Numerical and experimental study on cooling process in spiral

Overview

- Project goals
- Up-to-date efforts
- Basics of heat transfer: Thermal & hydynamic boundary layers
- Experimental work on single pasties
- Numerical simulation of the whole spiral
- Next steps?
- Conclusion

Project objectives

- Reduction in retention time in spiral
  - Improving product quality (dehydration, texture, flavour)
  - Freezing the product
  - Increasing company profitability

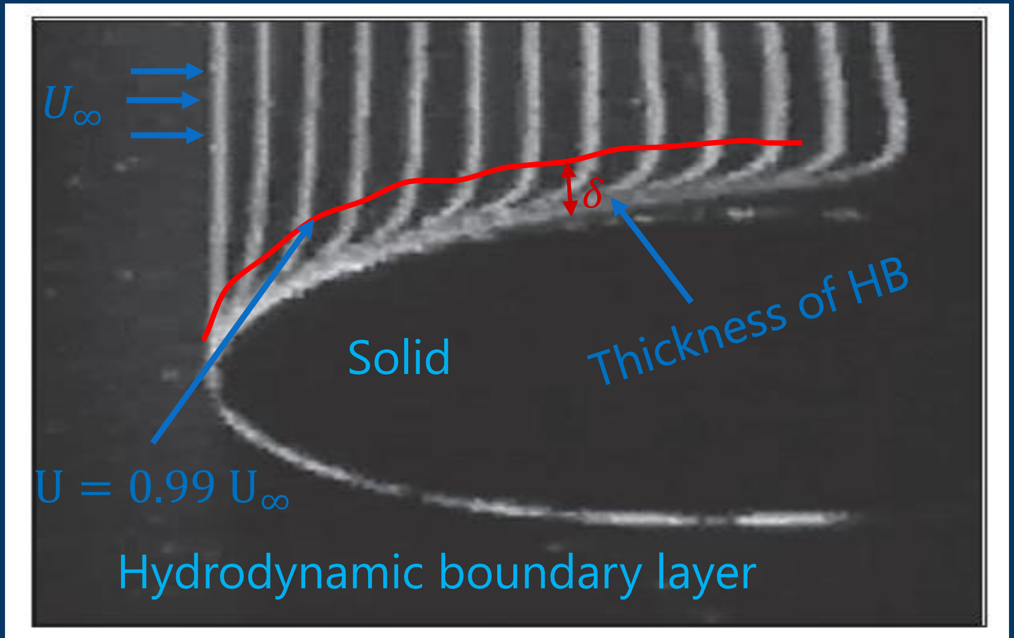
Up-to-date efforts and next steps

- Completed: CFD 2D analysis
  - Simulation showed that impingement is more efficient than spiral approach
- In progress: 3D Numerical and experimental analysis
  - 3D numerical analysing of a single pasty is ongoing
  - Analysing of a cooling spiral model
  - Experimental data obtained for a single pasty

Heat Transfer basics: Boundary layer concept

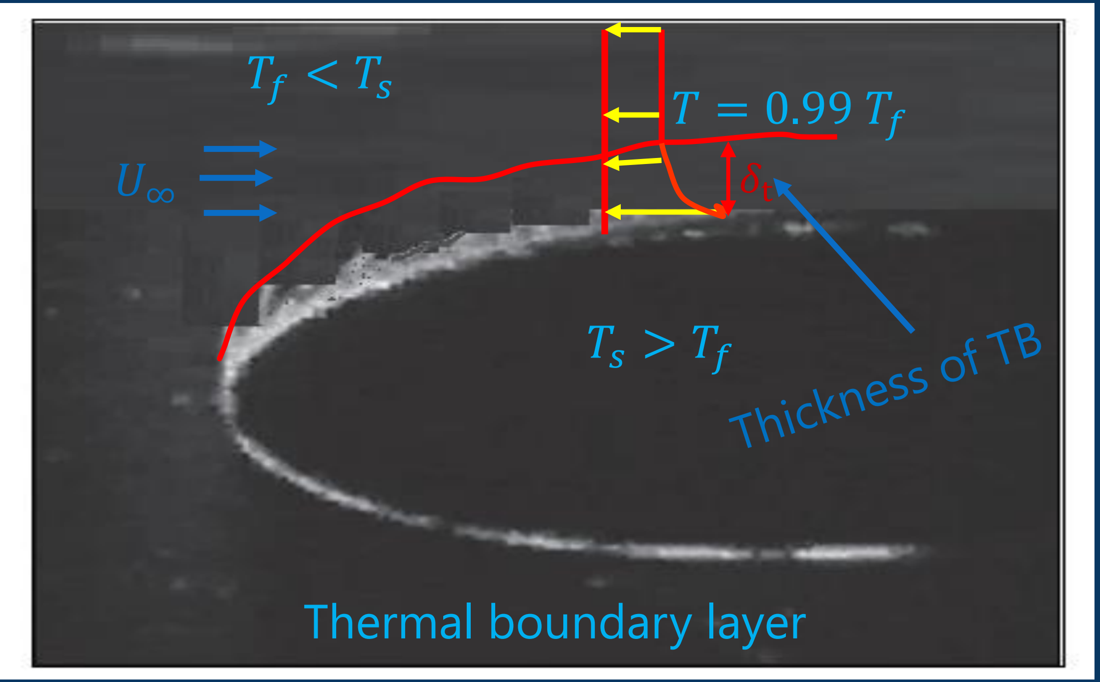
No-slip condition: when a fluid brought in in direct contact with a solid, it comes to rest "sticks" to the surface due to viscous effects, and there is no slip. This causes the development of Hydrodynamic boundary layer (HB)

Viscosity of a fluid is responsible for the no-slip condition and the development of the HB

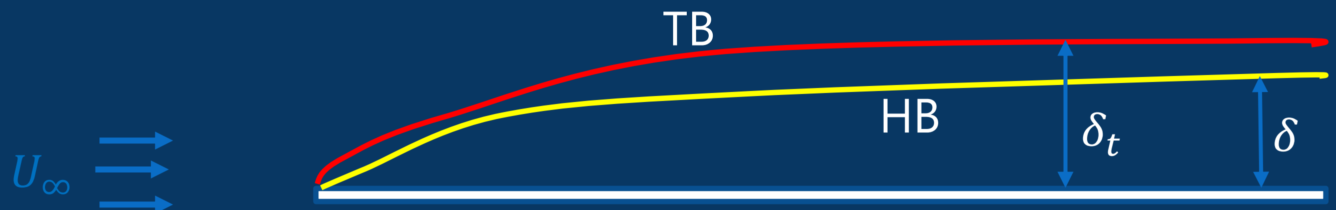


Thermal boundary layer (TB) develops when a fluid brought into contact with a solid surface with a different temperature. The flow region (TB) developed, due the temperature variation, over the surface is thermally significant.

The *thickness* of the thermal boundary layer δ_t at any location along the surface is defined as *the distance from the surface at which the temperature difference $T - T_s$ equals to* $0.99\ (T_f - T_s)$.



Heat Transfer in Conjugate systems



Flat plate

Reynolds number Re$= \frac{U\,x}{\nu}$

Prandlt number $Pr = \frac{\nu}{\alpha}$, $\frac{\delta}{\delta_t} \cong Pr^{\frac{1}{3}}$

where $\delta_t > \delta$ for $Pr < 1$ for air $Pr \sim 0.7$

$$\delta = \frac{4.91\,x}{\sqrt{Re_x}} \Longrightarrow \delta_t = \frac{4.91\,x}{Pr^{\frac{1}{3}}\sqrt{Re_x}}$$

The average heat flux

$$\bar{Q} = \bar{h}\,A\,(T_s - T_f)$$

The average convective coefficient

$$\bar{h} = 0.332\frac{k_f}{L}\,Pr^{\frac{1}{3}}\,Re_L^{\frac{1}{2}}$$

The average Nusselt number

$$\overline{Nu} = \bar{h}\frac{L}{k_f} = 0.332\;Pr^{\frac{1}{3}}\;Re_L^{\frac{1}{2}}$$

