Robust and Computationally Efficient Dynamic Simulation of ORC Systems: The ThermoCycle Modelica Library

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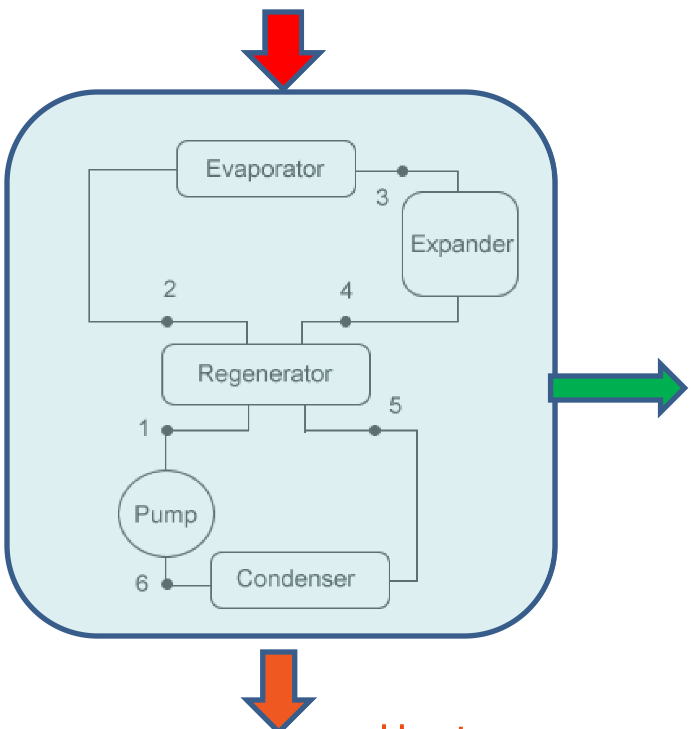
October 7th 2013

2nd International Seminar on ORC Power Systems, Rotterdam,

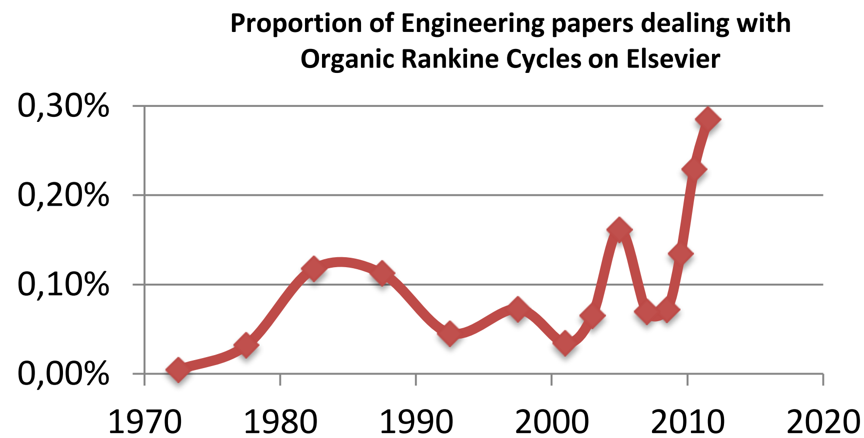
Introduction

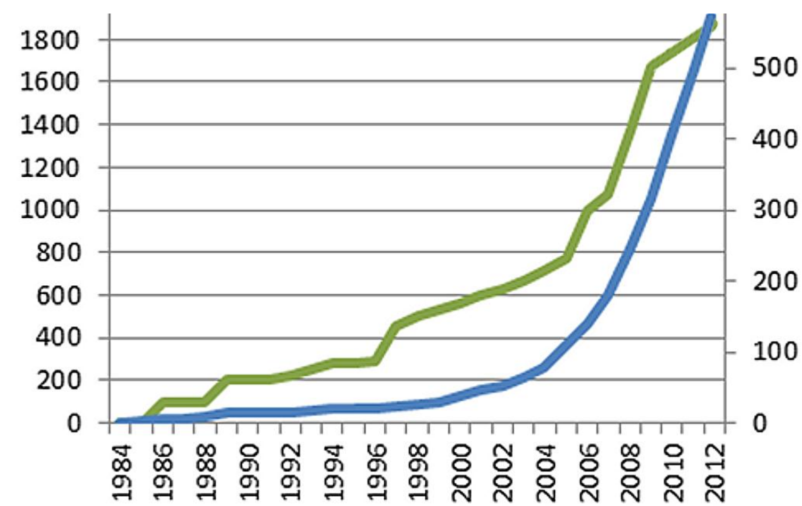
Waste heat recovery or renewable energies: solar, biomass, geothermal



