

FarmFlow sensitivity and validation study

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Summary

An actuator disk style turbine model was used in a wind tunnel at the Delft University of Technology, to be able to perform a benchmark study amongst simulation models. Results from this experiment are not usable for validation of the current FarmFlow version, because of numerical diffusion in the model, which forms a relatively large part of the total model diffusion at such low tunnel turbulence levels.

The solution may be to reduce the cell size in FarmFlow, which increases the calculation time. The task defined is to select and run a few validation cases with very small cell sizes, find an optimum with respect to calculation time and conclude if a validation with the PIV measurements from the TUDelft experiment becomes feasible.

This report concludes that the simulation results showing the wake expansion behind a 0.6m diameter, 1.2m high actuator-disk-style turbine, are of the correct magnitude. However, lack of resolution of the FarmFlow models prevents achieving a more accurate comparison with the experimental results. The highest resolution tuned version (FarmFlow 300t), which calculates at 18x higher cell numbers, still shows a coarse cell distribution across the rotor diameter, compared to the experimental results of the PIV measurements at Delft University.

To be able to improve this situation, ECN should look into reducing cell size by at least a factor 2, preferably 4 (FarmFlow 600t and FarmFlow 1200t respectively). This requires a Profound study into the convergence criteria that are imposed upon adjacent cells.

Alternatively, using conservation of mass, the diameter of the wake can be defined more accurately. The reduction of velocity should be constant over every cross section in the wake. Another possibility could be indirectly validation of FarmFlow. This requires ECNS to be validated with measurements from experiments with higher turbulence intensity values, which are more in the realistic/practical range of FarmFlow.

For now, validation of FarmFlow with the TUDelft experimental results is not possible. Besides that the numerical diffusion is not removed, only limited by tuning the various models.

1

Background

In 2014 a benchmark study was performed by Delft University of Technology. The purpose of the benchmark was to evaluate the accuracy and reliability of state-of-the-art numerical models in the near wake of a single actuator disc (AD), a case which is highly relevant for modelling the flow behind wind turbines.

Results from this experiment are not usable for validation of the current FarmFlow version, because of numerical diffusion in the model, which forms a relatively large part of the total model diffusion at such low tunnel turbulence levels. The solution is to reduce the cell size in FarmFlow, which increases the calculation time.

The task defined is to select and run a few validation cases with very small cell sizes, find an optimum with respect to calculation time and conclude if a validation with the PIV measurements from the TUDelft experiment becomes feasible.

2

FarmFlow settings

2.1 Menu settings

Table 1: Menu settings in FarmFlow (right column)

	TU Delft experiment	FarmFlow
Site view		
Height [m]	11,4	11,4
Width [m]	6,0	6,0
Grid scale [m]	-	0,6
Turbine data		
Type	AD	AD
Rotor diameter [m]	0,6	0,6
Hub height [m]	1,2	1,2
Air density	1,225	1,225
Performance	Not available	See PV-curve below
(Tip speed ratio)	6,97	See PV-curve below
(rpm)	17,38	See PV-curve below
Thrust coefficient	0,93	0,93
Drag coefficient	0,93	-
Porosity	32%	-
Turbulence intensity		
Wind direction dependence	no	no
Wind speed dependence	no	no
Turbulence intensity	0,5%	1%
Flow simulation		
Wind direction [°]	0	0
Wind speed [m/s]	4,7	4,7
Stability	-	Neutral

2.2 PV curve

FarmFlow requires a definition of a PV curve. For the project a turbine was defined called: "TUDelft AD 06". This turbine is a Betz-turbine of 10W. It's PV curve is defined as follows:

Table 2: Input table PV curve "TUDelft AD 06"-turbine

U	P	Ct	RS
[m/s]	[kW]	[-]	[rpm]
1	0.00009	0.93	17.4
2	0.00069	0.93	17.4
3	0.00234	0.93	17.4
4	0.00554	0.93	17.4
5	0.01000	0.93	17.4
6	0.01000	0.93	17.4
7	0.01000	0.93	17.4
8	0.01000	0.93	17.4
9	0.01000	0.93	17.4
10	0.01000	0.93	17.4

