

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

S. Quoilin, A. Desideri, I. Bell, J. Wronski, V. Lemort

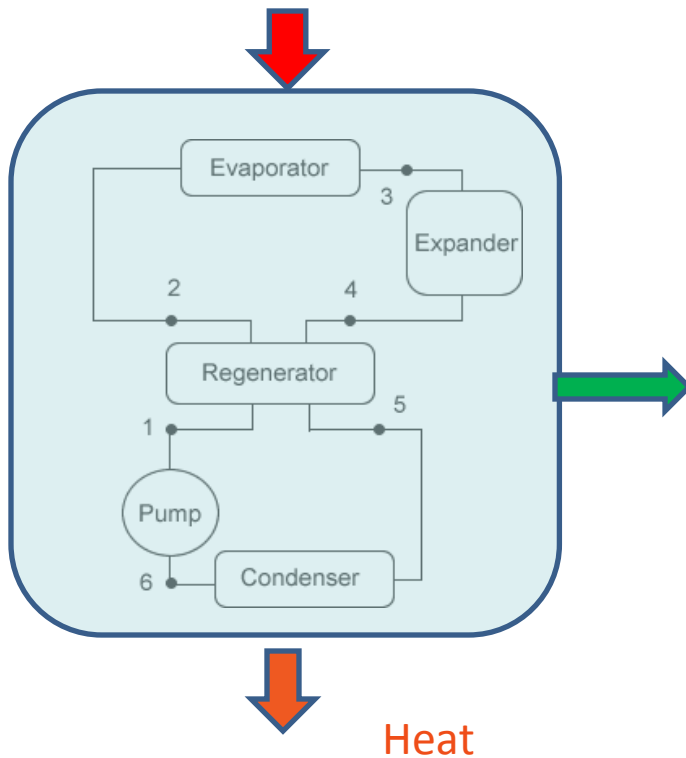
Thermodynamics Laboratory, University of Liège

October 7th 2013

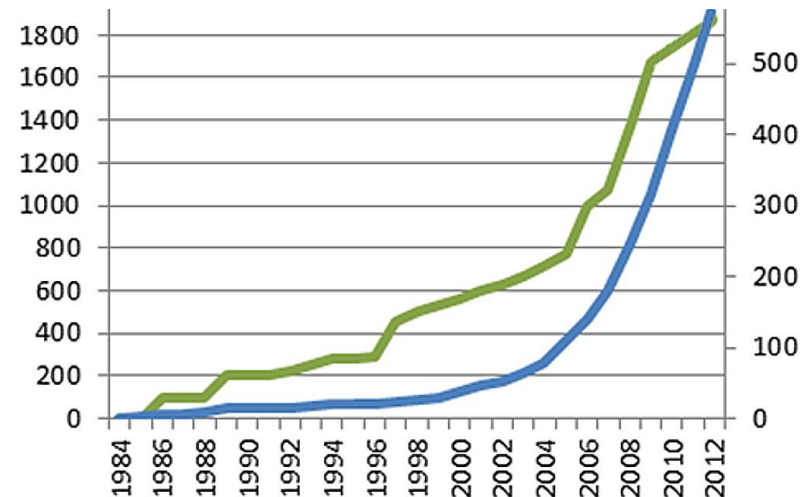
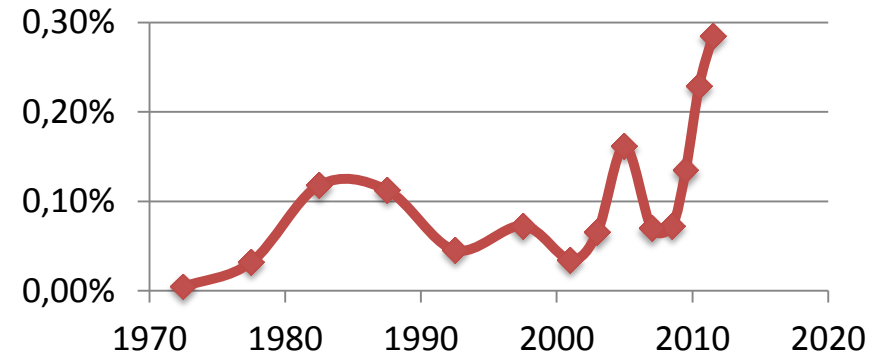
2nd International Seminar on ORC Power Systems, Rotterdam,

Introduction

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



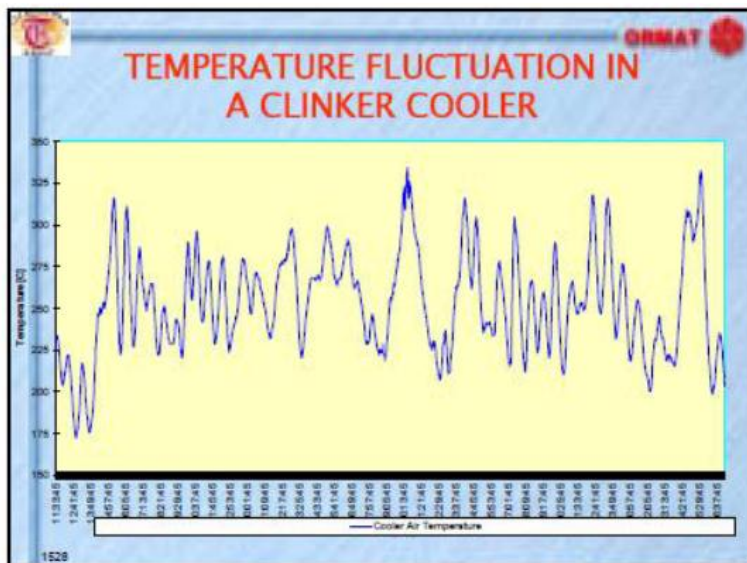
Proportion of Engineering papers dealing with
Organic Rankine Cycles on Elsevier



