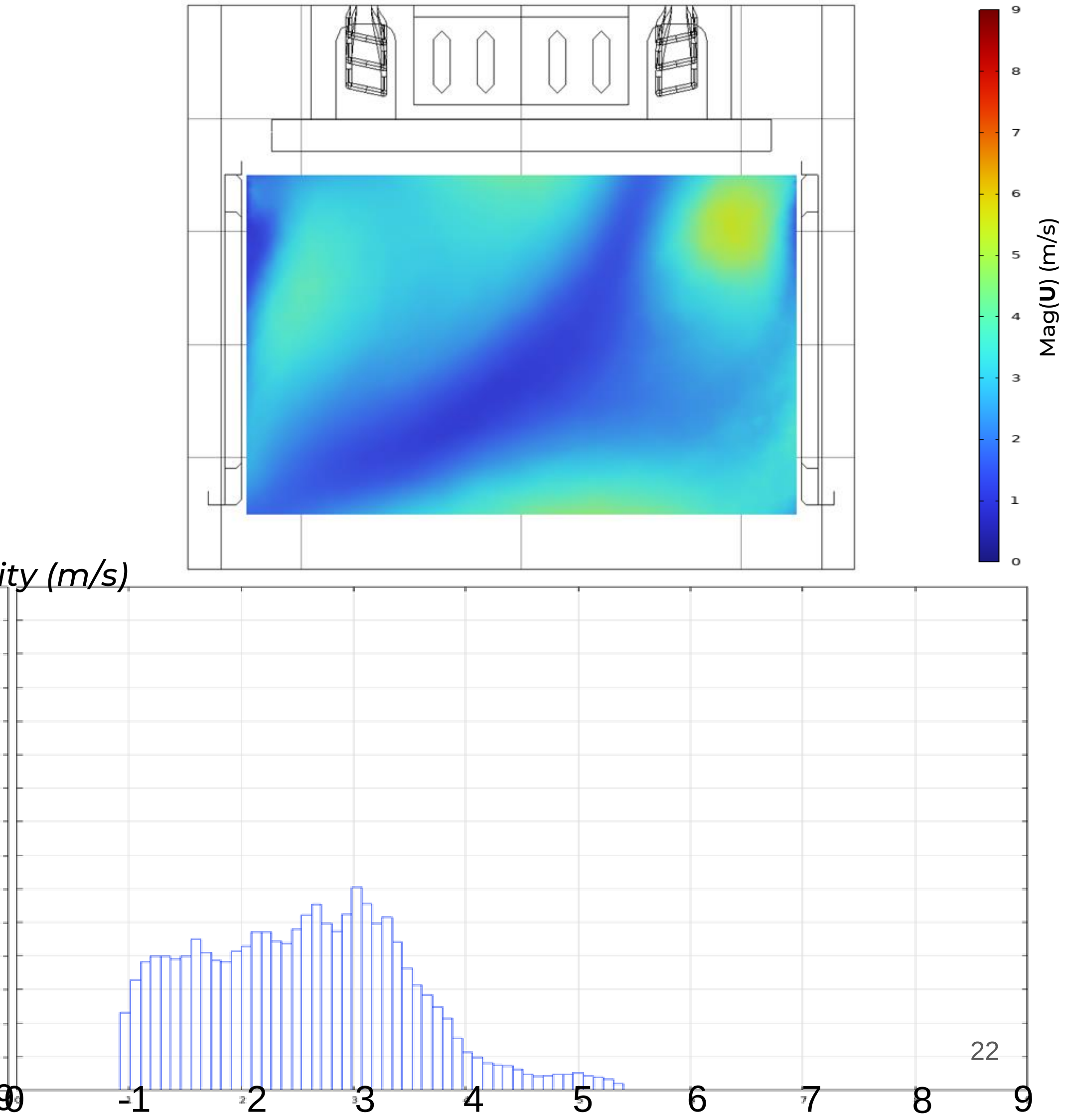
Step 1

Step 3

Mag(**U**) hystogram at h = 0,2 m from the bottom.



