

RENI

Practical: Microalgae cream production using Comsol

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Objectives & process

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Objectives

You are working as R&D engineer in a food factory specialized in desert cream

You just learned that a competitor launched a line of desert creams with goji berries and turmeric, all your clients want to try it

In order to counter this commercial move, the salesman of your company asked your regular clients if they would like to surf the *healthy food* wave even more and sale microalgae enriched dessert creams

Your client showed great interest in this proposal, they would like to buy a small production to test the products

In order to be in the game, you have to deliver in 5 days

Your job is to design the process using existing reactors already available in your factory

As you have no time for trial and error approach, you scheduled 2 days for numerical investigations, 1 day for process building, 1 day for production and 1 day for delivery

Constraints

Only 4 microalgae species have been accepted as *novel food*

Your salesman secured a batch of one of them, a green microalgae called *Dunaliella salina*

Sadly they are very sensible to shear stress and cannot be mixed with classical mixing apparatus

Furthermore, quality department is unsure of microalgae sterility, thus the advise a 12D cook to be ensured after *Dunaliella salina* incorporation

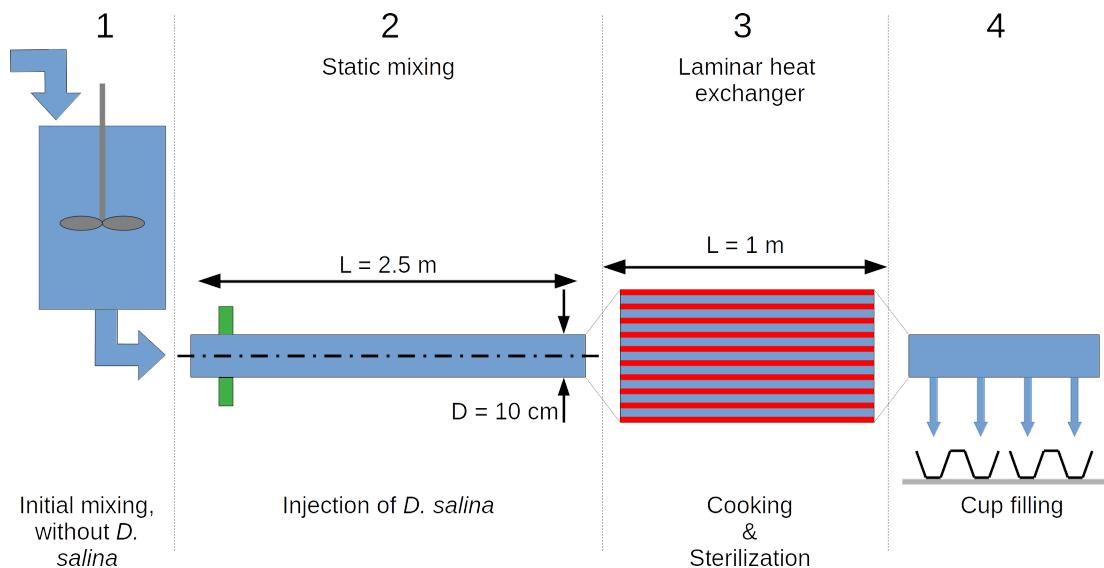
Finally, the cream has to retain its green color, thus the cooking procedure should not degrade microalgae chlorophyll too much

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Process

After discussing with your technical staff, a 4-stage process seems to be the optimal solution



Process

Stage 1

All the ingredients, except the microalgae are mixed together in a classical tank with a blade impeller

They are heated up to 40 °C No special design questions to be answered

Stage 2

Microalgae are added at the entrance of a 2.5 m tube carrying the cream to the cooker (stage 3)

This transport stage should also ensure proper microalgae mixing with the other ingredients In order to preserve the cells as much as possible, your salesman would like you to employ a laminar flow

Still, the maintenance technician warns you that mixing may not be adequate, **you are expected to argue** Several tubes diameter are available (20, 10 and 5 cm), ultimately **you have to chose one**

Process

Stage 3

The cream has to be cooked and sterilized, to do so, you have an adjustable flat plate heat exchanger

First, you have to ensure a laminar flow inside of the reactor so that the cream does not lose its texture once cooked

The exchanger/cooker is powered by overheated steam, still you have to ensure that the cream is sterile

Finally, you should assess for microalgae color loss due to cooking

Stage 4

The cream is distributed into the cups before they are sealed

It is a classical operation that does not require your expertise

General process information

A cup volume ($V_{cup} = 125 \text{ ml}$)

You aim at feeding 4 cups every 2 seconds

Dunaliella salina should represent 1 % of the total ingredients

Dunaliella salina can withstand turbulent flow if not too long

The manufacturer of your cooker specified an heat exchange coefficient of $h_{Exchanger} = 200 \text{ W/m}^2/\text{K}$ and a steam temperature of 200 °C

The cream temperature out of the cooker should at least be 121 °C

Assumptions

In order to simplify the problem, several assumptions will be dawned:

- Liquids are Newtonian
- Uncooked cream properties are taken as those of liquid water
- Cooked cream viscosity is $1.0 \cdot 10^{-2} \text{ Pa.s}$, taken constant of the cooking, other properties remaining those of liquid water
- Only the most resistant bacterium is considered for sterilization (*C. botulinum*)
- Process is in steady state

General properties

Critical Reynolds below (below \rightarrow laminar flow || above \rightarrow turbulent flow):

- In pipe: 2300, diameter as characteristic length
- Between two plate: 1400, 2 h as characteristic length

Microalgae diffusion coefficient in water: $D_{microalgae} = 1.0 \cdot 10^{-9} m^2/s$

Microalgae turbulent Schmidt number: $Sc_{turb,microalgae} = 0.7$

C. botulinum degradation kinetic can be modeled by a first order reaction, with the following temperature dependence:

$k_{C. botulinum} = 1.94 \cdot 10^{40} \exp\left(-\frac{300000}{RT}\right)$ with R the ideal gas constant and T the temperature in Kelvin

Chlorophyll degradation kinetic behaves in the same way:

$k_{Chlorophyll} = 4.51 \cdot 10^5 \exp\left(-\frac{60000}{RT}\right)$

Stage 2 - Static

mixing

Preliminary questions & Fluid flow

Tube geometry

The tube features numerous side injectors near the inlet through which microalgae will be incorporated

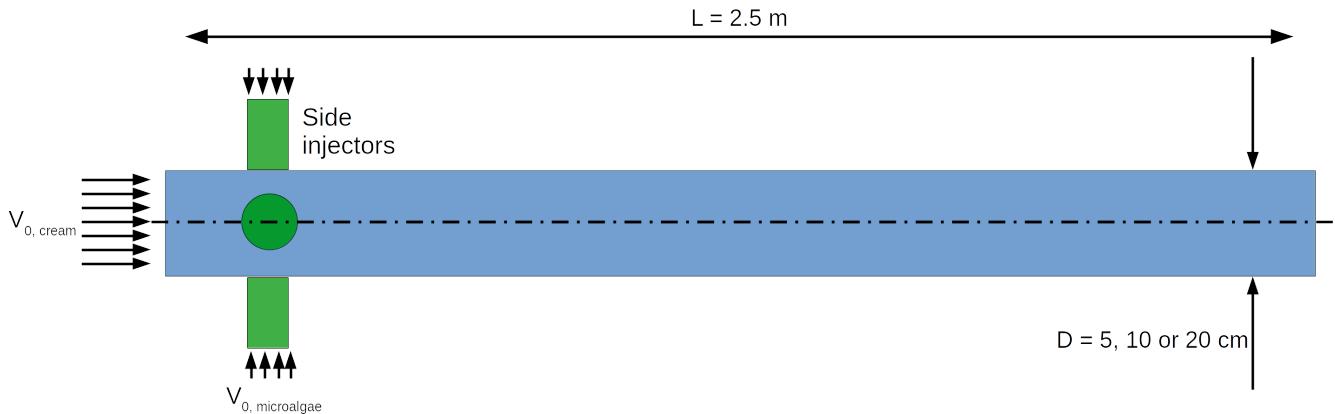


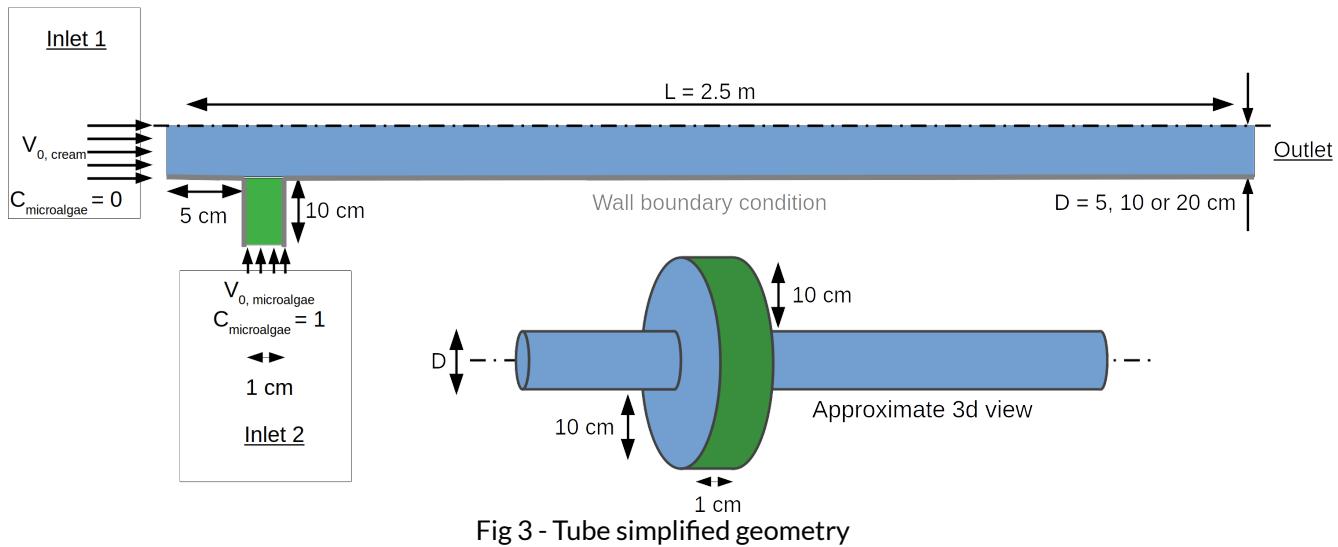
Fig 2 - Schematic of tube used in stage 2

Preliminary questions

1. Reduce the geometrical complexity using symmetry
2. Determine the total flow rate to be sent through the tube
3. Determine the Reynolds numbers associated to the 3 potential tubes
4. Choose a laminar and turbulent configuration to compare
5. Determine the inlet velocities for both cream and microalgae in the two configurations

Answers

1. The geometry can be simplified into a 2d axi-symmetrical problem. Still, a special attention will have to be paid in dealing with the side injectors