Electricity/ mechanical power

Heat

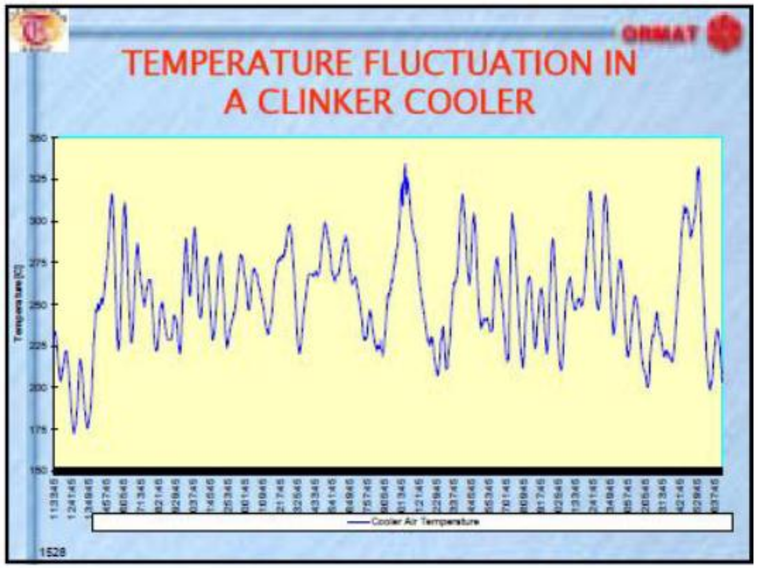




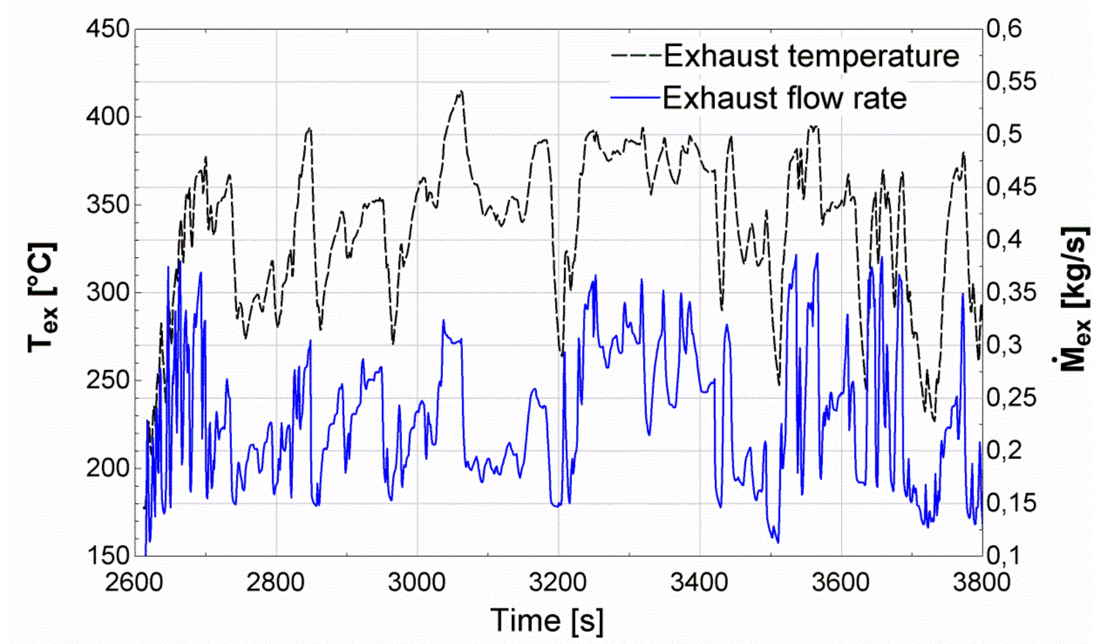
Why dynamic modeling?

Control aspects

⇨ **Time-varying boundary conditions require optimal control strategies**



Exhaust gases from vehicles:



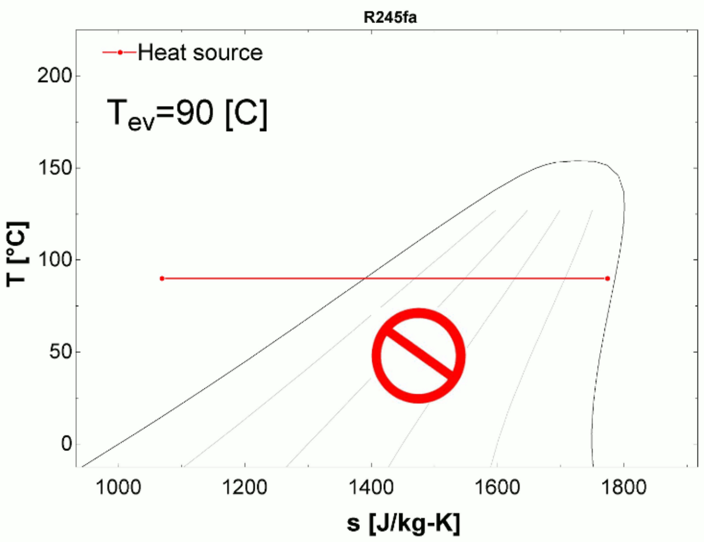
Why dynamic modeling?

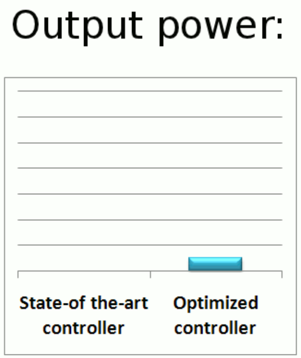
Control aspects

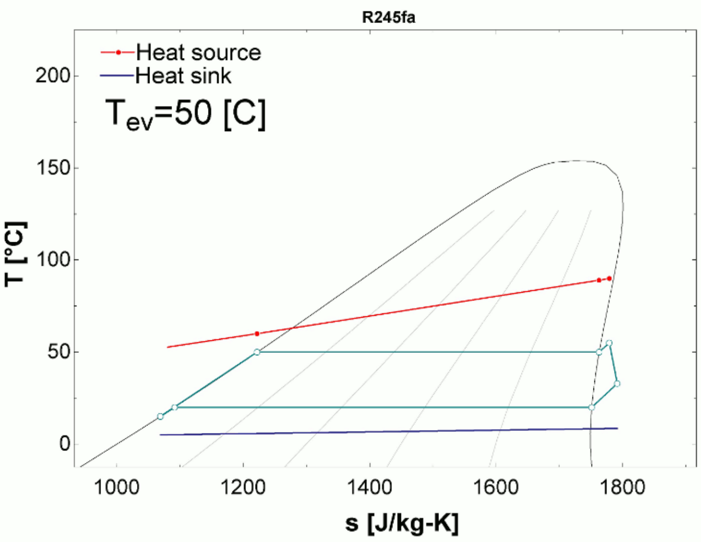
⇨ **Time-varying boundary conditions require optimized control strategies**

Traditional Control:

Optimized control



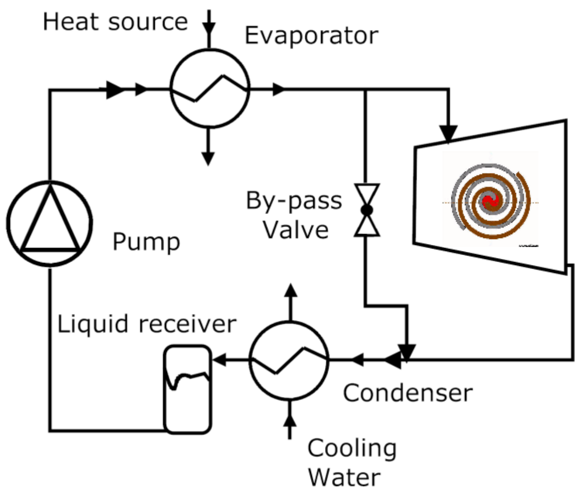




Why dynamic modeling?