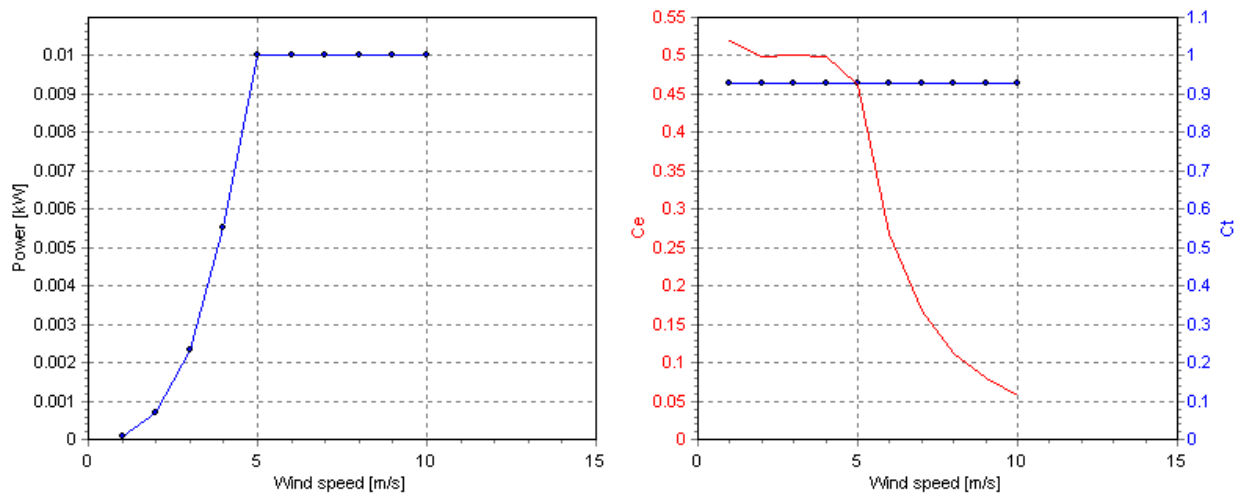


Figure 1. Graphical representation PV curve (left) and Ct/Ce curve (right)

3

Effect of cell size

By reducing the cell size of the simulation, we want to confirm that numerical diffusion indeed disappears at the extremely low turbulence intensity levels of the wind tunnel used. As shown in Section 2.1, the TI of the FarmFlow calculations is set to 1% rather than 0,5% (experimental). 1% is the minimum value used in FarmFlow and although this can be changed, we do not expect large differences between 0,5% and 1,0%, and thus omit from changing FarmFlow-settings.

Before diving into cell size resolution, it is important to explain the difference between grid and cell size. The grid size of the calculation raster depends on the dimensioning of the amount of cells. By definition, the amount of cells along the diameter of the turbine should be an odd integer, see equation 1.

$$\text{Eq. 1} \quad nD = \text{Round} \left(\frac{ny-1}{13} \right) \cdot 2 + 1$$

With: nD = number of cells along rotor diameter
 ny = number of cells in y direction

Grid size is then defined as:

$$\text{Eq. 2} \quad G = \left(\frac{ny}{nD} \right)$$

3.1 Cell size reduction

Default cell size setting is 49x49 cells for the 6.5D x 6.5D calculation grid. To investigate the influence of cell size on the FarmFlow calculation results, it was decided to define coarser and finer settings by changing the code of FarmFlow. The results are shown in **Table 3**.

Table 3: Cell size effect in un-tuned FarmFlow models

	ny · nx	Calculation time	Grid size	nD, number of cells along D
	[-]	[s]	[D]	[cell/D]
FarmFlow 25	13x13	0	4.33	3
FarmFlow 50	25x25	1	5.00	5
FarmFlow 100	49x49	7	5.22	9
FarmFlow 200	97x97	117	6.47	15
FarmFlow 300	144x144	871	6.26	23

The grid size of the calculation raster therefore reduces when the resolution reduces. This has an influence on the sharpness of the wake boundary. When comparing the graphical results of the calculations done for **Table 3** (see Appendix B) this is clearly seen for FarmFlow 25 and FarmFlow 50: the wake shows to be significantly weaker, due to fact that the rotor only extends to halfway the outer cells.

As the size of the cells reduces, the error becomes smaller and the wake boundary more defined, as can be seen in the same Appendix for the other FarmFlow versions.

3.2 Tuning of the turbulence model

Before fitting the FarmFlow results to the TUDelft results, the FarmFlow model must be tuned. The shape of the wake is strongly influenced by the k-epsilon values that should be tweaked to match the modelling/test conditions.

