Advanced Modeling of Transient Effects in Fluid Circuits and Engines

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Agenda

- Introduction
- "KULI transient 2.0"
- Transient delays
- Engine model
- Conclusions

Introduction

From our customer feedback we see that …

… the **stationary behavior** of cooling systems becomes better and better understood.

… people generally have gained a lot of **experience** with simulating cooling systems,

… there is a clear **trend towards transient simulation**.

Therefore one of our key goals is to **boost the transient capabilities of KULI**.

Current (and future) developments

Improvements in the field of transient simulation include:

- **"KULI transient 2.0"**: **KULI 8**
  - **Variable** transient step width
  - **Decoupling** of simulation and evaluation step width
  - Improved **stability and speed**
- **Flow length dependent delay** of components and **transient diffusion** of thermal shocks. **KULI 8**
- Improved transient behavior of KULI engine models (e.g. hot soaking) **KULI 7.0 / 7.1**

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"KULI transient 2.0"

Diploma thesis and cooperation with the Institute for **Numerical Mathematics** at the **Johannes Kepler University Linz**

Institut für NuMa Numerische Mathematik — JOHANNES KEPLER UNIVERSITÄT LINZ

- **Thorough analysis** of transient simulation in KULI 7
- Test of several different transient **solver strategies**
- Tailor made implementation based on **solid mathematical background**
- Test and **comparison with current solver**

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Algorithm changes

Up to now stationary and transient parts of the cooling system were solved alternately:

Stationary equations

Fluid circuits, air side, components without heat capacity

alternately

Transient equations

Thermal networks, point masses.

In **KULI 8** both will be combined to one **DAE system** (differential-algebraic equations)

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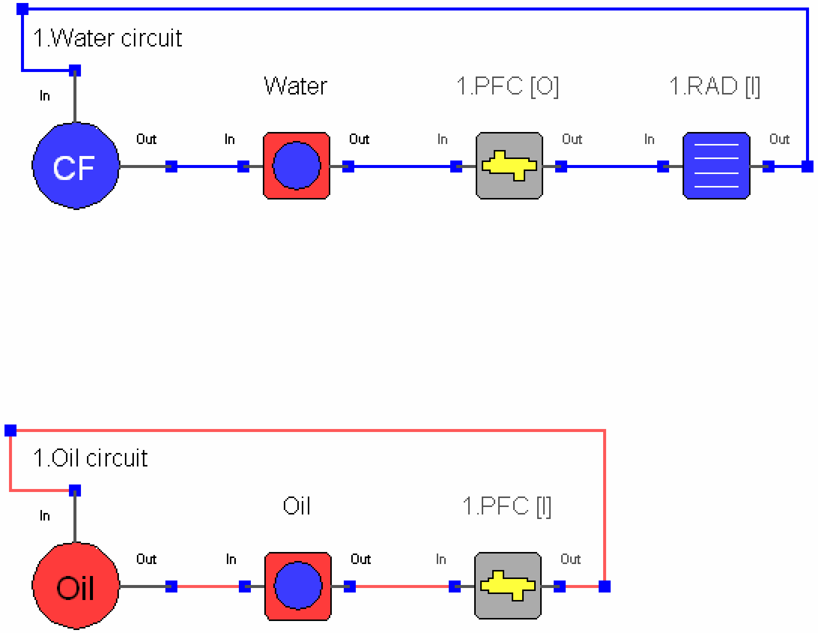
Reference example

For the analysis we use a very simple example:

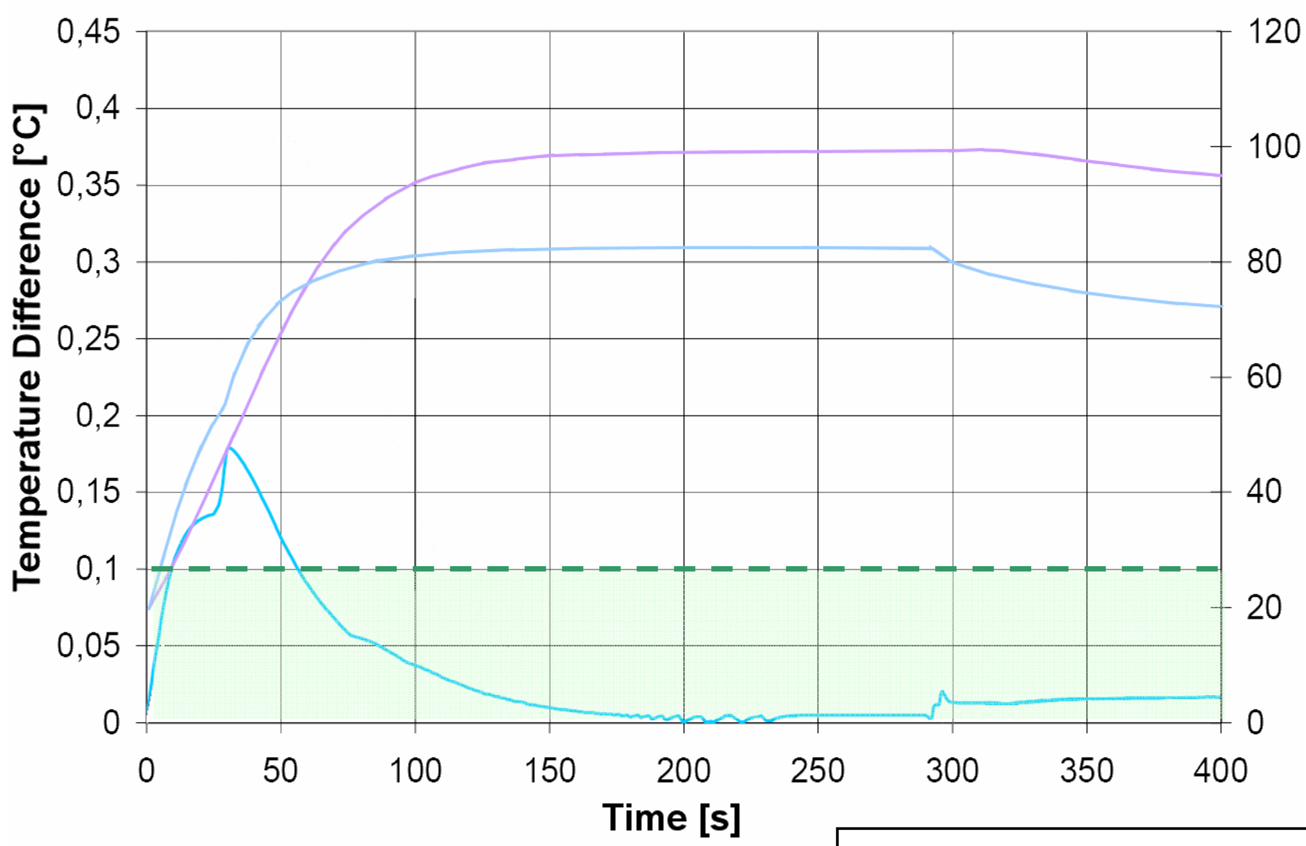


Heat **sources**

Heat **sinks**

We compare the **temperatures** of the point masses.