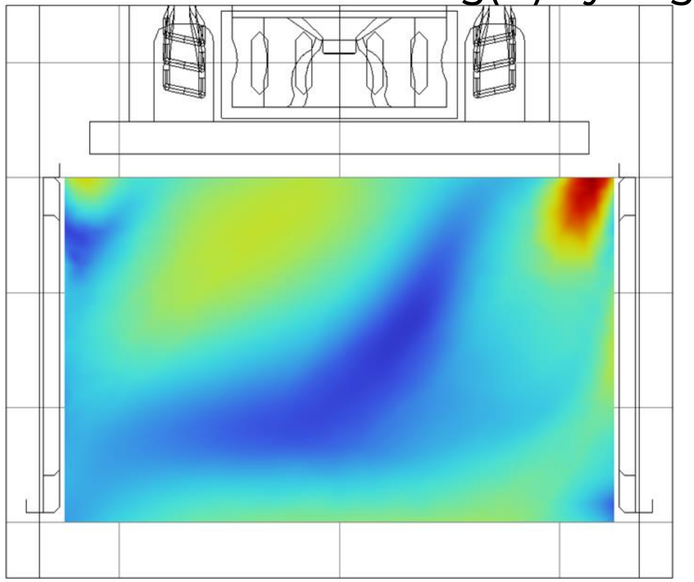
Velocity (m/s)