All models use the same tuned k,ε-model parameter values.

	ny · nx	Calculation time	Grid size	nD, number of cells along D
	[-]	[s]	[D]	[cell/D]
FarmFlow 25_t	13x13	0	4.33	3
FarmFlow 50_t	25x25	0	5.00	5
FarmFlow 100_t	49x49	2	5.22	9
FarmFlow 200_t	97x97	57	6.47	15
FarmFlow 300_t	144x144	303	6.26	23

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Validation with PIV measurements

The edge or boundary of the wake is defined as the locus of the points where the flow reaches 99% of the inflow velocity. For the lower resolution models, we define the edge as being the cells where the wind speed deviation has become 5-10% of the maximum deviation measured in the wake, in the centre.

When extracting the data from the 5 tuned simulations, we can superimpose the FarmFlow results onto the measurement results from the TUDelft experiments. The wake boundary has been rounded to the nearest cell-size.

The results of this effort are shown in Figure 2 below.

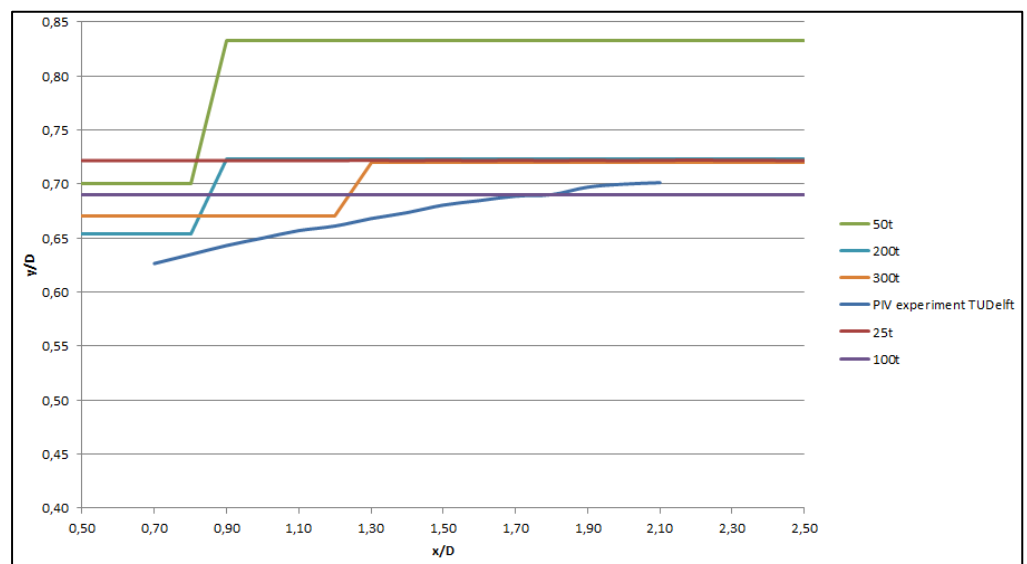


Figure 2. Wake expansion FarmFlow vs experiment

As Figure 2 indicates, the wake boundary defined by FarmFlow remains very coarse compared to the accuracy achieved by the wind tunnel tests. Getting higher resolution results from FarmFlow, will require more cells in the calculation grid. At resolutions higher than FarmFlow 300t (i.e. $3 \times 3 \times 2 = 18$ higher accuracy), the software returns a system error. Most probably, the error can be attributed to the convergence criteria that are programmed in the Fortran code that forms the basis of FarmFlow. The differences between cells at such high resolution become so small that the solution does not converge anymore. .

If we want to be able to validate FarmFlow simulations with wind tunnel test that have both low turbulence and high resolution measurements, we must look into adjusting the converging criteria.

An alternative would be to use conservation of mass criteria to define a more accurate diameter of the wake with the current software. The total velocity reduction in every cross section of the wake should be constant.

This exercise will be out of the scope of the FLOW project.

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Conclusions and recommendations

The simulation results showing the wake expansion behind a 0.6m diameter, 1.2m high actuator-disk-style turbine, are of the correct magnitude. However, lack of resolution of the FarmFlow models prevents achieving a more accurate comparison with the experimental results.

The resolution of the current version of FarmFlow is (probably) limited by the convergence criteria embedded in the CFD code. The highest resolution tuned version (FarmFlow 300t), which calculates at 18x higher cell numbers, still shows a coarse cell distribution across the rotor diameter, compared to the experimental results of the PIV measurements at Delft University.