Load step – KULI 7 results



Error T water (step width 0,1s)

Calculation time: **1600s**

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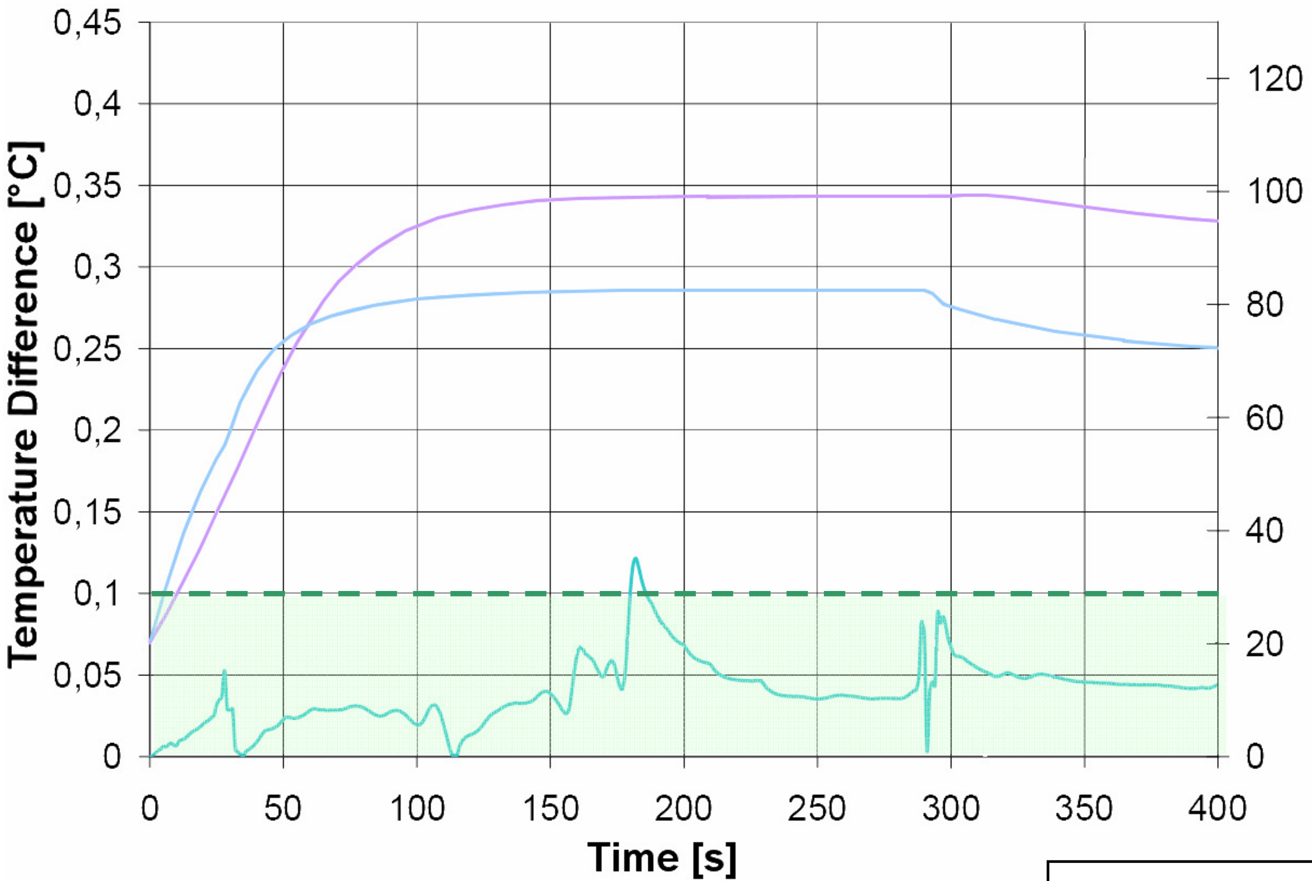
Load step – KULI 8 preview



Calculation time: **150s**

Benefits

The **key advantages** of the new strategy are:

- Much **faster** (factor 10 for test case)
- More **user-friendly** (user defined step width changes only output density, but not the results)
- Automatic **adaptive step width** allows user defined solver precision. Algorithm detects critical points.

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Transient delays

If we take a tube with

Tube length: 75cm

Diameter: 15mm

and assume

Mass flow: 0,5kg/s

we get a flow speed of ~**0,7m/s** and thus a transient delay of ~**1s**.

An abrupt temperature change takes **more than one second** to reach the other end of the tube.

Delays can have an effect on transient simulations!

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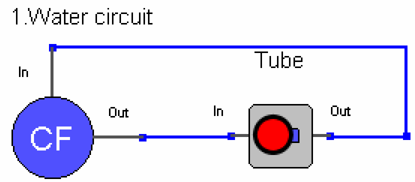
Why diffusion is necessary

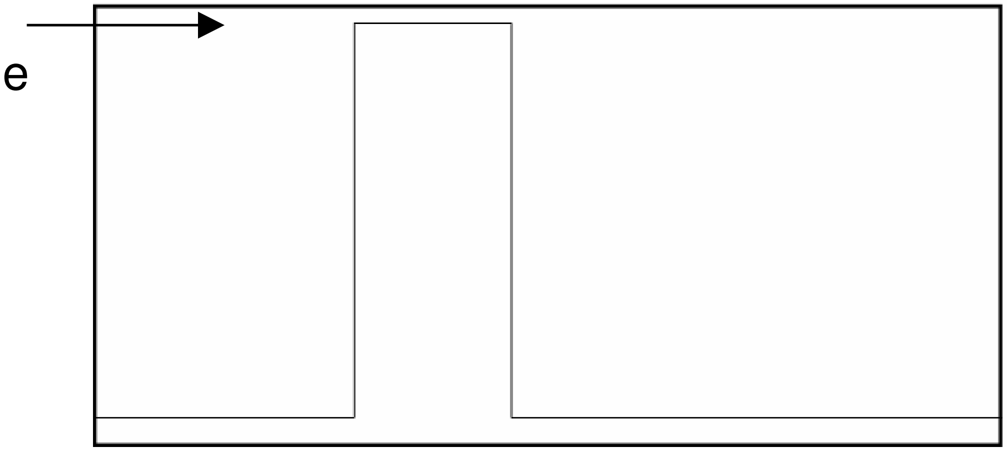
If we model the delay in a tube and apply a **temperature step function** to a circuit…



… this step circulates in the System **“for ever”**.

This obviously is not what happens in a **real** cooling system!

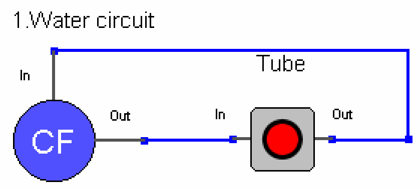
Initial step function value



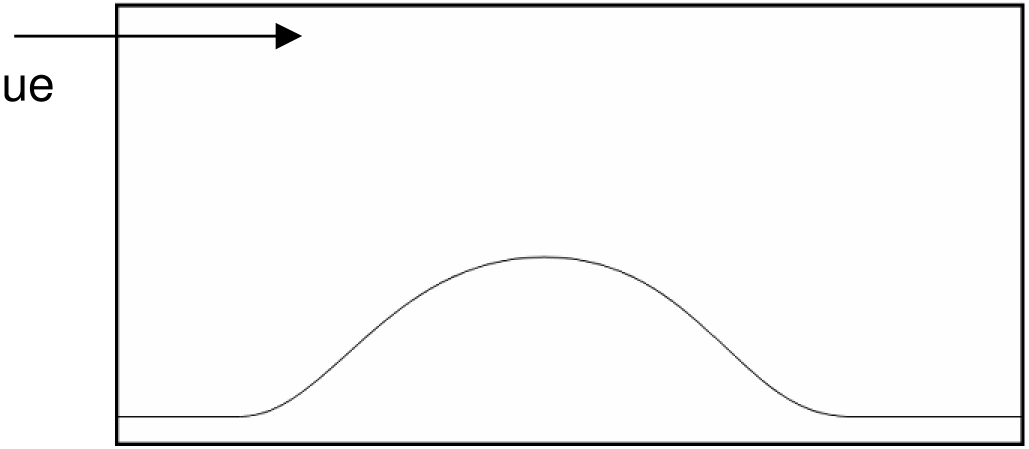
Diffusion

In a real cooling system the temperature step function will **diverge** as time passes.