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Answers

2. The total flow rate can be derived from the cup volume and the feeding rate

$$Q_{total} = V_{cup}f, \text{ with } f = 2 \text{ cups per seconds}$$

$$Q_{total} = 250 \text{ ml/s} = 2.50 \cdot 10^{-4} \text{ m}^3/\text{s}$$

3. Reynolds number is defined as:

$$Re = \frac{\rho DV}{\mu}, \text{ with } \rho = 1000 \text{ kg/m}^3, \mu = 1.0 \cdot 10^{-3} \text{ Pa.s}$$

$$Re = \frac{\rho D \frac{Q}{\pi \frac{D^2}{4}}}{\mu} = \frac{4\rho Q}{\pi \mu D}$$

Answers

3. Yielding three different values for the Reynolds number

$$Re_{20cm} = 1592, Re_{10cm} = 3183 \text{ and } Re_{5cm} = 6366$$

4. Critical Reynolds number in tubes is 2300. Thus 20 cm diameter will yield a laminar flow and the two others a turbulent one

For the turbulent configuration, we will chose 10 cm diameter, as it would be easier to clean

5. The cream inlet section is $A_{cream} = \frac{\pi D^2}{4}$ and the lateral one simulating the injector (assuming axi-symmetrical configuration) can be taken as

$$A_{microalgae} = \pi(D + 2 \times 0.1m) \times 0.01m$$

Furthermore, we know that $Q_{cream} = 0.99 Q_{total}$ and $Q_{microalgae} = 0.01 Q_{total}$

Yielding $V_{0,cream,20cm} = 7.88 \cdot 10^{-3} \text{ m/s}$ and $V_{0,microalgae,20cm} = 1.99 \cdot 10^{-4} \text{ m/s}$

And $V_{0,cream,10cm} = 3.15 \cdot 10^{-2} \text{ m/s}$ and $V_{0,microalgae,10cm} = 2.65 \cdot 10^{-4} \text{ m/s}$

Case setup

You will use Comsol for investigating mixing for both laminar and turbulent flow

An incremental approach will be used, starting by the laminar case:

- First, you will draw the geometry
- Then, chose fluid properties
- Compute the flow in the tube
- Add species transport
- Evaluate mixing quality at the outlet of the pipe

Once done with the laminar case, you will move onto the turbulent one and compare results

Comsol

Start Comsol, chose a geometry and a set of equations to solve:

→ Model Wizard → 2D Axi-symmetric
Fluid flow → Single-phase Flow → Laminar Flow → Add → Study

Chose a steady state resolution:

→ Stationary → Done

Remember to frequently save your work

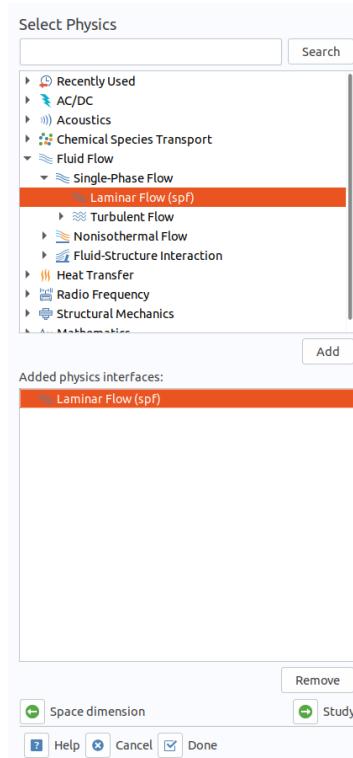


Fig 4 - Equation selection

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Geometry

Create the fluid domain:

Right click on 'Geometry' → Rectangle (twice, once for the two parts)

Specify size and position

Click on 'Build All Objects'

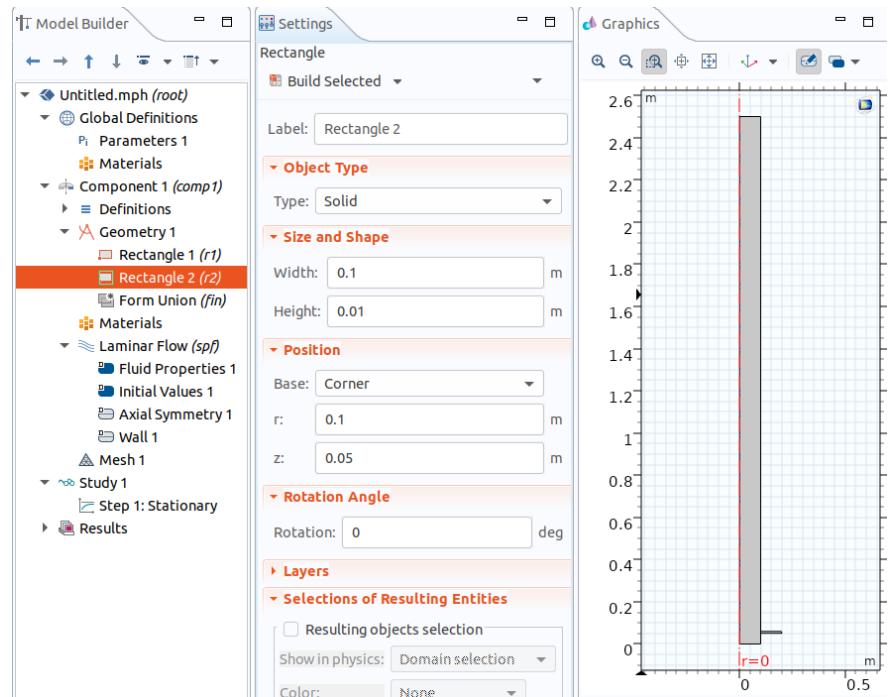


Fig 5 - Geometry for the 20 cm pipe

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Material

Specify the body the domain is made of, here water:

Right click on 'Materials' \mapsto
Add material from Library \mapsto
search 'Water' \mapsto Double
click to add

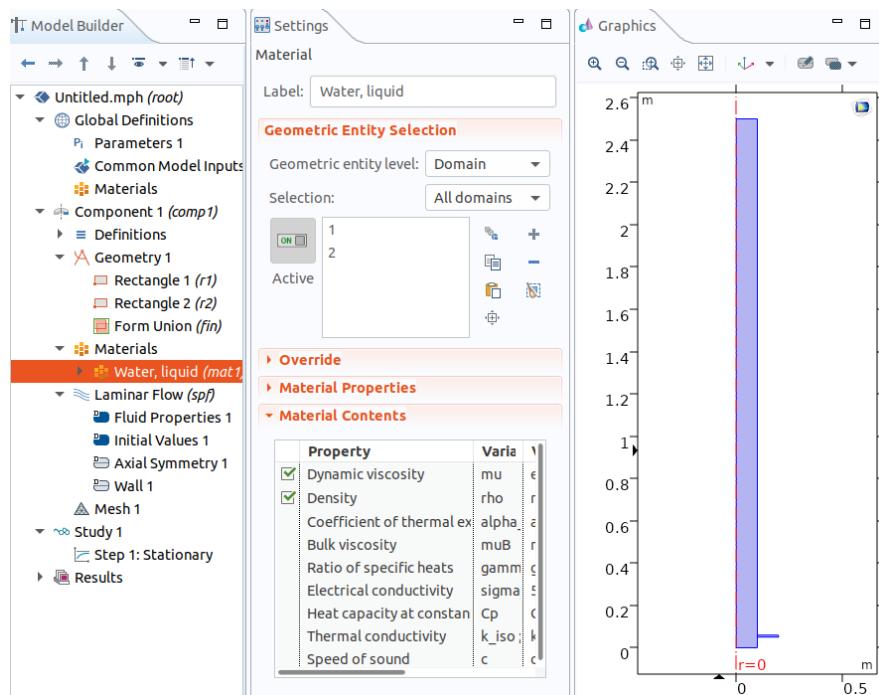


Fig 6 - Water is specified for both rectangles

Boundary conditions

You will add to inlets and one outlet, the remaining boundary conditions being walls by default

Right click on 'Laminar Flow'
 \mapsto Inlet \mapsto Select the desired section on the graph

Specify the velocity calculated previously

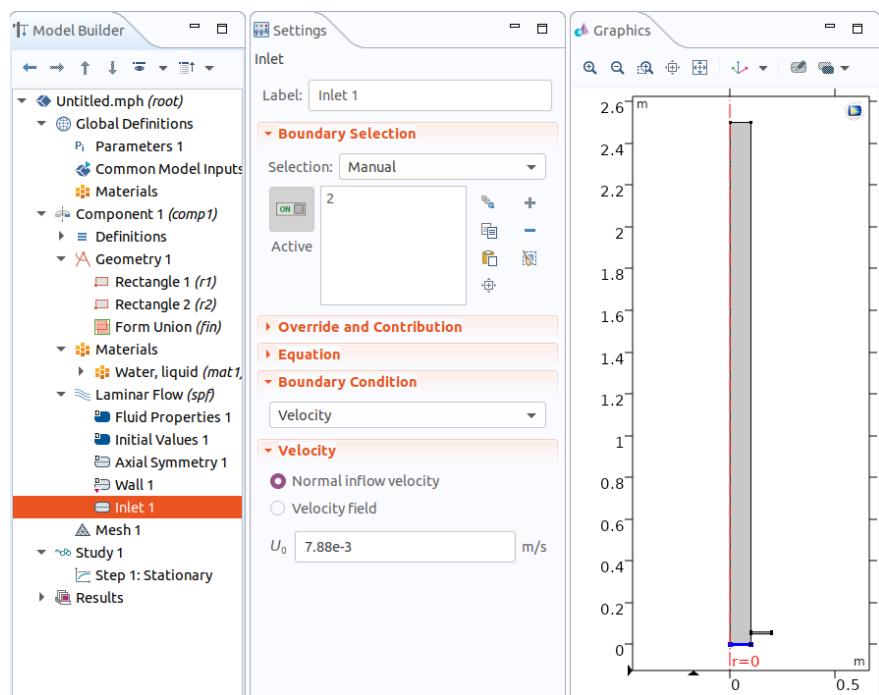


Fig 7 - Inlet selection

Boundary conditions

Do the same with the second inlet and the outlet

You can move around the domain view to ease selection using view tools:

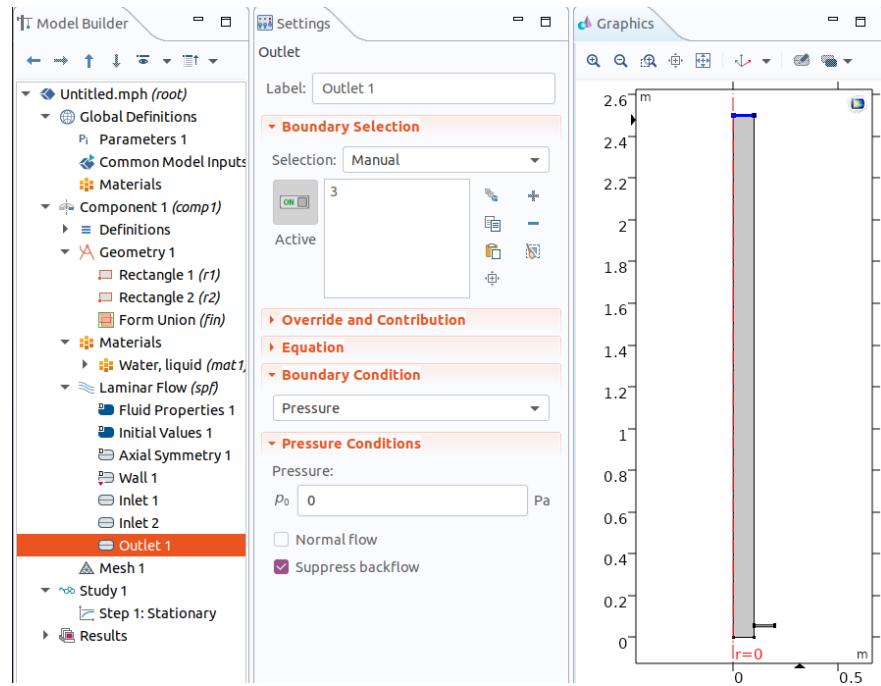


Fig 8 - View after boundary conditions specification

Generate the mesh by selecting "Mesh1" then click "Build All"

As you can see, Comsol automatically dispatched the cells so that that the boundary layer near the wall is more refined than the core of the fluid domain

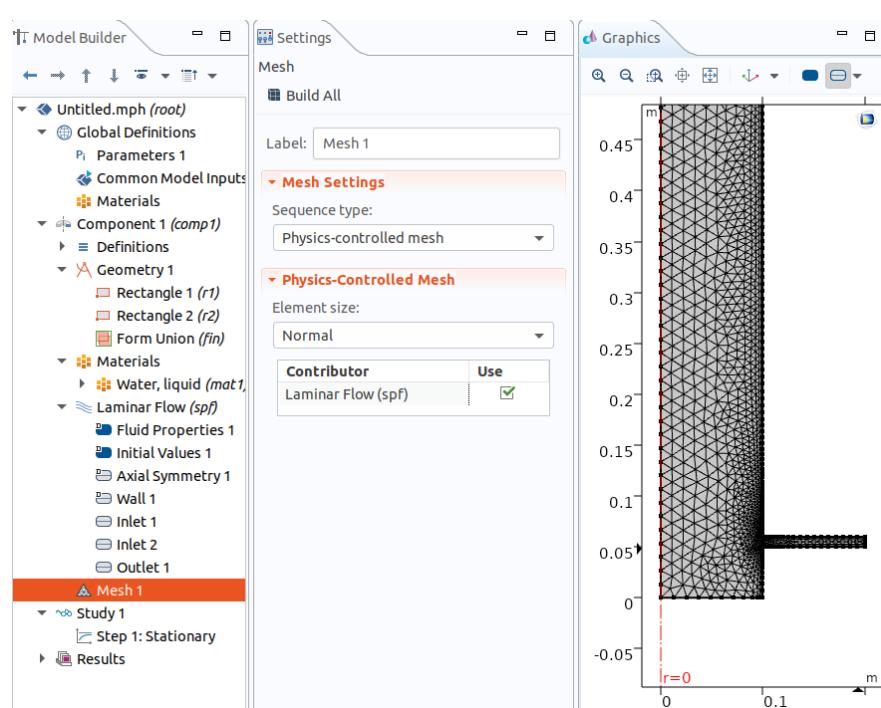


Fig 9 - Meshed domain, zoomed view

Compute

Compute the case by selecting "Study1" then click "Compute"

Some graphs will be plotted automatically (velocity, pressure)

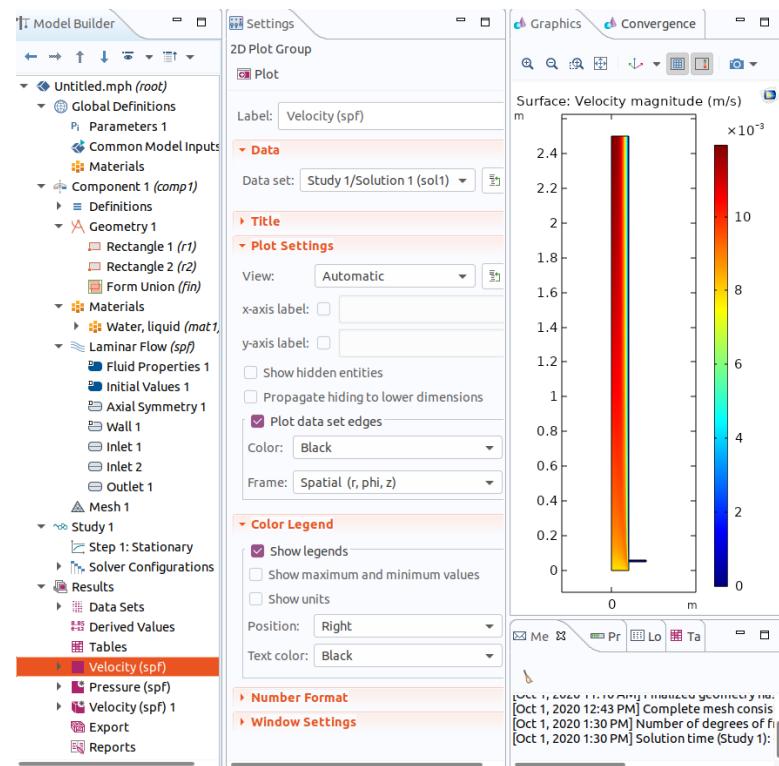


Fig 10 - Velocity magnitude field

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Extracting profile

Some more qualitative processing can be done. For example, by extracting the velocity profile at the outlet of the tube

To do so, right click on 'Results' \mapsto 1D Plot Group

Then, right click on the new '1D Plot Group' \mapsto Line Graph \mapsto Select the outlet boundary (velocity - spf.U - is selected by default) \mapsto Plot

The code compute the classical Poiseuille flow in a cylindrical tube, i.e. a parabola

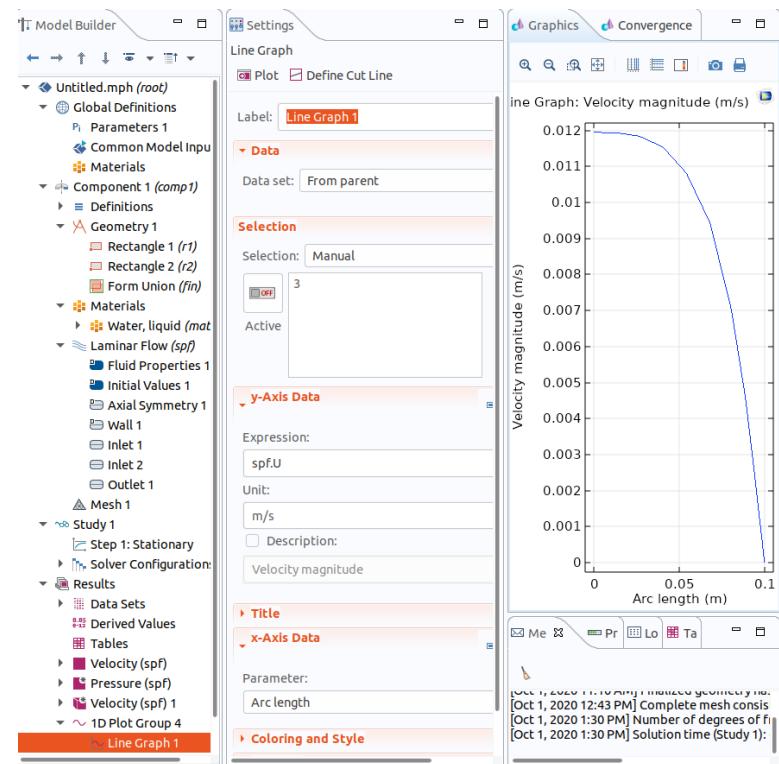


Fig 11 - Velocity profile at the outlet

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Stage 2 - Static mixing

Mass transport

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5 . 1

Adding mass transport

You will add a mass transport equation and couple it with the fluid flow

To do so, right click on
'Component1' \mapsto Add physics
 \mapsto Chemical Species
Transport \mapsto Transport of Diluted Species \mapsto Double click to add

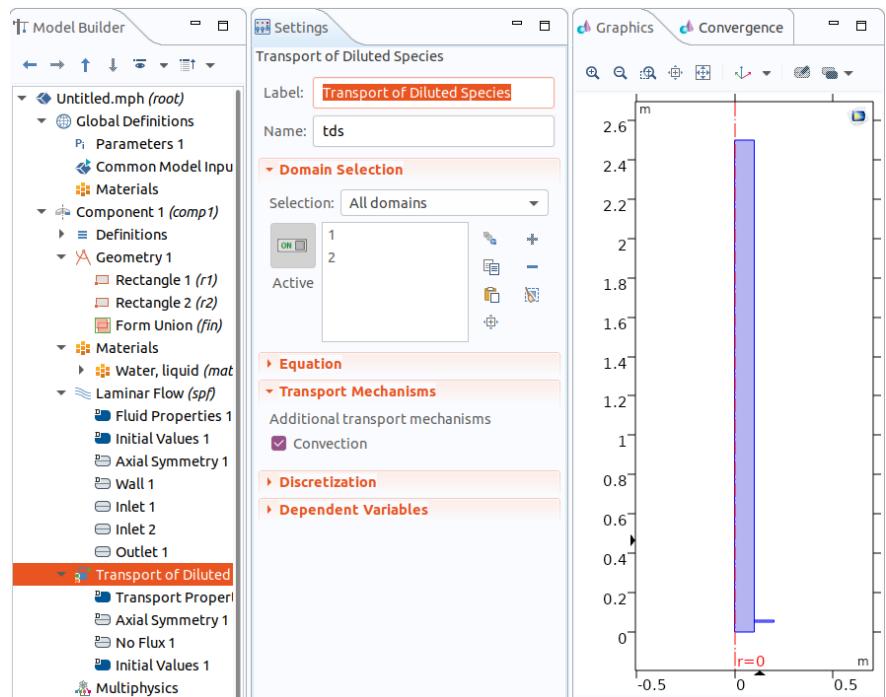


Fig 12 - Addition of mass transport module

Coupling the physics

To specify that the new module will use the velocity field from the previous, click on 'Transport properties' \mapsto Convection section \mapsto Select 'Velocity field (spf)'