To be able to improve this situation, ECN should look into reducing cell size by at least a factor 2, preferably 4 (FarmFlow 600t and FarmFlow 1200t respectively). This requires a profound study that includes optimization of the convergence criteria of the wake model.

Furthermore, it is advisable to look into using conservation of mass criteria in the wake. This requires the reduction in velocity in every cross section of the wake to be constant.

Alternatively, we could indirectly validate FarmFlow. This would require ECNS to be validated with measurements from experiments with higher turbulence intensity values, which are more in the realistic/practical range of FarmFlow.

For now, validation of FarmFlow with the TUDelft experimental results is not possible. Besides that the numerical diffusion is not removed, only limited by tuning the various models.

Appendix A. References

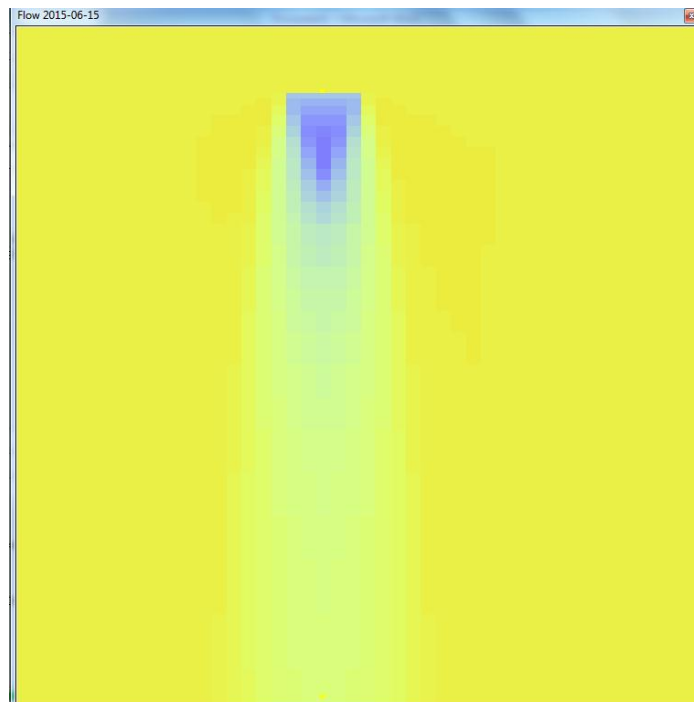
- [1] Lorenzo, E.M. et. al., 2015, *Validation of four LES and a vortex model against stereo-PIV measurements in the near wake of an actuator disc and a wind turbine*, Delft Univeristy of Technology, Delft