It will flatten more and more… this can be modeled by **diffusion** processes.



Initial step function value



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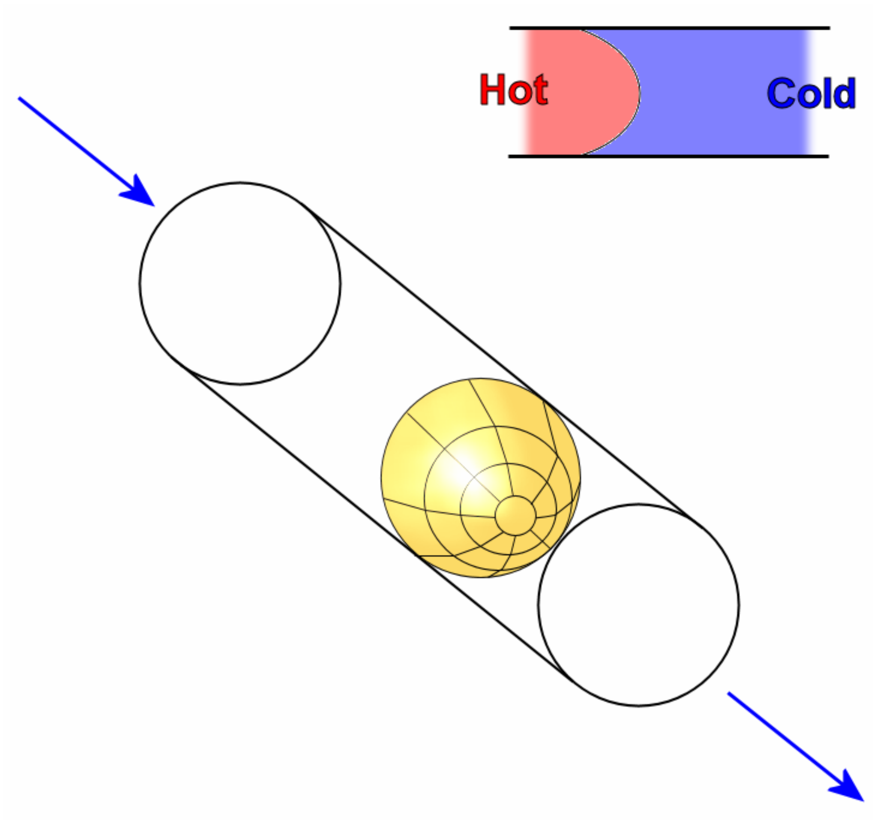
Different Flow Speed

In a tube the flow speed **varies across the diameter**.

In the center the flow speed is always highest (e.g. **Hagen-Poisseuille** for laminar flows)

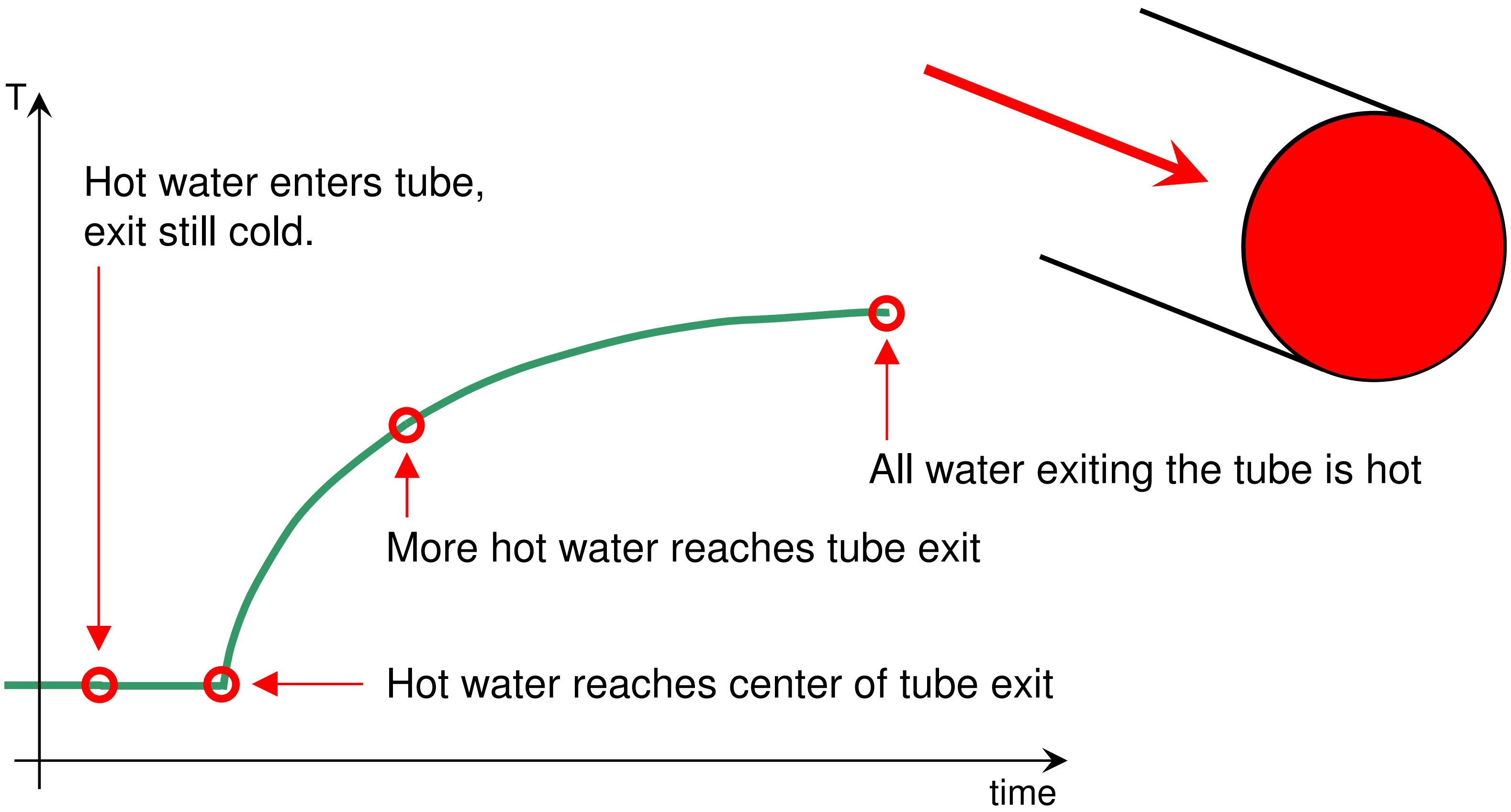
A **heat step** will reach the end of a tube **in the center** first.



The speed profile depends on the **Reynolds number**.