Control aspects

- **Start, stop or emergency procedures should be modeled and optimized!**
- **Performance monitoring**



Micro-CHP units can undergo several ON/OFF cycles per day

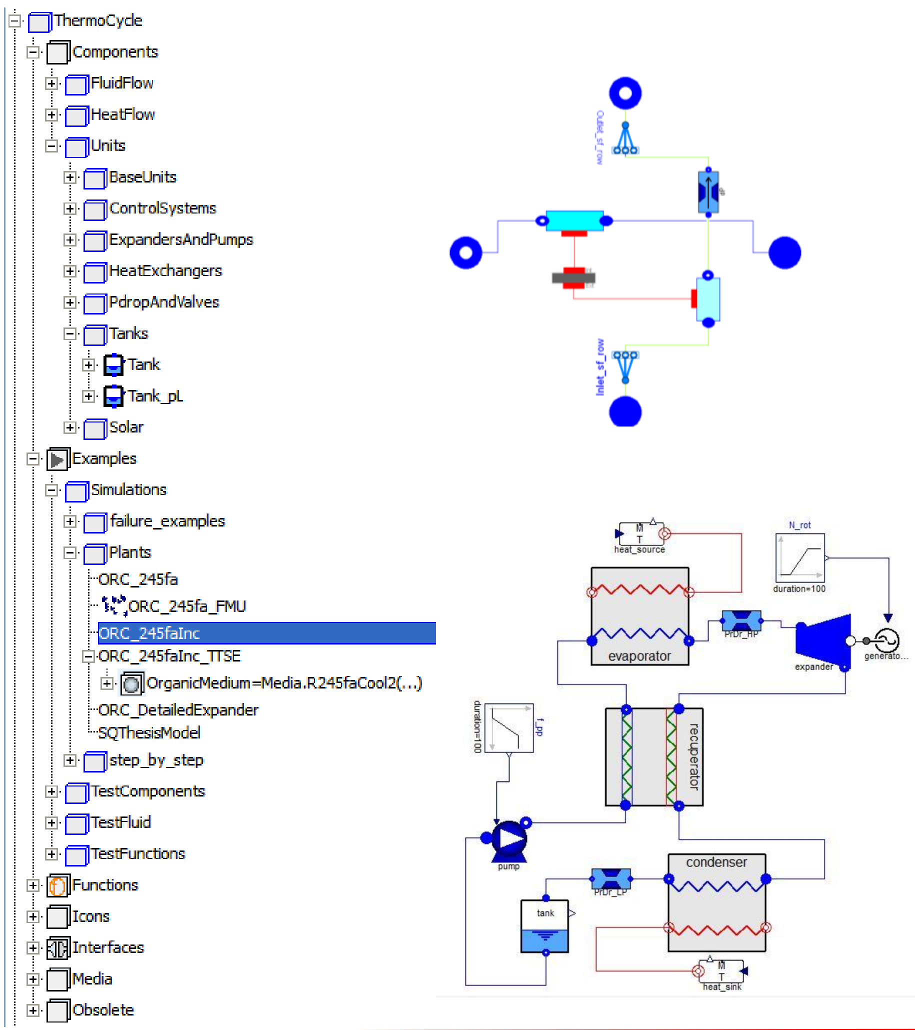
Typical questions:

- ✓ Control sequence to connect the generator to the grid?
- ✓ Overpressure in case of emergency opening of the by-pass valve?

Challenges of dynamic modeling for ORC systems

1. Thermodynamic properties of working fluids
2. Computational efficiency (speed)
3. Robustness
   – Initialization
   – Integration

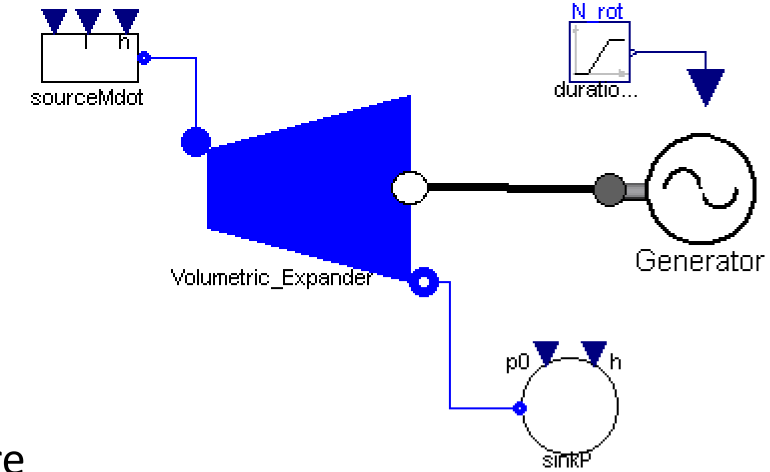
The ThermoCycle Library



- ✓ Modelica: Open-source language for the modeling of complex multiphysics systems.
- ✓ Acausal language
- ✓ ThermoCycle => Open-source Library for the modeling of thermal systems
- ✓ Cross-Platform
- ✓ Special focus on thermodynamic cycles
- ✓ Computational efficiency and robustness are key aspects of the library

Causal/acausal modeling

Example: Expander model



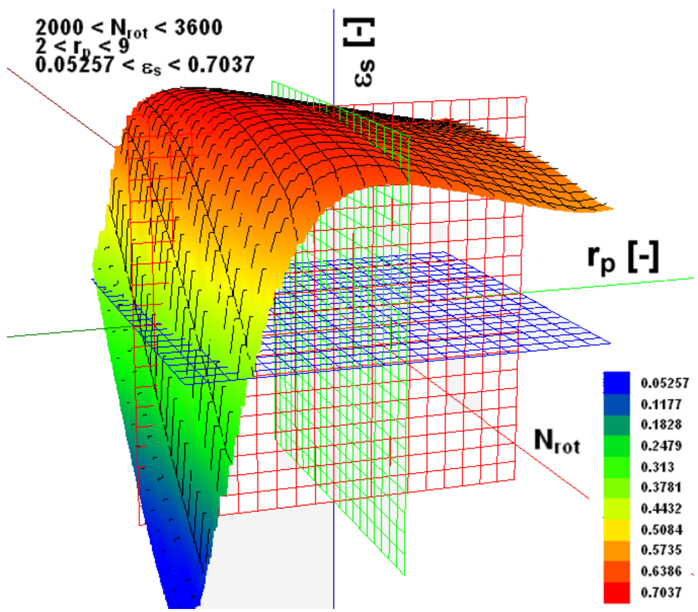
Inputs		**Outputs**
Mass flow rate Rotating speed Outlet pressure Inlet temperature	→	Inlet pressure Torque Outlet temperature
Inlet pressure Torque Outlet pressure Inlet temperature	→	Mass flow rate Rotating speed Outlet temperature