A common correlation of average Nusselt number

$$\overline{Nu} = C\;Pr^{n}\;Re_L^{m}$$

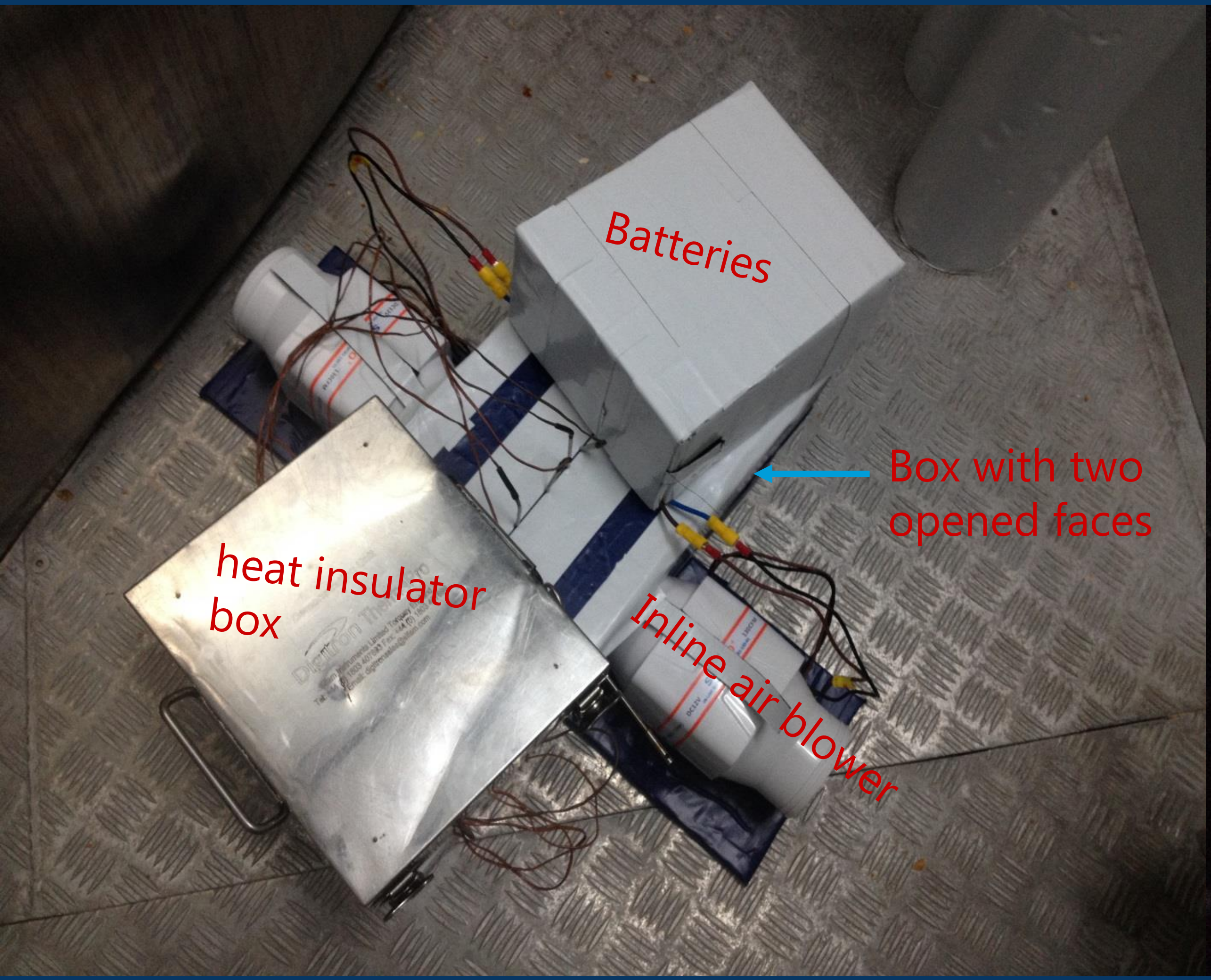
where C stands for geometry, 0<n<1 and 0<m<1

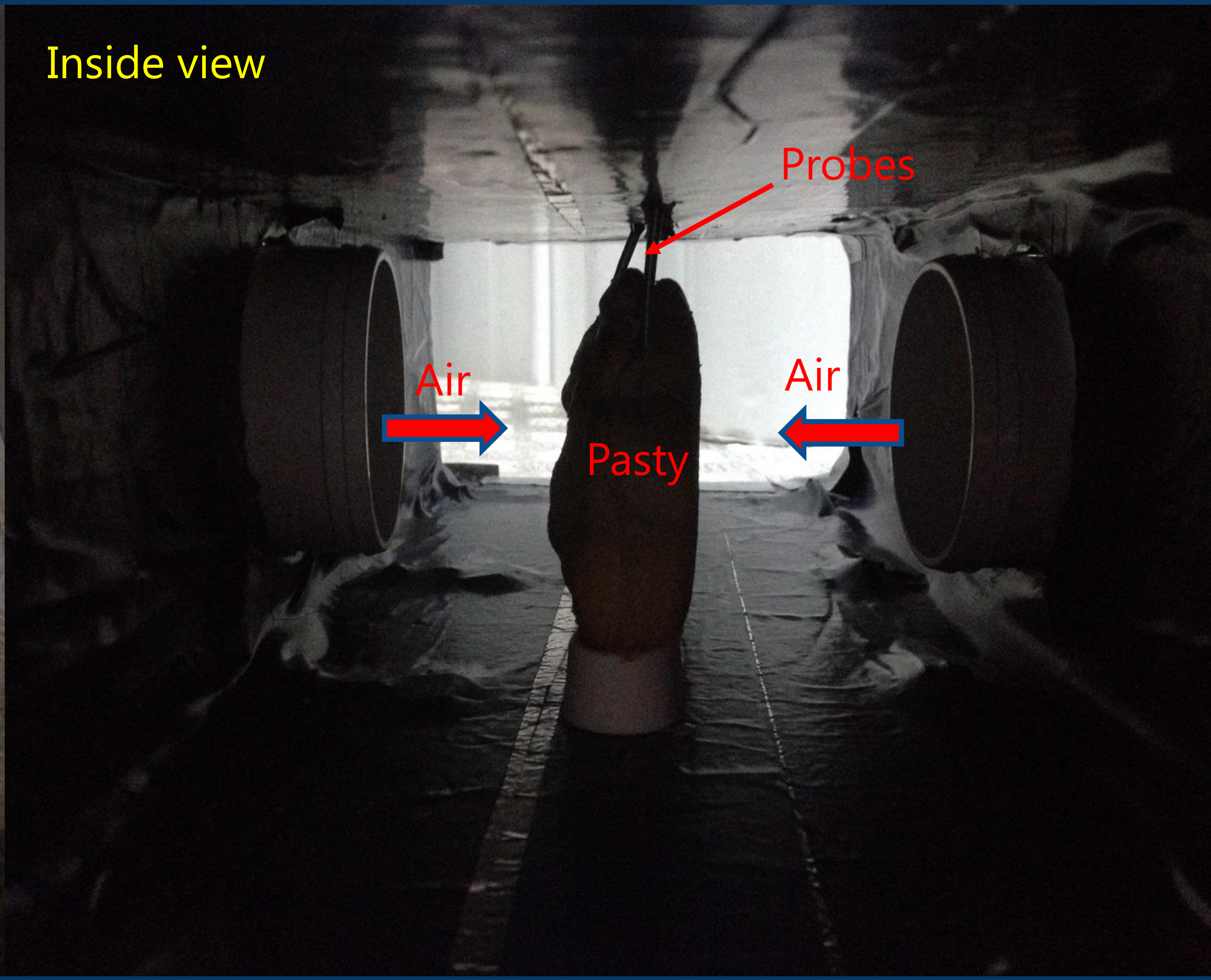
Simple experimental work

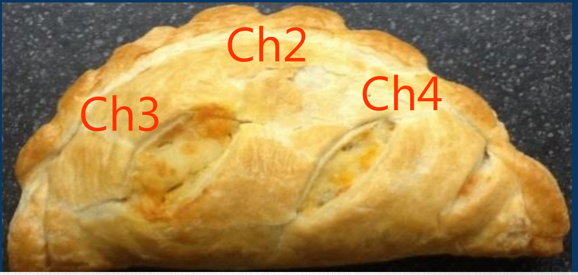
Aims

- Monitoring the effect of the velocity of air on heat transfer
- Determine limits and possibilities of an ticipated achievement
- Identifying the base point for further optimization

