Influence of the load positioning during a steam sterilization cycle:

An experimental and numerical study

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Overview

I. **Background**
II. **Methods**
- Experiments
  - Sterilizer
  - Cycle
  - Loads
- Simulations
  - Computational fluid dynamics (CFD)
  - Modeling of the sterilizer

III. **Results**
- Load temperatures
- Flow field
- Steam distribution

IV. **Conclusion**

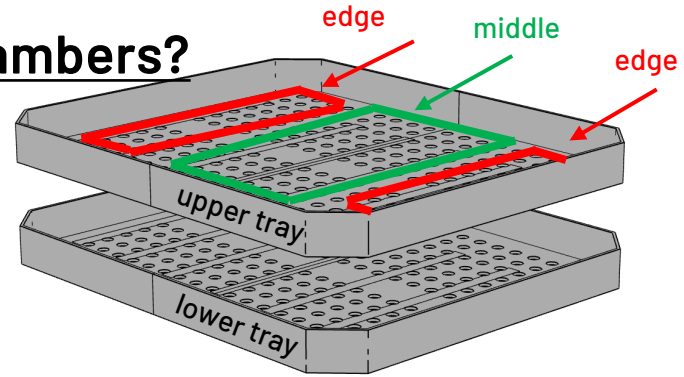
Background

- **Cooperation** between **TU Graz** and **W&H Sterilization S.r.l. since almost 10 years**
  - Improve the understanding of physical processes within a steam sterilizer
  - Decrease the water and energy consumption
  - Supporting the development process of new sterilizers and new components (ejector, heaters, etc.)
  - Simulations of bacteria killing rates on surfaces

- **Support** the **development** of a **small** chamber **sterilizer**
  - 5 liter (also 2.5 liter)
  - Experiments and numerical simulations
    - Steam distribution
    - Heating process of the chamber and the loads

Source: https://shop-de.wh.com/de-at/produkt/lisa-mini

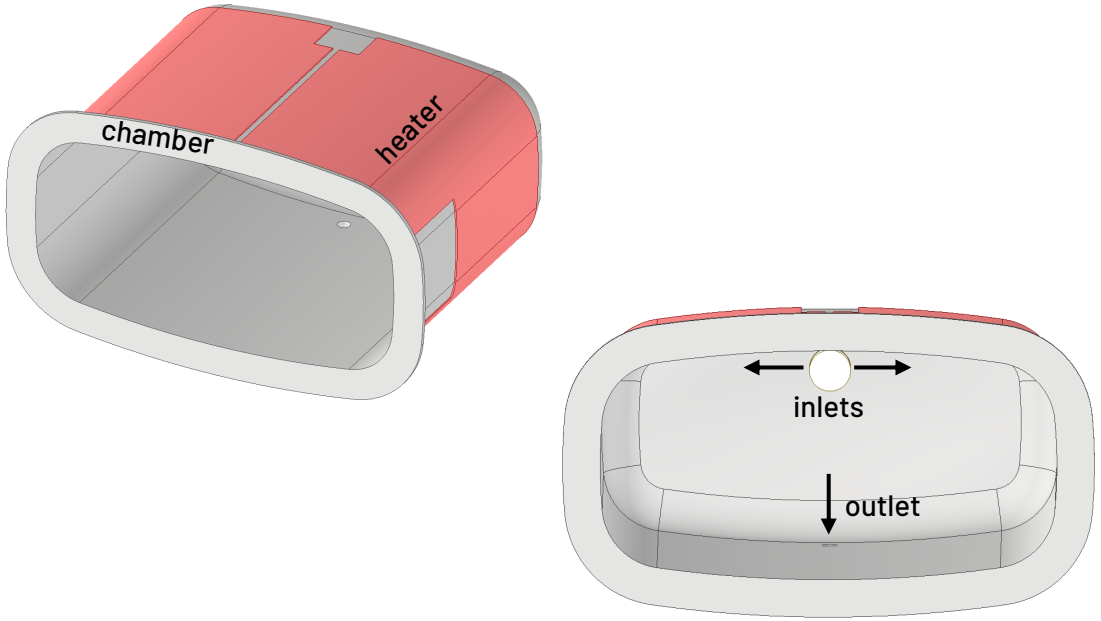
- **Is there a influence on the load positioning even inside small chambers?**
  - Investigation on the heating process of the loads
  - Better to place the loads on the lower or the upper tray?
  - Better to place the loads in the middle or on the edge of a tray?



Methods
experimental

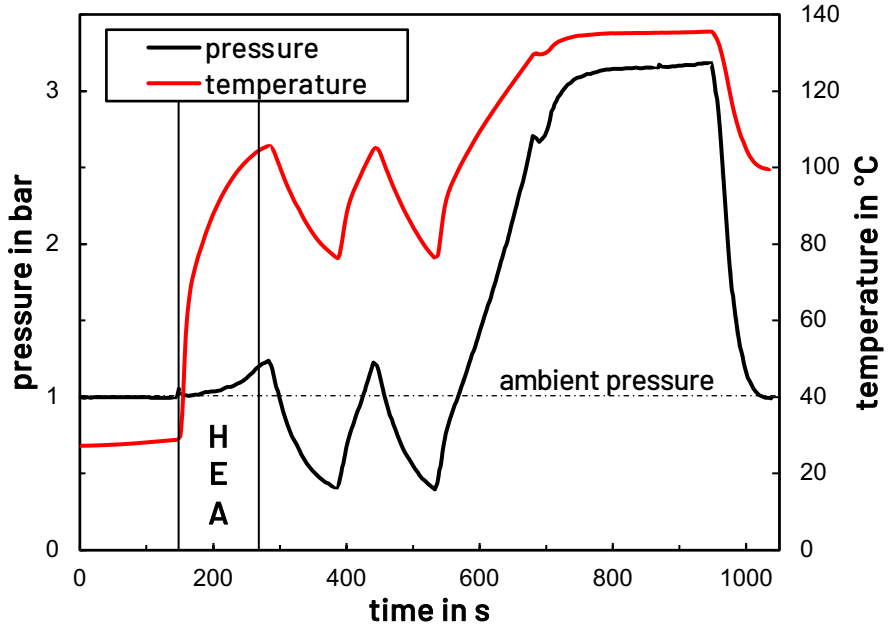
Chamber

- Stainless steel chamber
  - 5 liter internal volume



Sterilization cycle

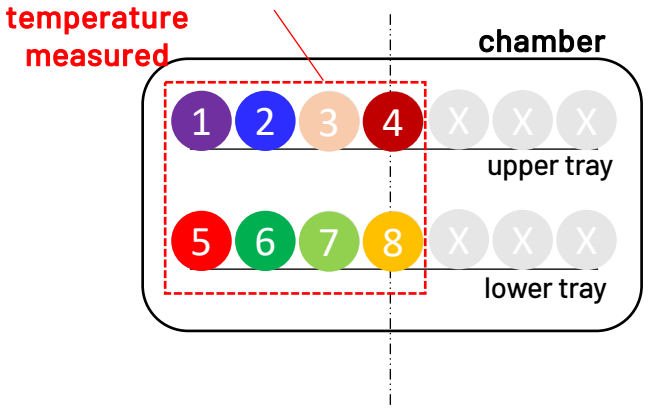
- Adapted universal 134 °C cycle
  - Special heating phase HEA (t = 140-245 s)
  - Outlet is open, when steam is fed into the chamber
    - Internal surfaces (chamber, loads) are preheated
    - Air is flushed out before the first vacuum phase