You can also see that you can choose the diffusion coefficient, here

$$D_{microalgae} = 1.0 \cdot 10^{-9} \text{ m}^2/\text{s}$$

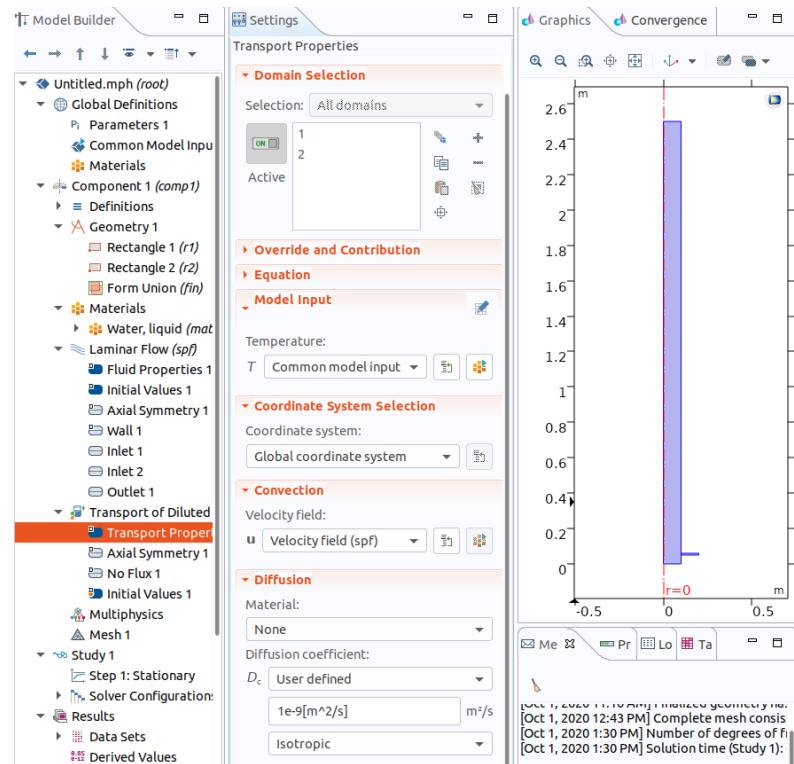


Fig 13 - Coupling between the physics

Boundary conditions

Just like for the fluid flow, you will add to inlets and one outlet, the remaining boundary conditions being walls by default

Right click on 'Transport of Diluted Species' \mapsto Inflow

The largest inlet does not carry microalgae, so the concentration is set to 0 mol/m³

In this case, the outlet boundary condition is called 'Outflow'

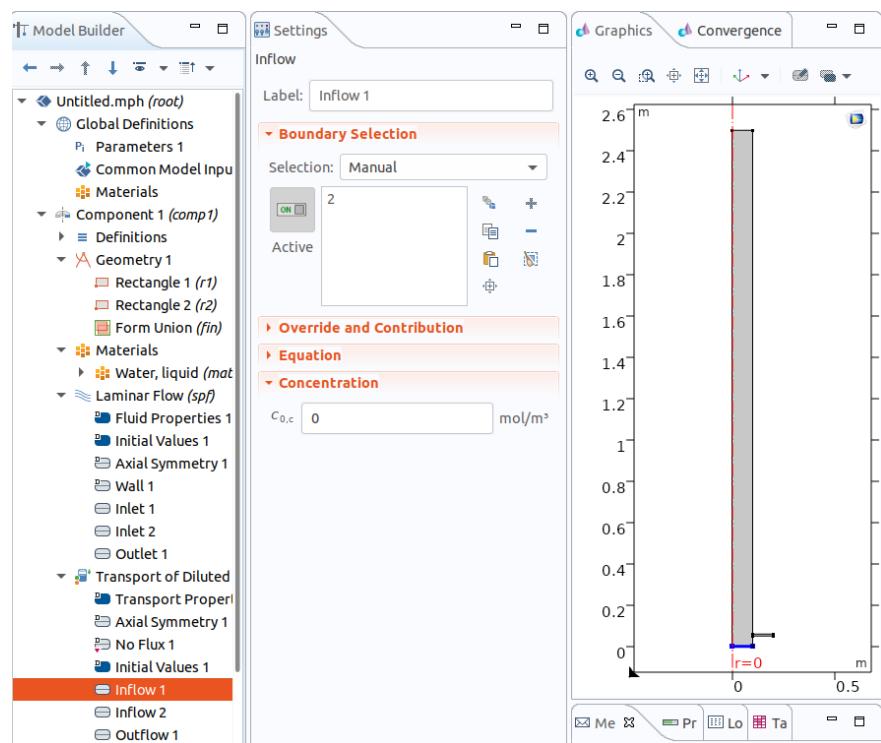


Fig 14 - Boundary conditions for mass transport

Compute

Compute the case by selecting "Study1" then click "Compute"

You can view the concentration field by adding a new 2D plot: right click on 'Results' \mapsto 2D Plot Group

Right click the new 2D Plot Group \mapsto Surface \mapsto Specify 'c' in the expression \mapsto Plot

You can explore the various expressions you can plot by pressing:

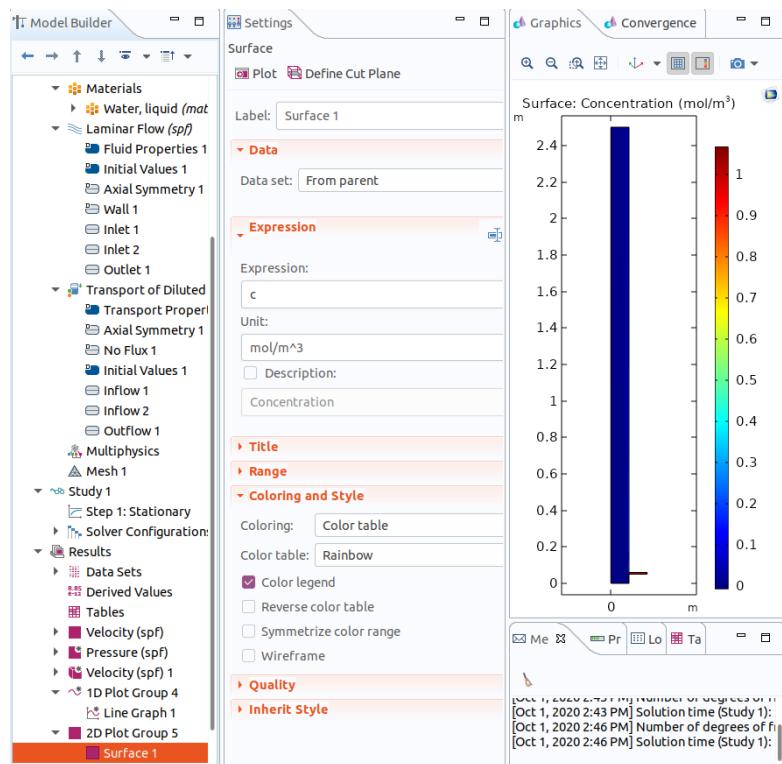


Fig 15 - Microalgae concentration field in the laminar case

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5.5

Concentration profile

The same way you plotted the velocity profile at the outlet, you can plot the concentration profile at the outlet

The mixing is far from optimal

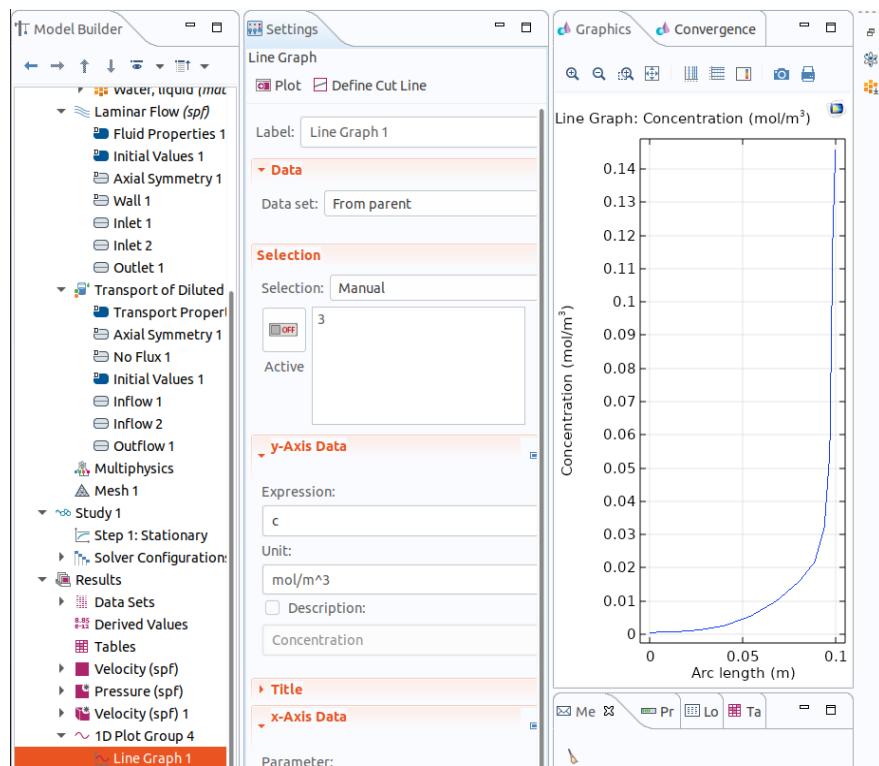


Fig 16 - Microalgae concentration profile at the outlet

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Stage 2 - Static mixing

Turbulent flow

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Turbulent flow

This time, you will compute the 10 cm diameter tube (turbulent reynolds number)

You will be able to reproduce the previous steps, only key modification are reported in the document

Start a new Comsol document:

→ Model Wizard → 2D Axi-symmetric → Fluid flow → Single-phase Flow → Turbulent Flow, $k - \epsilon$ (spf) → Add → Study

Remember that the tube diameter changed

For turbulence, Comsol will provide 'classical' values. As a tube is a classical configuration, they are fine

Turbulent mass transport

As seen in the course, mass transport coefficient to account for turbulence. Thus we use:

$$D_{microalgae,turb} = \frac{\nu_t}{Sc_{turb,microalgae}}$$

You can specify this in 'Transport Properties' of 'Transport of Diluted Species' module

The turbulent viscosity field is called 'spf.nuT'