Experiment set up and the equipment

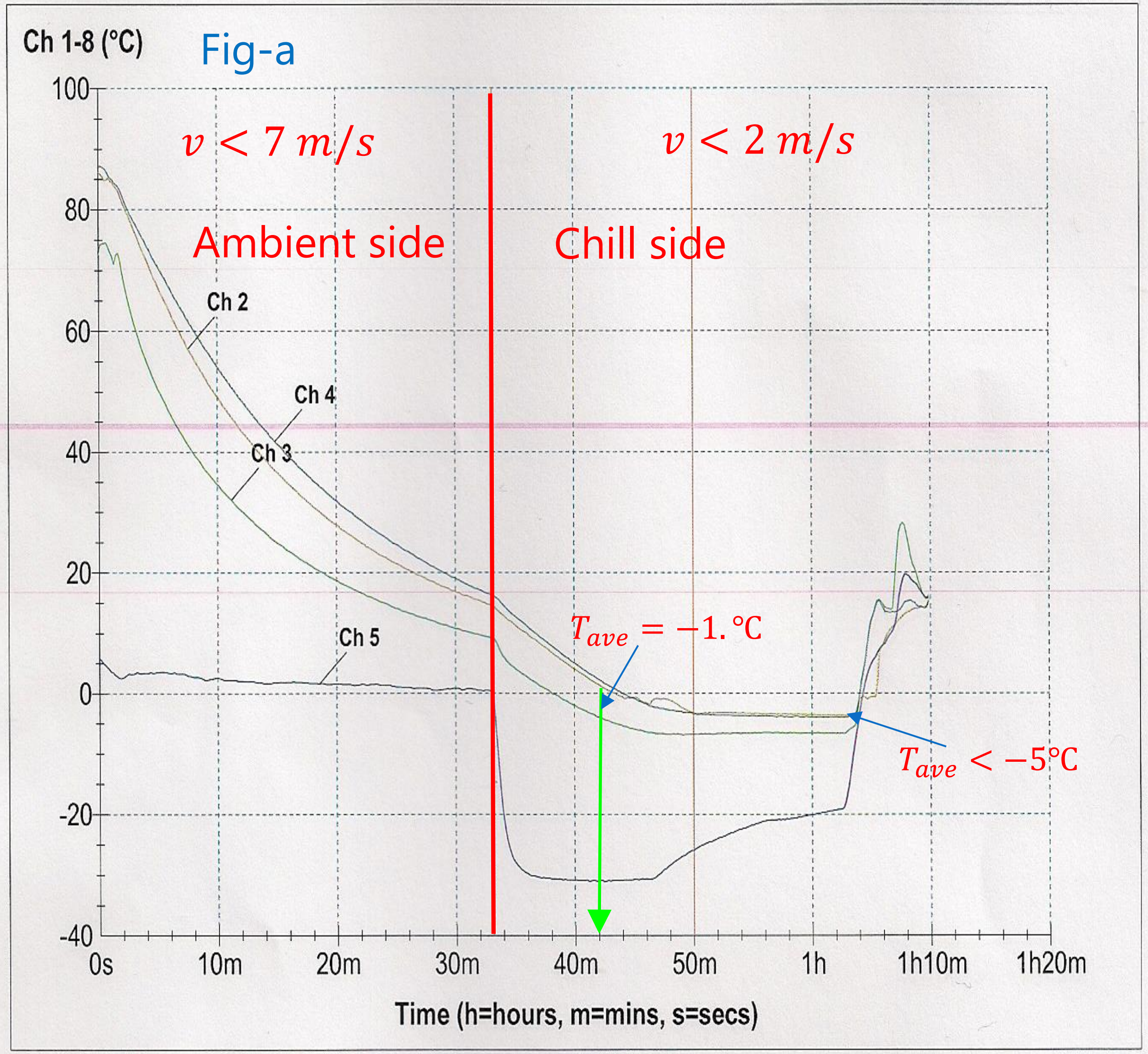


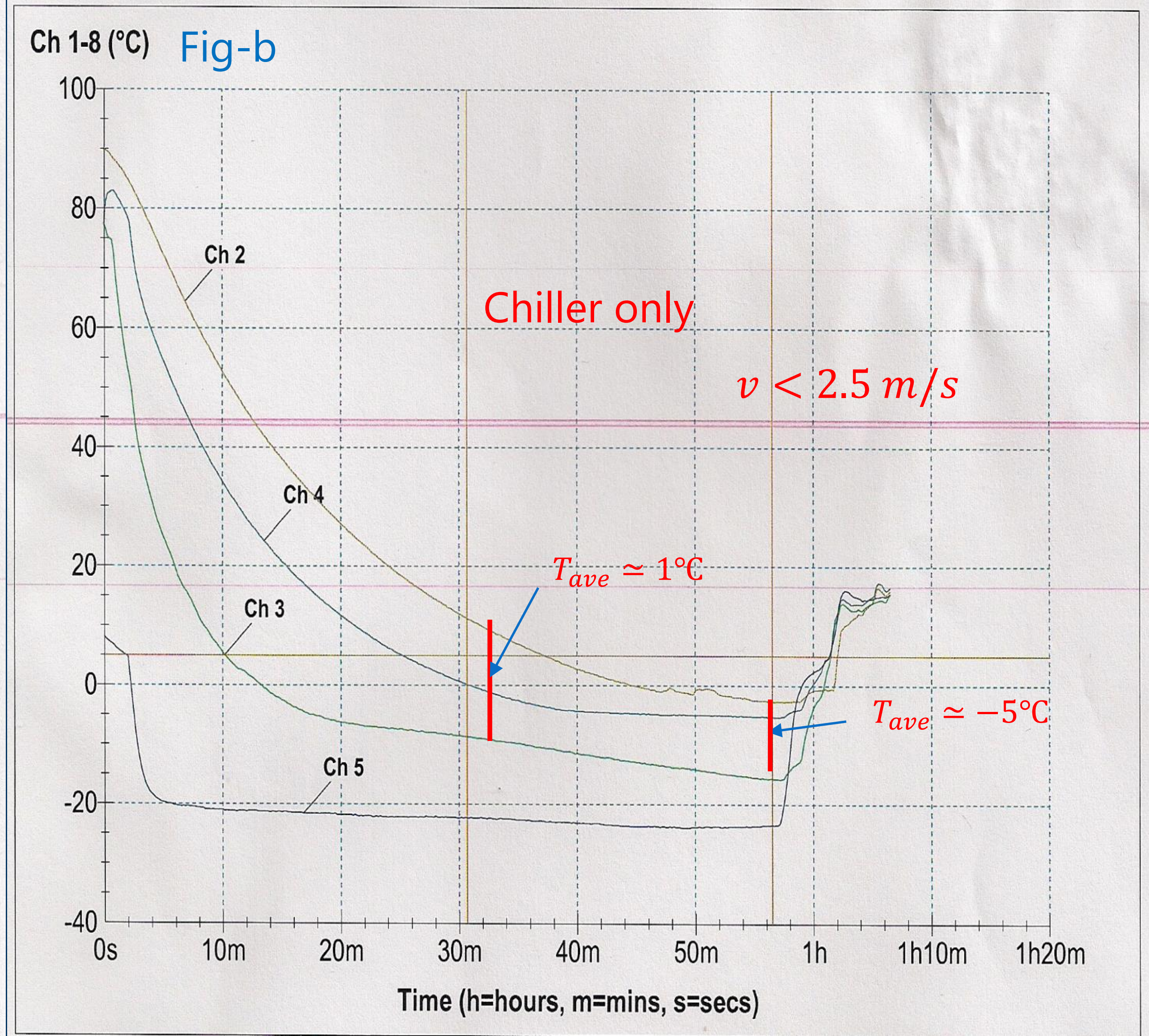




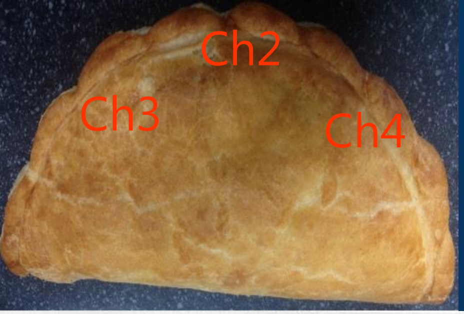
Experimental Results: Tesco4Pak C&O

Temperature profiles at three different locations in a pasty:
Fig-a data obtained from the combined cooling of ambient and chiller spirals
Fig-b data obtained from chiller spiral only