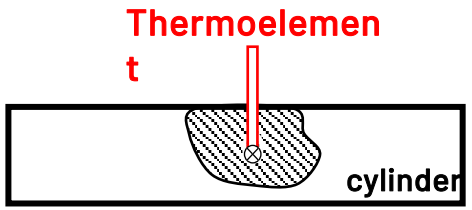


Methods
experimental

Loads

- 14 cylinders were placed on two trays
  - 0.1 kg each
  - Stainless steel
  - Same properties as bolts according to EN 13060
- Temperature measurement in the center of gravity in 8 different cylinders
  - symmetric chamber





Methods
numerical

- Above experiments were simulated using **Computational Fluid Dynamics (CFD)**

- **Why CFD?**
  - Experiments give only information on a few single measurement points (load temperature only in the center of gravity)
  - Prototypes are expensive
  - Parameter studies using CFD decreases the development costs
  - Real life applications (steam sterilization) are very complex → no analytical solution

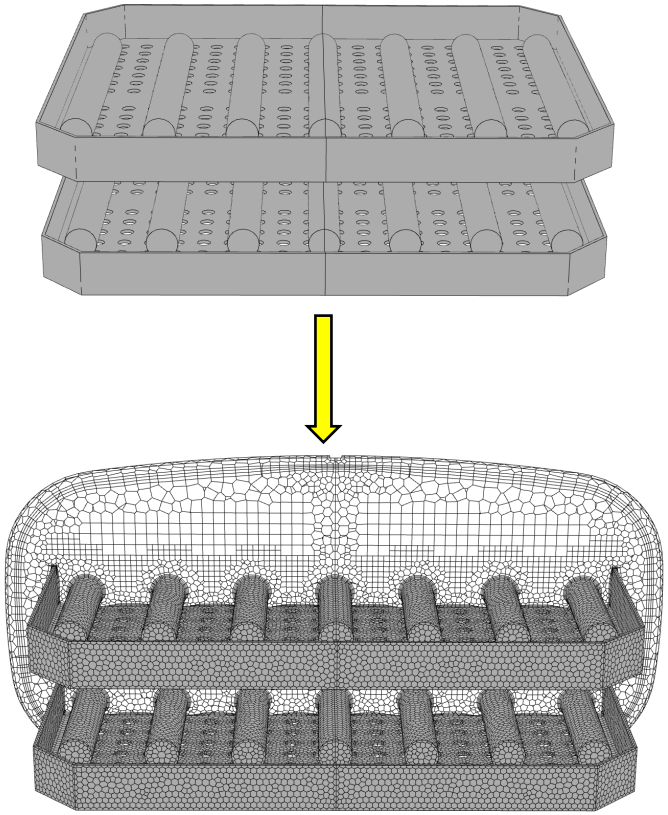
- **Can CFD results be trusted?**
  - YES!!
  - experienced engineers are needed to perform and validate these simulations
  - otherwise, danger of creating only colorful pictures which lead to wrong results and conclusions
  - Validation process:
    - Comparison between experiments and simulations (load temperature)
    - Simulations provide useful information about the entire investigated domains

Methods
numerical

- **What is CFD?**
  - Powerful tool to simulate the fluid flow of real life applications
    - Aerodynamics around cars, combustions processes, etc.
    - Condensation/evaporations effects inside steam sterilizers
  - A system of differential equations are solved iteratively → Navier Stokes equations
    - Mass continuity, momentum, energy, turbulence, etc.
    - 17 equations were needed for the simulation of the presented experiments
      - Momentum equation for the multiphase flow:

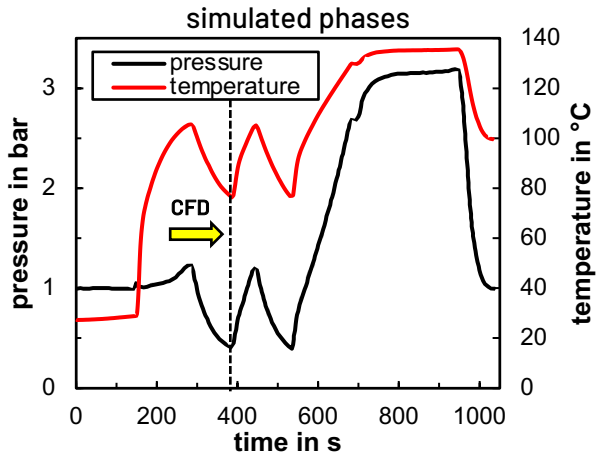
$$\frac{\partial}{\partial t}(\alpha_q \rho_q \vec{v}_q) + \nabla \cdot (\alpha_q \rho_q \vec{v}_q \vec{v}_q) = -\alpha_q \nabla p + \nabla \cdot \bar{\bar{\tau}}_q + \alpha_q \rho_q \vec{g} + \sum_{p=1}^{n} (K_{pq}(\vec{v}_p - \vec{v}_q) + \dot{m}_{pq}\vec{v}_{pq} - \dot{m}_{qp}\vec{v}_{qp})$$

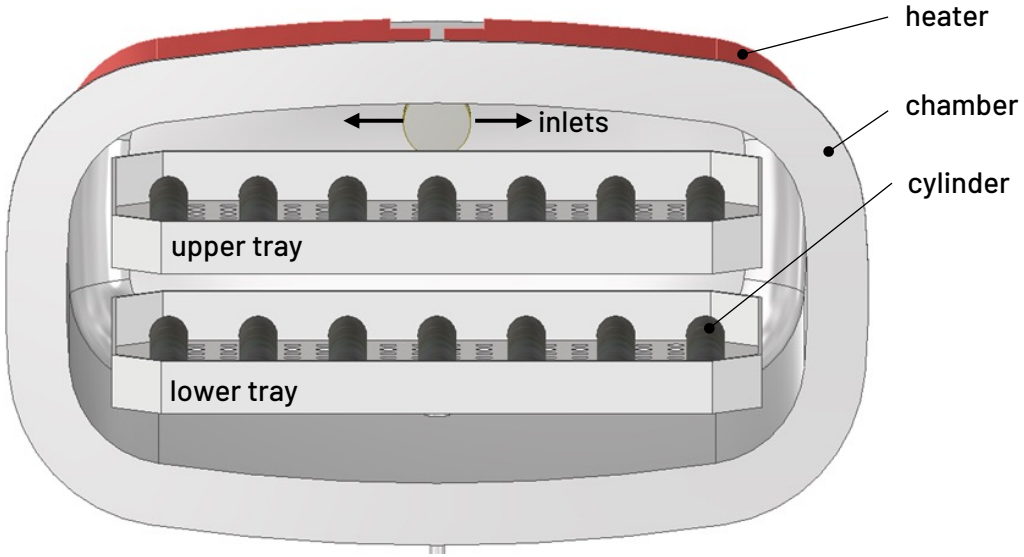
  - The investigated domain is divided into tiny little boxes (cells)
    - Each cell interacts with its neighbors
    - In every iteration all 17 equations are solved for each cell (17 x 500 000 cells = 8.5 million equations)
    - 60 iterations were needed for one time step
    - 50 time steps were needed to calculate 1 s of the real sterilizer process (= 3000 iterations)
    - 1 s of real process time ~ 1.5 h calculation time
      - Considering the complex process, incredibly fast
      - Special inhouse developed heat transfer model