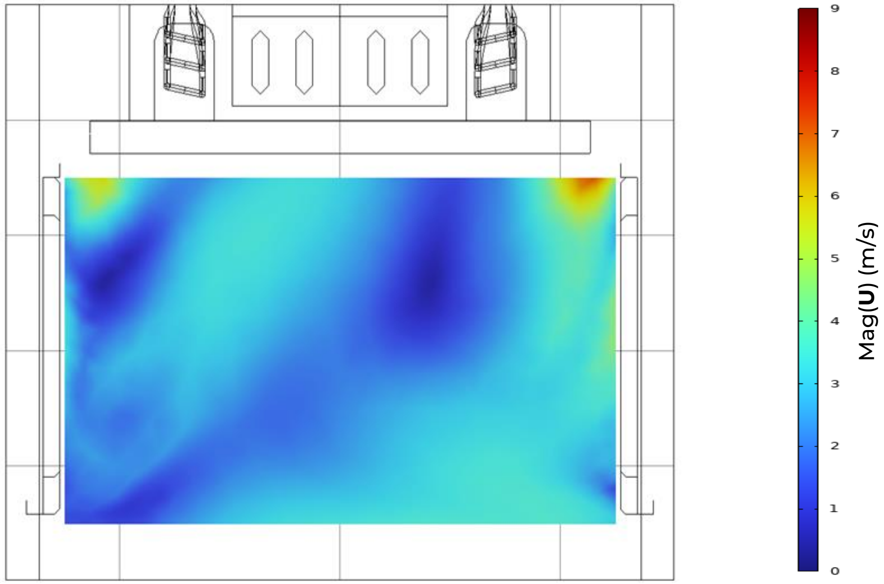


Results Tray 3 position – step 1 vs step 3

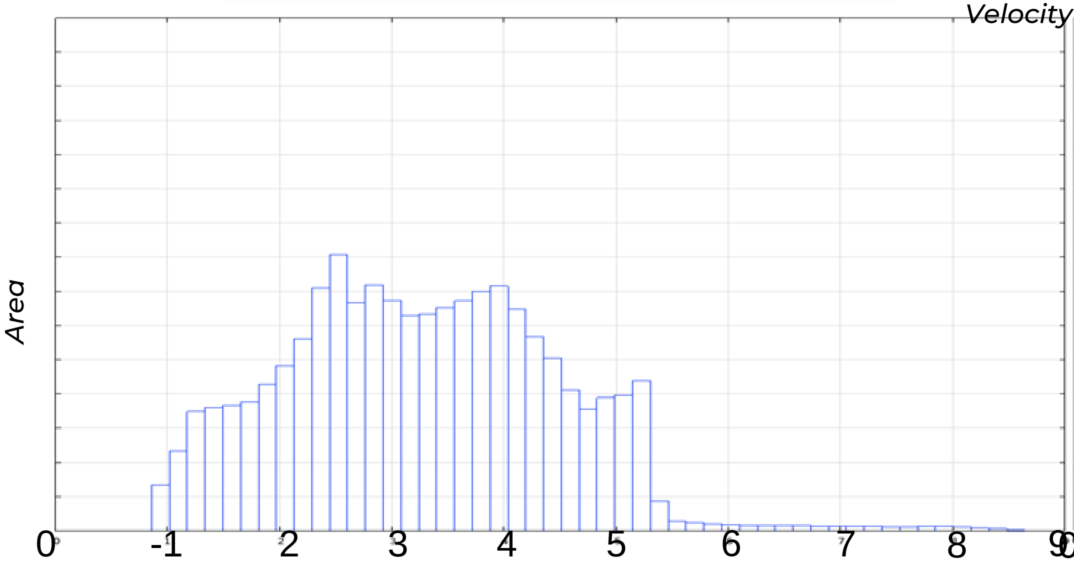
Step 1 *Step 3*

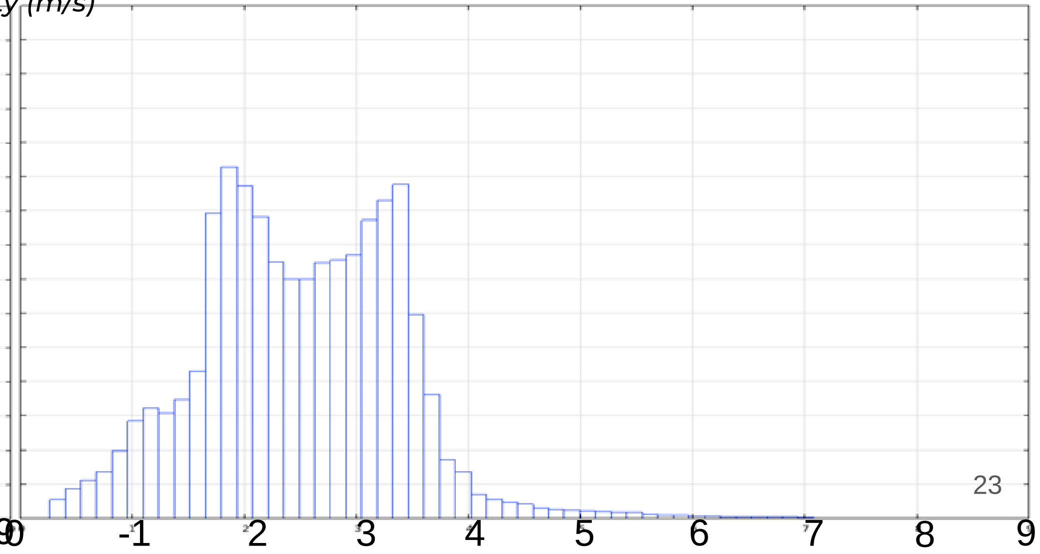
Mag(**U**) hystogram at h = 0,3 m from the bottom.





Velocity (m/s)





Results Tray 4 position – step 1 vs step 3

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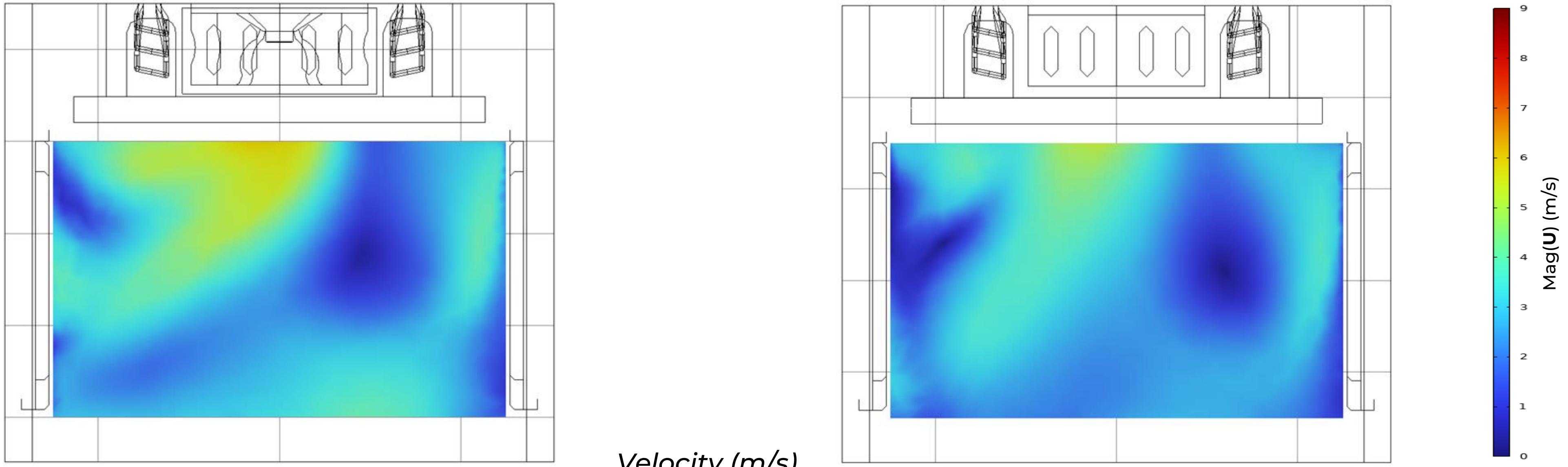
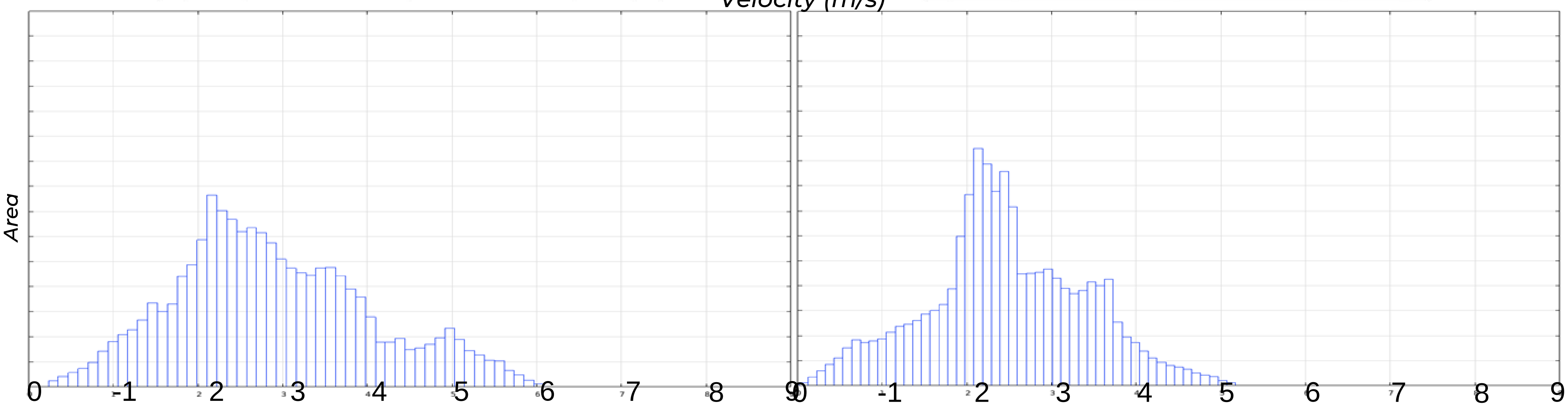
Step 1 *Step 3*