Appendix B. Graphical simulation results

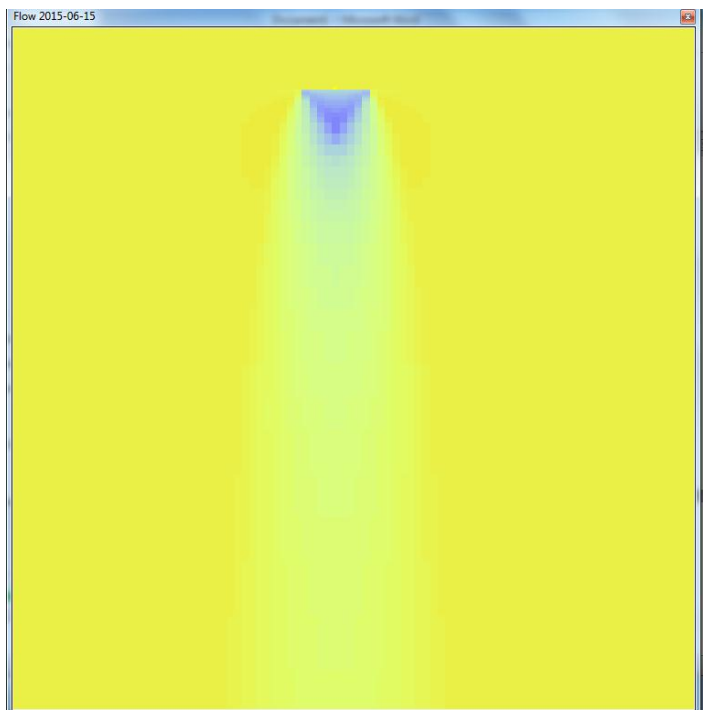
FarmFlow_25_TI0.01



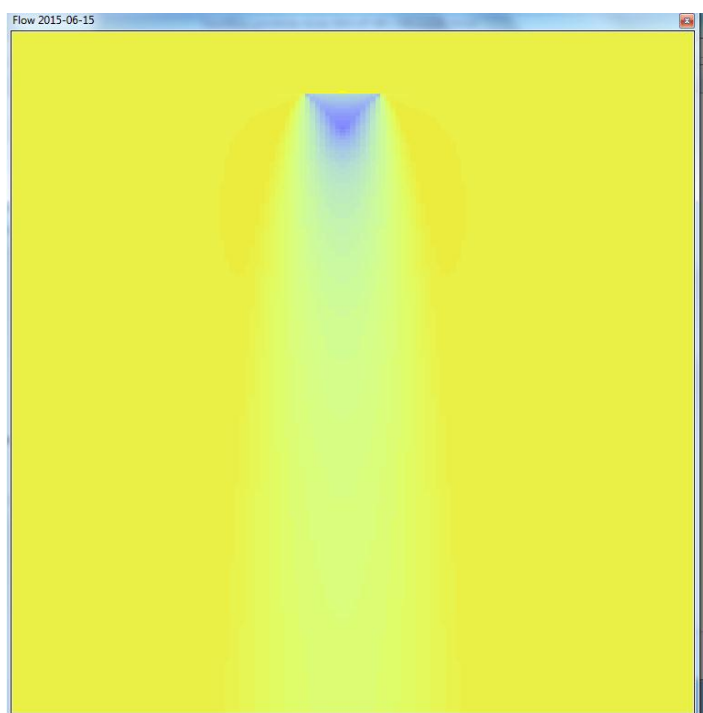
FarmFlow_50_TI0.01



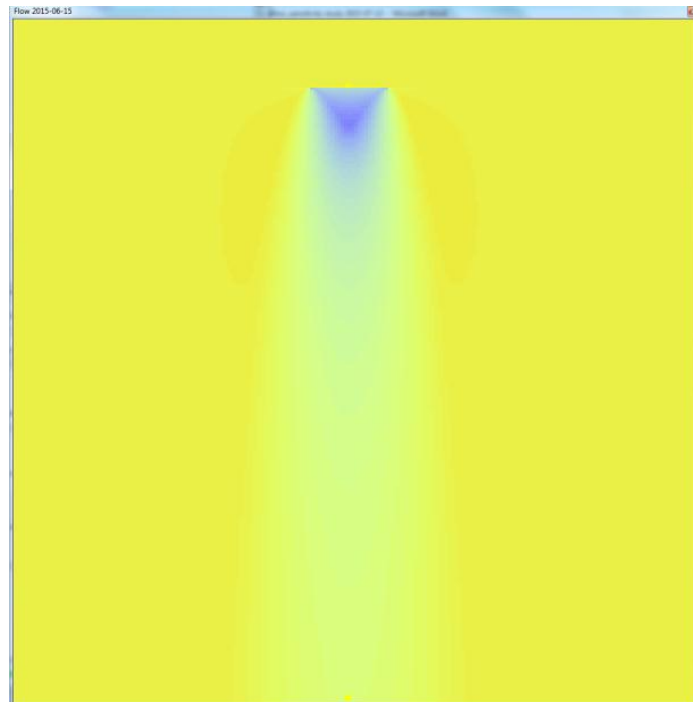
FarmFlow_100_TI0.01