Experimental Results: OCP 270g



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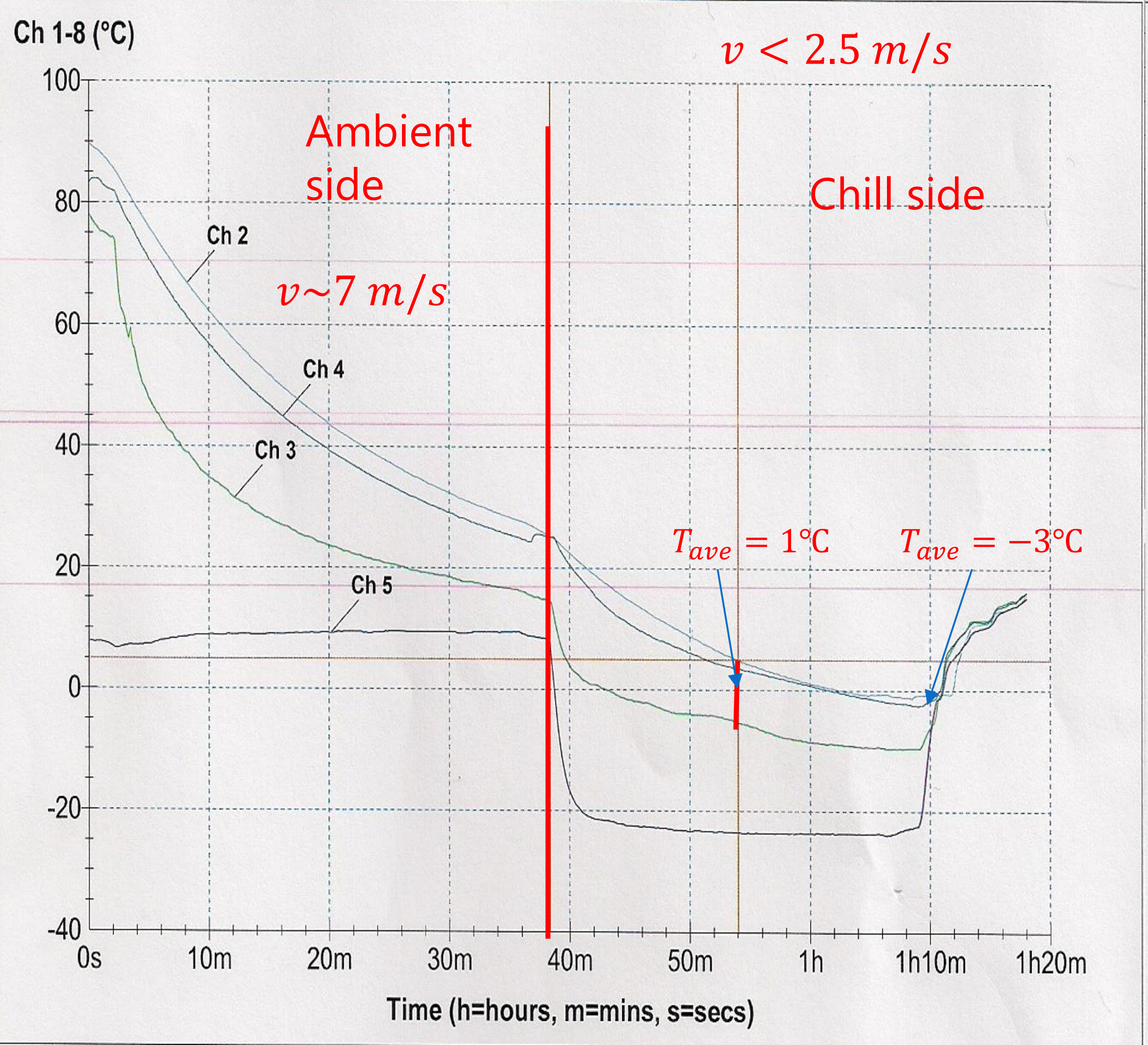
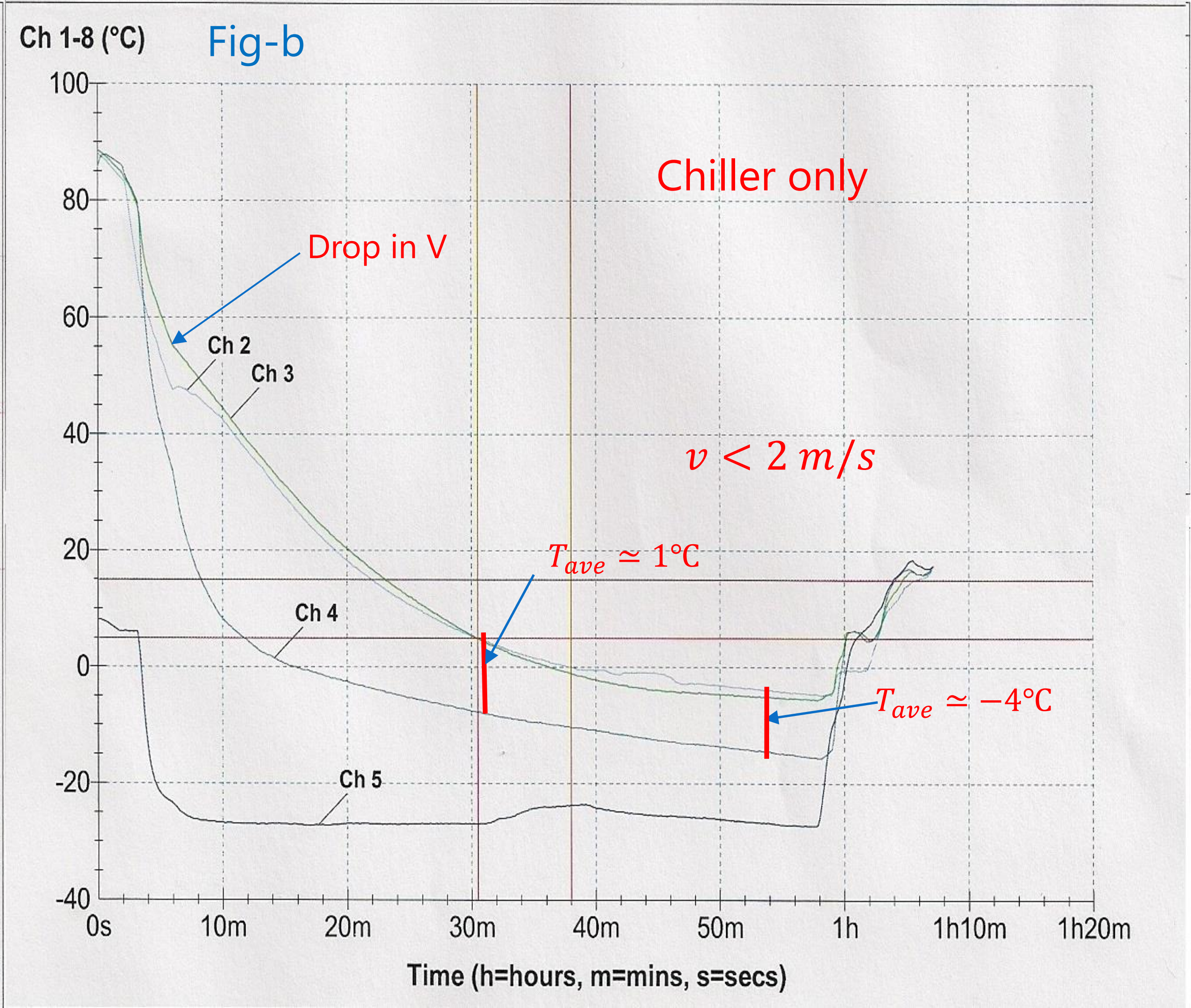
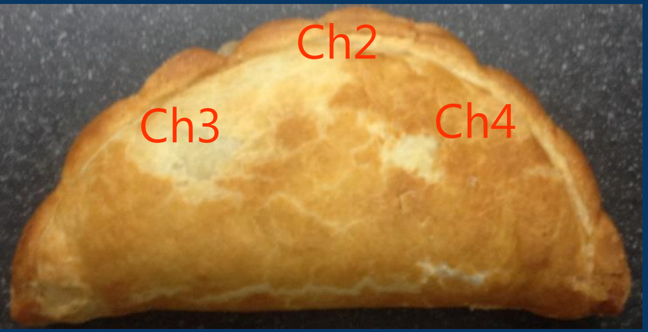
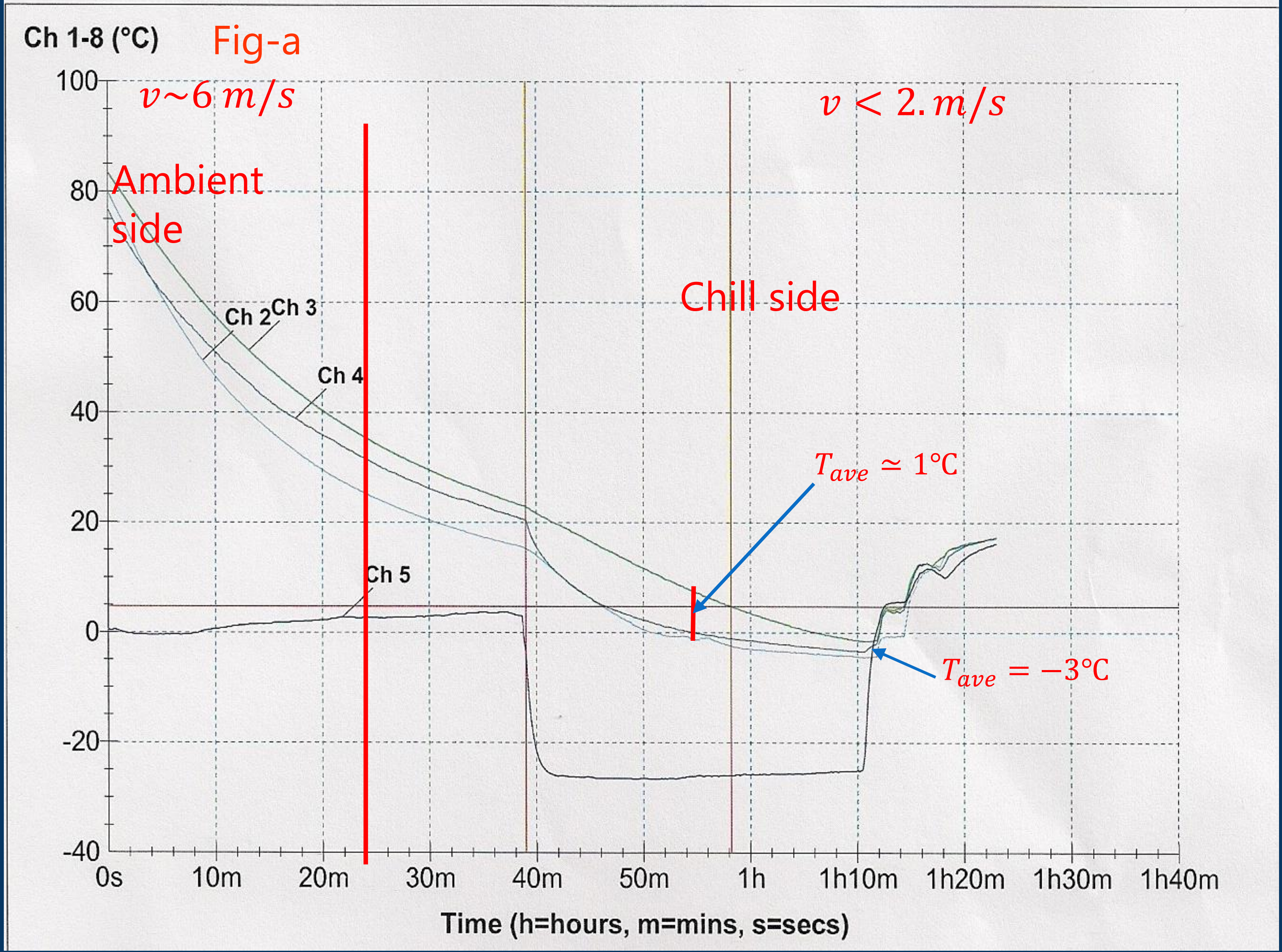