Exit Temperature

We now look at the **average exit temperature** of a tube:



KULI Component Data

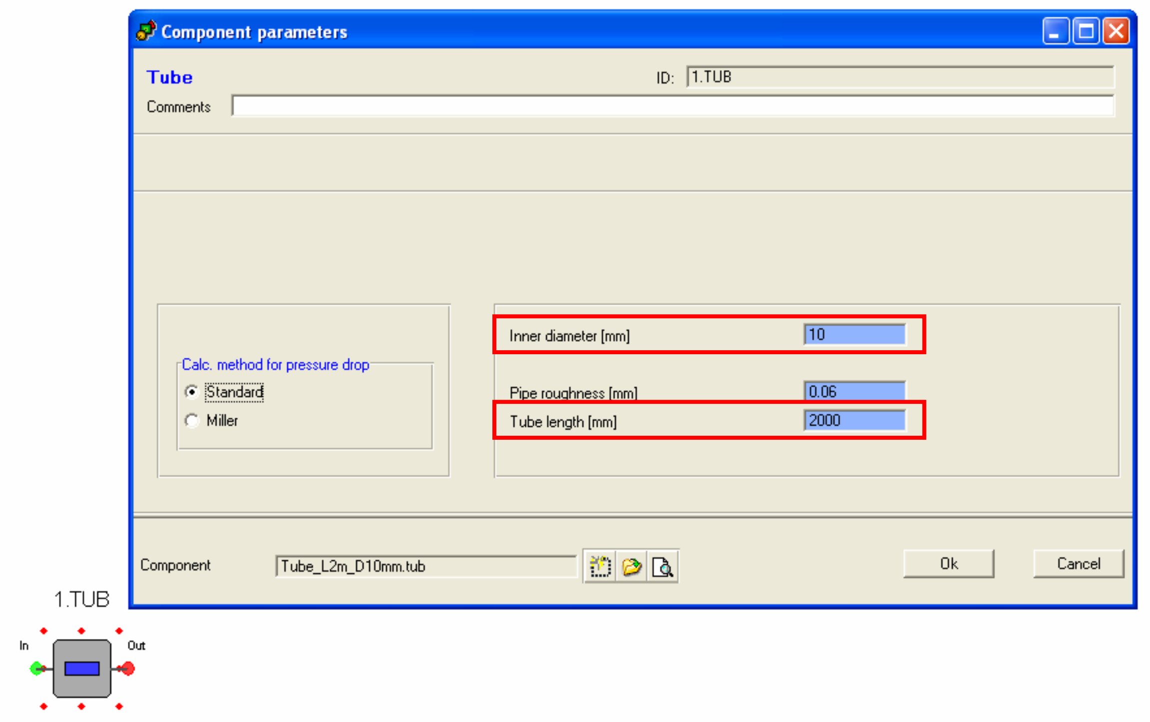
To calculate this effect in KULI, no additional measurement data is required.

Inner diameter

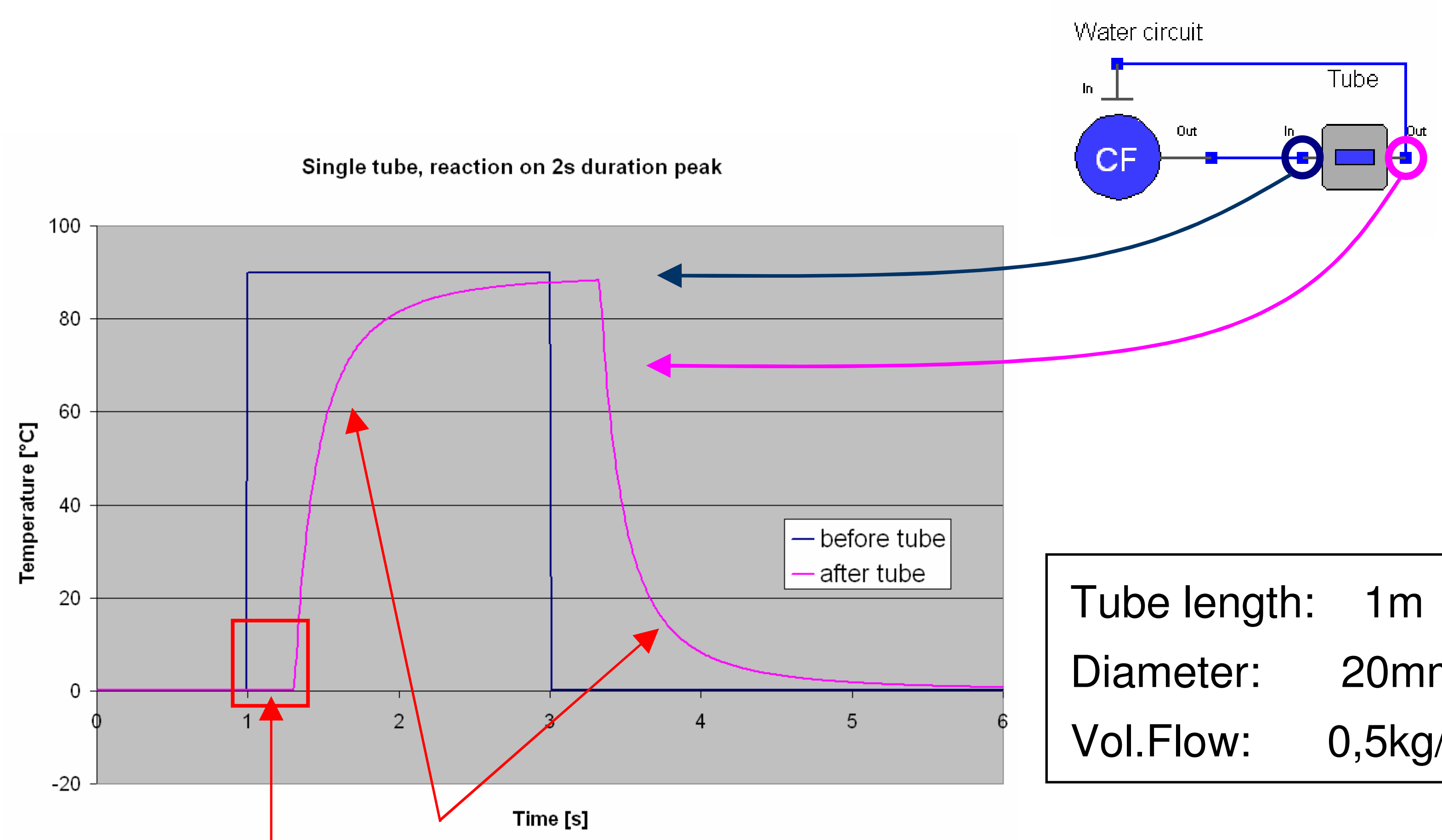
and

tube length

are already available!