FarmFlow_200_TI0.01

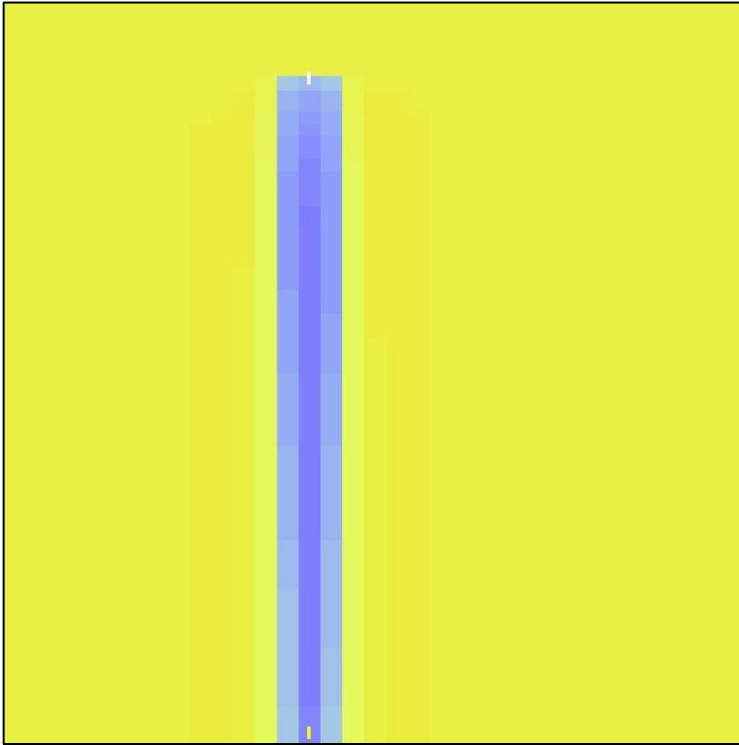


FarmFlow_300_TI0.01

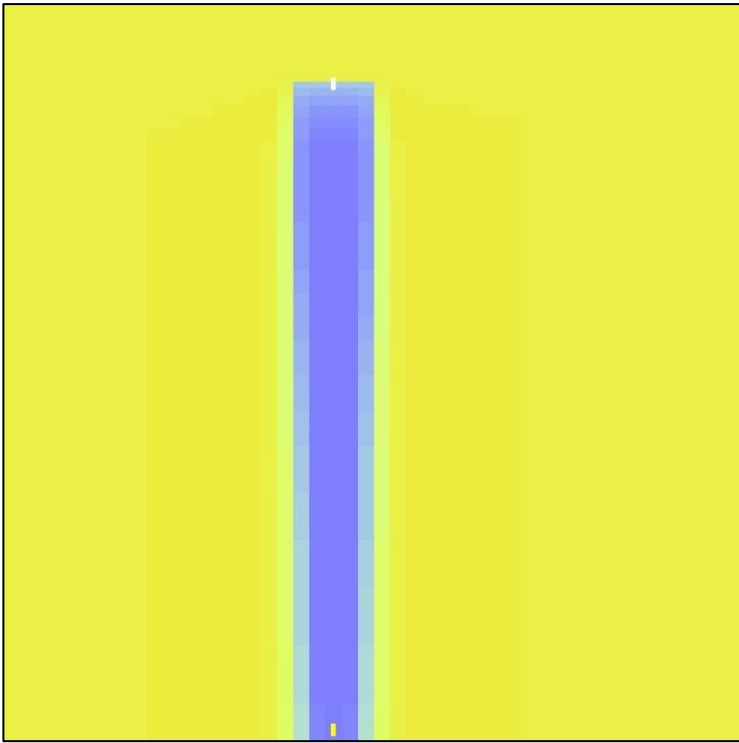


Appendix C. Tuned results

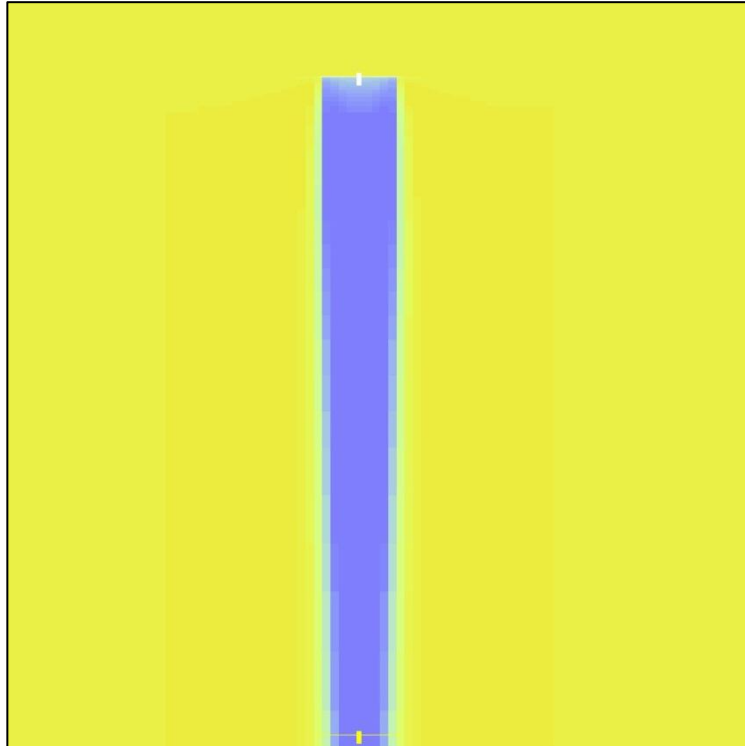
FarmFlow_25t_TI0.01