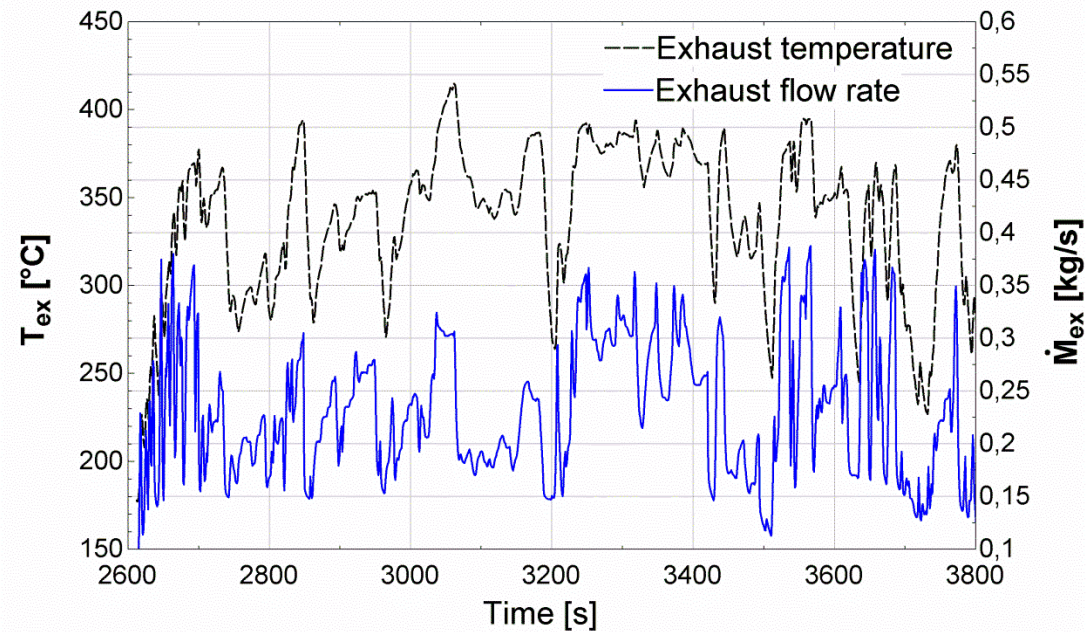
Why dynamic modeling?

Control aspects

⇒ Time-varying boundary conditions require optimal control strategies



Exhaust gases from vehicles:

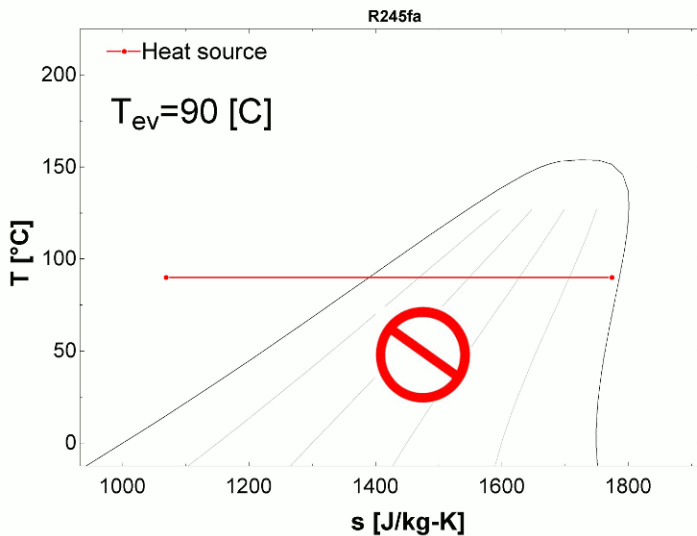


Why dynamic modeling?

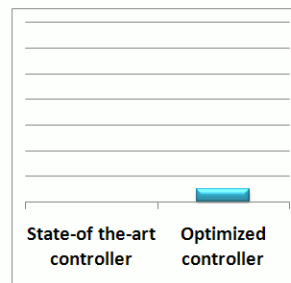
Control aspects

⇒ Time-varying boundary conditions require optimized control strategies

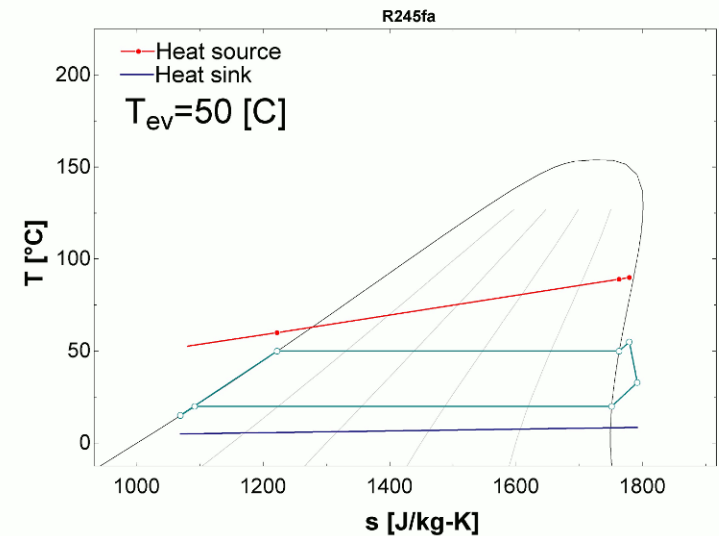
Traditional Control:



Output power:



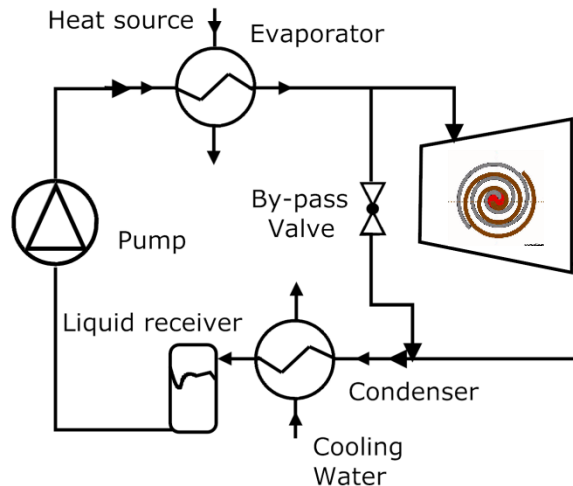
Optimized control



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



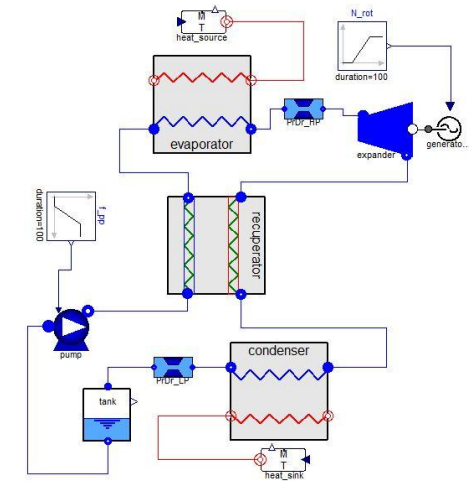
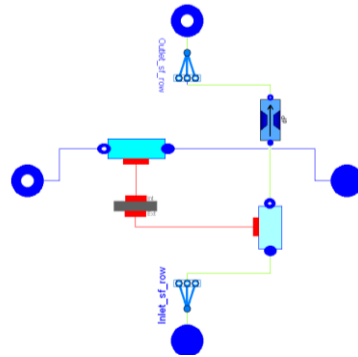
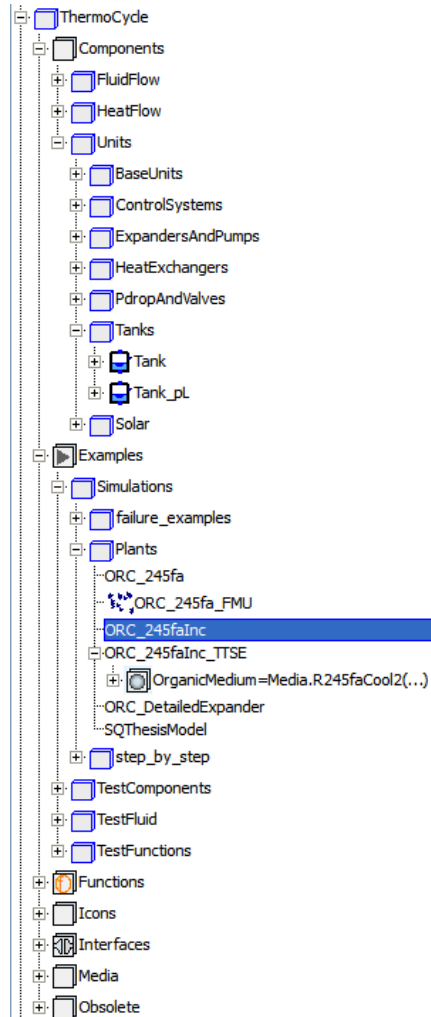
Typical questions:

- ✓ 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

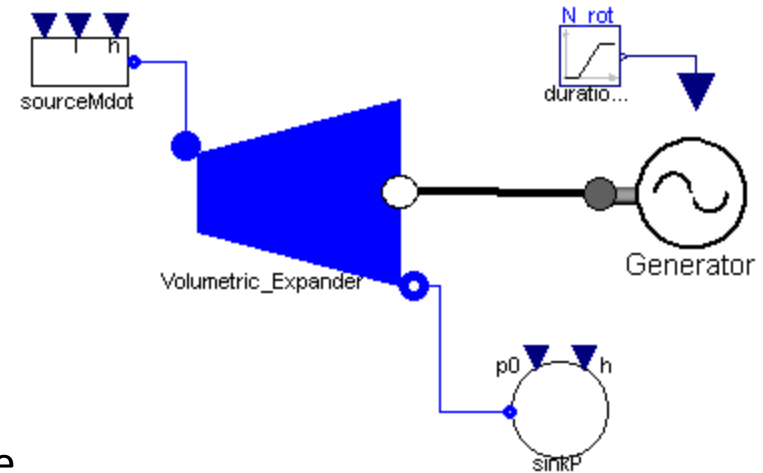
The ThermoCycle Library



- ✓ 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

Mass flow rate
 Rotating speed
 Outlet pressure
 Inlet temperature



Outputs

Inlet pressure
 Torque
 Outlet temperature

Inlet pressure
 Torque
 Outlet pressure
 Inlet temperature



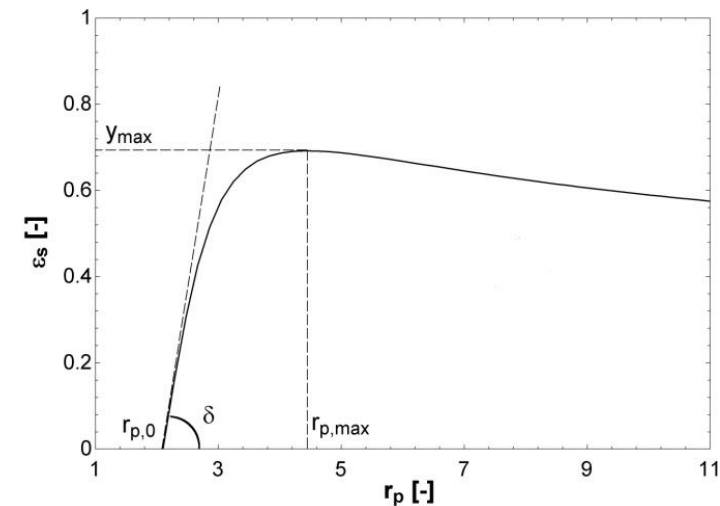
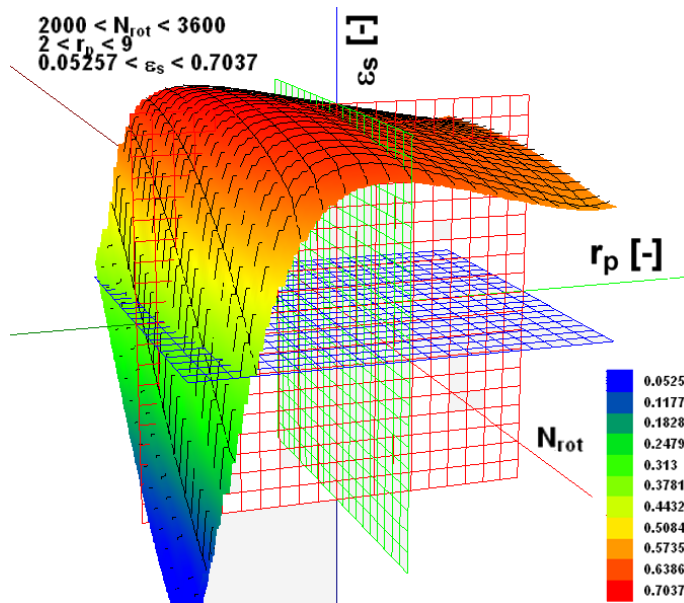
Mass flow rate
 Rotating speed
 Outlet temperature