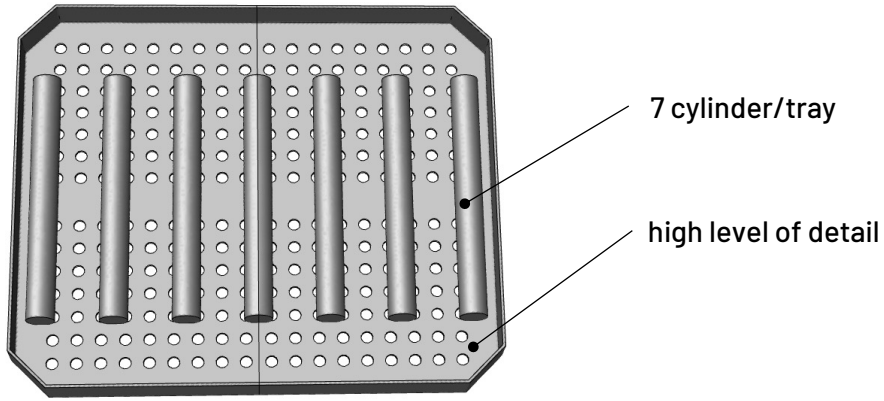


Methods
numerical

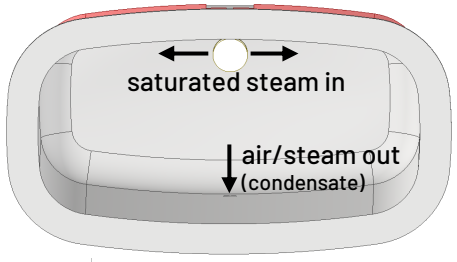
- **Numerical model**
  - Whole chamber incl. the door are considered as solids
    - Implementation of a special developed heat transfer model
      → numerically inexpensive
  - Heater was modeled as well (incl. its heating process)
  - Steam mass flow into the chamber was set according to measurements
  - Both trays were modeled with a high level of detail
    - all holes were considered