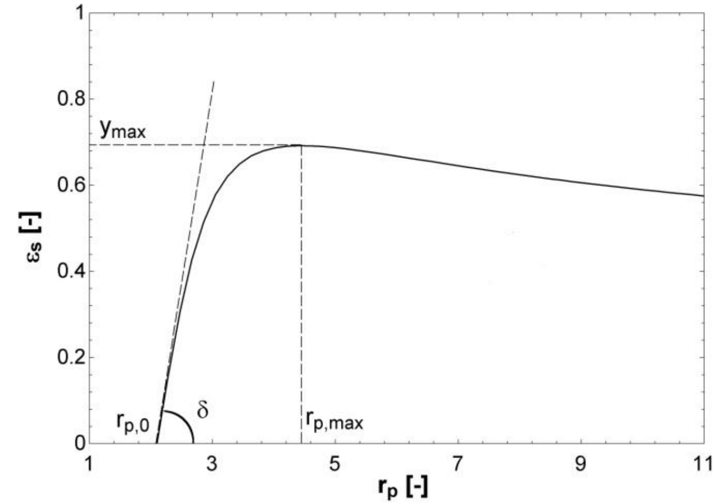
Available Models:

Expanders and pumps

- ✓ Dynamics of the heat exchangers larger than that of the expansion machine
  - ➢ not necessary to use a detailed simulation model
  - ➢ an empirical model is sufficient

$$\varepsilon_s = y_{max} \cdot \left(\xi \cdot \text{artan}\left(B \cdot (r_p - r_{p,0}) - E \cdot \left(B \cdot (r_p - r_{p,0}) - \arctan\left(B \cdot (r_p - r_{p,0}) \right) \right) \right) \right)$$

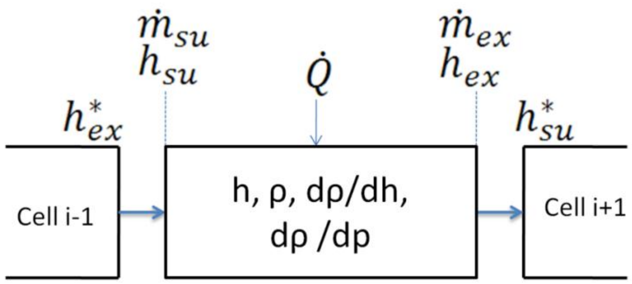




Parameters identified based on experimental data

Available Models:

Finite volumes models



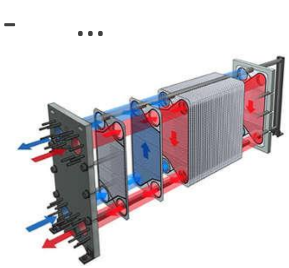
Cell model: Conservation of mass and energy:

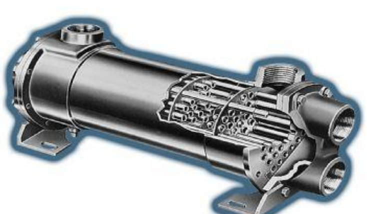
$$\dot{M}_{ex} - \dot{M}_{su} = V \cdot \frac{d\rho}{dt} = V \cdot \left(\frac{\partial \rho}{\partial h} \cdot \frac{dh}{dt} + \frac{\partial \rho}{\partial p} \cdot \frac{dp}{dt} \right)$$

$$V \cdot \rho \cdot \frac{dh}{dt} = \dot{M}_{su} \cdot (h_{su} - h) - \dot{M}_{ex} \cdot (h_{ex} - h) + \dot{Q} + V \cdot \frac{dp}{dt}$$

Counter flow heat exchangers

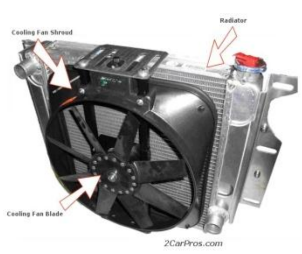
- Evaporator
- Recuperator
- Peheater
- …





Cross-flow heat exchangers

- Air condenser
- Radiator (vehicles)
- …

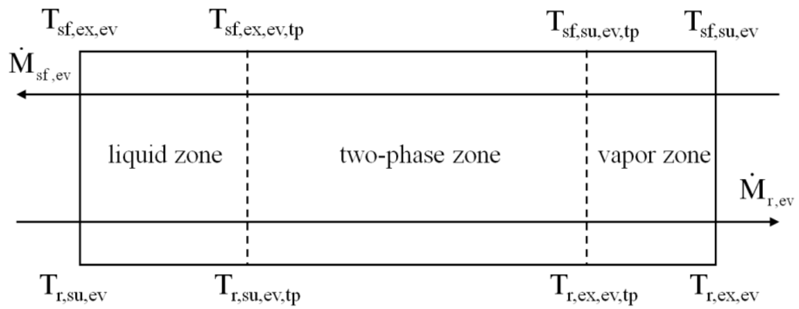


Available Models:

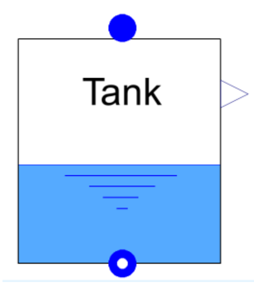
Miscellaneous

Solar collector models

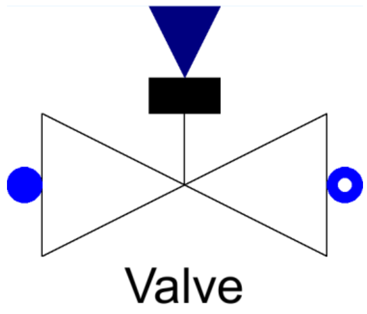
Moving boundaries heat exchanger model



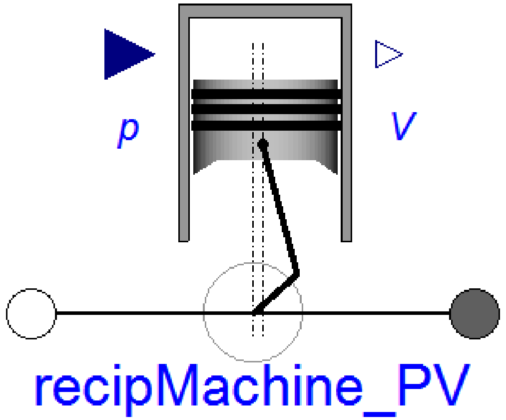
Tanks and liquid receiver



Valves and Pressure drops



Reciprocating expander



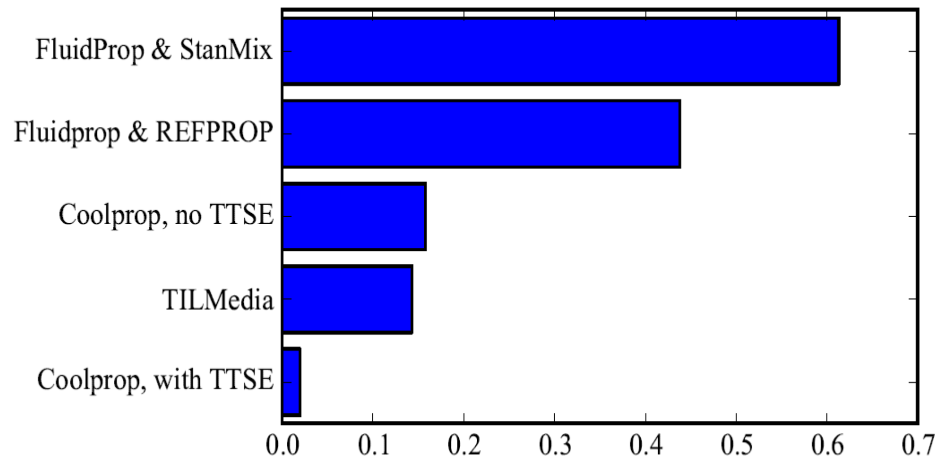
Thermodynamic properties model: *The CoolProp Library*

