Homogeneous Heating of Milk

Andrea Reichmuth, Andreas Stahel
Bern University of Applied Sciences

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Goal of the Project

Take a bottle of milk out of the fridge and heat it up to 37°.

- fast
- uniformly heated
- never exceeding 40°
- no measurements inside the bottle

- Use *COMSOL* as simulation tool and methods to test ideas.
- Calibrate the simulations by measurements on a physical model.
- Improve the heating.

Measurement Setup

We built a mechanical setup of a typical milk bottle with:

- Three sets of heating foils glued to the surface:
    - one foil covering the bottom
    - one foil covering the lower part of the bottle
    - one foil covering the upper part of the bottle
- Five temperature sensor mounted on the inside of the bottle with the help of a thin wooden structure.
- DAQ cards and a Labview program to control and measure.
- A thermal insulation as a casing of foamed polystyrene.

Simulation Setup I

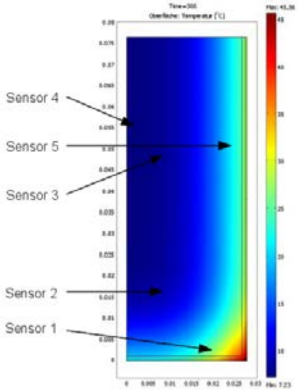
Using *COMSOL* we built a mathematical model of the device.

- Use radial symmetry to obtain a $2+1$ dimensional model.
- Use the `conduction and convection module` (cc) to model the heat distribution.
- Use the `weakly compressible Navier-Stokes module` (chns) to model the moving liquid.
- Couple the two moduls by
  - The moving liquid will transport thermal energy (convection)
  - The heated liquid will have a lower density leading to a boyance force on the moving liquid.

We obtain a model for **free convection**.

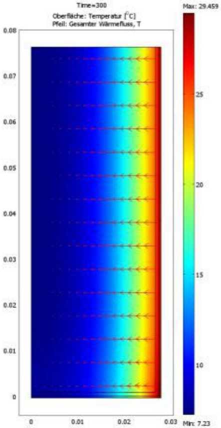
Simulation Setup II

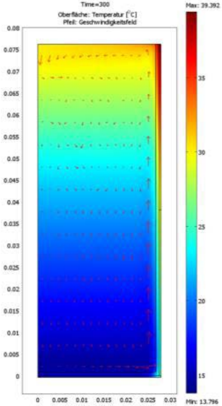
- Observe the temperatures at the location of the five sensors.
- Use a few calibrating measurement to determine what percentage of the energy of the heating foil effectively ends up in the liquid.



Uniform heating, conduction versus convection

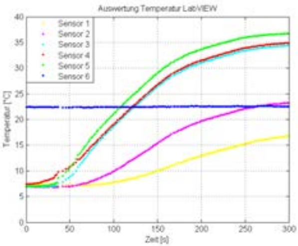
Upper and lower part of the sides are heated uniformly. The bottom is not heated. The applied energy decreases with time to avoid temperatures above 40°. On the left find the result with pure diffusion, on the right with free convection taken into account.

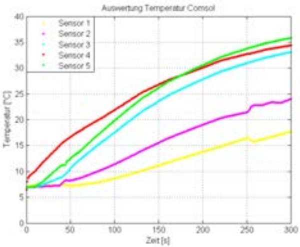




Compare Simulation and Measurement I

- Use *COMSOL* to modify the input power, such that the 40° C limit is respected.
- Adjust the heating efficiency the the foils to obtain similar results for the temperatures at the five spots by measurements (left) and simulation (right).





Compare Simulation and Measurement II

- The shape of the temperature curve are very similar,
- At the final time of 300 sec we observe small temperature differences.

	measured	simulation	difference
Sensor 1	16.90	17.66	+0.76
Sensor 2	23.29	24.03	+0.74
Sensor 3	34.45	33.08	-1.37
Sensor 4	34.93	34.41	-0.52
Sensor 5	36.78	35.83	-0.95

Now we are ready to take advantage of the power of simulation.

Compare Diffusion and Convection

Using *COMSOL* we can compute the contribution of convection and diffusion to the thermal energy transport to the inner part of the bottle.

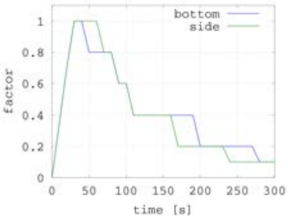
$$
\begin{aligned}
\text{Flux}_{\text{diff}} &= \int_0^H 2\,\pi\,r\,k\,\frac{\partial\,T}{\partial r}\,dz \\
\text{Flux}_{\text{conv}} &= \int_0^H 2\,\pi\,r\,c\,\rho\,v_r\,T\,dz
\end{aligned}
$$

time [s]	convection [W]	diffusion [W]
100	27.5136	0.0154
200	26.8178	0.0214
300	25.8276	0.0065

Within 50 sec the convective energy flux settles on a stable value. As a consequence only the energy transport caused by convection is important.

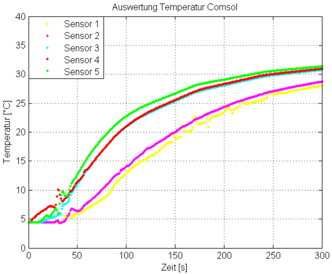
Uniform Temperature by Nonuniform Heating I

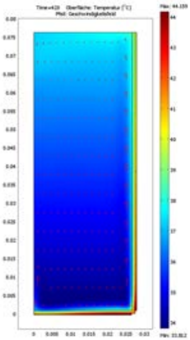
Aiming for a uniform temperature distribution throughout the heating process we try to start the convection as quickly as possible. We apply a higher heating power in the lower sections of the side of the bottle. We heat the bottom too and use different time profiles for bottom and sides.



Uniform Temperature by Nonuniform Heating II

We succeed to keep the temperatures at the different points much closer together than before. The high heating in the early phase causes some turbulence in the *COMSOL* simulation. By extending the heating time we arrive at temperature distribution shown on the right. We observe the desired uniform heating.





That's all folks

Thank you for your attention