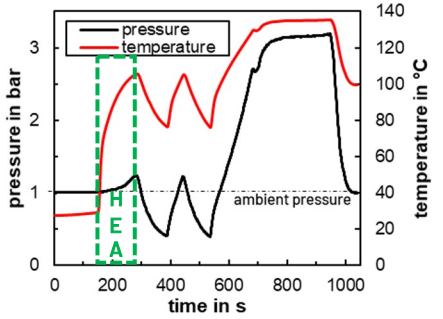


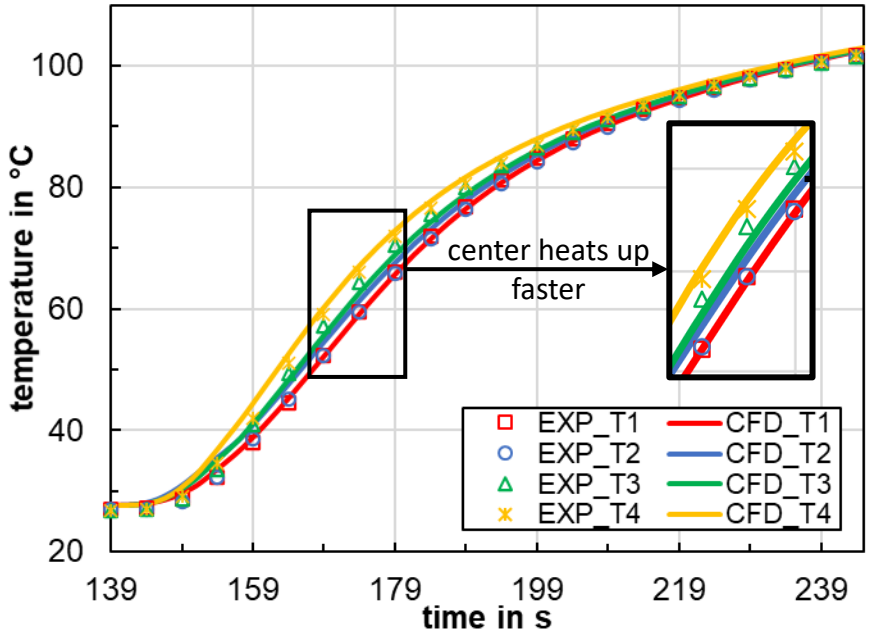


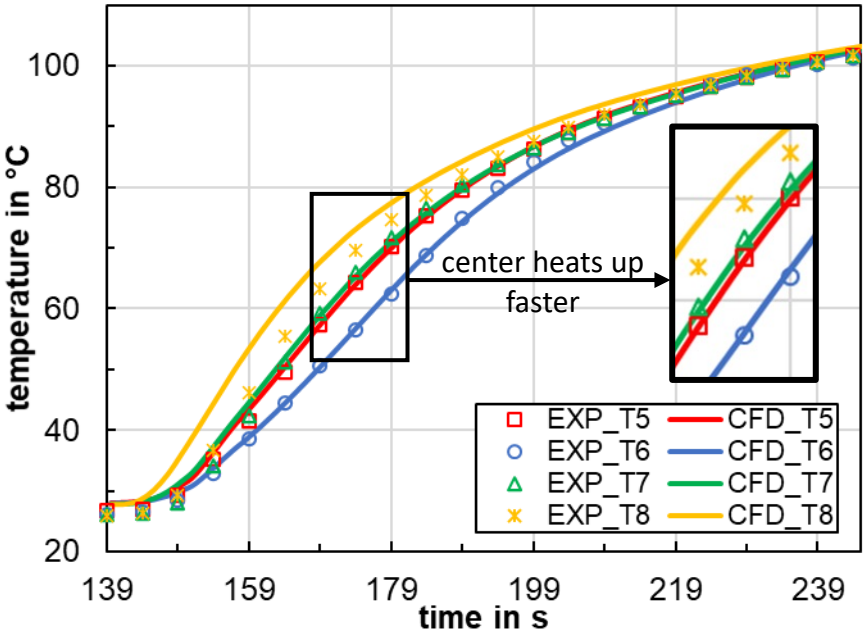
Heating Phase – HEA

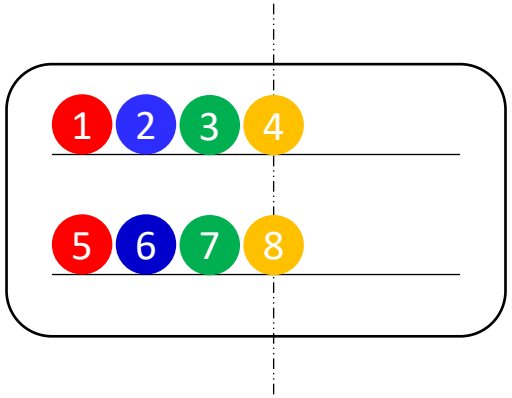


Results
heating phase





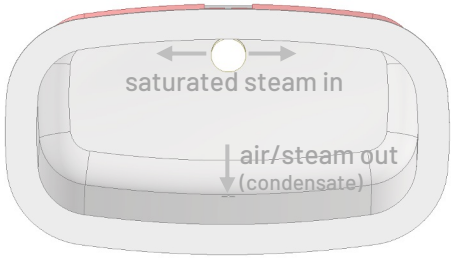




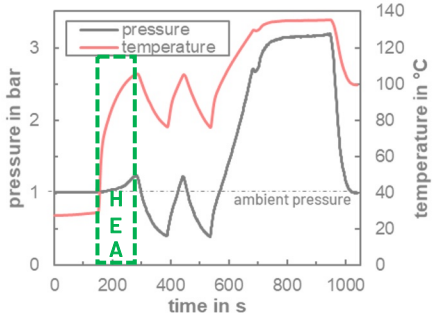
Loads get heated up faster in the center of the tray

Simulation predicted the temperatures of the loads with high accuracy in time and space

Heating Phase – HEA

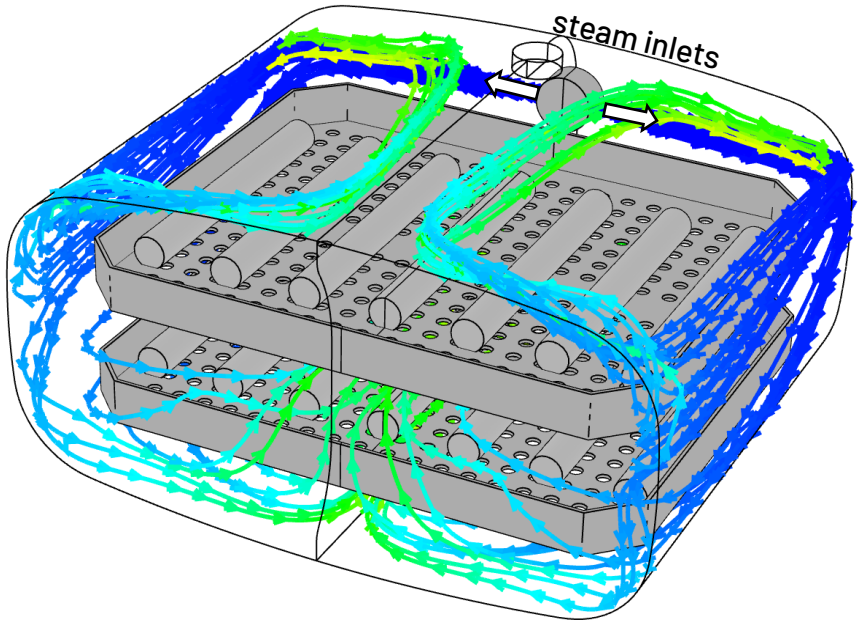


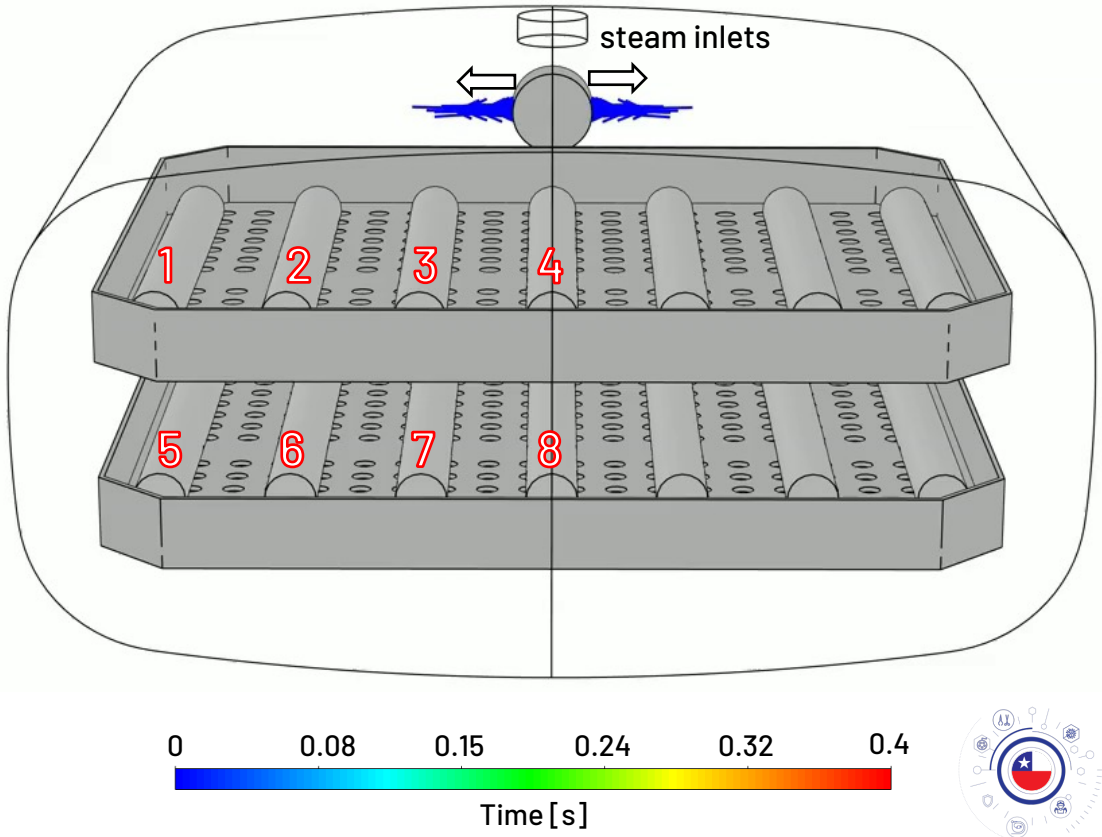
Results
heating phase



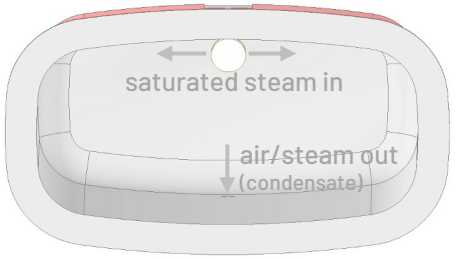
Flow field:

(1) The flow moves forward along the side walls
(2) and is reflected off the door at the front
(3) The flow field enhances the heat transfer to the center pieces

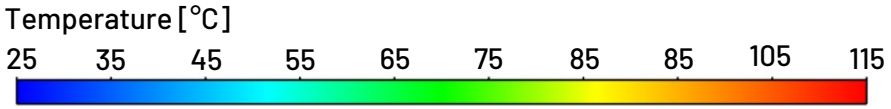


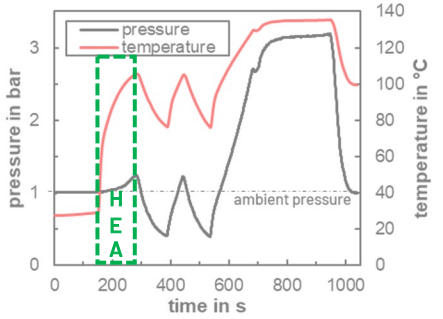


Heating Phase – HEA

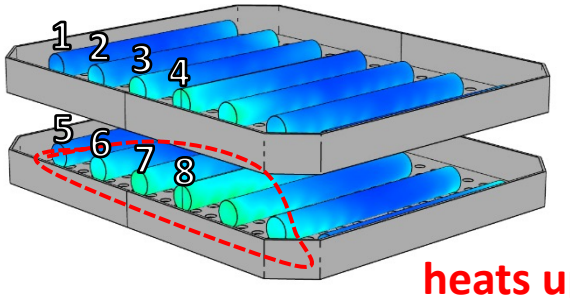


Results
heating phase

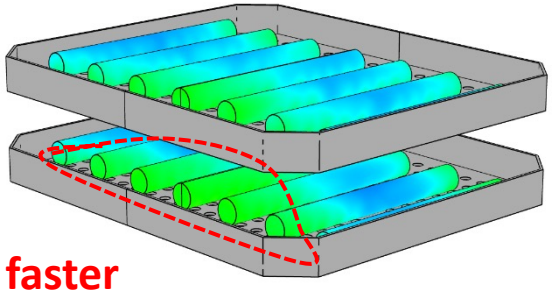




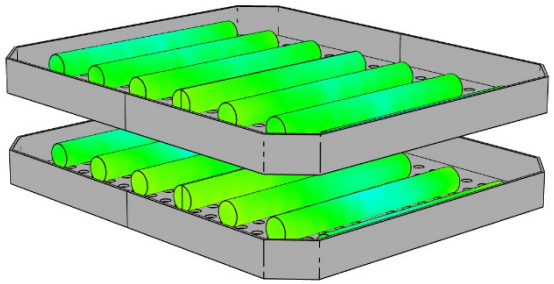
t = 158 s



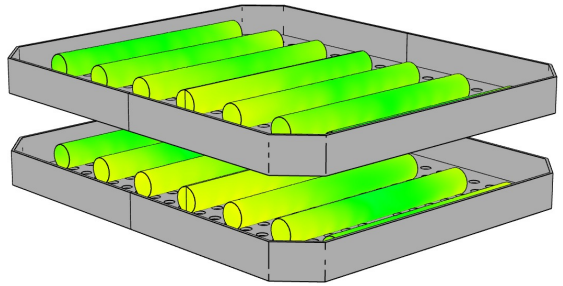
t = 168 s



t = 178 s

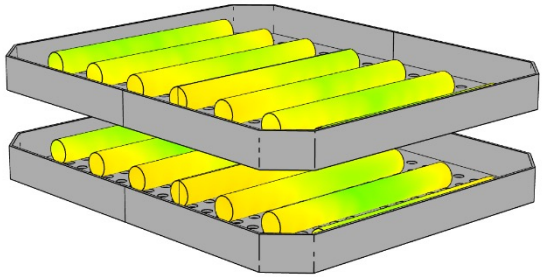


t = 188 s

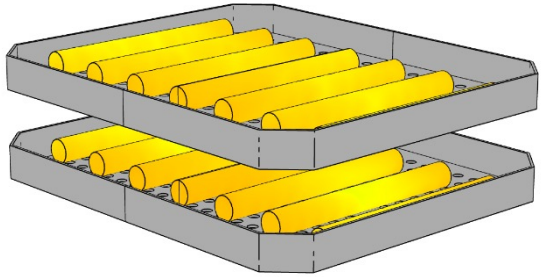


heats up faster

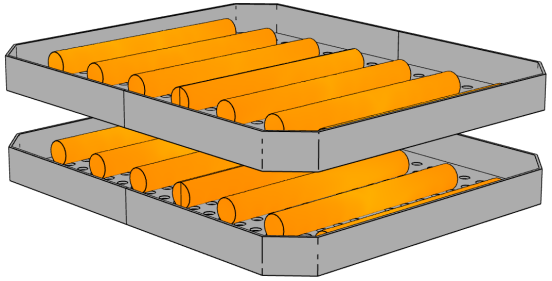
t = 198 s



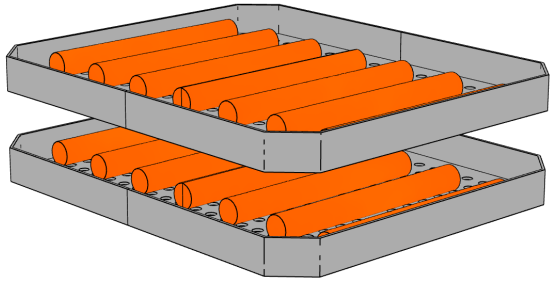
t = 208 s



t = 228 s

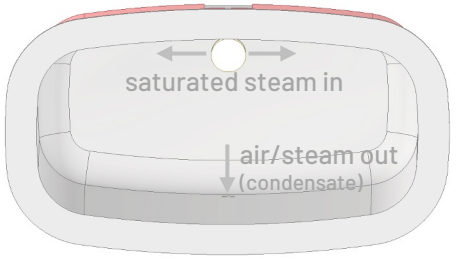


t = 245 s (end HEA)