- Peculiarity of ORC/refrigeration cycles: require external thermophysical libraries to computes the properties.
- Available in Modelica:
  - TILMedia + Refprop
  - ExternalMedia + FluidProp
  - CoolProp2Modelica + CoolProp
- CoolProp is the only fully open-source solution
- 110 fluids and pseudo-pure fluids
- Transport properties
- Incompressible fluids and brines
- Mixtures: work in progress

Numerical Methods

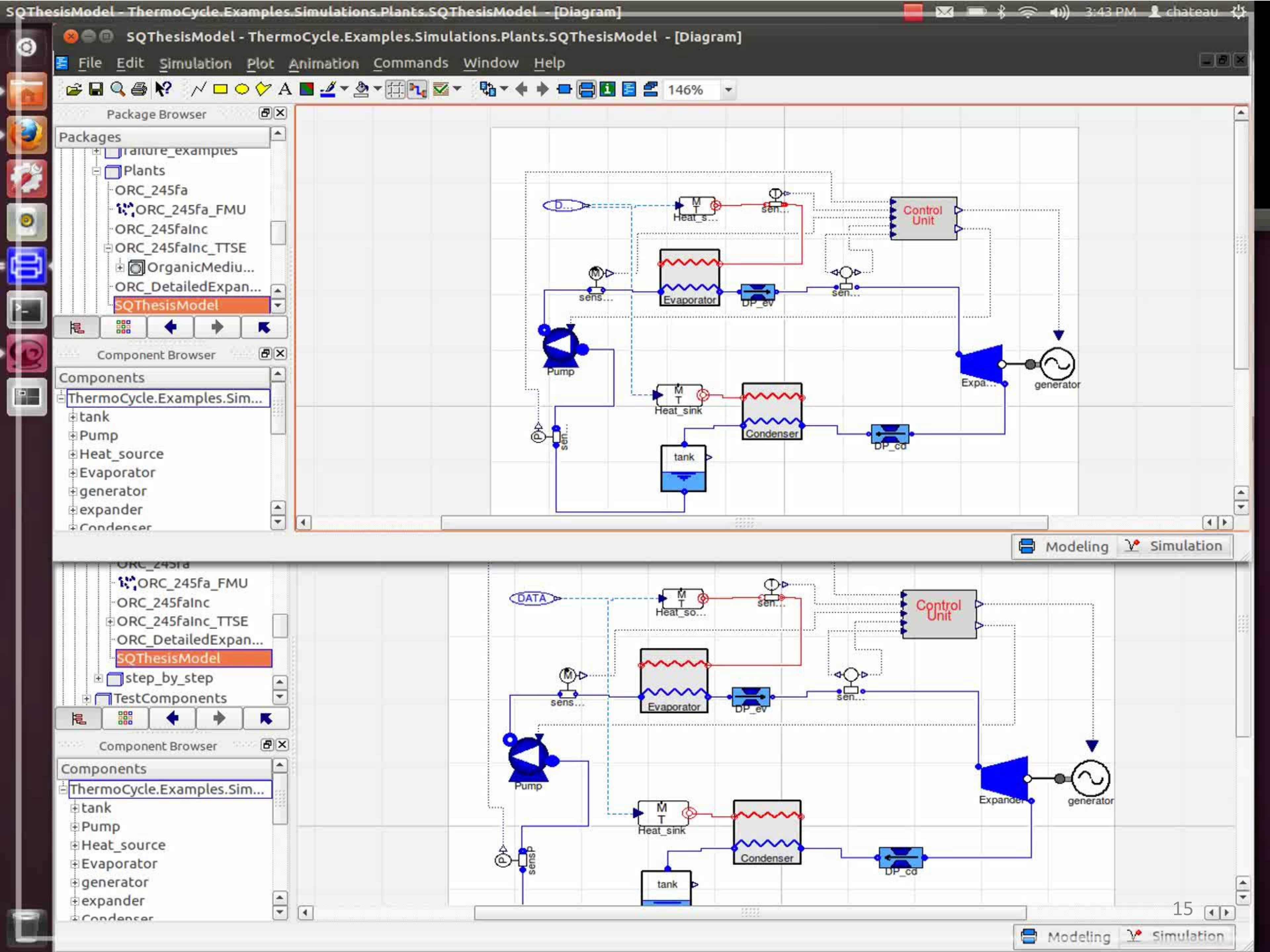
Computational efficiency:
Interpolation methods

- Either TTSE or bicubic
- Process:
  1. Build table (at the first property call)
  2. Cache table
  3. Re-use table for the following property calls



Elapsed time per property call from Modelica

```
package R245faCool2
  extends CoolProp2Modelica.Interfaces.ExternalTwoPhaseMedium(
    mediumName = "R245fa",
    libraryName = "CoolProp",
    substanceNames = {"R245fa|enable_TTSE=1"});
end R245faCool2;
```


SQThesisModel - ThermoCycle.Examples.Simulations.Plants.SQThesisModel - [Diagram]
File Edit Simulation Plot Animation Commands Window Help
146%
Package Browser
Packages
Plants
ORC_245fa
ORC_245fa_FMU
ORC_245faInc
ORC_245faInc_TTSE
OrganicMediu...
ORC_DetailedExpan...
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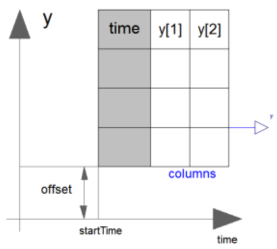
step_by_step
TestComponents
Component Browser
Components
ThermoCycle.Examples.Sim...
tank
Pump
Heat_source
Evaporator
generator
expander
Control Unit
DATA
Heat_so...
Evaporator
DP_ev
Pump
Expander
generator
Heat_sink
Condenser
DP_cd
tank
sensP
Modeling
Simulation