Mag(**U**) hystogram at h = 0,4 m from the bottom.





Results Tray 5 position – step 1 vs step 3

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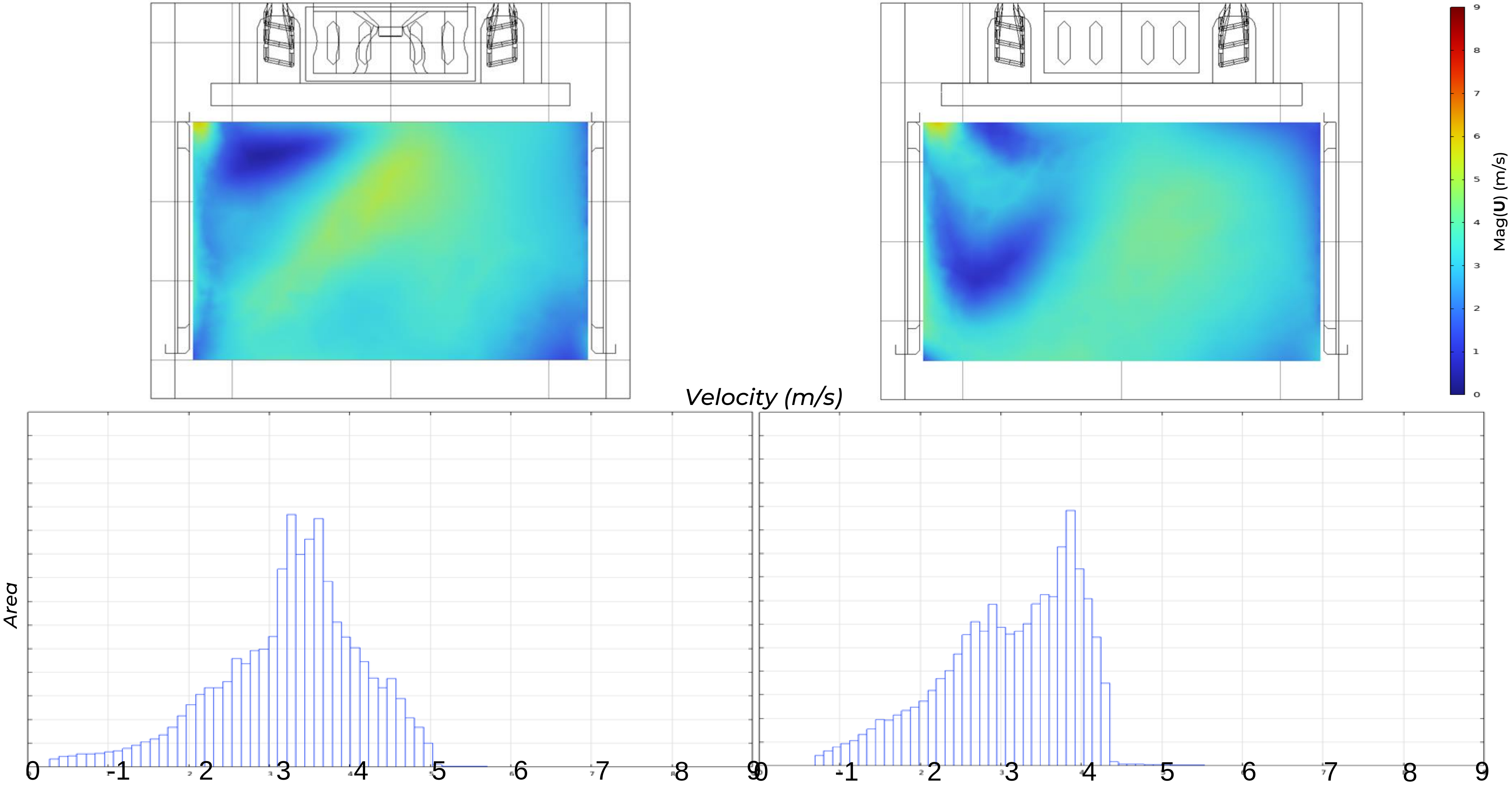
Step 1 *Step 3*