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

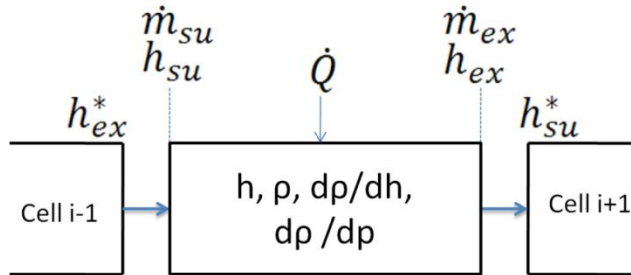
$$\varepsilon_s = y_{max} \cdot \left(\xi \cdot \arctan \left(B \cdot (r_p - r_{p,0}) - E \cdot \left(B \cdot (r_p - r_{p,0}) - \arctan \left(B \cdot (r_p - r_{p,0}) \right) \right) \right) \right)$$



Parameters identified based on experimental data

Available Models:

Finite volumes models



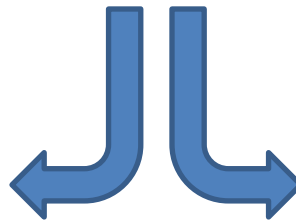
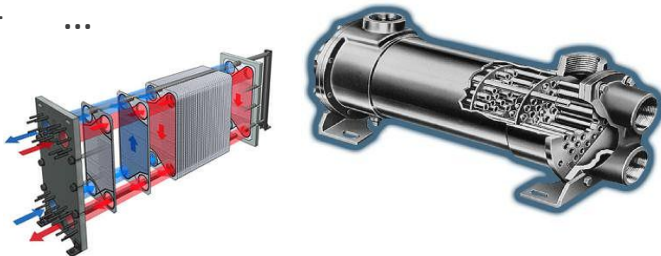
Cell model: Conservation of mass and energy:

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

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

Counter flow heat exchangers

- Evaporator
- Recuperator
- Peheater
- ...



Cross-flow heat exchangers

- Air condenser
- Radiator (vehicles)
- ...

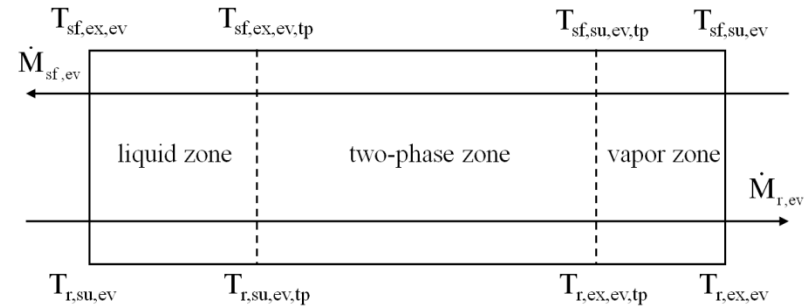


Available Models: *Miscellaneous*

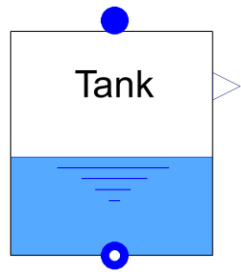
Solar collector models



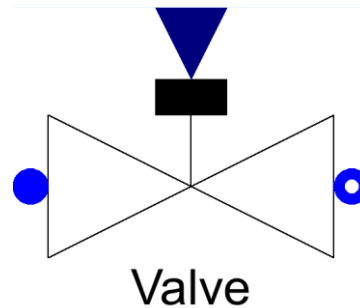
Moving boundaries heat exchanger model



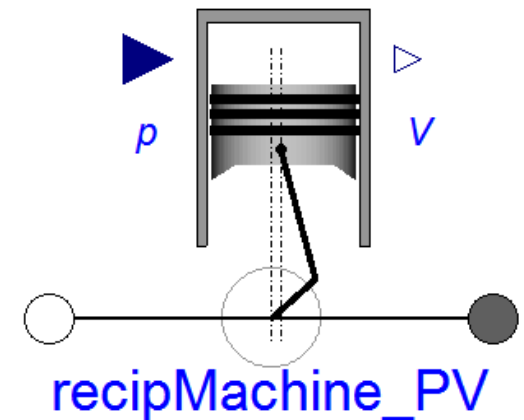
Tanks and liquid receiver



Valves and
 Pressure drops



Reciprocating expander



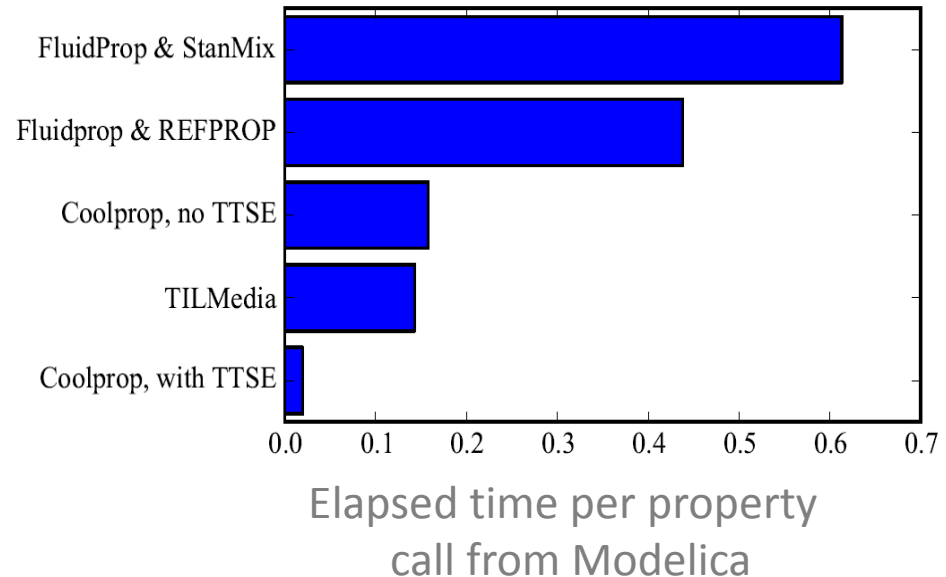
Thermodynamic properties model: *The CoolProp Library*

- Peculiarity of ORC/refrigeration cycles: require external thermophysical libraries to compute 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