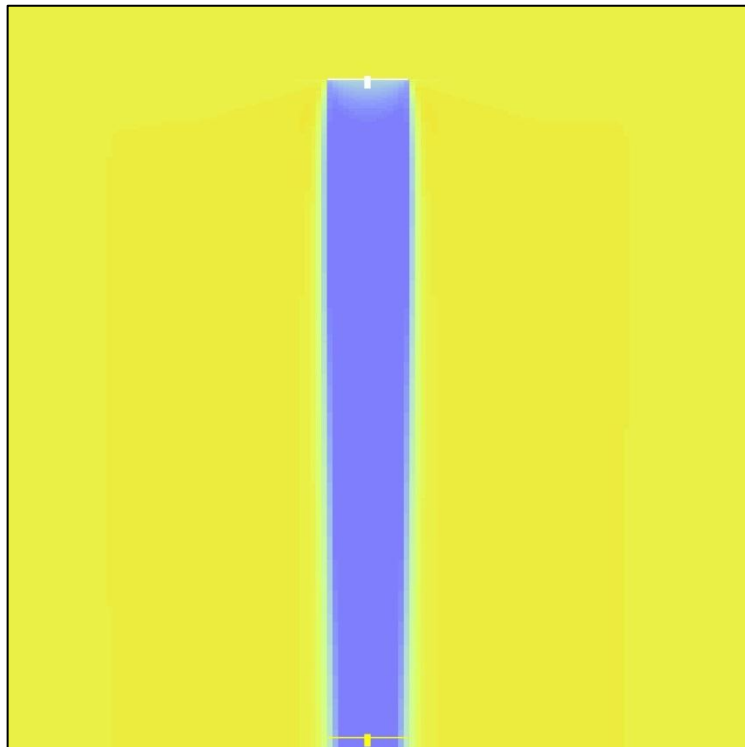
FarmFlow_50t_TI0.01



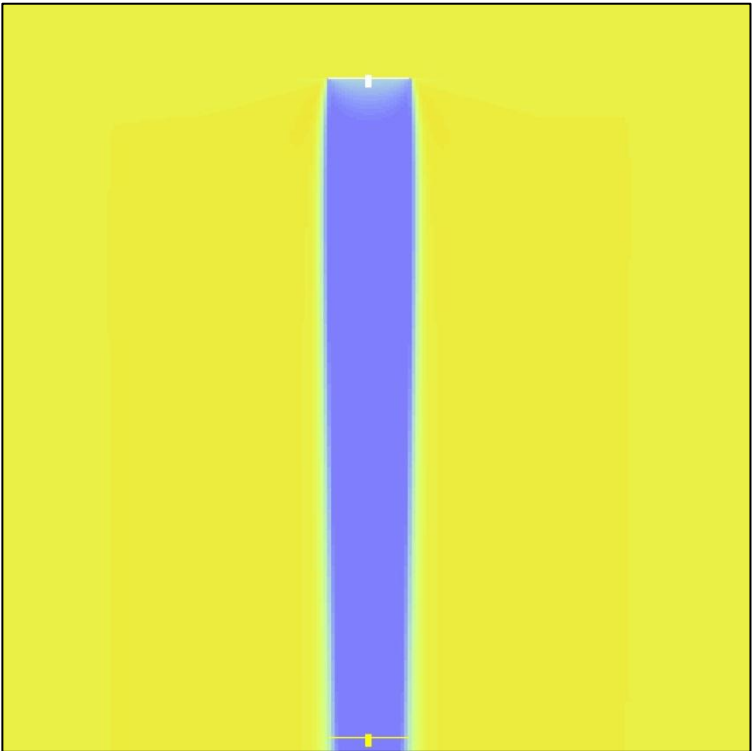
FarmFlow_100t_TI0.01



FarmFlow_200t_TI0.01



FarmFlow_300t_TI0.01



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