Transient delay and diffusion of a single tube



Tube length: 1m

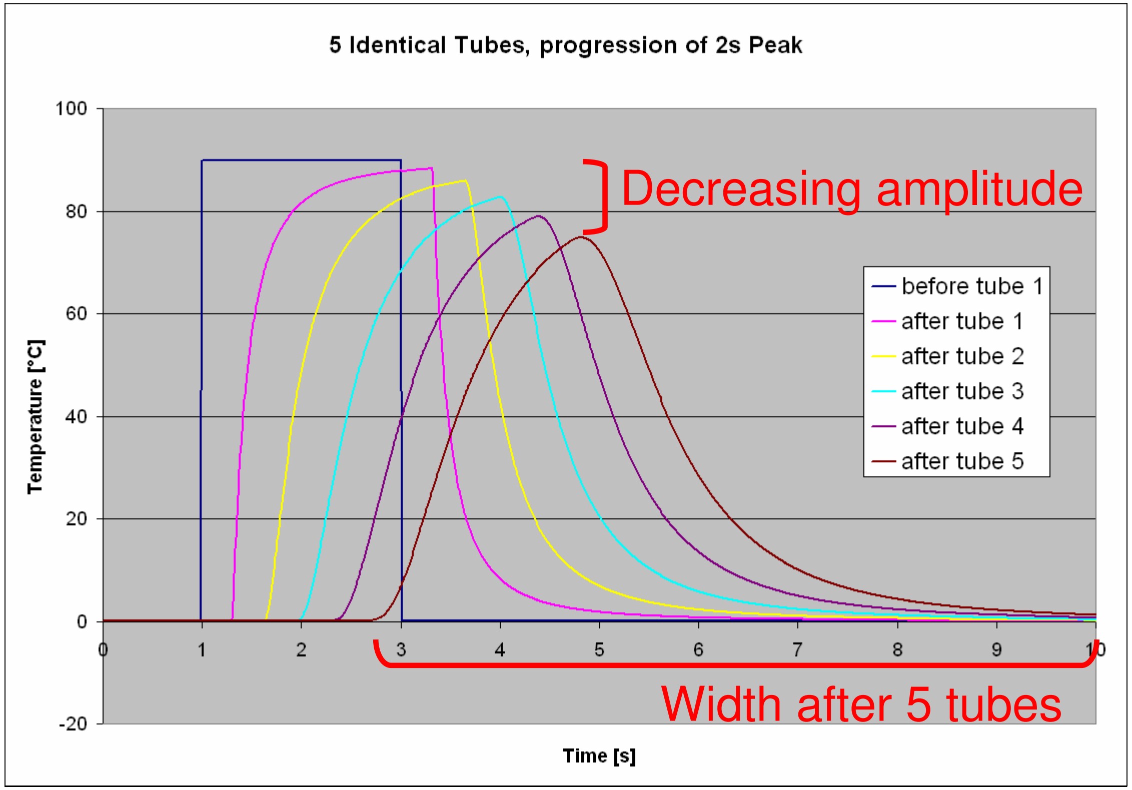
Diameter: 20mm

Vol.Flow: 0,5kg/s

Diffusion effects

Initial delay

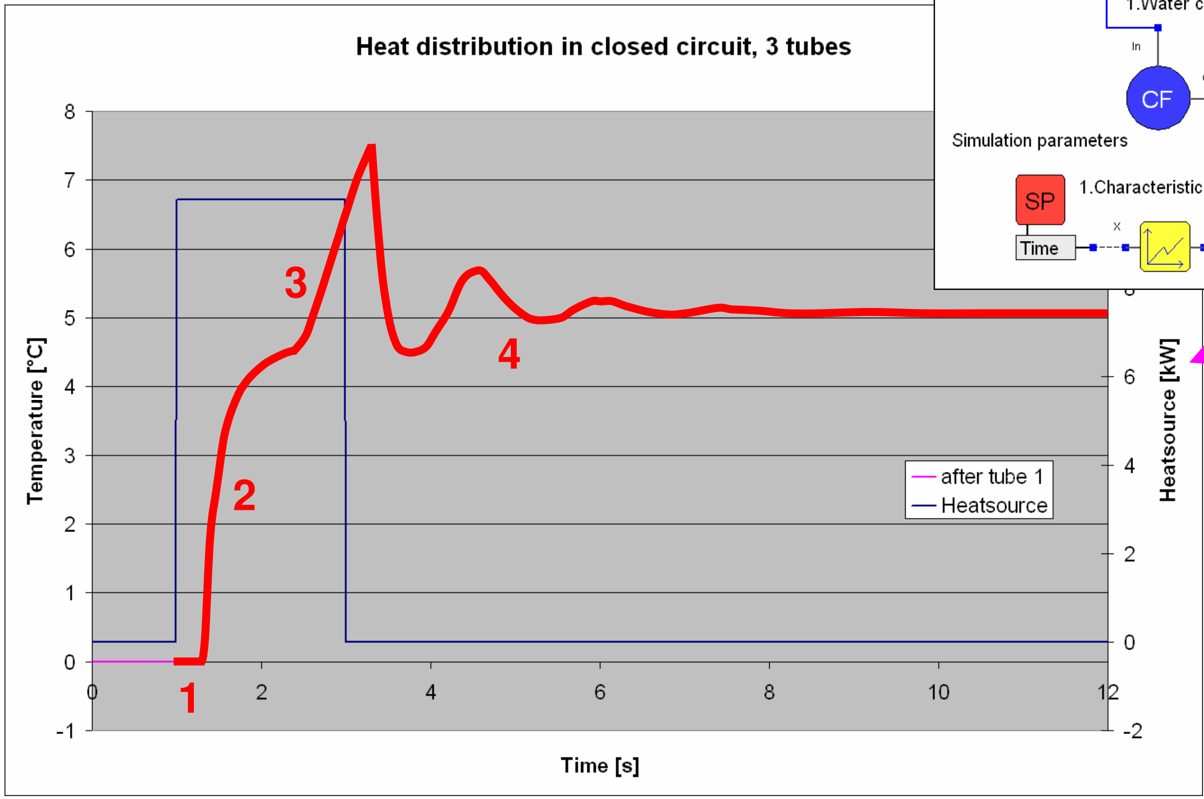
Delay and diffusion, 5 consecutive tubes

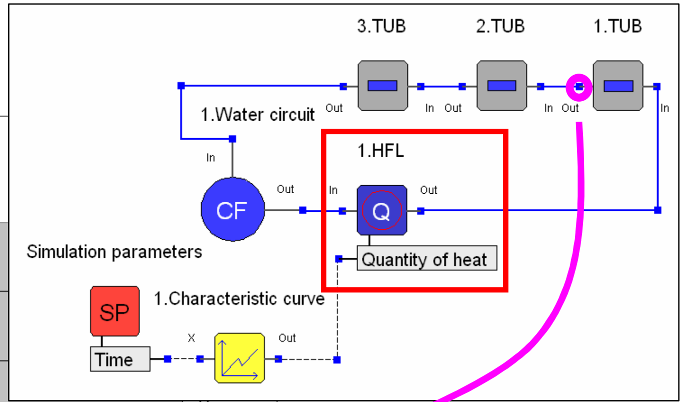


Same situation as before, this time 5 consecutive tubes.

Closed Circuit

Heat source is switched on for 2 seconds.





1) Delay
2) Warm-up
3) Warm-up with recirculated hot water
4) Diffusion, no heat source

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Remarks

- Different **flow speeds** – different **speed profiles**
- **No 3D modeling**, KULI is and remains a **1D tool**
- **Thermal capacity of media in tubes** is considered
- Thermal capacity and **heat conduction to tube walls** modeled by **point masses**.
- This approach also improves handling of **zero mass flow** operating points