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

Package Browser

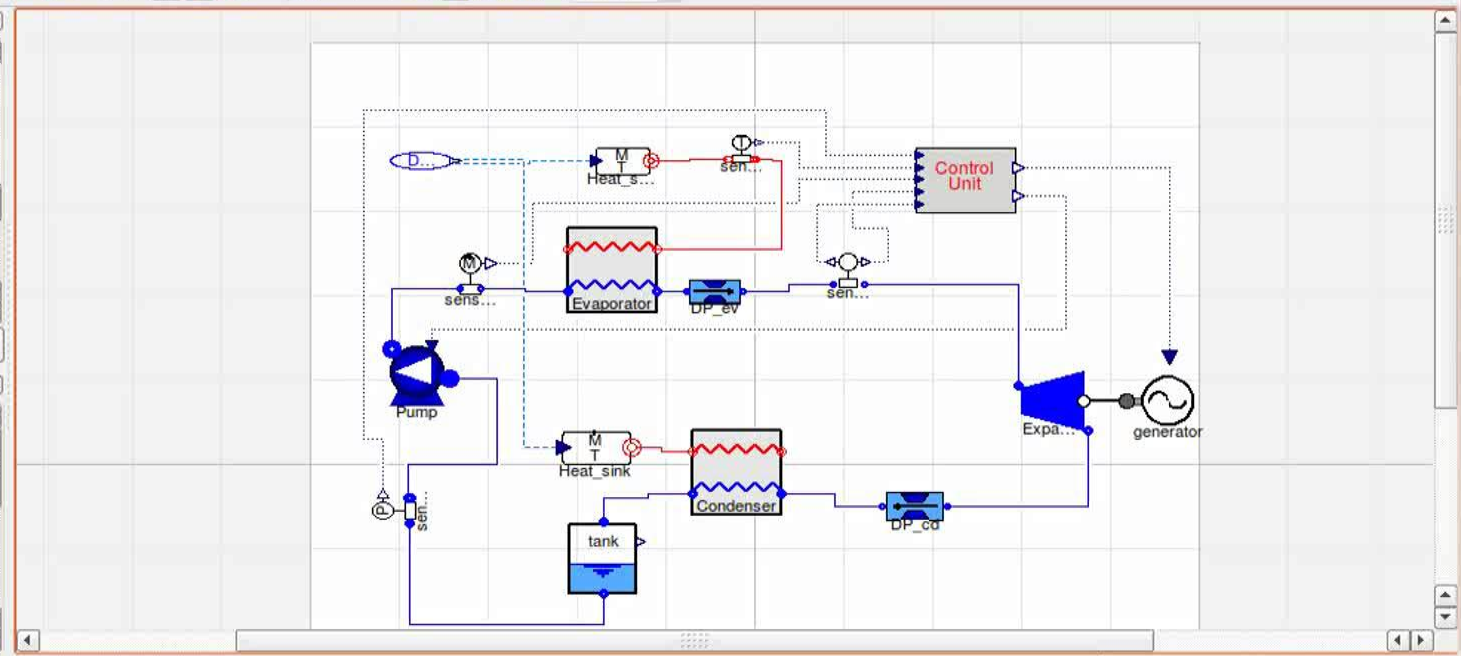
Packages

- temperature_examples
- Plants
 - ORC_245fa
 - ORC_245fa_FMU
 - ORC_245falnc
 - ORC_245falnc_TTSE
 - OrganicMediu...
 - ORC_DetailedExpan...
 - SQThesisModel**

Component Browser

Components

- ThermoCycle.Examples.Sim...
- tank
- Pump
- Heat_source
- Evaporator
- generator
- expander
- Condenser



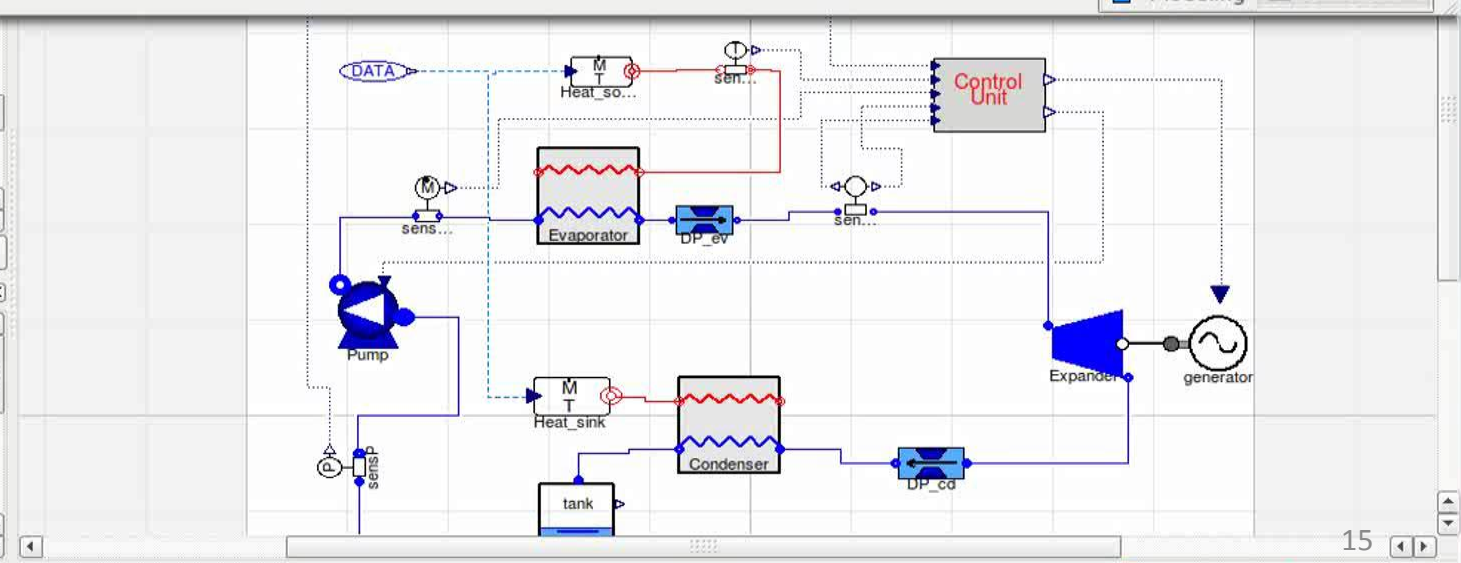
ORC_245fa

- ORC_245fa_FMU
- ORC_245falnc
- ORC_245falnc_TTSE
- ORC_DetailedExpan...
- SQThesisModel**
- step_by_step
- TestComponents

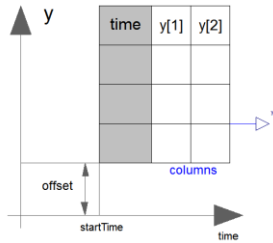
Component Browser

Components

- ThermoCycle.Examples.Sim...
- tank
- Pump
- Heat_source
- Evaporator
- generator
- expander
- Condenser