Experimental Results: OCP 284g



Temperature profiles at three different locations in the OCP284g pasty:
Fig-a data obtained from the combined ambient and chiller spirals



Comparison between the current retention time and the tests

Product name and number of experiments	Current Spiral				Test 1				Test 2	
	Time (A) [minutes]	T_{ave} [°C]	Time (C) [minutes]	T_{ave} [°C]	Time (A) [minutes]	T_{ave} [°C]	Time (C) [minutes]	T_{ave} [°C]	Time (C) [minutes]	T_{ave} [°C]
Tesco4Pack135g (3 tests)	40	~ 45	40	< 3	~ 35	~ 19	~ 8	< 3	~ 31	< 1
OPC227g (3 tests)	45	~ 50	45	< 3	~ 36	~ 22	~ 15	< 3	~ 32	< 2
OPC284g (1 test)	45	~ 50	45	< 3	~ 38	~ 24	~ 18	< 3		

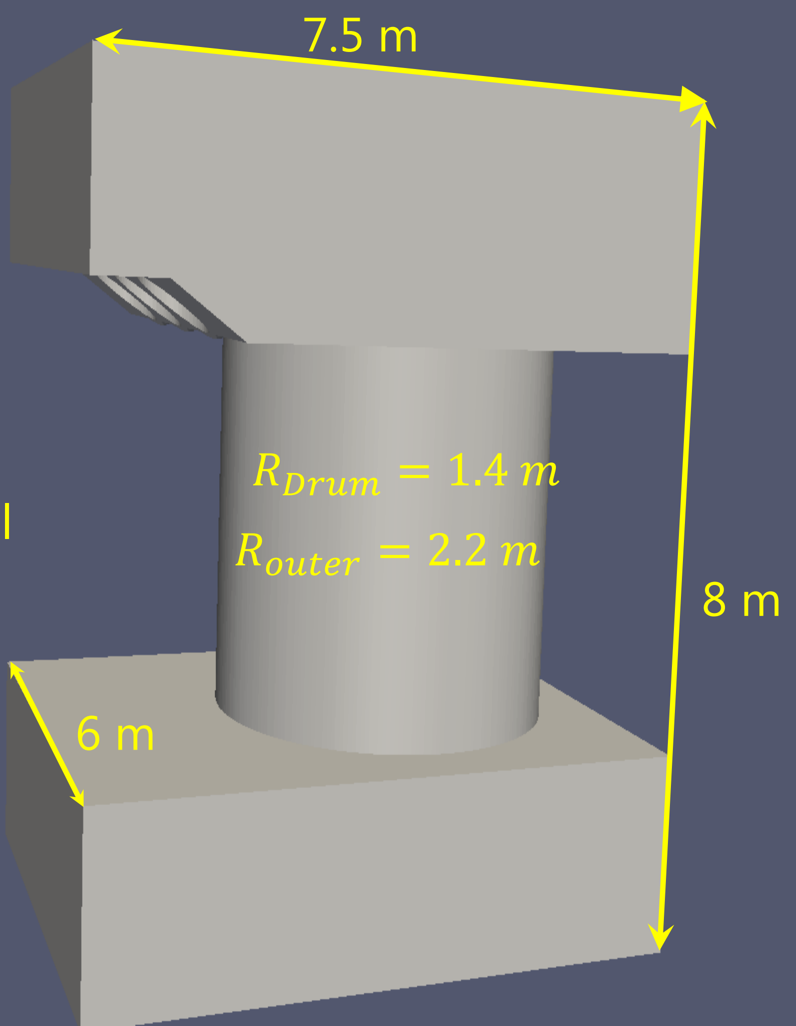
The improvement that can be achieved in percentage against the current system

Product name	Test1 gain in the side Ambient [%]	Test1 gain in the Chill sides [%]	Test1 over all gain [%]	Test2 over all gain [%]
Tesco4Pack135g	12.5	80	46.25	61.25
OPC227g	20	66.66	43	60
OPC284g	15	61	39	

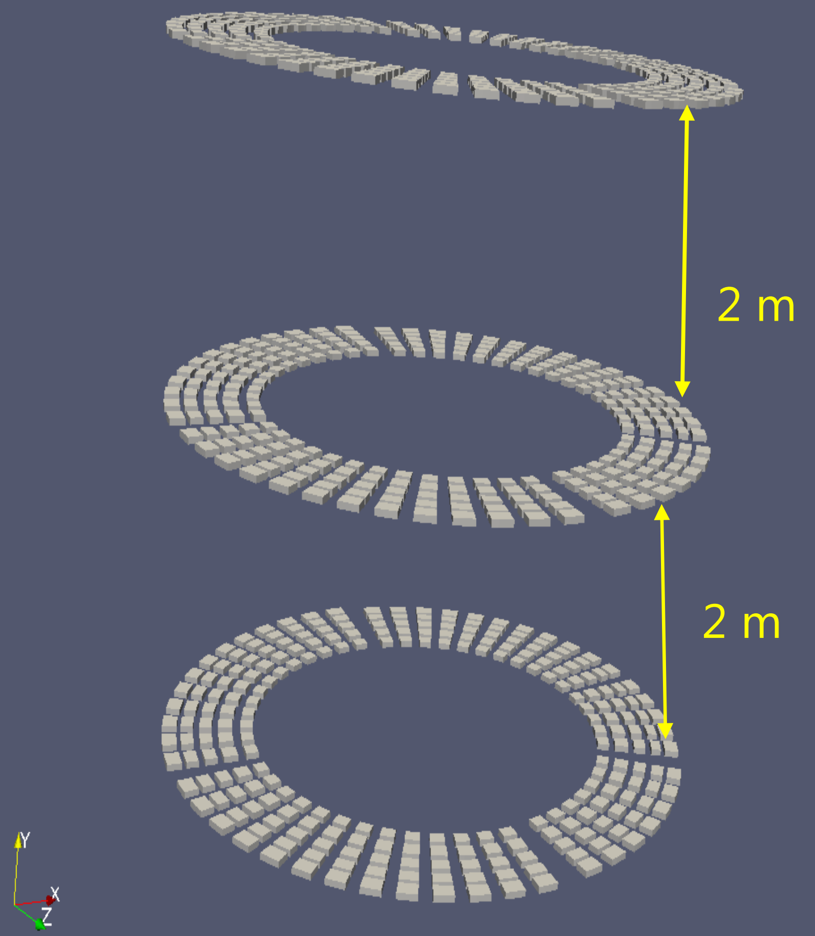
Numerical simulation of spiral

Aims

- Predicting the air circulation within the spiral
- Extraction the velocity profile and compare it against the actual one (later)
- Identifying the base point for further optimization