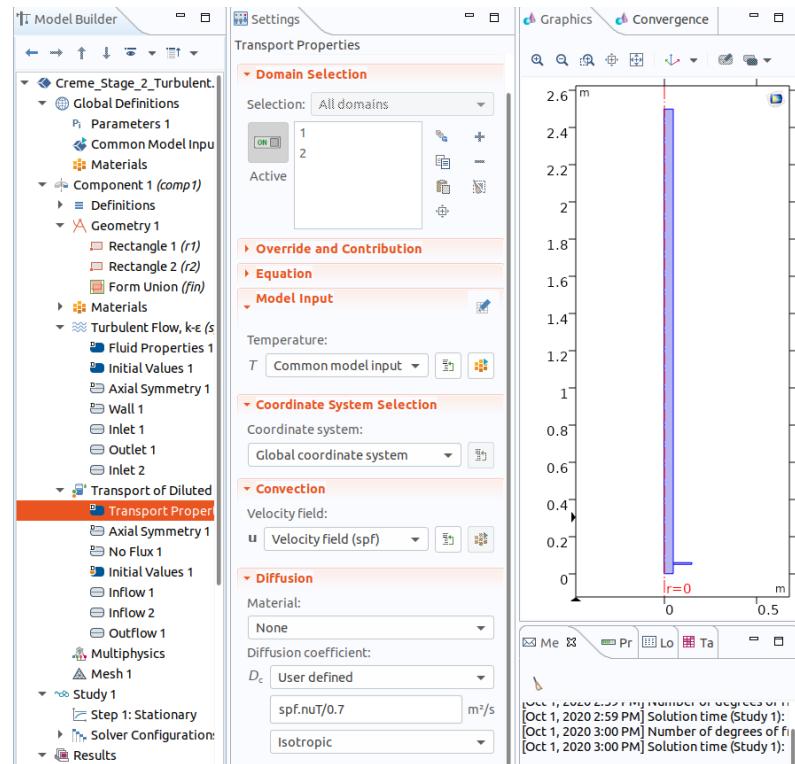


Fig 17 - Turbulent mass transport coupling

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6 . 3

Outlet profile

This time the mixing is much better, the concentration at the outlet is almost uniform

You can conclude on which tube to use

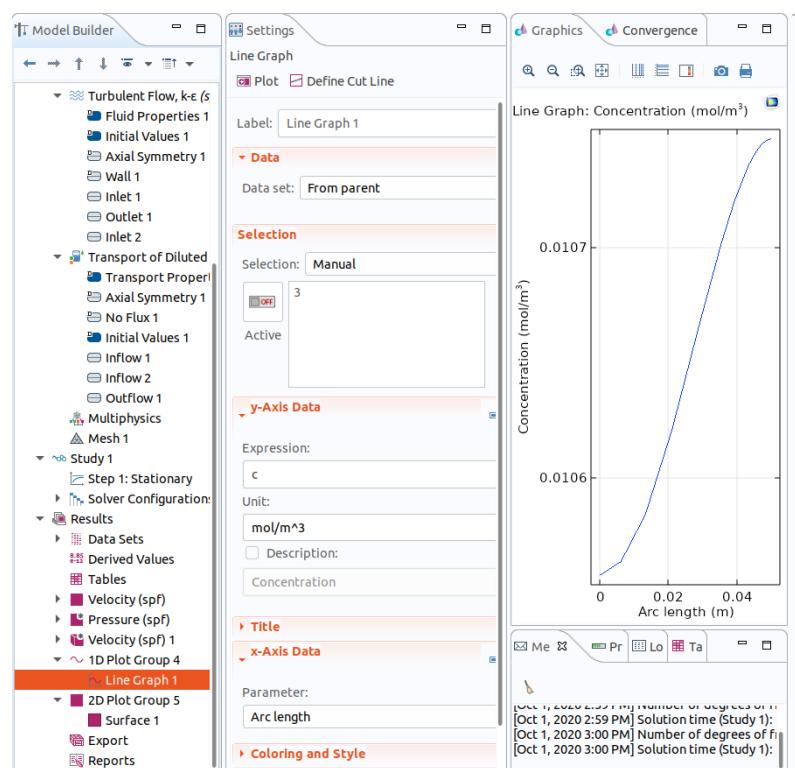


Fig 18 - Microalgae concentration profile at the outlet for the turbulent case

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6 . 4

Stage 3 - Laminar cooking

Preliminary questions

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7.1

Cooker geometry

The cooker is flat plat exchanger. On side of the plates, the cream is going to flow, on the other overheated steam

In order to prevent texture loss the cream has to flow in laminar regime

The cooker is made of 25 channels of 1m long (l) x 10 cm wide (w), your technical staff can adapt the gap between two plates

They are waiting for your instructions on how to adjust thickness between the plates

Preliminary questions

1. Reduce the geometrical complexity using symmetry
2. Determine the total flow rate to be sent through one channel
3. Determine the Reynolds numbers associated to the flow

Answers

1. The geometry can be simplified into a 2d planar geometry. Only one channel will be considered

Answers

2. The flow passing through one channel is the total flow divided by the number of channel, hence $Q_{1channel} = 1.00 \cdot 10^{-5} \text{ m}^3/\text{s}$

3. Reynolds number is defined as:

$$Re = \frac{\rho 2hV}{\mu}, \text{ with } \rho = 1000 \text{ kg/m}^3, \mu = 1.0 \cdot 10^{-2} \text{ Pa.s}$$

$$Re = \frac{\rho 2h \frac{Q_{1channel}}{wh}}{\mu} = \frac{2\rho Q_{1channel}}{\mu w} = 20$$

The first comment is that the Reynold number does not depends upon the gap between the plates if Reynolds is expressed with the flow rate

The second comment is that 20 is far below 1400, thus the flow will be laminar

Stage 3 - Laminar cooking

Fluid flow and temperature field

Comsol

Start Comsol, chose a geometry and a set of equations to solve:

→ Model Wizard → 2D → Fluid flow → Single-phase Flow → Laminar Flow → Add

Heat Transfer → Heat transfer in Fluids → Add → Study

Chose a steady state resolution:

→ Stationary → Done

Remember to frequently save your work

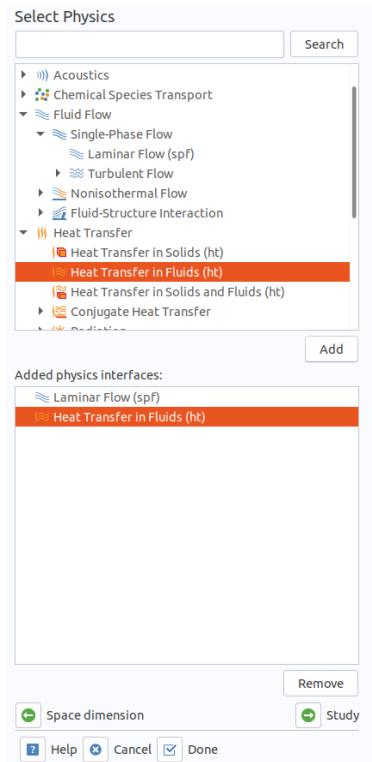


Fig 21 - Model selection

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8 . 2

Geometry

Create the fluid domain:

Right click on 'Geometry' → Rectangle

Your technical staff can adapt the gap to three values: 20, 10 and 5 mm. Choose one to start with

Specify size and position

Click on 'Build All Objects'

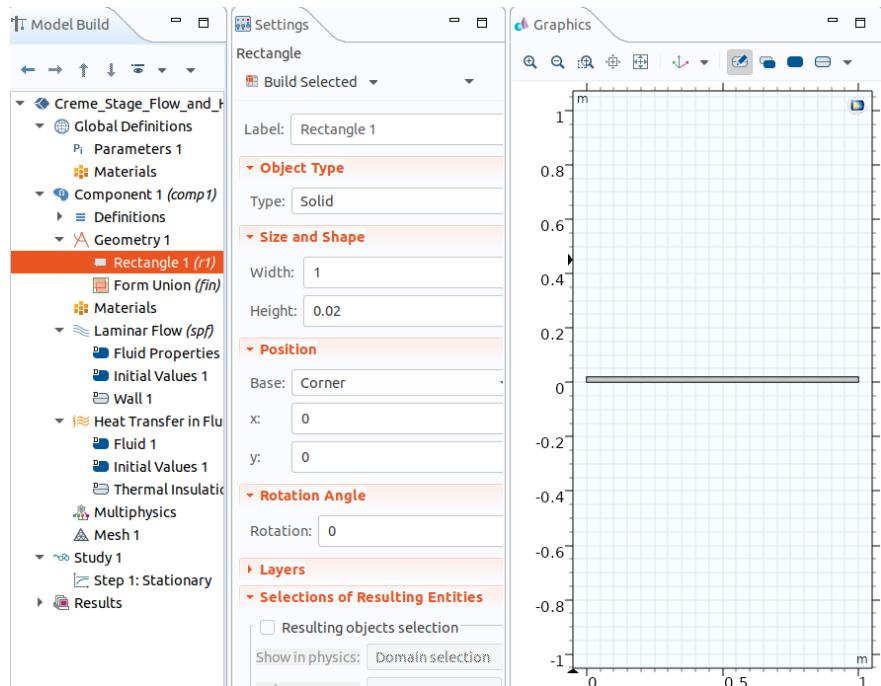


Fig 22 - Geometry for the 20 mm gap

Material

Specify the body the domain is made of, here water:

Right click on 'Materials' ↪ Add material from Library ↪ search 'Water' ↪ Double click to add

Modify viscosity value to $1.0 \cdot 10^{-2}$ Pa.s (replace 'eta(T)')

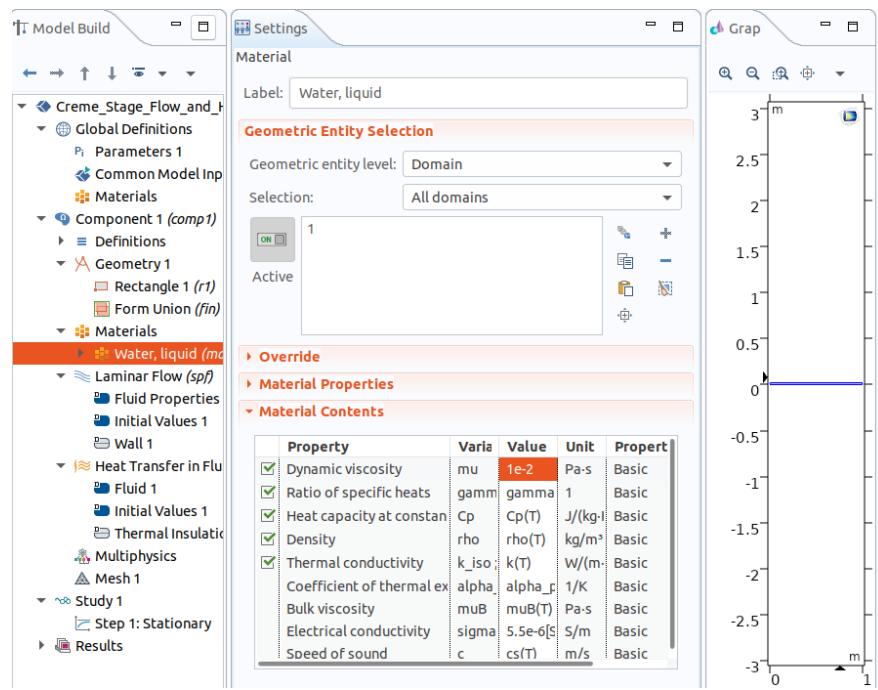


Fig 23 - Water is specified with custom viscosity

Coupling the physics

Specify the coupling between heat transfer module and the velocity field, click on 'Fluid1' in 'Heat Transfer in Fluids' module ↪ Velocity section ↪ Select 'Velocity field (spf)'