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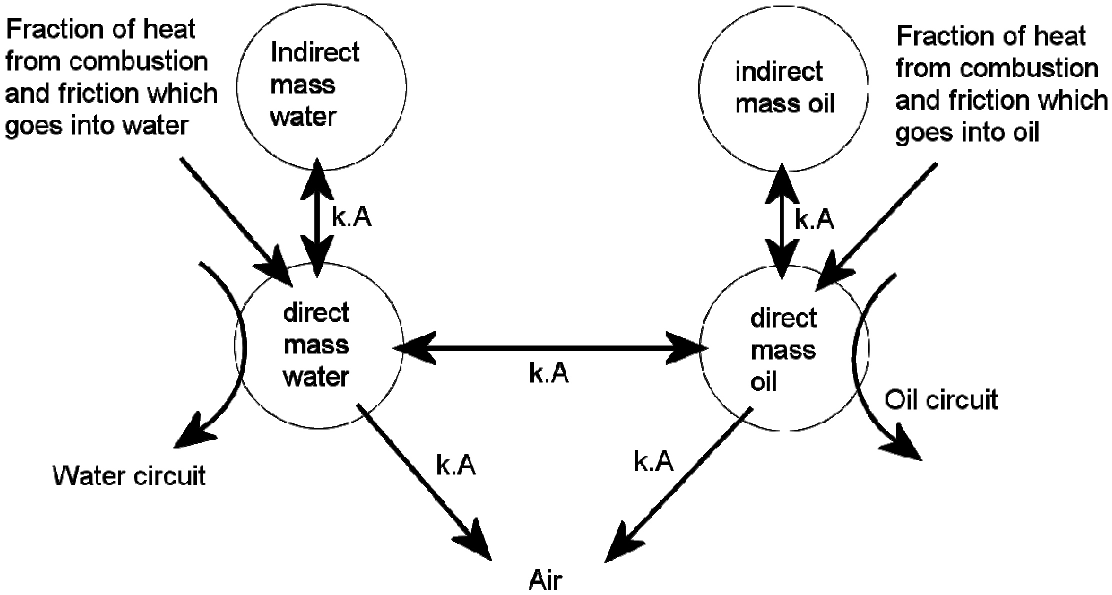
The 4-mass model



The model consists of four masses.

Oil- and water side are separated.

The masses are connected by heat conduction

The direct masses are heated by com-bustion and friction.

This is the simplest possible model to fulfill the main demands for cooling system simulation.

Heat dissipates to water, oil and air.

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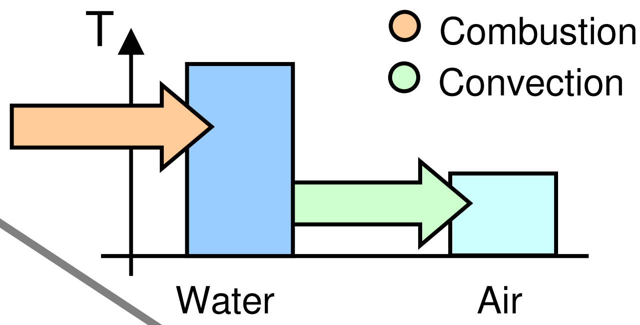
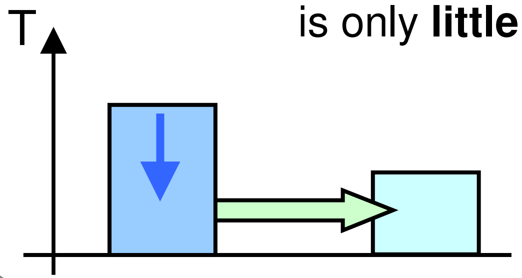
Hot-soaking and 4-mass models

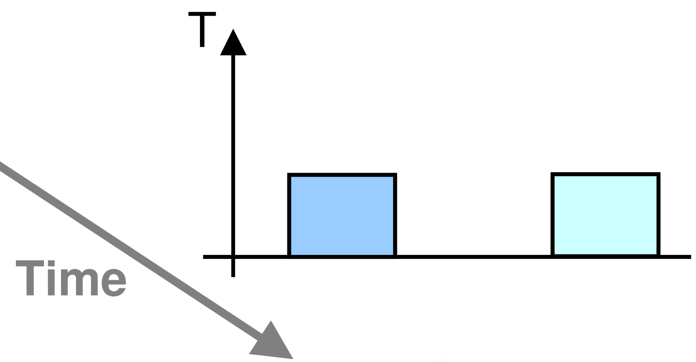


1) In **stationary operation** the **engine heat** is dissipated to the air by convection.



2) Now the **car stops**. The engine produces **no more heat** and there is only **little convection**.

3) The water temperature decreases slowly, it **cannot increase**, once the engine has stopped.



For 4-mass models no hot-soaking can be observed!

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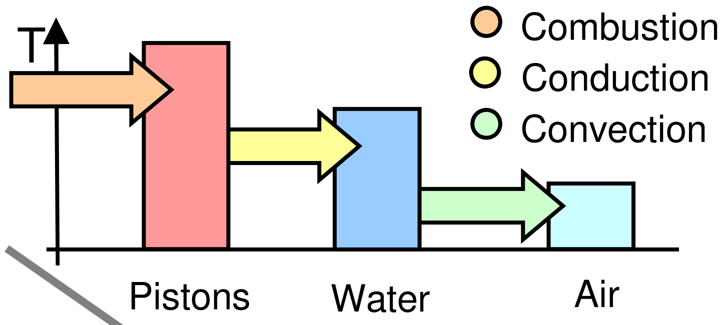
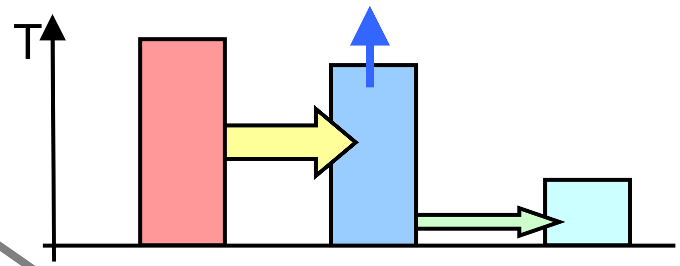
Hot-soaking and 5-mass models

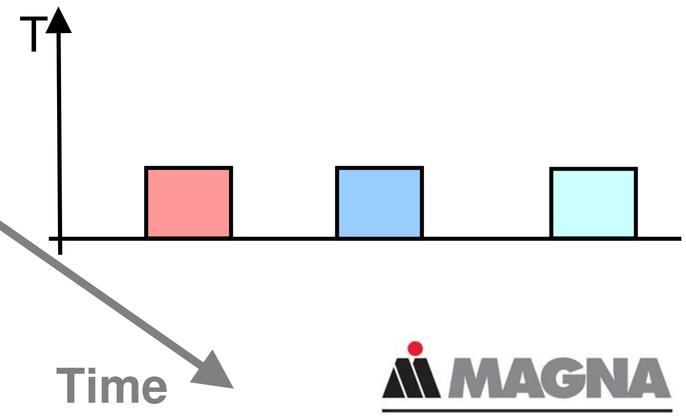


1) Now the combustion heat goes **to the pistons**, from there to the water and finally to the air.



2) The engine stops, but the **pistons are still hot**. The water is still heated by the pistons, but convec-tion is close to zero.

3) The water temperature **increases**, before both water and pistons eventually assume the air temperature.



This model can simulate hot-soaking!