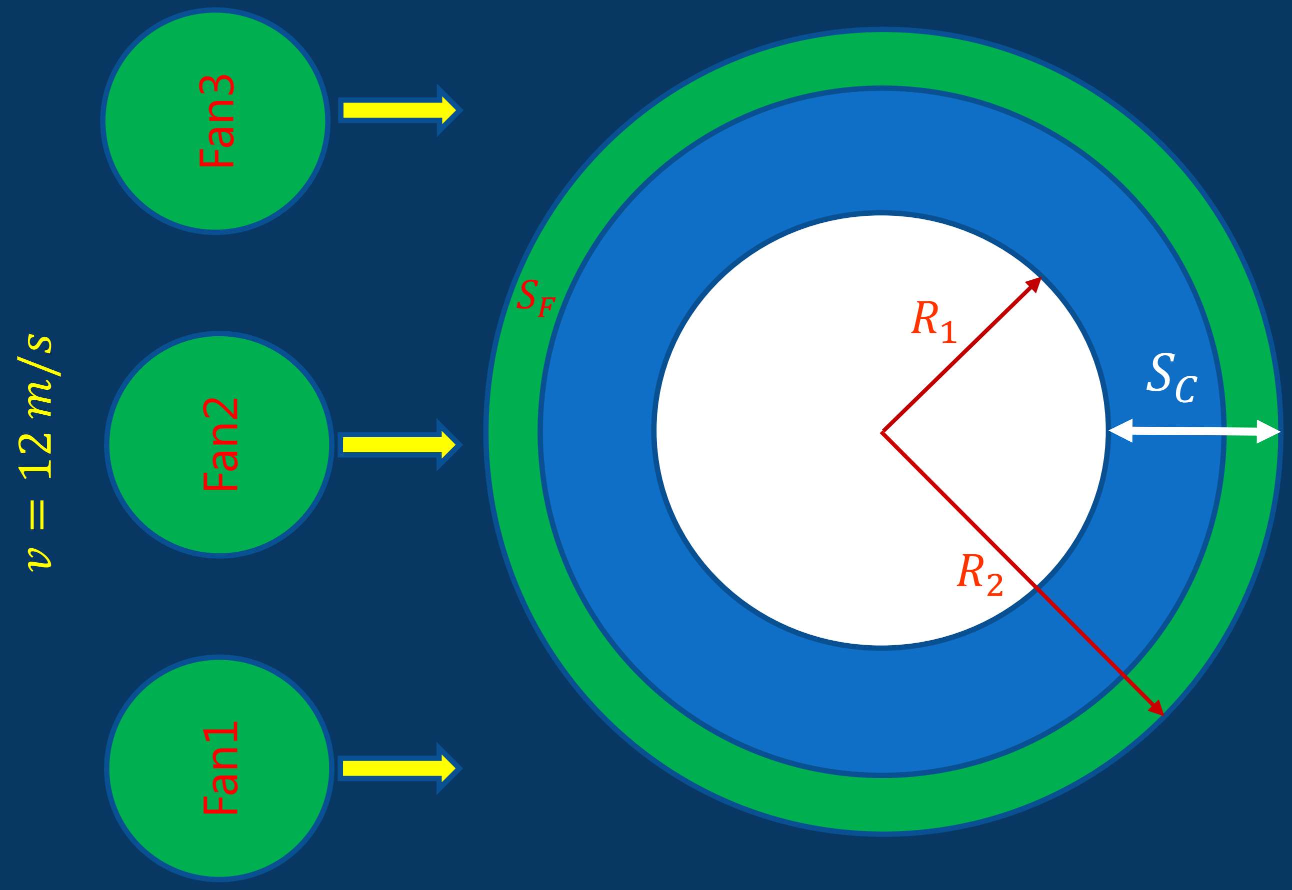


Computational Domain



Set of pasties at three different levels

Estimation of air distribution across the Conveyer



$$S_F = 3 \times (\pi r^2 - 0.1 \times D)$$
$$= 3 \times (3.14 \times 0.5^2 - 0.1) = 3 \times 0.685$$
$$= 2.055\ m^2$$

$$S_C = \pi\,(R_2^2 - R_1^2)$$
$$= 3.14\,(2.2^2 - 1.4^2)$$
$$= 9.0432\ \mathrm{m}^2$$

Mass conservation

$$\dot{Q}_F = \dot{Q}_C$$

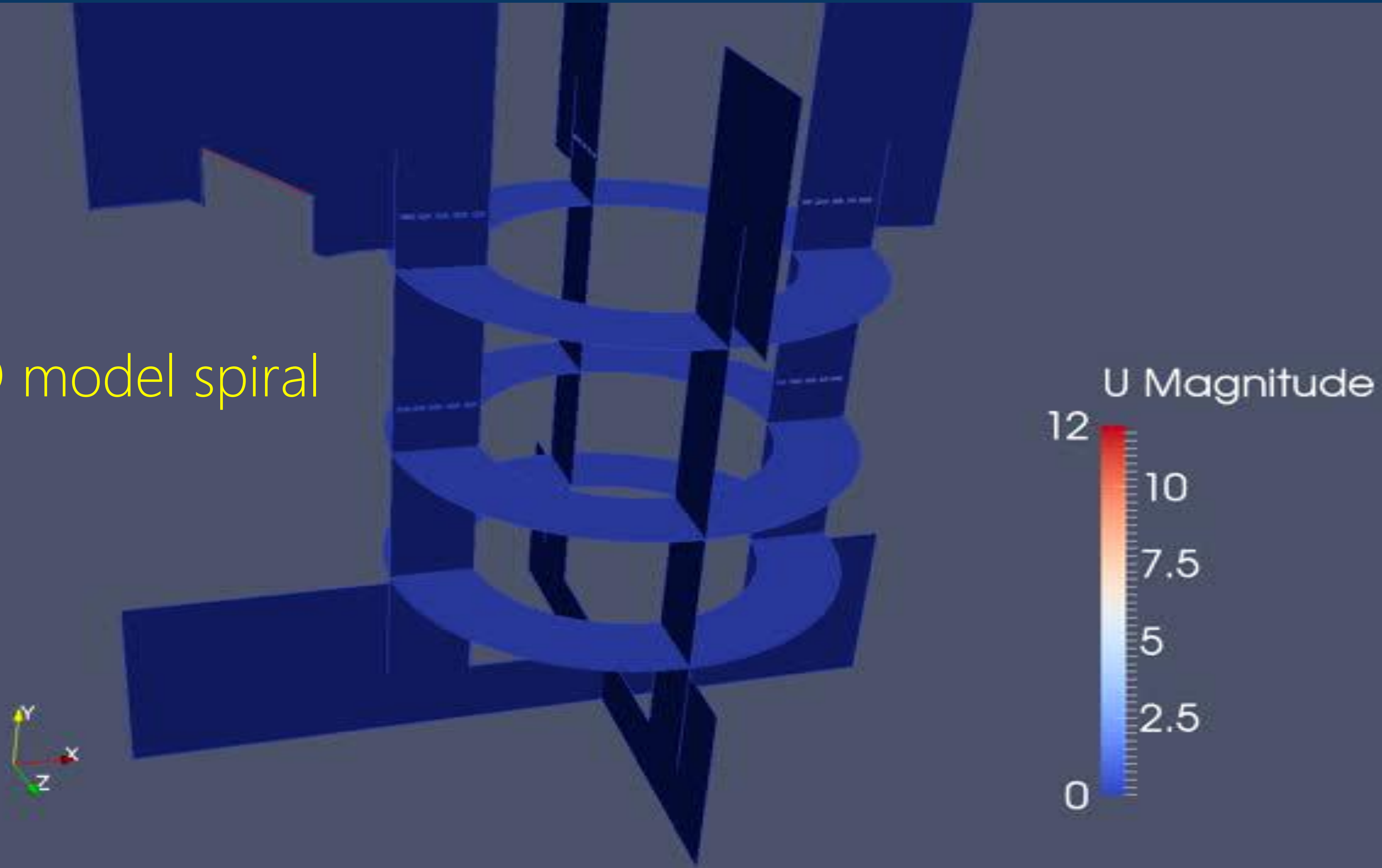
$$V_F \times S_F = V_C \times S_C$$

$$V_C = V_F \times \frac{S_F}{S_C}$$

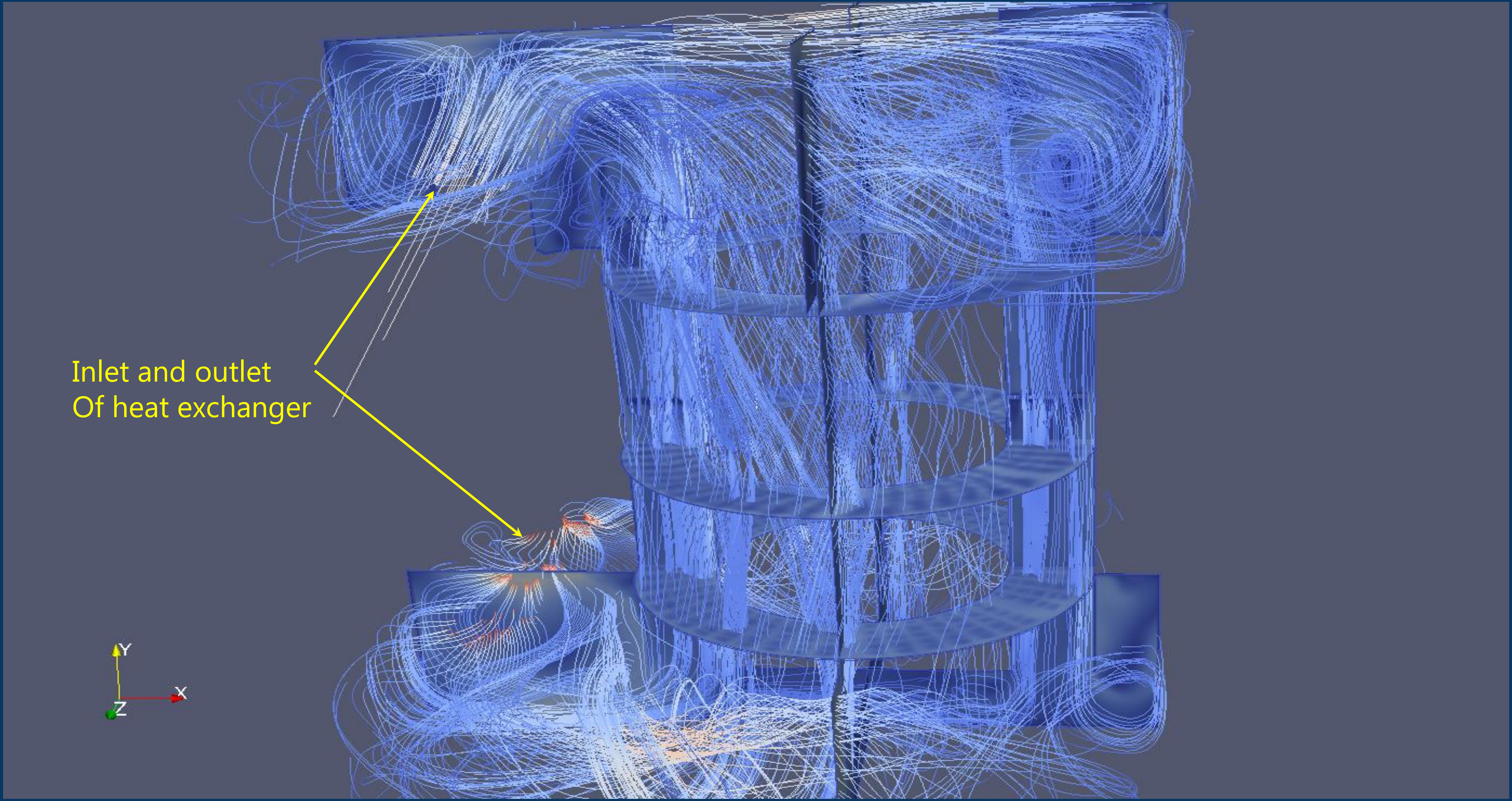
Velocity between the belt & drum:

$$\mathrm{V_C} = 2.7269\ m/s$$

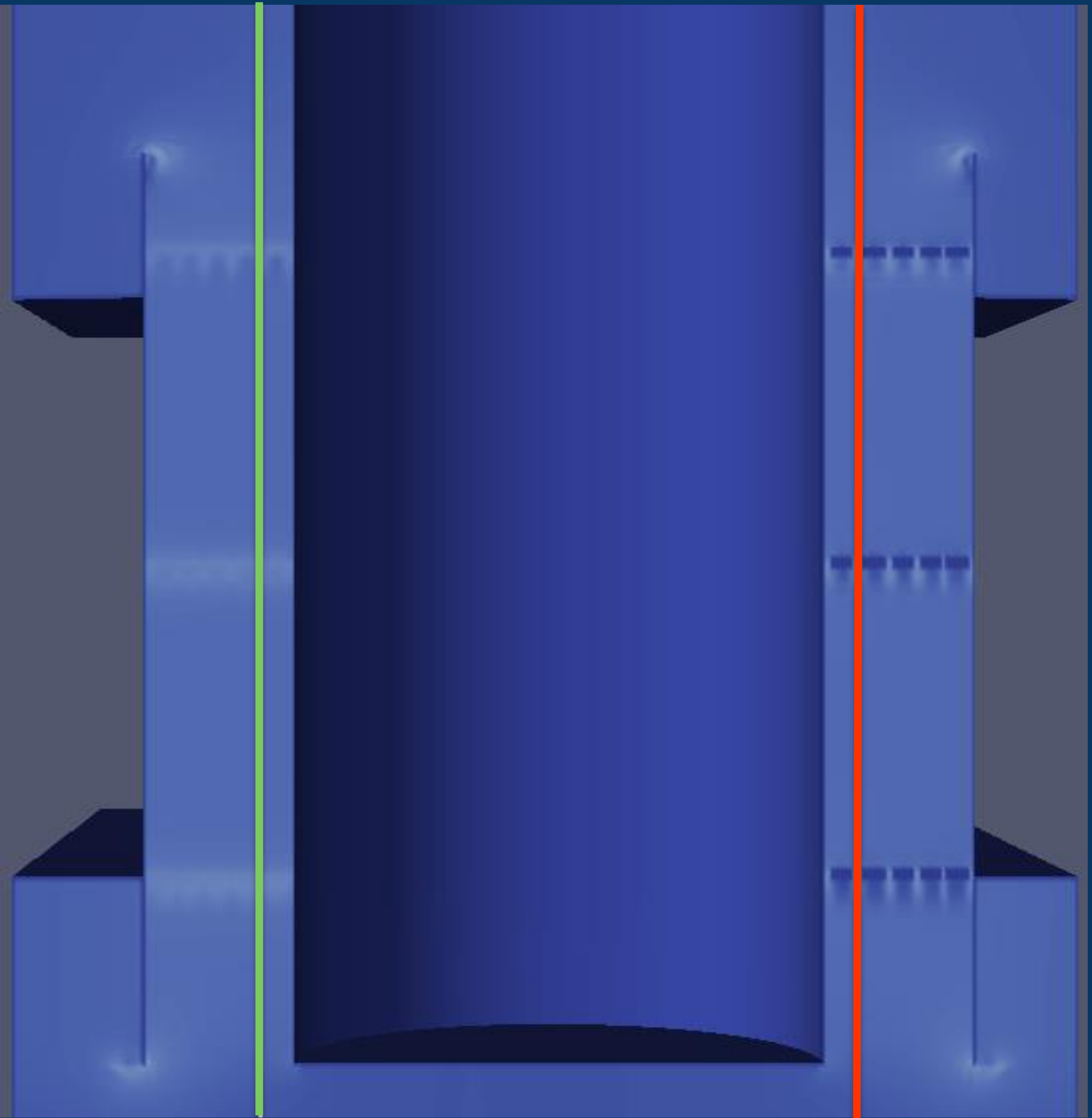
3D model spiral

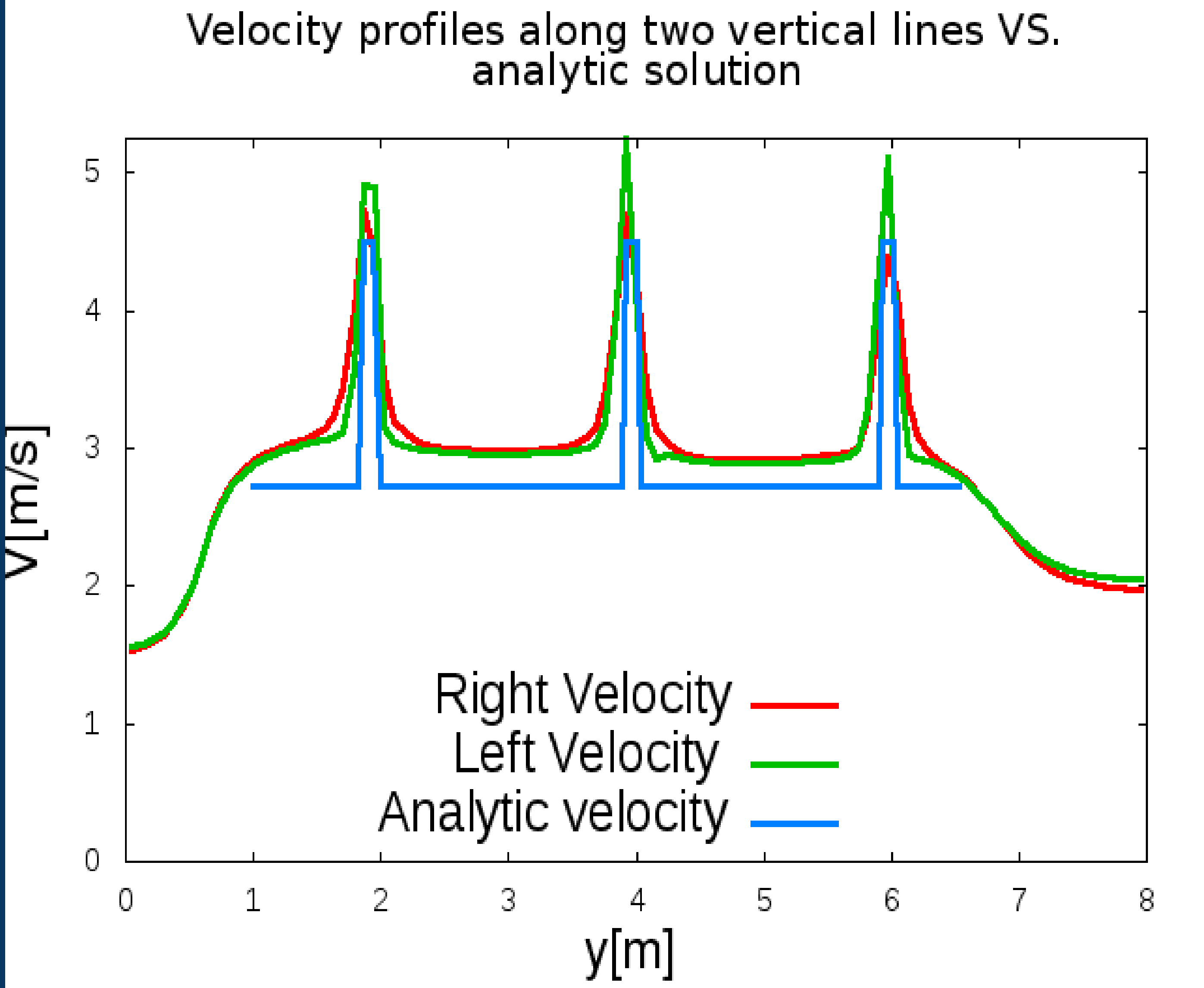


Stream lines of the air flow

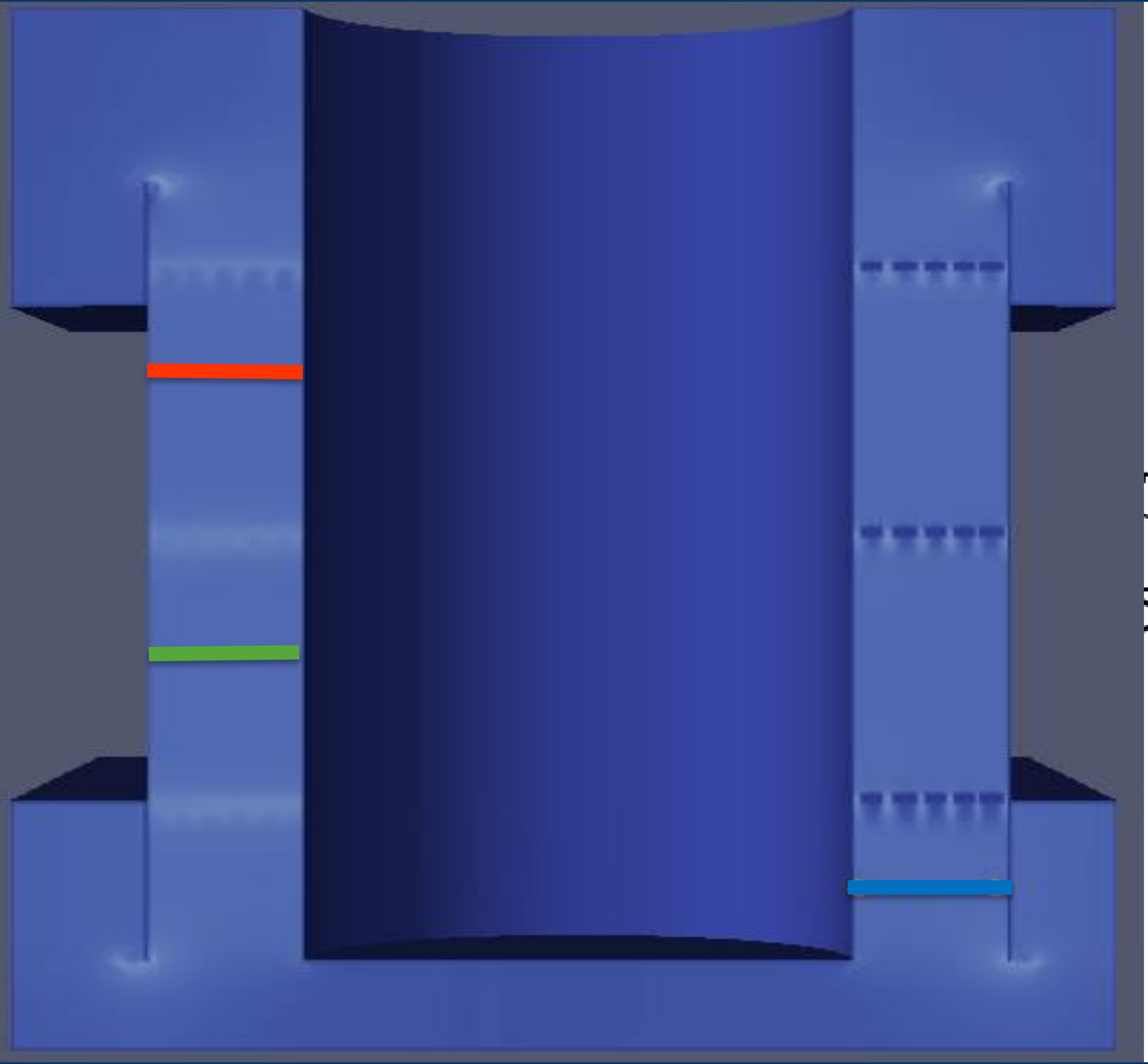


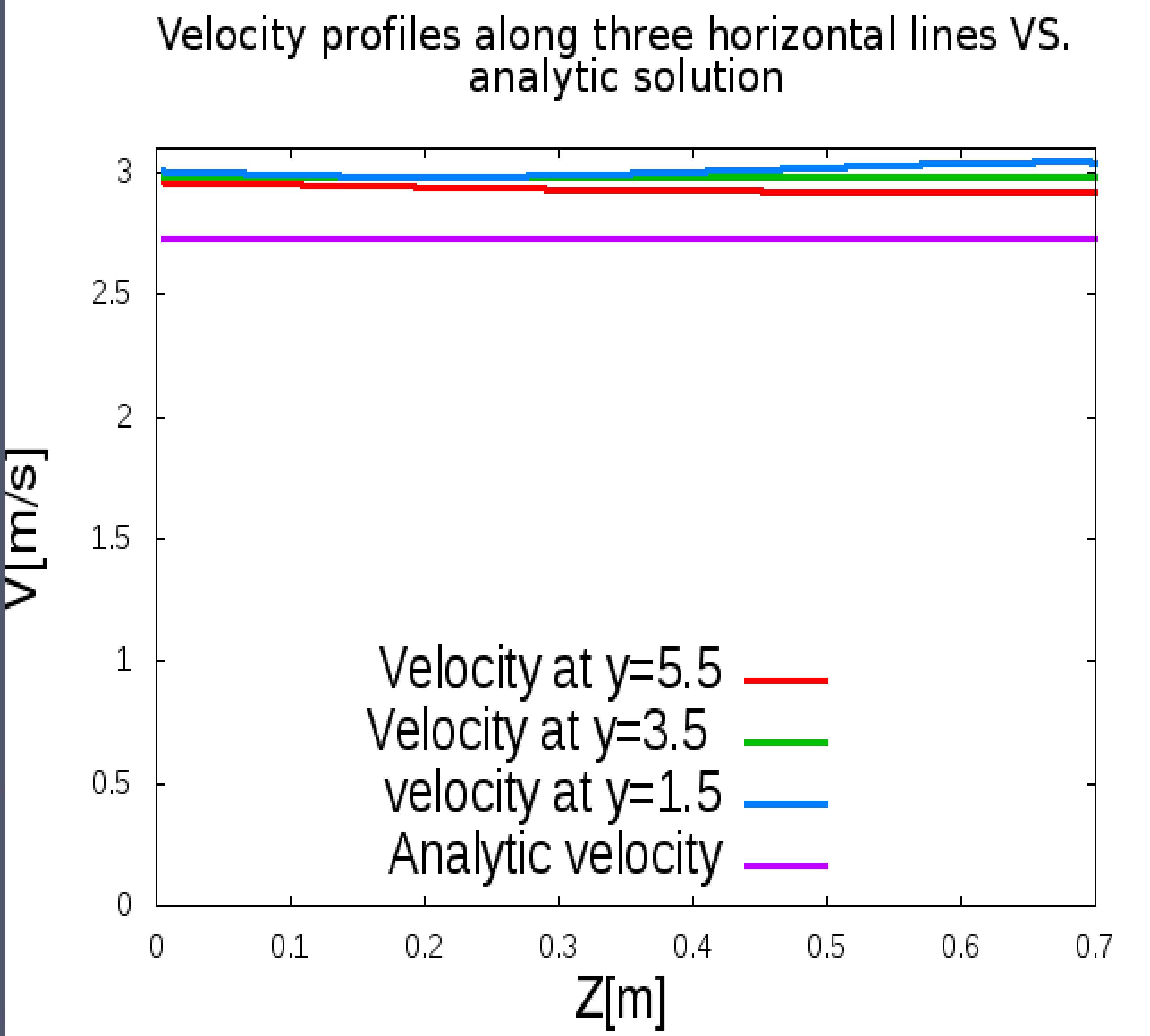
Validation of numerically calculated velocity against analytical values





Validation of horizontal Velocity at 3 different locations VS. analytical solution





Next Steps

- Simulation of whole spiral (4 weeks)
  - ✓ Numerical evaluation of the velocity of air and temperature inside the spiral (in particular improving air circulation)
  - ✓ Simulation a set of pasties inside of the spiral
- Conducting experiments on set of pasties (4 weeks)
  - ✓ Continuing investigating the effect of velocity on retention time including the effect of multiple units
  - ✓ The immediate action: monitoring the actual velocity of air inside the spiral

Conclusion

- It was found that the retention time for cooling could be reduced
- The velocity was validated against analytical solution
- The flow rate should be increased for better air circulation
- Further investigations (Numerical and experimental) are required,

  the actual air circulation in the spiral must be detrmined

The end of presentation