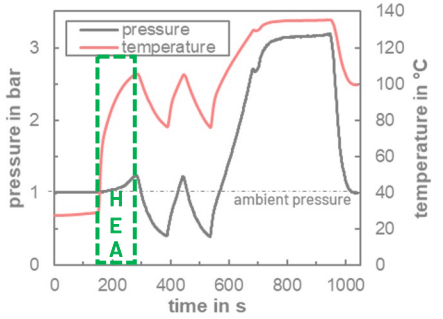


Maximum heating efficiency is concentrated at the front of the lower tray

Heating Phase – HEA

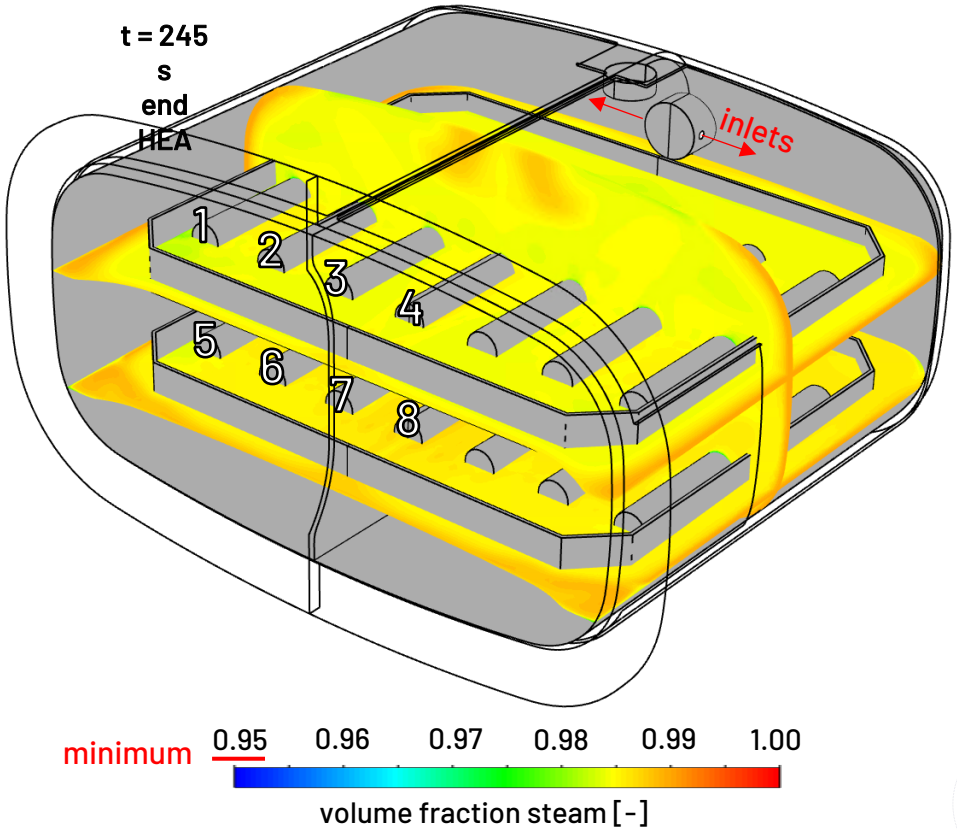


Results
heating phase

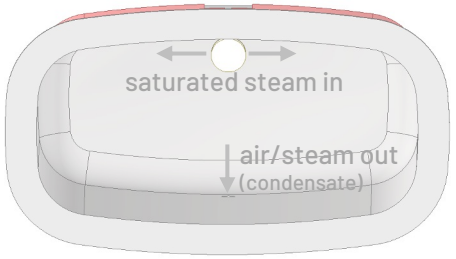


Steam distribution:

(1) The flow field promotes an uniform steam distribution
(2) Minimal air remains inside the chamber, even prior to the first vacuum phase.
(3) The average steam volume fraction inside the chamber is 0.983

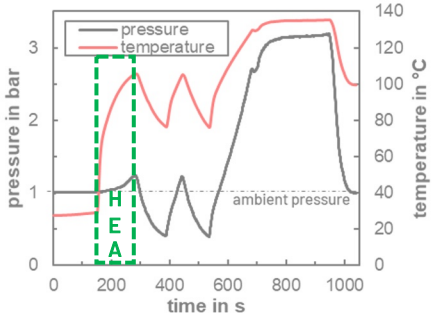


Heating Phase – HEA



Conclusion

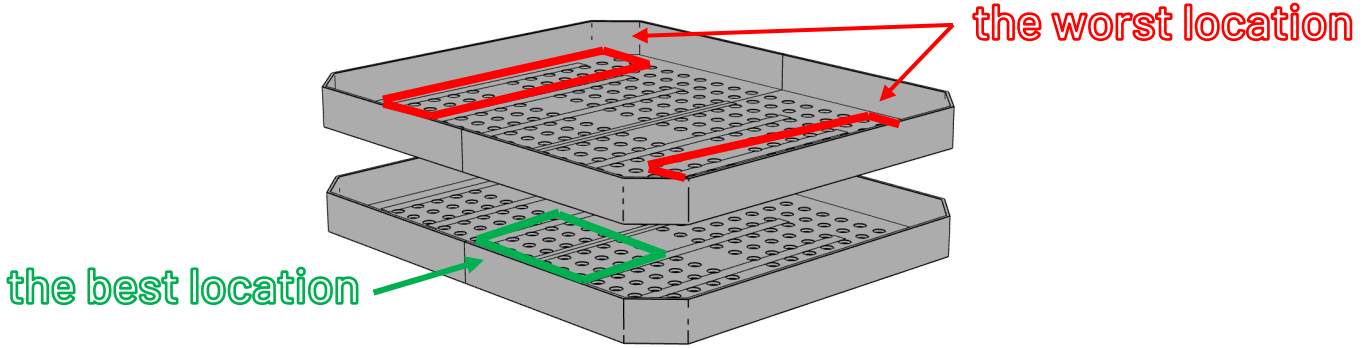
Heating phase



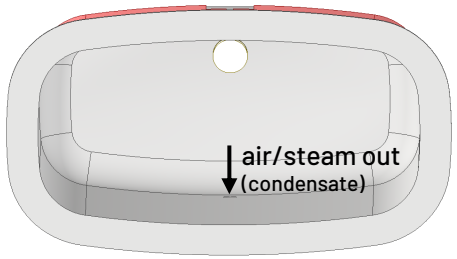
I. The simulation closely matched experimental results for all eight cylinders throughout the entire testing period

II. The simulation revealed an ideal steam distribution throughout the chamber (min = 0.95 steam)

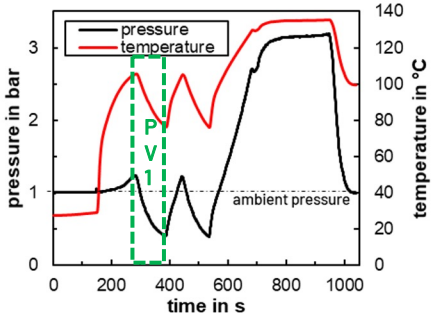
III. CFD analysis identified the optimal locations for maximizing heating efficiency of the load