Heat transfer physical properties are taken from the material library

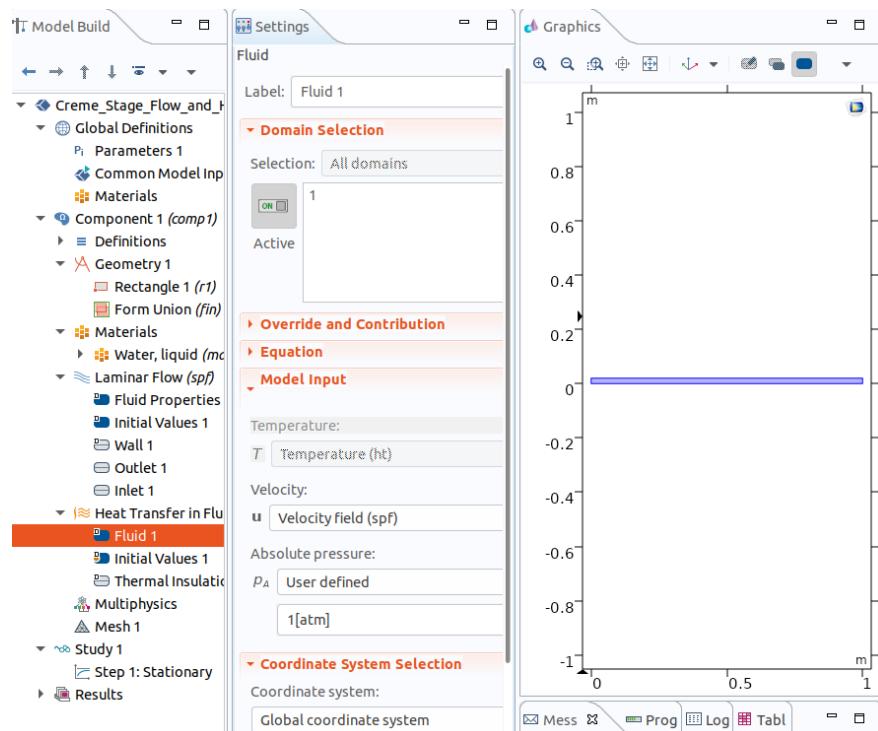


Fig 24 - Coupling between the physics

Boundary conditions

You will add the fluid inlet and outlet, the remaining boundary conditions being walls by default

Right click on 'Laminar Flow'
 ↪ Inlet ↪ Select the desired section on the graph

Specify the velocity calculated based on the flow rate and the gap between the plates

$$V_{0,cream} = \frac{Q_{1channel}}{wh}, \text{ with } w = 10 \text{ cm and } h = 20 \text{ mm,}$$

$$V_{0,cream} = 5.0 \cdot 10^{-3} \text{ m/s}$$

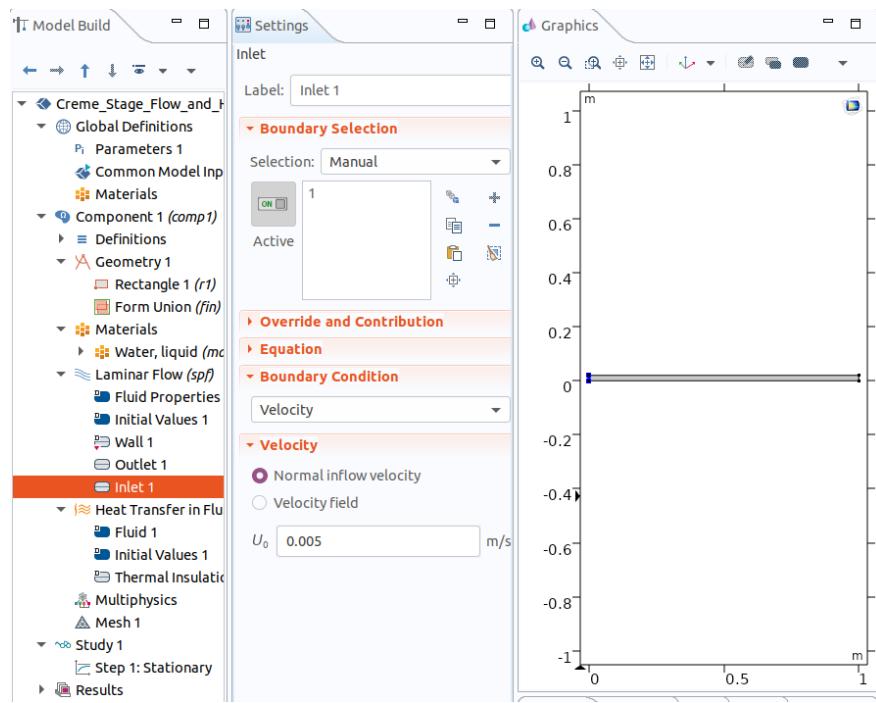


Fig 25 - Fluid inlet boundary conditions

Boundary conditions

Right click on 'Laminar Flow'
 ↪ Outlet ↪ Select the desired section on the graph

Right click on 'Heat Transfer in Fluids' ↪ Inflow ↪ Select the channel inlet and specify the cream temperature (40 °C)

Right click on 'Heat Transfer in Fluids' ↪ Outflow ↪ Select the channel outlet

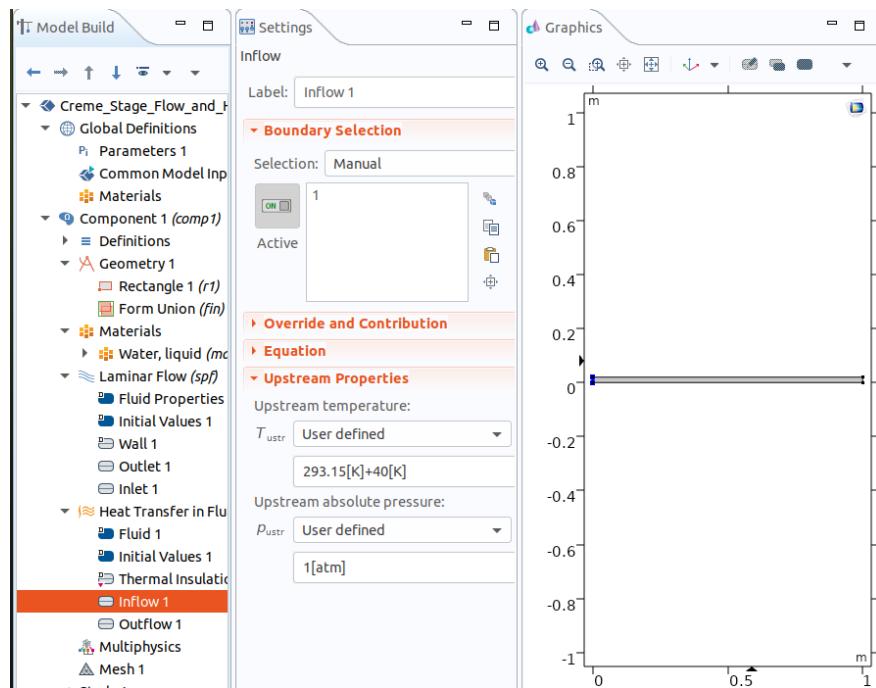


Fig 26 - Heat transfer inlet boundary conditions

Boundary conditions

Right click on 'Heat Transfer in Fluids' \mapsto Heat Flux \mapsto
Select the channel walls

Specify a 'Convective heat flux' with the parameter supplied by the cooker manufacturer:

$h_{Exchanger} = 200 \text{ W/m}^2\text{K}$ and a steam temperature of 200°C

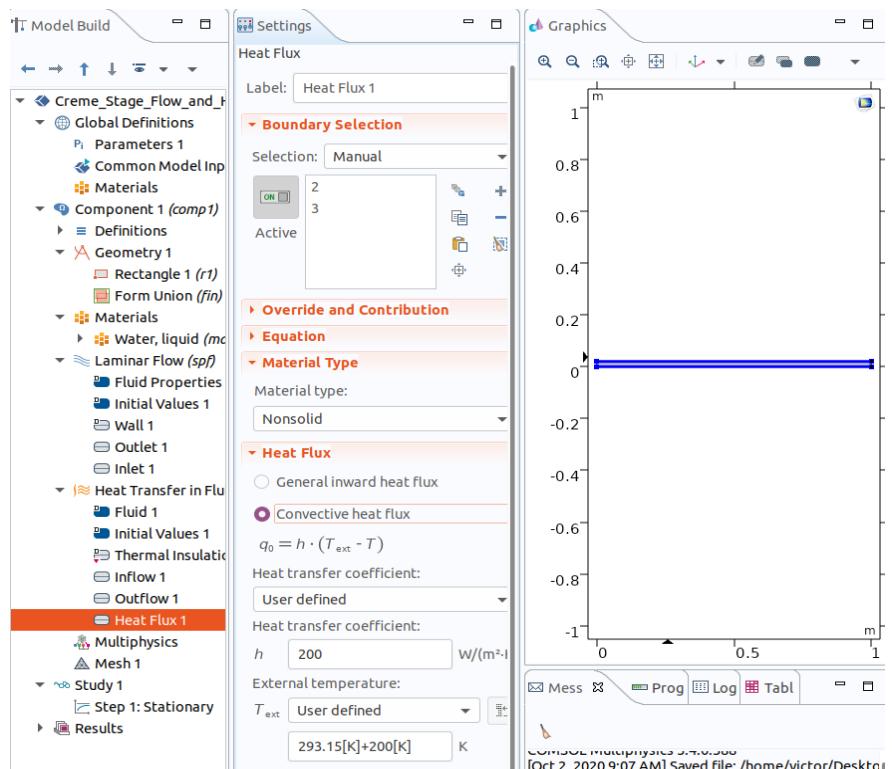


Fig 27 - Heat transfer wall boundary conditions

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8 . 8

Meshing

Generate the mesh by selecting "Mesh1" then click "Build All"

As you can see, Comsol automatically dispatched the cells so that the boundary layer near the wall is more refined than the core of the fluid domain