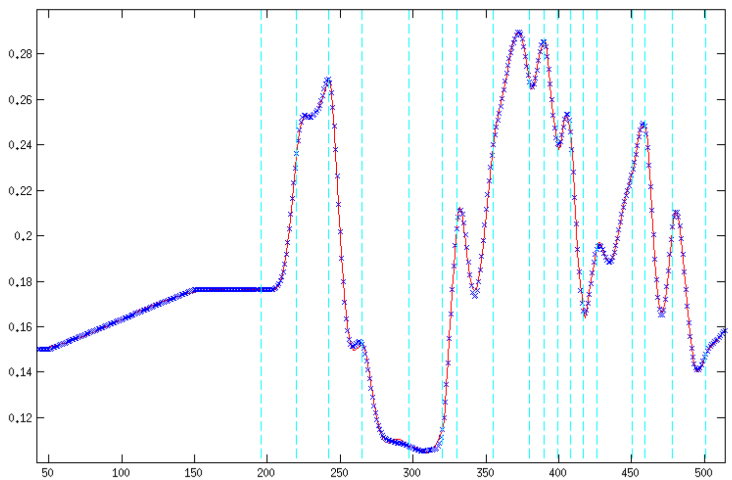
Computational efficiency:
Efficient exogenous inputs



Standard Modelica solution: *CombiTimeTable*

- Highly innefficient
- Generates events

Proposed solution: Smooth *Piecewise Polynomial Regression (SPPR):*



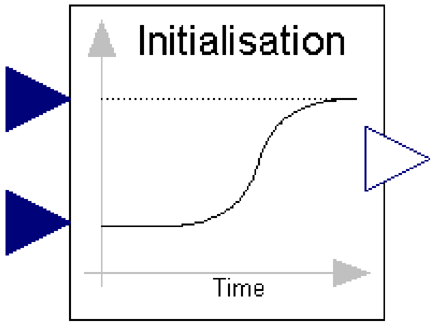

```
model SourceMdot1
Real x;

equation
   x = time;
   y =
smooth(1, noEvent(
if x < 1
 then 0.15
 elseif
        x <= 54
 then   + 0.15 + 7.4856e-18*(x-1)^1 + 3.4646e-06*(x-1)^2-2.0235e-07*(x-:
 elseif
        x <= 105
 then   + 0.15145 + 0.00031053*(x-54)^1 + 4.3129e-06*(x-54)^2-1.0944e-0'
 elseif
        x <= 154
 then   + 0.16993 + 0.00036228*(x-105)^1-3.4097e-06*(x-105)^2 + 2.1923e-
 elseif
        x <= 249
 then   + 0.18623 + 5.1754e-05*(x-154)^1-1.6837e-06*(x-154)^2 + 8.1053e-
 elseif
        x <= 294
 then   + 0.18864 + 0.00019294*(x-249)^1 + 1.2029e-05*(x-249)^2-8.1095e-
 elseif
        x <= 380
```

Robustness:
Initialization

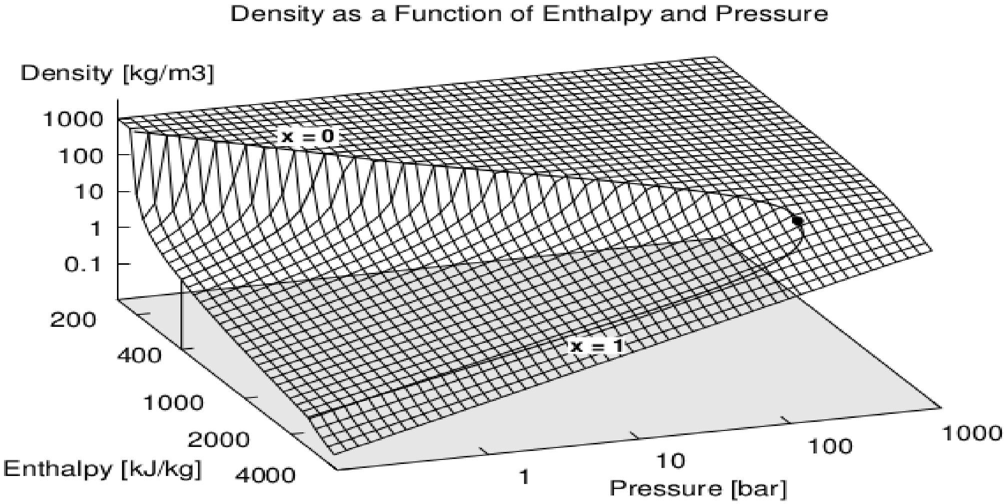
- Especially important for acausal solvers
- Newton solver can fail to converge towards an initial solution, especially in complex models
- Importance of start values
- Initiate simulation with a simplified model

$$h = \begin{cases} h_{cst} & \text{for} \quad t < t_{init} \\ h_{cst} + \frac{(h_{corr} - h_{cst})}{2} \cdot \left(1 + \sin\left(\frac{\pi \cdot t}{2 \cdot \Delta t}\right)\right) & \text{for} \quad t_{init} < t < t_{init} + \Delta t \\ h_{corr} & \text{for} \quad t > T_{init} + \Delta t \end{cases}$$



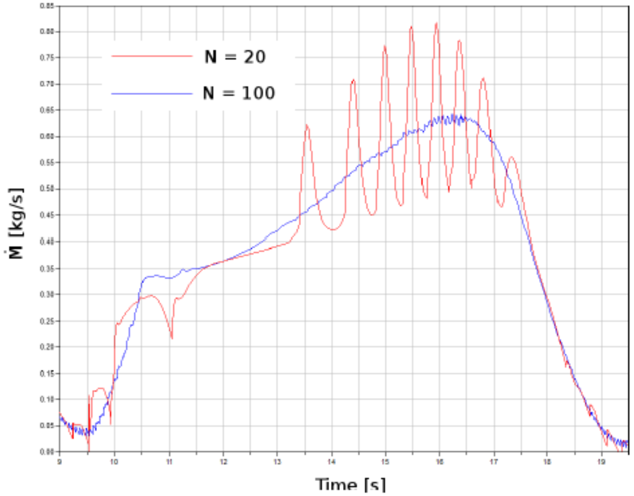
Robustness:

Chattering



Non-physical flow reversals and simulation failures can occur if:

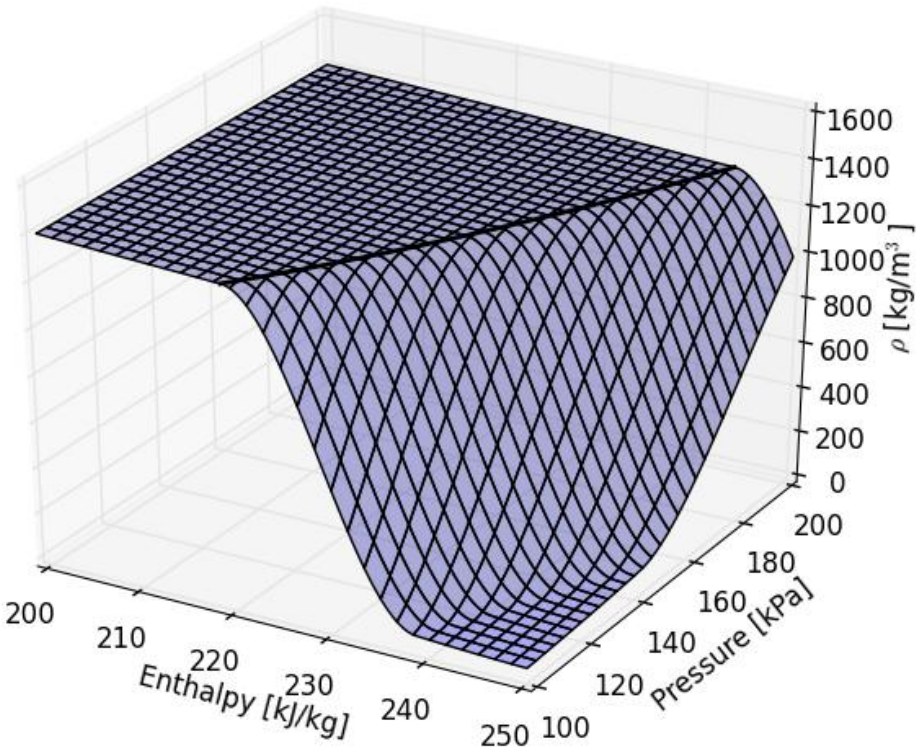
$$V_i \cdot \frac{d\rho_i}{dt} \approx \dot{M}_{su}$$



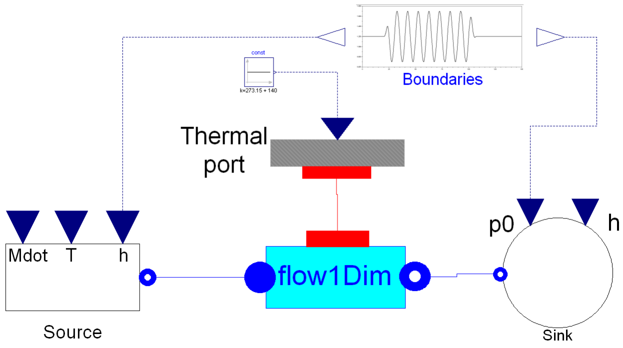
Implemented solutions:

1. Truncation of density derivative
2. Filtering of the density derivative
3. Smoothing of the density
4. Smoothing of the density derivative
5. Mean densities
6. Smooth reversal enthalpy
7. Enthalpy limiter

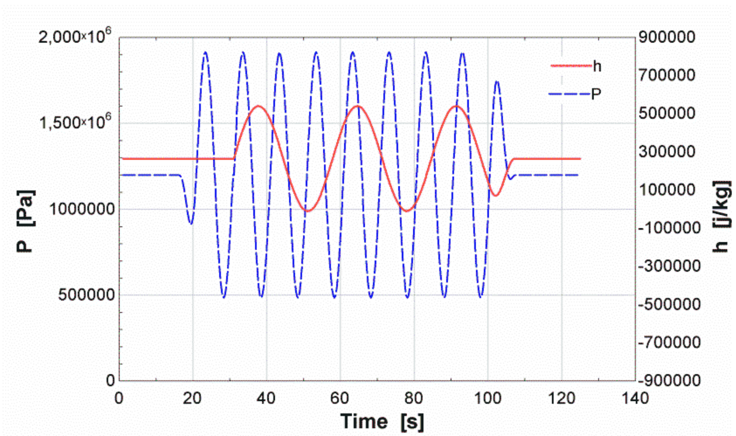
Density smoothing



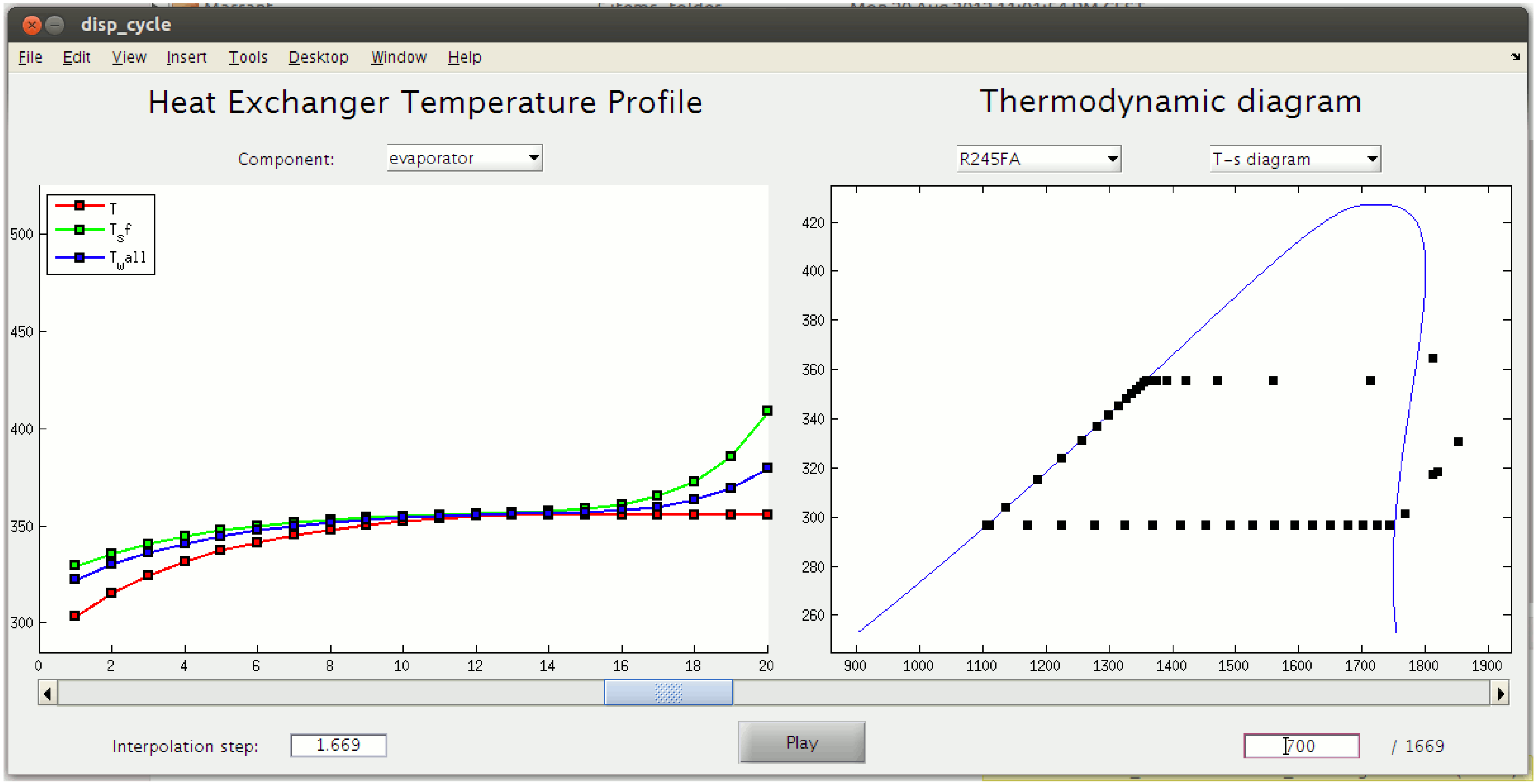
Test System:



Boundary counditions before Failure:



Simulation display



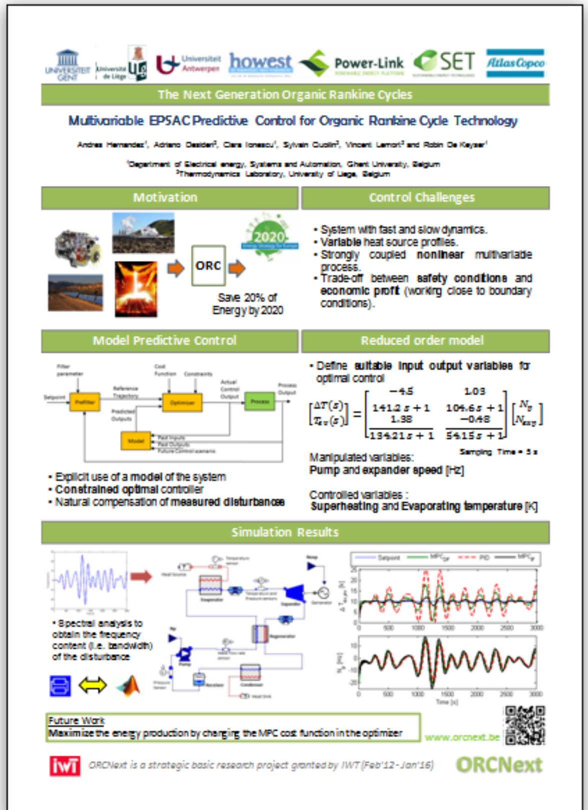
Conclusions

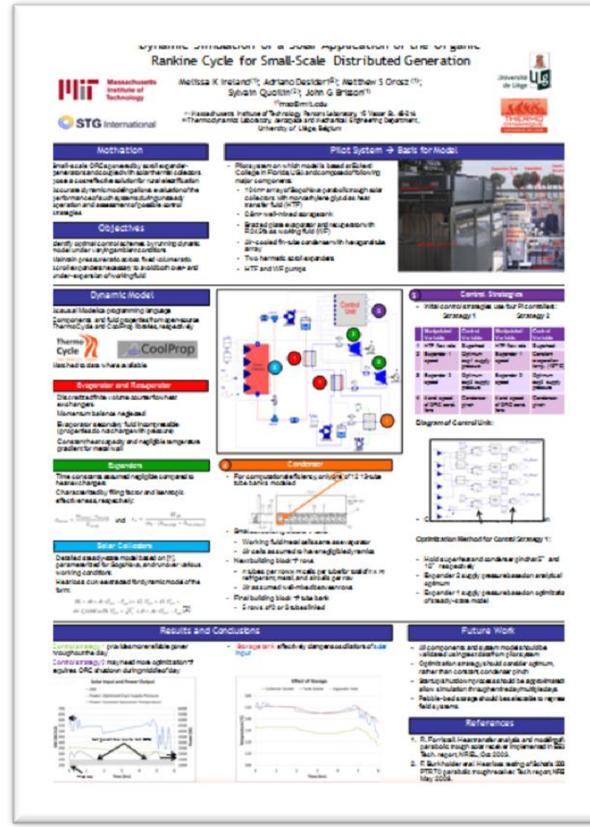
- ✓ Open-source library of dynamic models
- ✓ Open-source fluid properties library
- ✓ Open-source language
- ✓ Proprietary simulation platform

  ➡ Goal: Use of OpenModelica

- ✓ Ability to run complex ORC models, with very low CPU times and high robustness
- ✓ However, not ready for an official release yet

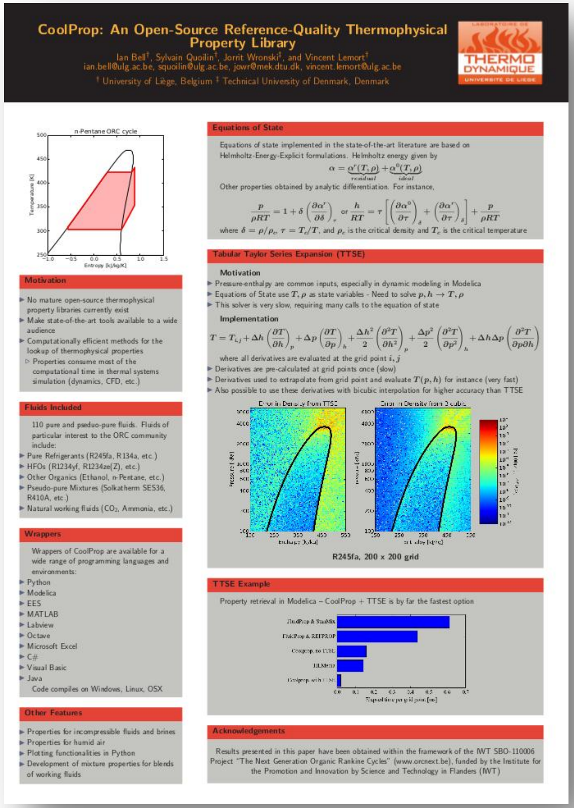
Further information





www.thermocycle.net

Further information



ORCNext

The next generation Organic Rankine Cycles

Thank you!

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