1st Vacuum phase – PV1



Results
1st vacuum phase

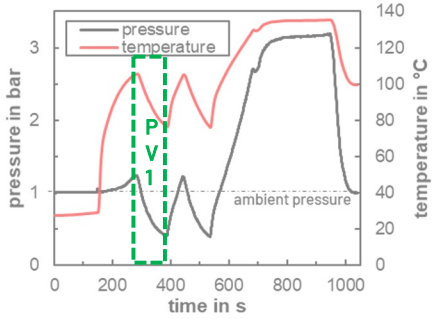


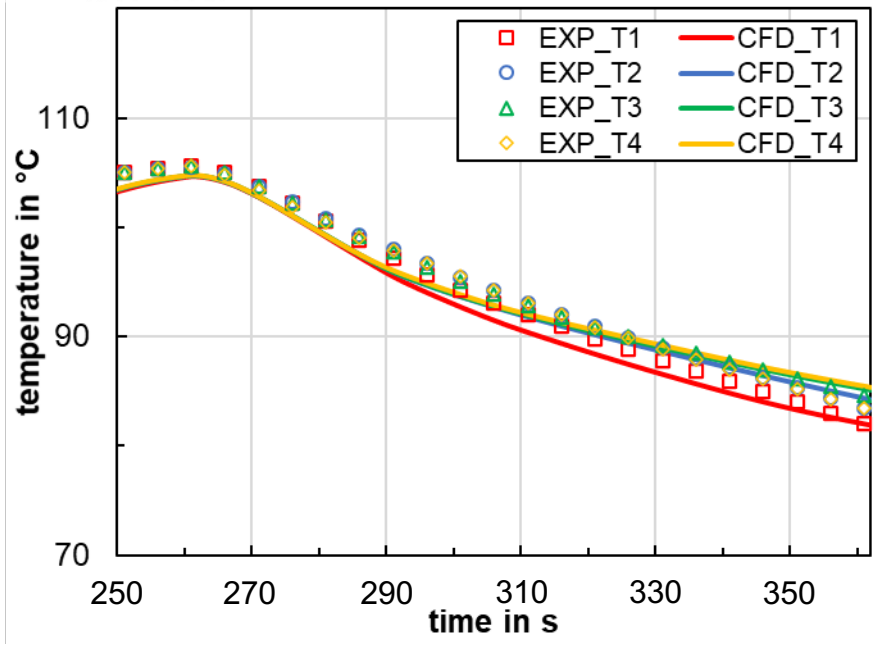
- **Theoretical background**
  - In the previous heating phase (HEA) the solids were heated by the condensation of steam
    - Formation of condensate on the surfaces
  - During vacuum generation the absolute pressure is reduced
  - Evaporative cooling effect during vacuum generation
    - previously formed condensate starts to evaporate/boil
    - energy/heat is extracted from the solids (chamber, loads, and trays)
    - affected parts need more energy to be reheated in the next phases
  - Which loads cool down the most?

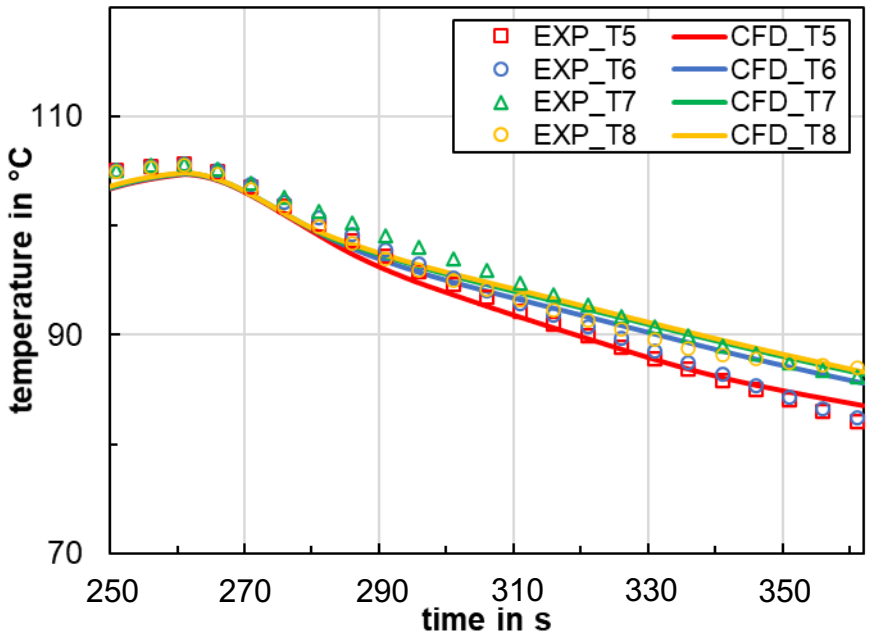
1st Vacuum phase – PV1

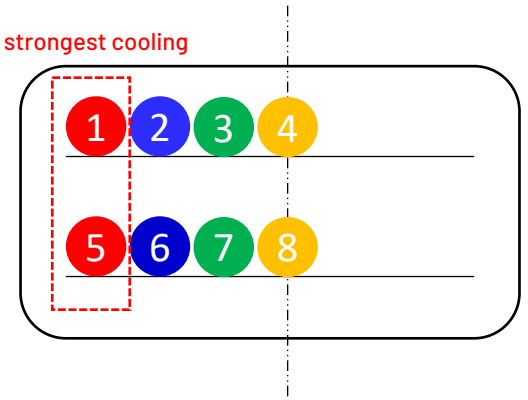
Results

1st vacuum phase









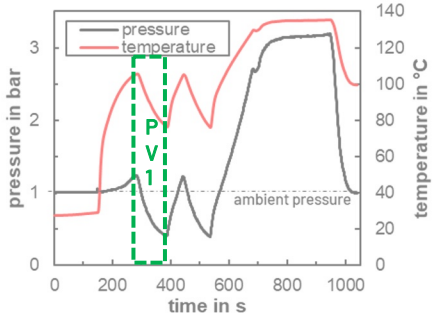
Loads on the edge of the trays cool down the most

Simulation predicted the worst case locations of the loads

1st Vacuum phase – PV1

Results

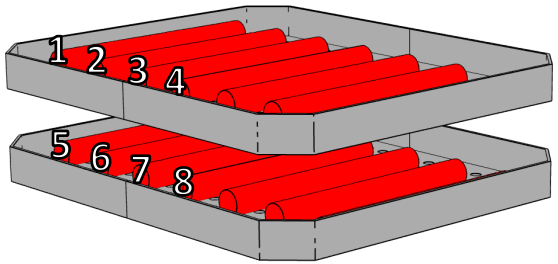
1st vacuum phase



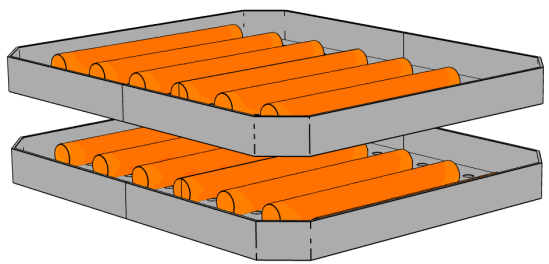
Temperature [°C]