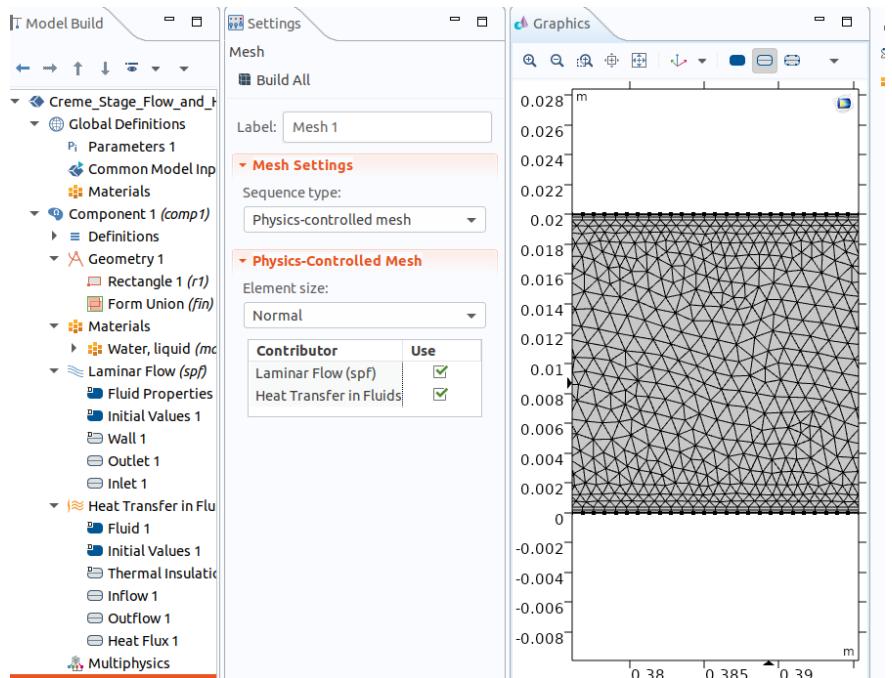


Fig 28 - Meshed domain, zoomed view

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8 . 9

Compute

Compute the case by selecting "Study1" then click "Compute"

Some graphs will be plotted automatically (velocity, pressure)

Temperature is what is interesting here, the core seems to be at a low temperature

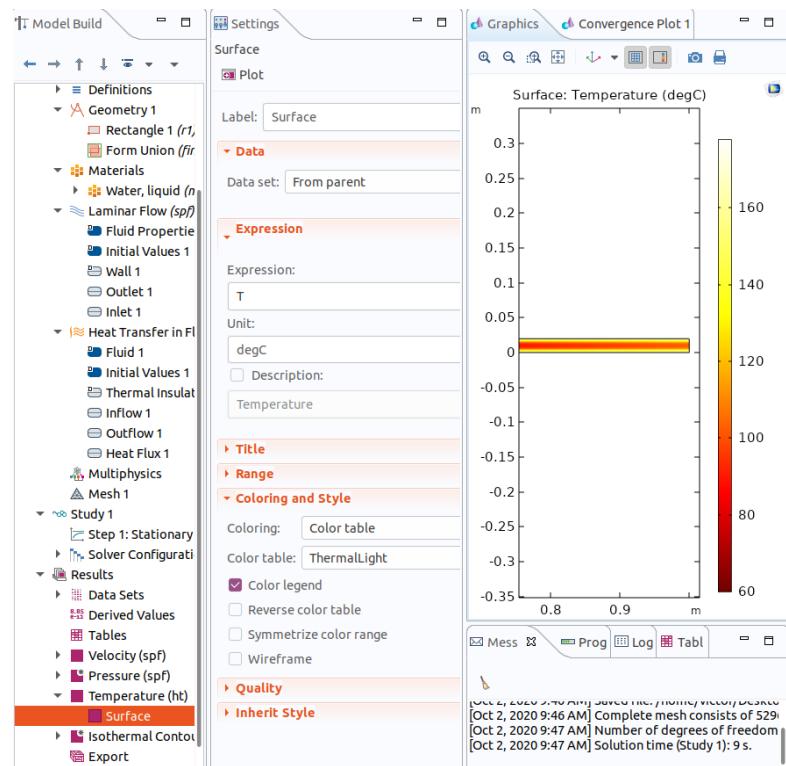


Fig 29 - temperature field, zoomed at the outlet

Extracting profile

As you did before, you will extract the temperature profile at the outlet of the tube

To do so, right click on 'Results' \mapsto 1D Plot Group

Then, right click on the new '1D Plot Group' \mapsto Line Graph \mapsto Select the outlet boundary (T, use 'degC' as unit) \mapsto Plot

As you can see, the core temperature at the outlet is about 105 °C, which is not enough to sterilize the cream

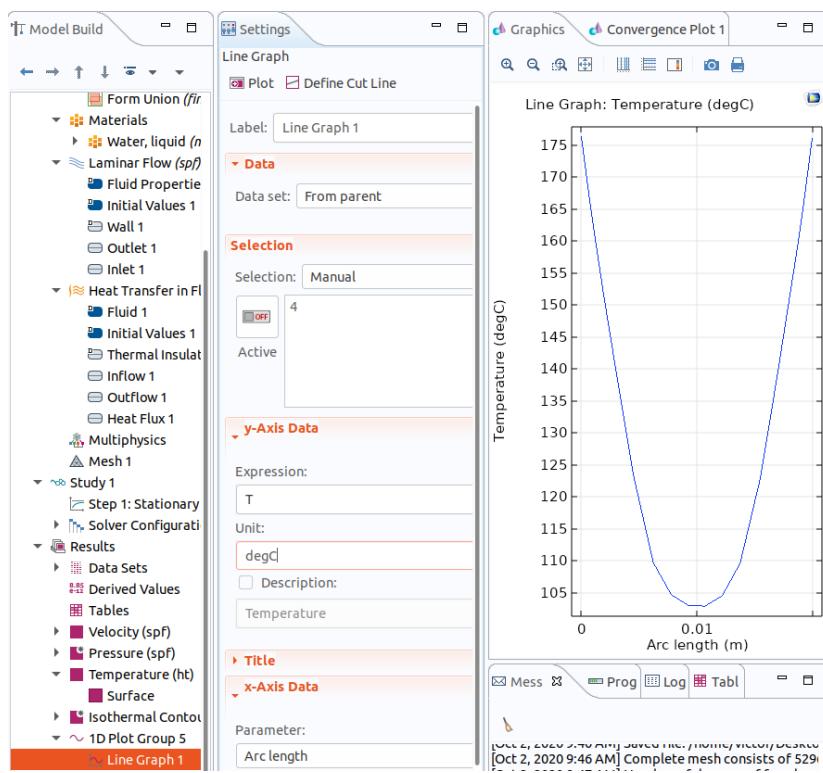


Fig 30 - Temperature profile at the outlet for 20 mm gap

Testing other gap values

Now test the two other options

To do so, modify the domain size in 'Geometry1'

Adjust the velocity in fluid flow module

If everything works well, 10 and 5 mm allow to reach a core temperature higher than 121 °C

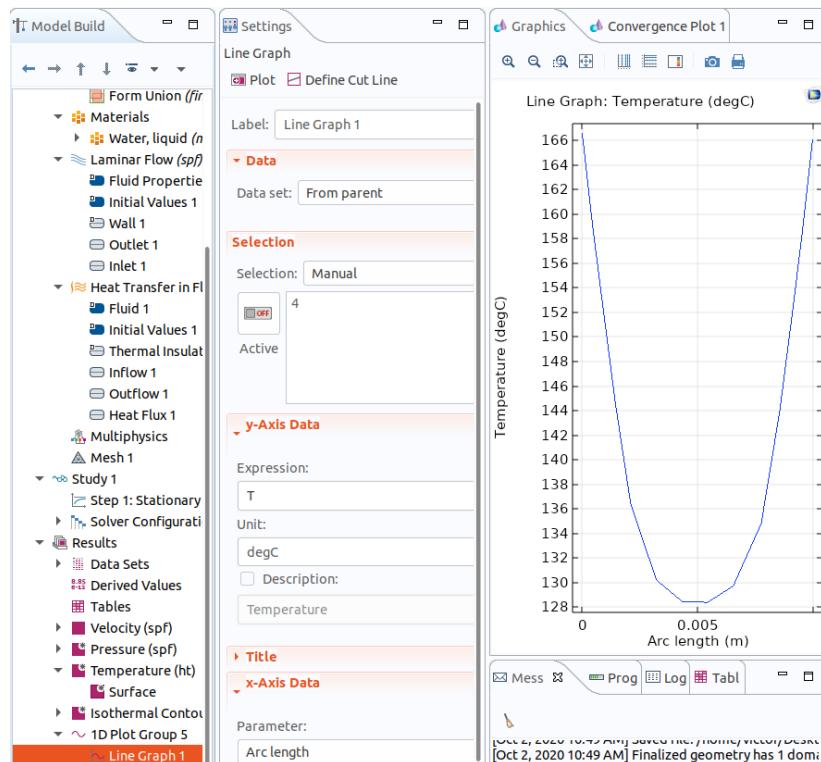


Fig 31 - Temperature profile at the outlet for 10 mm gap

Stage 3 - Laminar cooking Sterility

Sterility

Sterility is not only linked to temperature, but also to the residence time

You will check actual bacteria destruction using a degradation kinetic applied to a bacteria concentration field

To do so, right click on 'Component1' → Add physics → Chemical Species Transport → Transport of Diluted Species → Double click to add

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9.2

Adding bacteria transport

To specify that the new module will use the velocity field from the fluid flow one, click on 'Transport properties' → Convection section → Select 'Velocity field (spf)'

You can also see that you can choose the diffusion coefficient, here
 $D = 1.0 \times 10^{-9} \text{ m}^2/\text{s}$ is fine

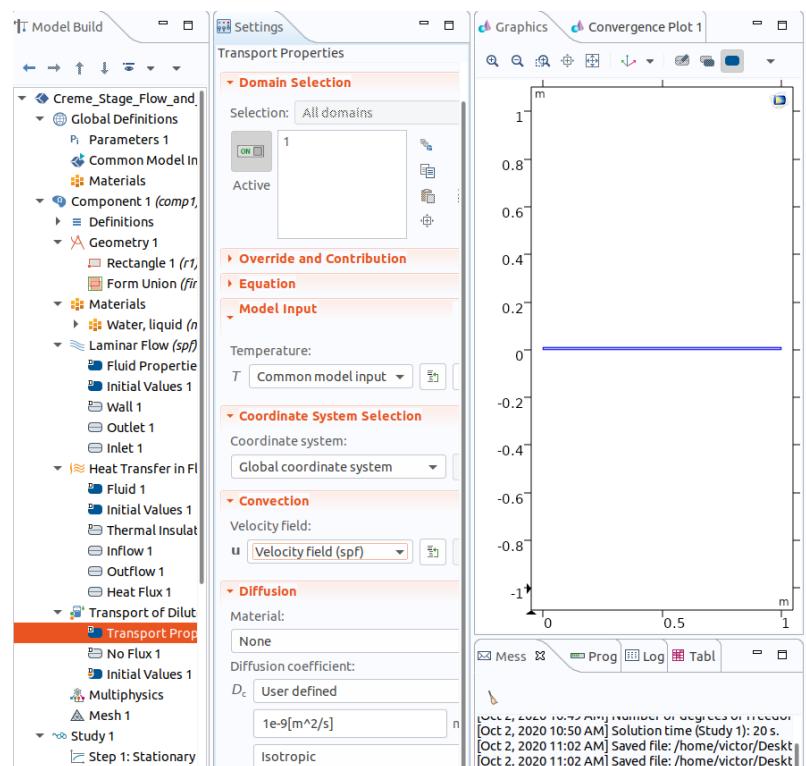


Fig 32 - Addition of bacteria transport module

Boundary conditions

Right click on 'Transport of Diluted Species' \mapsto Inflow \mapsto Select the channel inlet