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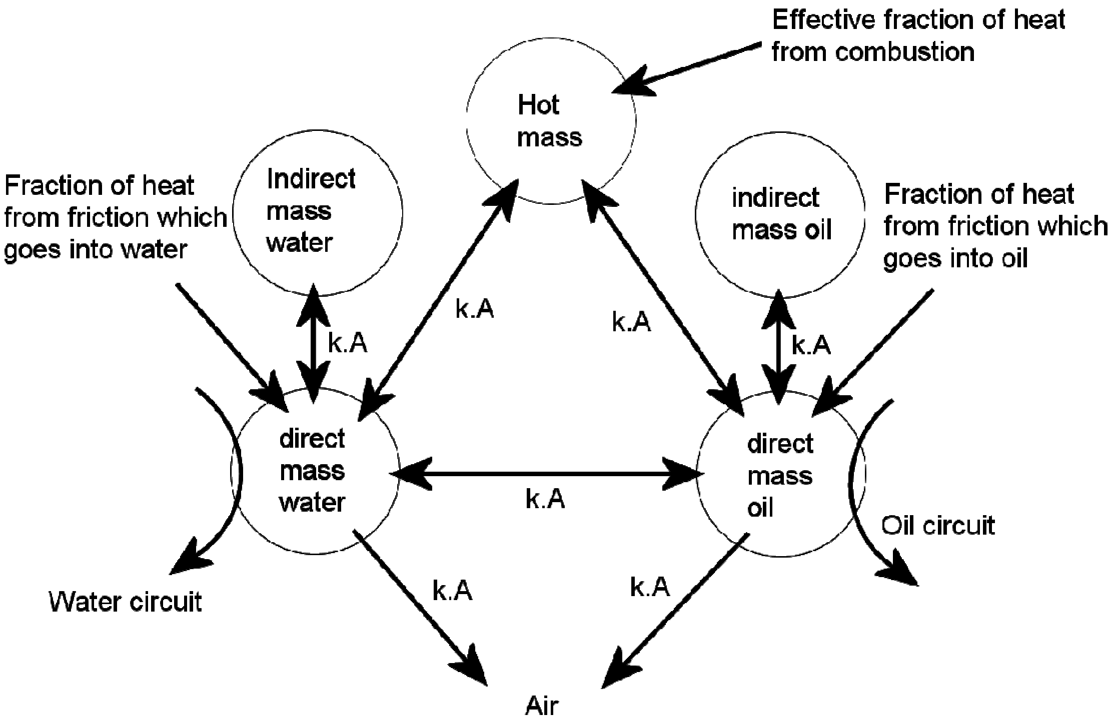
The 5-mass model



The different heat distribution offers the additional possibility to simulate hot-soaking effects.

This model again is based on the four mass model.

The hot pistons are included as an additional mass.

The combustion heat now goes to the piston mass.

This makes the pistons to the hottest parts of the 5-mass model.

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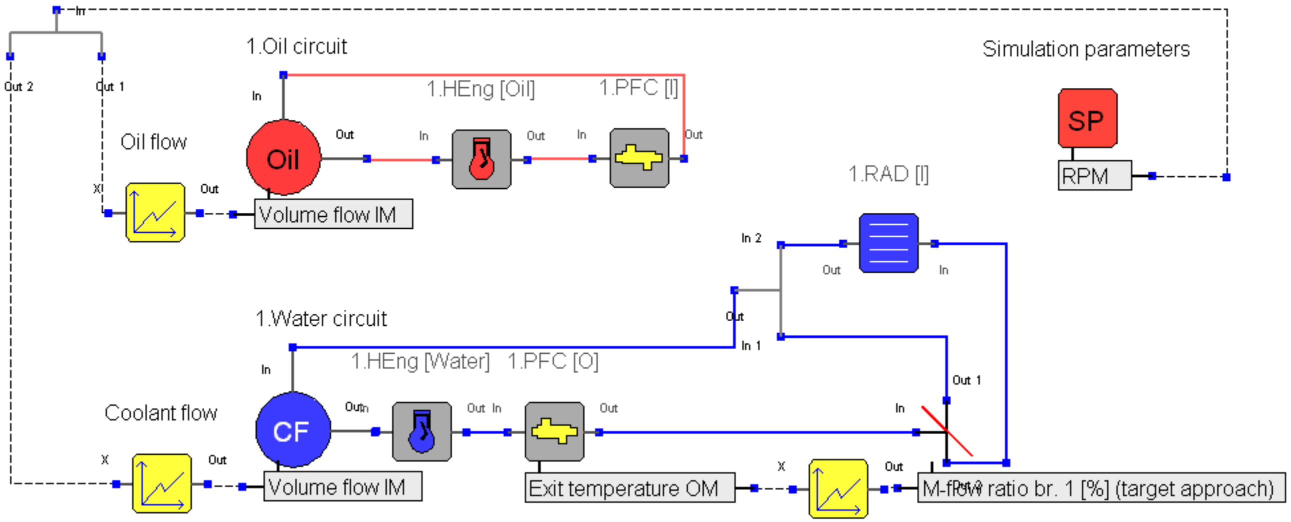
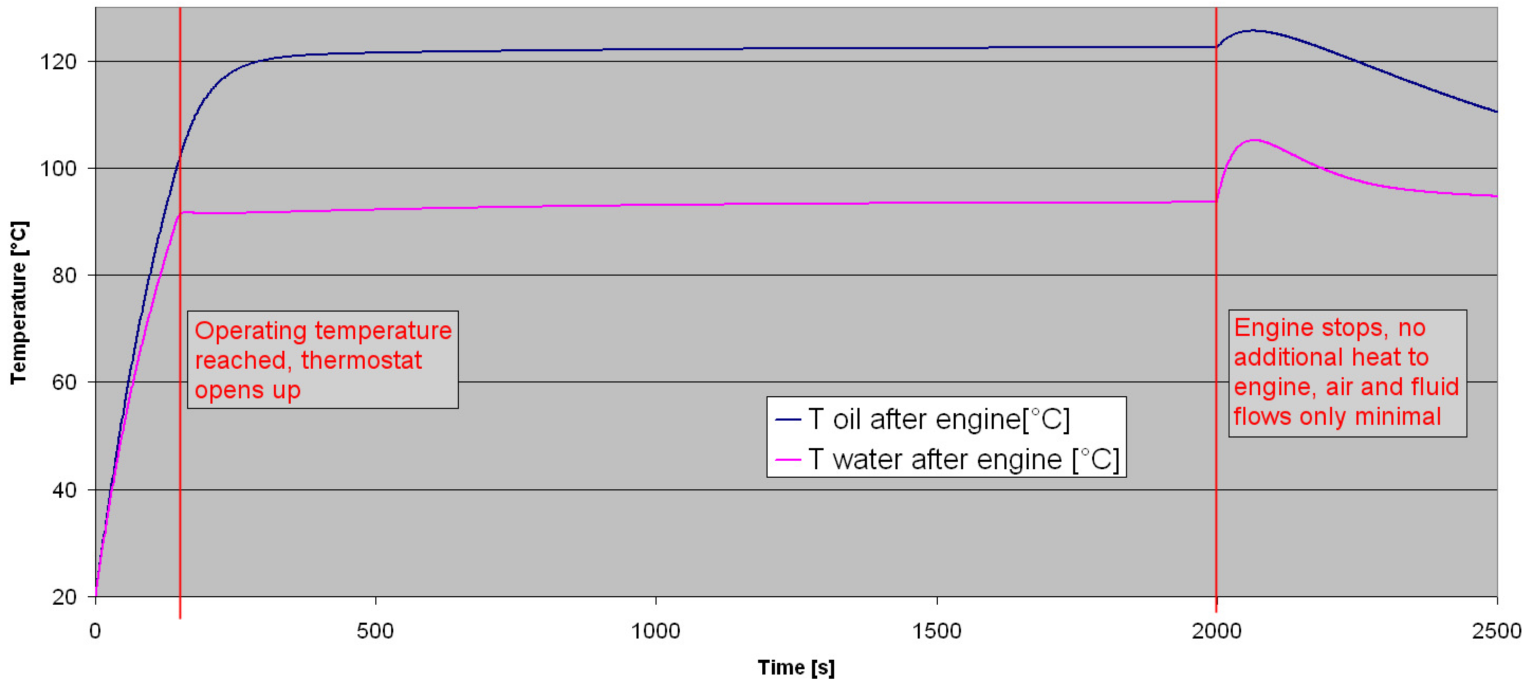
Hot soaking simulation in KULI

We use a **5-mass model** for a truck engine and a simplified cooling system model to first **heat up the engine** at a high operating point and then **stop abruptly**.