75 80 85 90 95 100 105

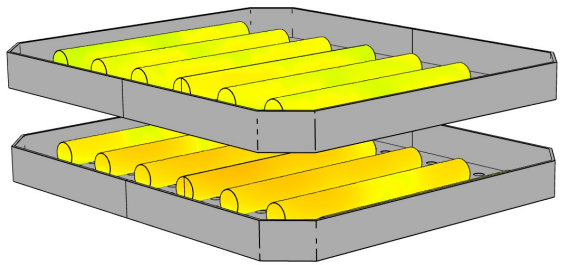
t = 265 s



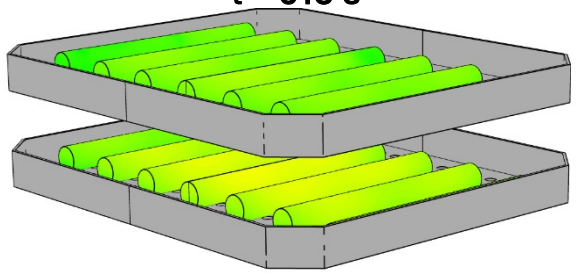
t = 280 s



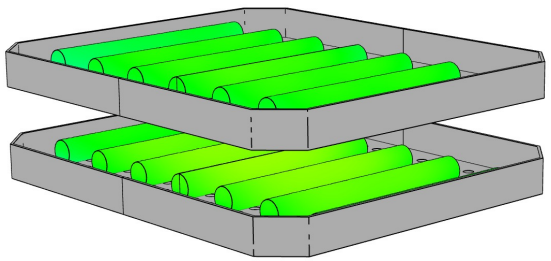
t = 295 s



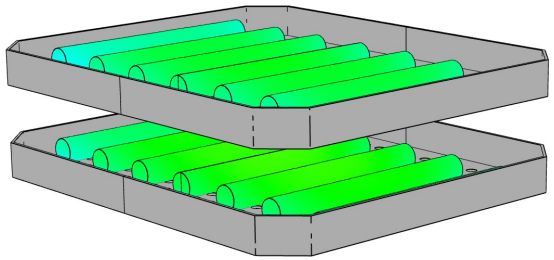
t = 310 s



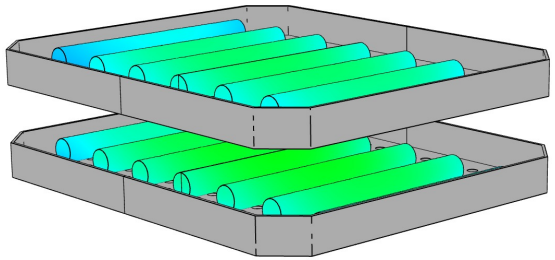
t = 345 s



t = 360 s

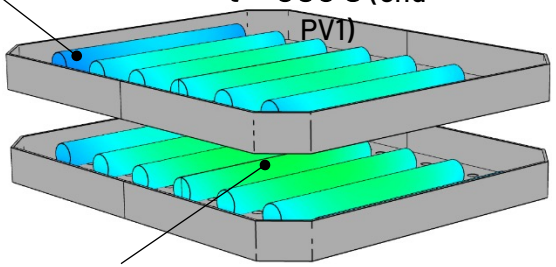


t = 375 s



T_{min} = 78.3 °C

t = 385 s (end PV1)

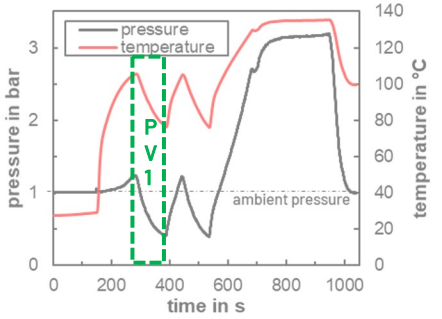


T_{max} = 88.3 °C

More condensate was flushed away in the center of the trays during the previous heating phase → weaker cooling effect

1st Vacuum phase – PV1

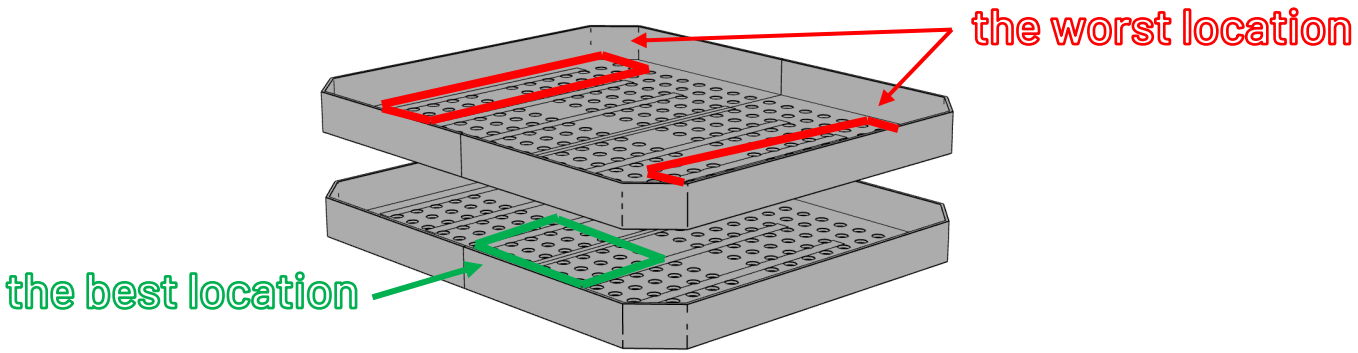
Conclusion
1st vacuum phase



I. Loads on the edge of the trays cooled down the most, especially on the upper tray

II. Simulation predicted the worst case locations

III. Recommendation on the positioning are consisting with those of the previous heating phase (HEA)



Summary
overall

TU Graz

- **Influence of the load positioning was shown experimentally and numerically**
  - Findings are exclusively valid for the presented configuration
    - chamber shape
    - tray shape
    - locations and sizes of the steam inlets

- **Numerical simulations (CFD) exhibited an excellent agreement with experimental data**
  - Numerical model is successfully validated
  - Parameter studies are now possible without additional experiments
  - CFD makes the invisible visible
    - steam distribution
    - temperature distribution inside the whole chamber
  - CFD is a powerful development tool also in the field of steam sterilization

- **Independent researchers evaluated the numerical models during the peer review process**
  - Publication I: *Numerical Investigation of the Heating Process of the Walls in Steam Sterilizers*
    https://doi.org/10.1002/cite.202200135
  - Publication II: *Numerical modelling of the evaporative cooling effect on solid walls in steam sterilizers*
    https://doi.org/10.1016/j.ijheatmasstransfer.2023.124396