As you aim at a 12D cooking, you will set inlet bacteria concentration to 10^{12} and try to get an average value below 1 at the outlet

Right click on 'Transport of Diluted Species' \mapsto Outflow \mapsto Select the channel outlet

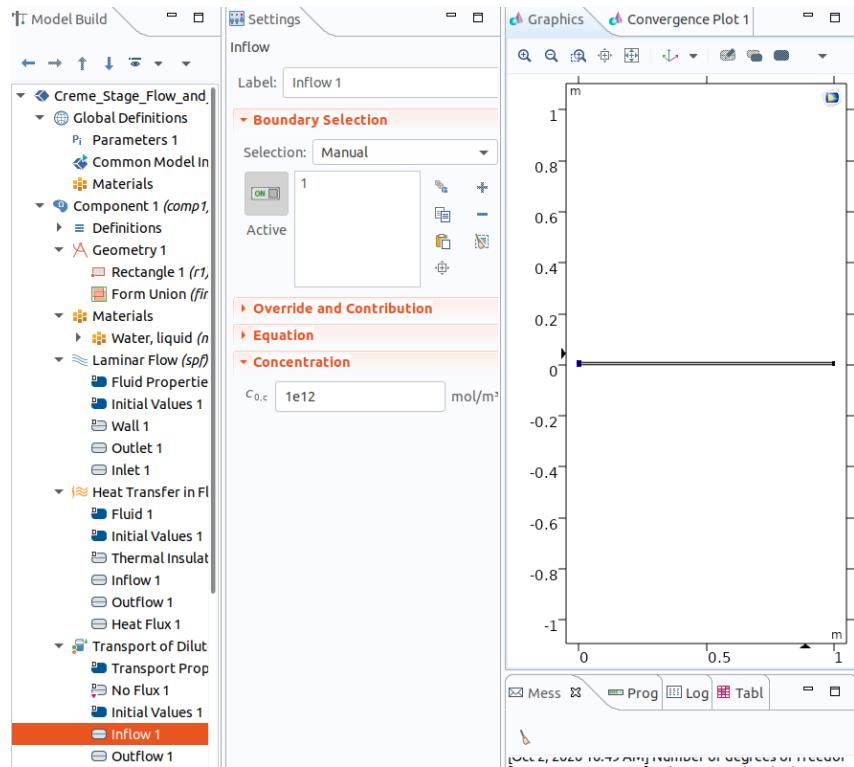


Fig 33 - Addition of bacteria transport module

Adding degradation kinetic

Right click on 'Transport of Diluted Species' \mapsto Reactions \mapsto Reaction \mapsto Select the computational domain

As the degradation kinetic follows a first order reaction, the source term is:

$$R_c = k \times c \text{ or}$$

$$R_c = 1.940 \cdot 10^{40} \exp\left(-\frac{300000}{RT}\right) c$$

Right click on 'Transport of Diluted Species' \mapsto Outflow \mapsto Select the channel outlet

Compute the case by selecting "Study1" then click "Compute"

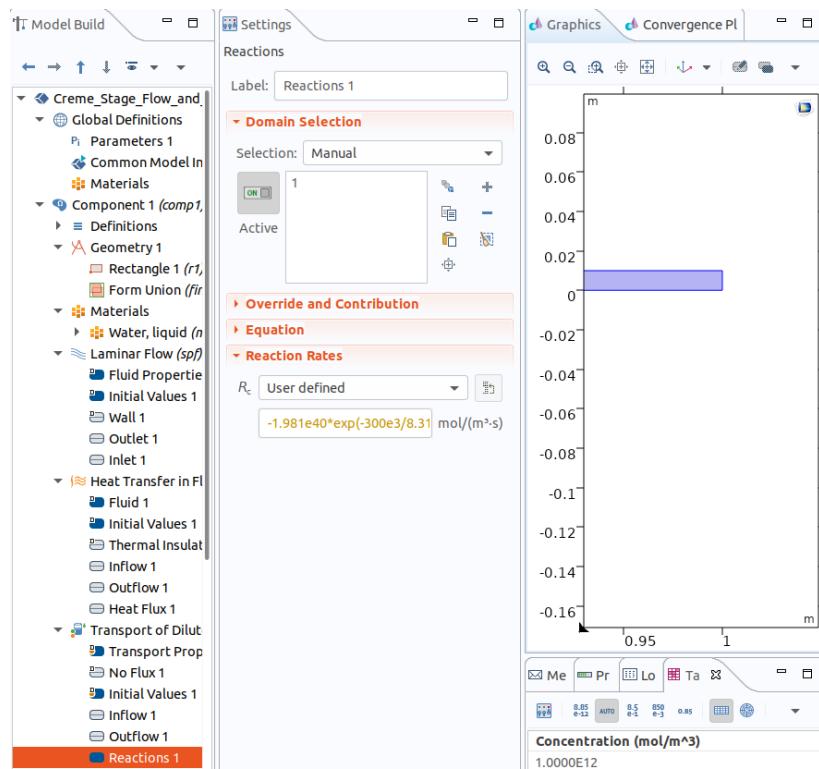


Fig 34 - Addition of bacteria degradation

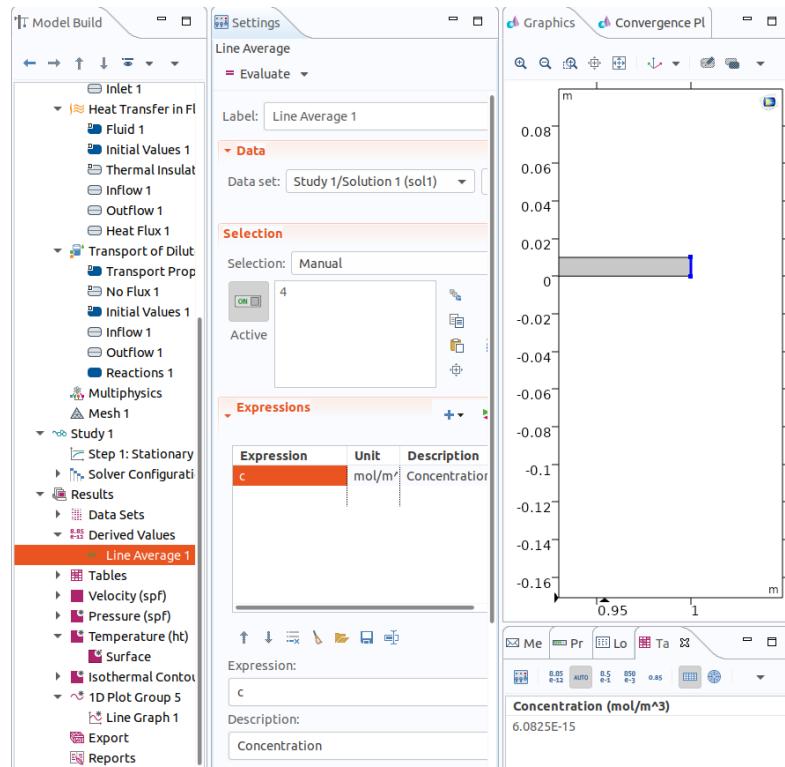
Average outlet concentration

Right click on 'Derived values'
(in 'Results' section) ↪
Average ↪ Line Average ↪
Select the Outlet

Specify 'c' as variable in the
table and click 'Evaluate'

The average value appears
below the geometry
schematic

A value far below 1 appears,
meaning that the cream is
sterile



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Stage 3 -

Laminar

cooking

Additional investigations

In case you have time

You can try the 5 mm gap between the plate

You can investigate chlorophyll degradation (inlet concentration of 1), the same way you did for bacteria

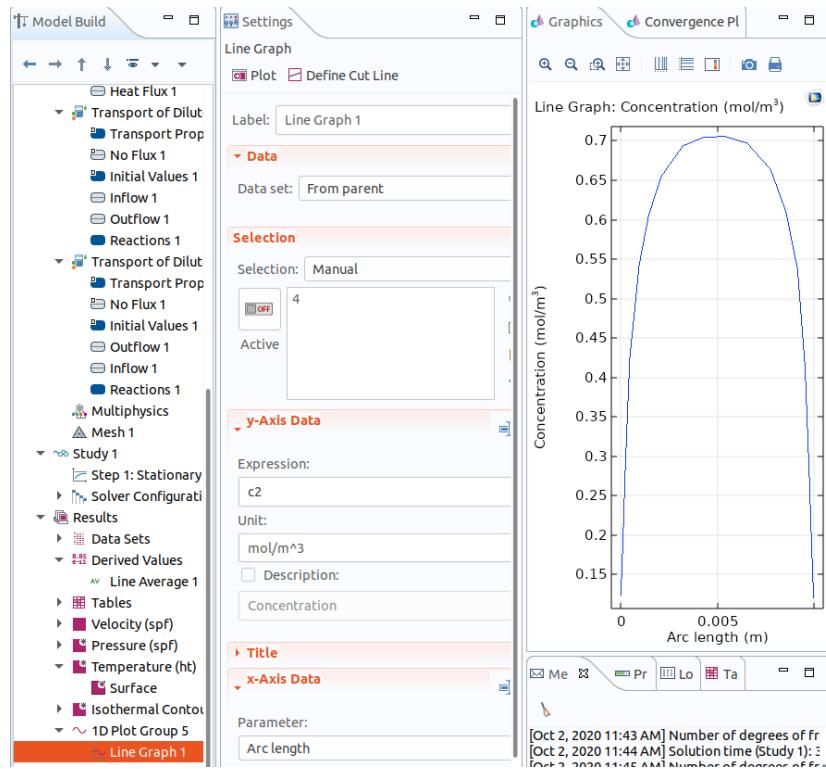


Fig 36 - Chlorophyll outlet profile

In case you have time

Finally the conclusions are:

- 20 mm \mapsto the core temperature is too low to properly sterilize
- 5 mm \mapsto sterilization is successful, but chlorophyll is too degraded
- 10 mm \mapsto best compromise, sterilization is successful and chlorophyll is preserved

You can now instruct your technical to setup the production line

Conclusion

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General conclusion

You designed a process featuring non-ideal reactors:

- Non-trivial geometry
- 2D concentration and temperature fields
- Coupled convection, diffusion and reaction setups
- Laminar and turbulent flows

All that to answer key questions:

- Mixing
- Sterility
- Nutrient preservation

Thus you adjust your process before deploying it and save both time and money

Thank you for your attention



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