Transient simulation

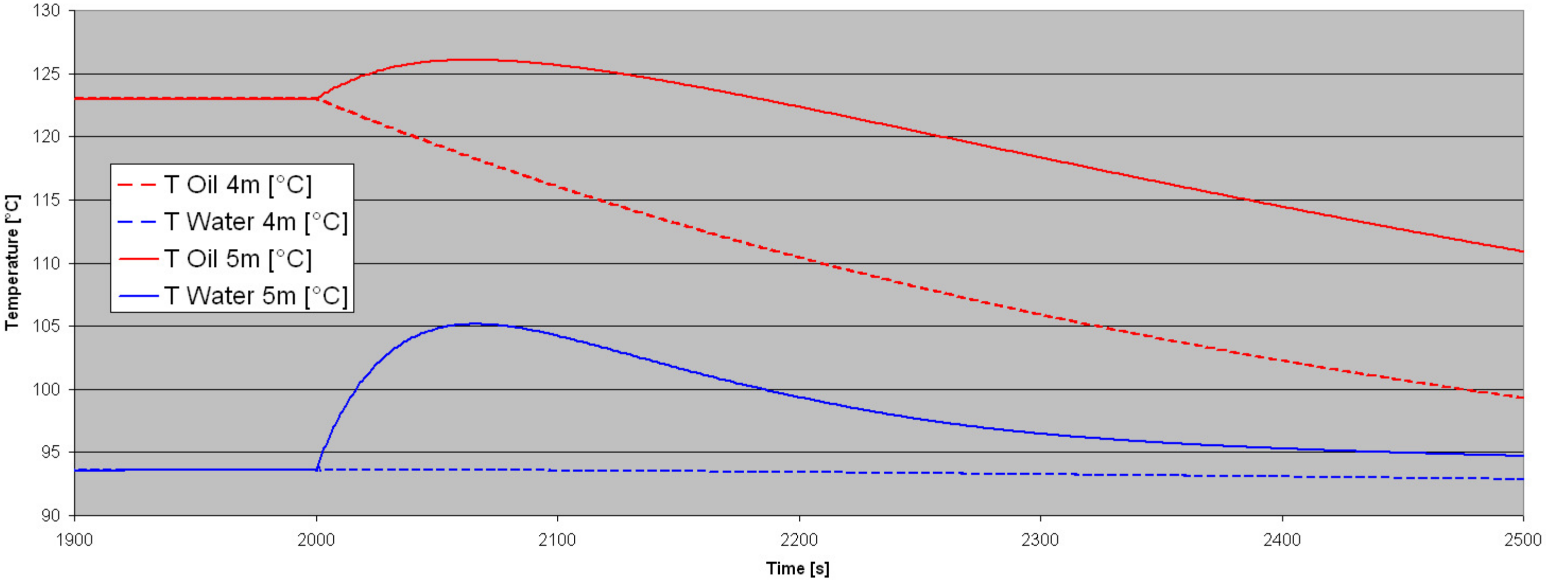
After high load stationary operation the vehicle stops…



… the Cooling air flow stops, but the engine is still heating up the water and oil circuits.

Comparison of 4- and 5-mass engine models

For **4-mass** engine models **no hot soaking** can be simulated.



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Conclusions

Simulation of **complex transient effects** requires relatively high

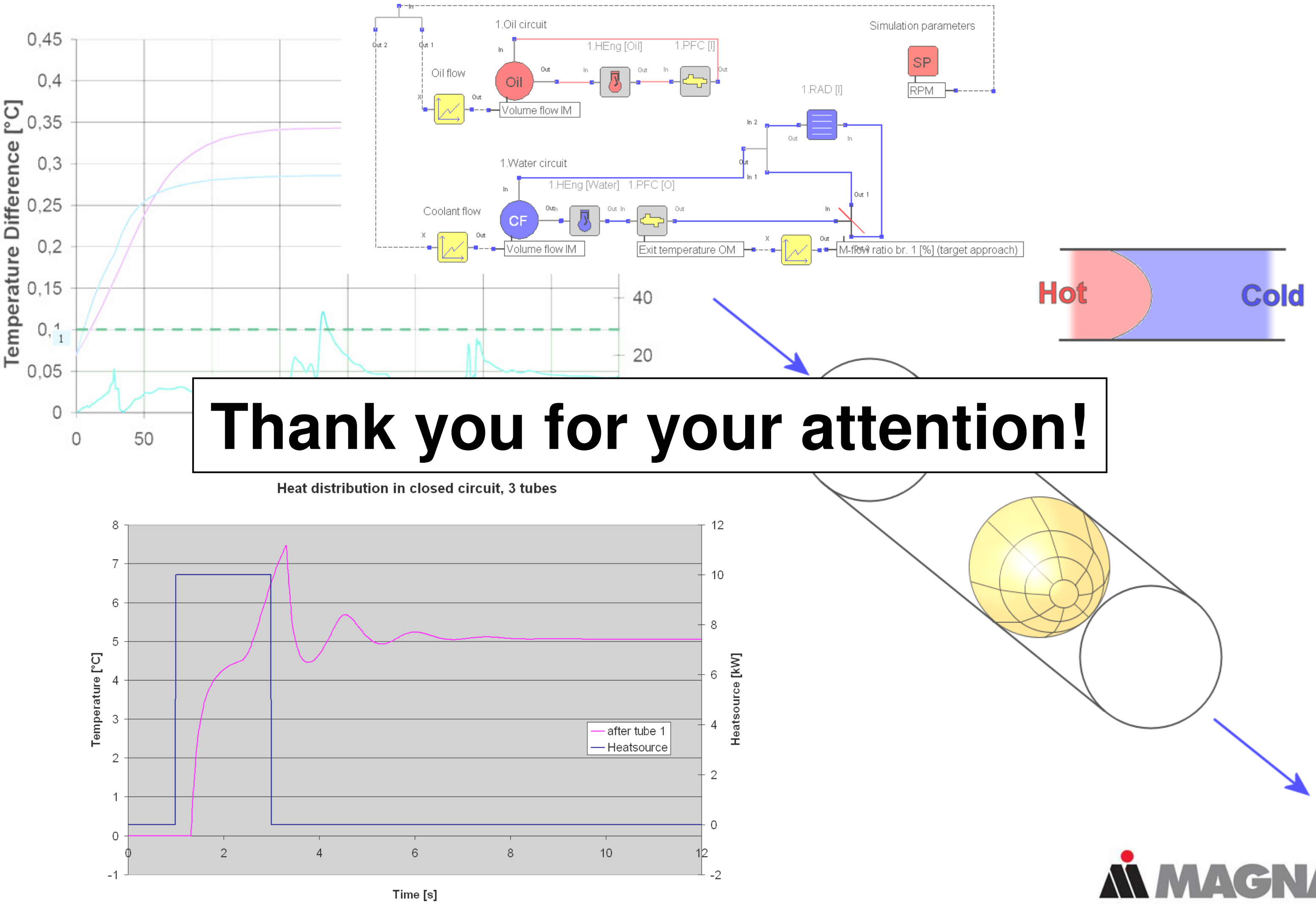
temporal resolution (transient solver) and

geometrical resolution (tube, engine-model).

Time steps should be kept short **only where necessary**.
Adaptive time discretization.

3D discretization has to be **avoided** (calculation time!).
Good **approximations** and **closed mathematical formulations** should be used whenever possible!

Discussion…



Thank you for your attention!