Mag(**U**) hystogram at h = 0,5 m from the bottom.



Results Comparison step 1 vs step 3

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Let’s consider how off are the mean values for each tray position between the two steps given the previous hystograms

Tray	shift 1-3 (%)
1	6,45
2	5,48
3	5,60
4	3,03
5	2,30
average	4,57

Final considerations

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1. The numerical model has been experimentally validated for step 2 and deviation from the experimental values can be considered good.

2. The average deviation of the speed distribution in the trays between step 1 and step 3 is less than 5% at all the levels.

3. Qualitatively, the velocity profiles between step 1 and step 2 are very similar, and the main difference is due to loss of some turobent components at the outlet of the fan along the suction axis.

Conclusion

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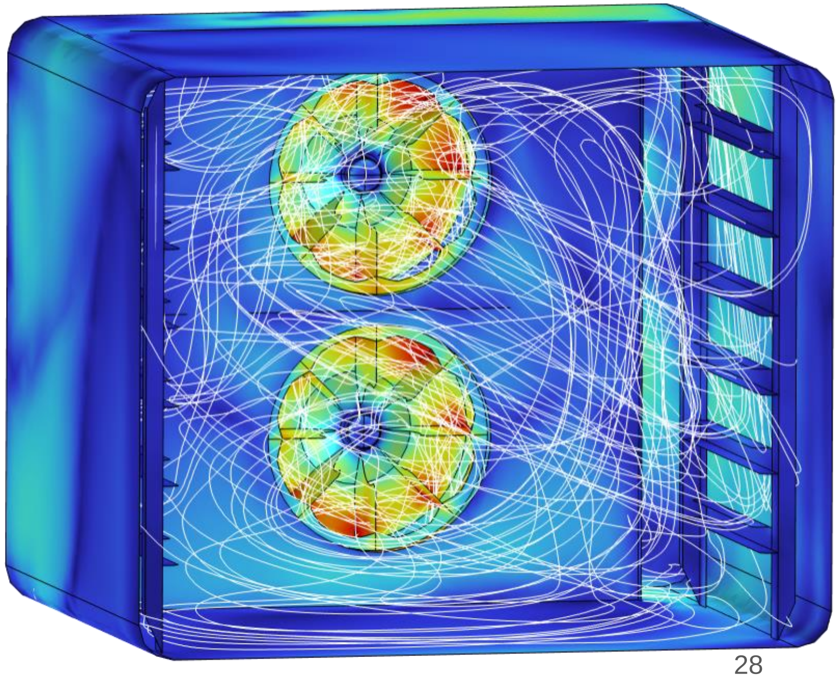
A good balance between accuracy and computational performances can be achieved by studing the fan alone and then imposing velocity profile and pressure

A better usage of the modules can be achieved differentiating the analysis in different steps as presented



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