Computational efficiency: *Efficient exogenous inputs*

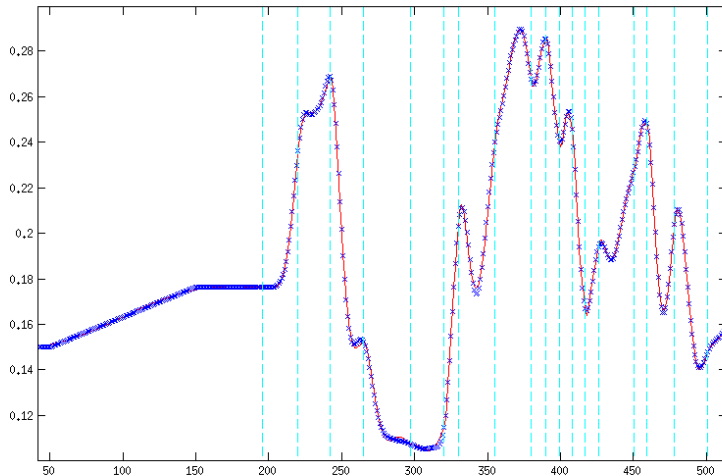


Standard Modelica solution: *CombiTimeTable*

- Highly inefficient
- Generates events



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



```

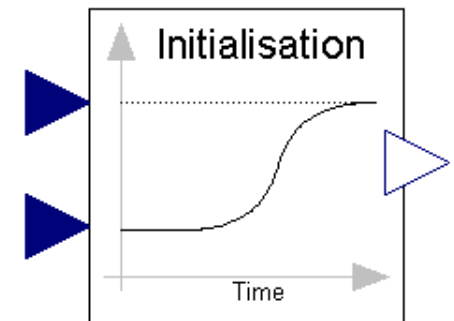
model SourceMdot1
  Real x;
  equation
    x = time;
    y =
  smooth(1, noEvent(
  if x < 1
  then 0.15
  elseif
    x <= 54
  then + 0.15 + 7.4856e-18*(x-1)^1 + 3.4646e-06*(x-1)^2-2.0235e-07*(x-1)^3
  elseif
    x <= 105
  then + 0.15145 + 0.00031053*(x-54)^1 + 4.3129e-06*(x-54)^2-1.0944e-07*(x-54)^3
  elseif
    x <= 154
  then + 0.16993 + 0.00036228*(x-105)^1-3.4097e-06*(x-105)^2 + 2.1923e-07*(x-105)^3
  elseif
    x <= 249
  then + 0.18623 + 5.1754e-05*(x-154)^1-1.6837e-06*(x-154)^2 + 8.1053e-07*(x-154)^3
  elseif
    x <= 294
  then + 0.18864 + 0.00019294*(x-249)^1 + 1.2029e-05*(x-249)^2-8.1095e-07*(x-249)^3
  elseif
    x <= 380
  then + 0.14
  end if
  end smooth
end equation
end SourceMdot1

```


Robustness: *Initialization*

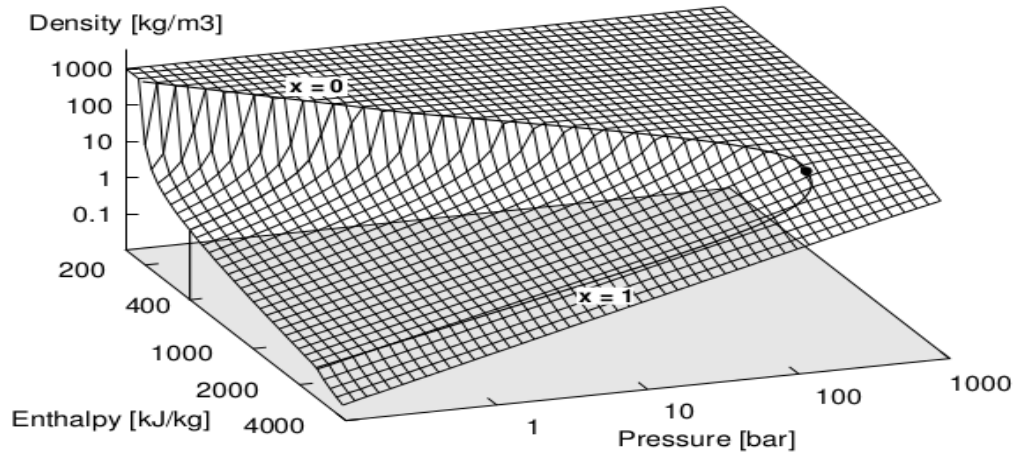
- Especially important for acausal solvers
- Newton solver can fail to converge towards an initial solution, especially in complex models
- Importance of start values
- Initiate simulation with a simplified model

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



Robustness: *Chattering*

Density as a Function of Enthalpy and Pressure

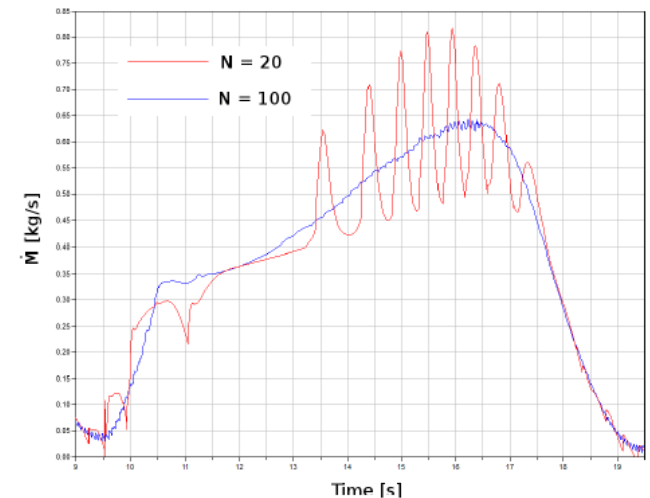


Non-physical flow reversals and simulation failures can occur if:

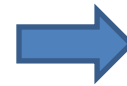
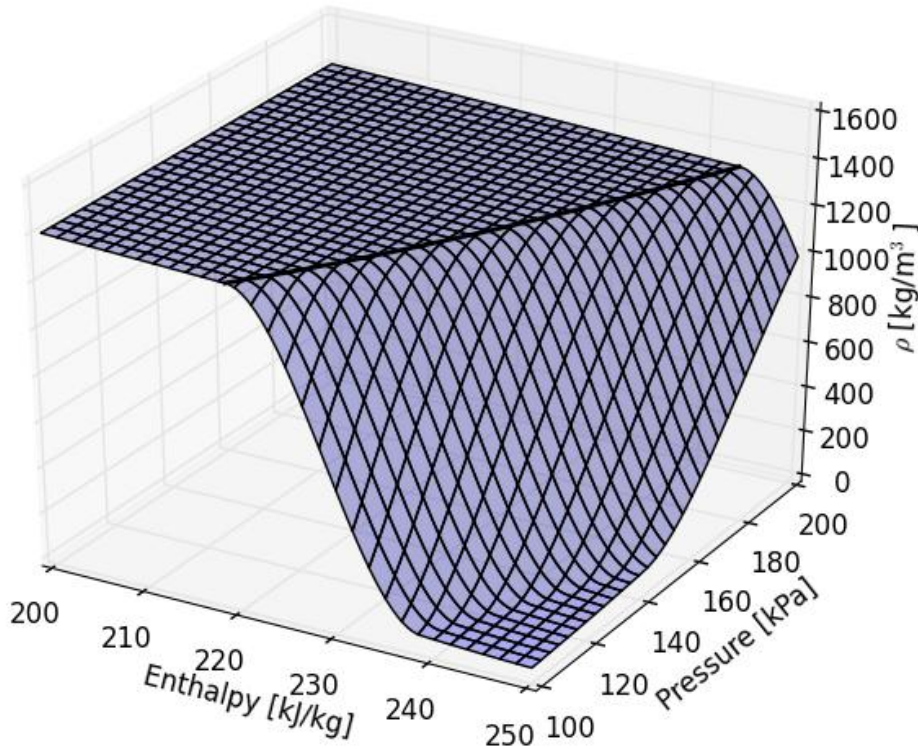
$$V_i \cdot \frac{d\rho_i}{dt} \approx \dot{M}_{su}$$

Implemented solutions:

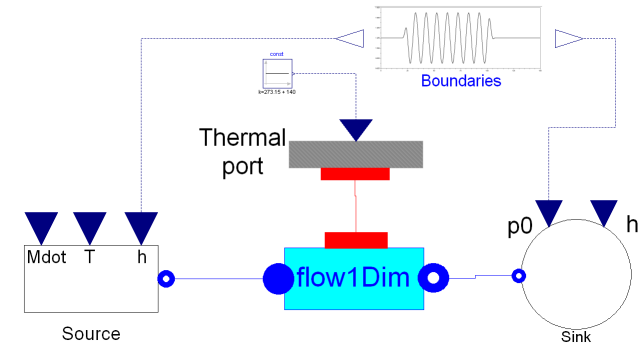
1. Truncation of density derivative
2. Filtering of the density derivative
3. Smoothing of the density
4. Smoothing of the density derivative
5. Mean densities
6. Smooth reversal enthalpy
7. Enthalpy limiter



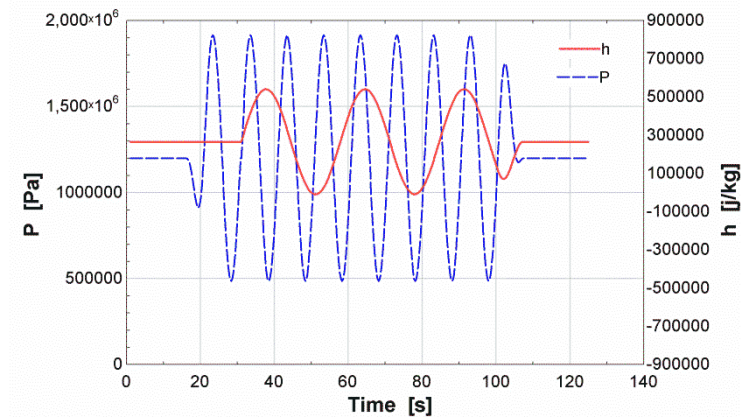
Density smoothing



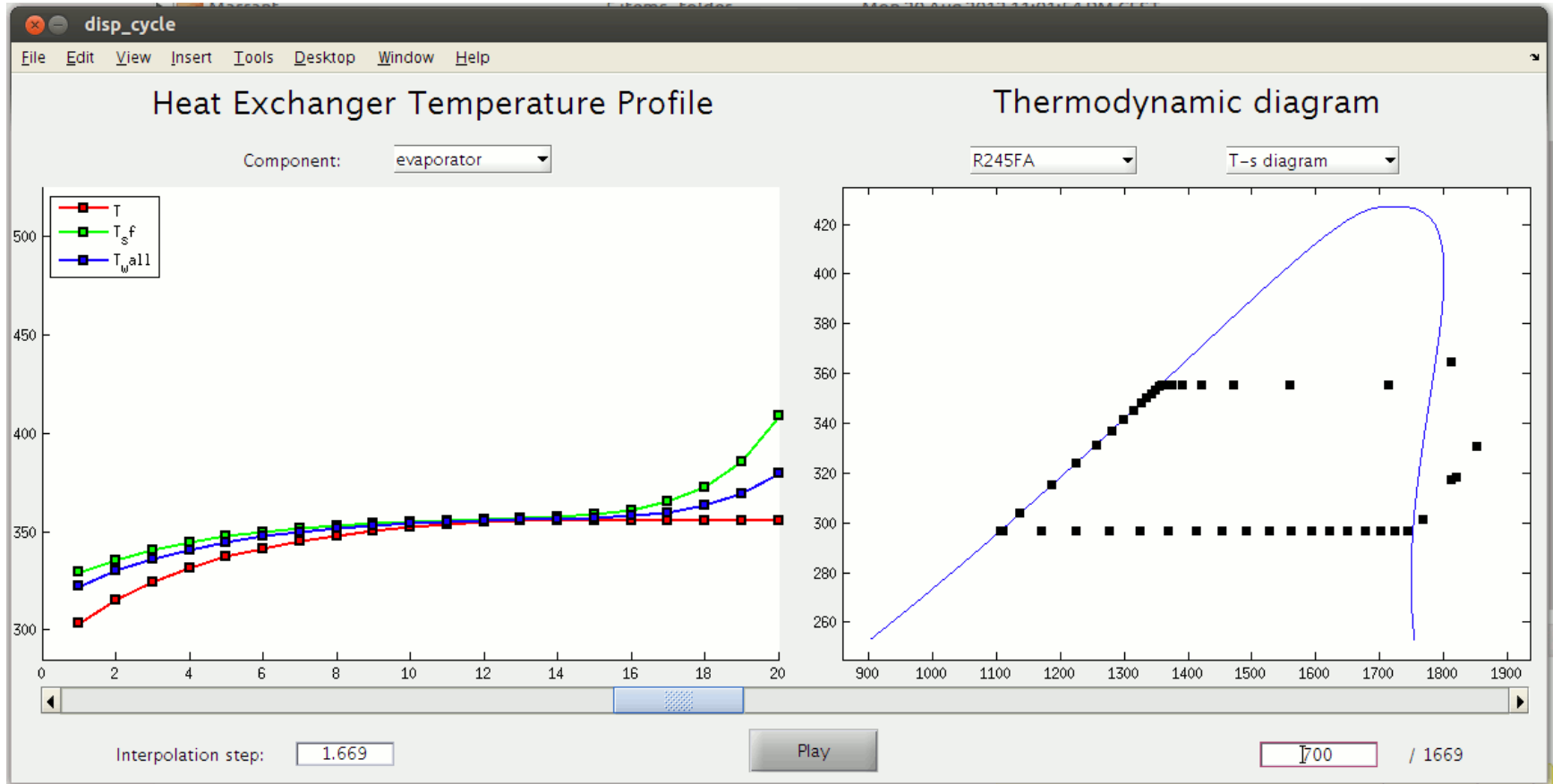
Test System:



Boundary conditions 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

The Next Generation Organic Rankine Cycles

Multivariable EPSAC Predictive Control for Organic Rankine Cycle Technology

Andrés Hernández¹, Adriano Desideri², Clara Ionescu³, Sylvain Quinot⁴, Vincent Lemaire⁵ and Robin De Keyser¹

¹Department of Electrical Energy, Systems and Automation, Ghent University, Belgium
²Thermodynamics Laboratory, University of Liège, Belgium

Motivation

Save 20% of Energy by 2020

Control Challenges

- System with fast and slow dynamics.
- Variable heat source profiles.
- Strongly coupled nonlinear multivariable process.
- Trade-off between safety conditions and economic profit (working close to boundary conditions).

Model Predictive Control

- Explicit use of a model of the system
- Constrained optimal controller
- Natural compensation of measured disturbance

Reduced order model

Define suitable input/output variables for optimal control

$$\begin{bmatrix} \Delta T(z) \\ \bar{T}_v(z) \end{bmatrix} = \begin{bmatrix} -4.5 & 1.03 \\ 1411z + 1 & 104.6z + 1 \\ 1.38 & -0.83 \\ 13421z + 1 & 3415z + 1 \end{bmatrix} \begin{bmatrix} N_1 \\ N_{exp} \end{bmatrix}$$

Manipulated variables: Pump and expander speed [Hz]

Controlled variables: Superheating and Evaporating temperature [°C]

Simulation Results

- Spectral analysis to obtain the frequency content (i.e. bandwidth) of the disturbance

Future Work
Maximize the energy production by changing the MPC cost function in the optimizer www.orcnest.be

ORCNest is a strategic basic research project granted by IWT (Feb 12 - Jan 16)

Systemic Implementation of a Model Representation of a Small-Scale Organic Rankine Cycle for Small-Scale Distributed Generation

Melissa K. Ireland¹, Adriano Desideri², Matthew S. Orszag¹, Sylvain Quinot³, John G. Brannon⁴

¹Massachusetts Institute of Technology
²Thermodynamics Laboratory, University of Liège
³Department of Electrical Energy, Systems and Automation, Ghent University, Belgium
⁴STG International

Motivation

Integrate ORC technology and expand performance to both industrial leaders and small-scale distributed generation

Objectives

Derive optimal control, dynamic models, and full plant representation for the ORC and its associated components

Dynamic Models

Develop a modular programming language for ORC and its associated components

Supervisor and Regulator

Develop a modular supervisor and regulator for ORC and its associated components

Supervisor

The supervisor manages multiple components and their interactions

Solar Cycles

Develop a modular supervisor and regulator for ORC and its associated components

Plant System - Basis for Models

- Plant representation model based on Cycle Cycle in Florida, US and components following major components
- 1000 MW Organic Rankine Cycle with solar collectors, off-grid power plant heat transfer fluid (HTF)
- Class-reduced expansion
- Brilliant cycle expander and recuperator in 2000 kW testing facility
- On-grid power plant with recuperator
- Two hermetic seal expanders
- HTF and HTF pumps

Control Strategy

- Initial control strategy: use for 10 Control Strategy 1
- Control Strategy 2

Diagram of Control

Combination Method for Control Strategy 1:

- Hold superheating and condenser pressure and HTF recirculation
- Regulator 2 only (pressure control and HTF recirculation)
- Regulator 1 only (pressure control and HTF recirculation)

Results and Conclusions

Future Work

- Develop a modular supervisor and regulator for ORC and its associated components
- Develop a modular supervisor and regulator for ORC and its associated components
- Develop a modular supervisor and regulator for ORC and its associated components


References

1. P. F. Brannon, "Thermodynamic analysis and modeling of ORC systems with solar collectors," Ph.D. thesis, MIT, Dec 2005.
2. P. F. Brannon, "Thermodynamic analysis and modeling of ORC systems with solar collectors," Ph.D. thesis, MIT, Dec 2005.

Further information

CoolProp: An Open-Source Reference-Quality Thermophysical Property Library

(Jan Benf¹, Sylvain Quoilin¹, Jørgen Wronski², and Vincent Lemort¹)
 (an.be@uliege.be, sylvain@ulg.ac.be, jorg@teknik.dtu.dk, vincent.lemort@ulg.ac.be)
¹ University of Liège, Belgium | ² Technical University of Denmark, Denmark



Equation of State

Equations of state implemented in the state-of-the-art literature are based on Helmholtz Energy Explicit formulations. Helmholtz energy given by

$$a = \frac{u(T, p)}{RT} + \frac{v(T, p)}{RT}$$

Other properties obtained by analytic differentiation. For instance,

$$\frac{p}{\rho RT} = 1 + \delta \left(\frac{\partial a}{\partial v} \right)_T, \quad \alpha = \frac{h}{RT} = \tau \left[\left(\frac{\partial a}{\partial T} \right)_v + \left(\frac{\partial a}{\partial T} \right)_p \right] + \frac{p}{\rho RT}$$

where $\delta = p/\rho_0$, $\tau = T_c/T$, and ρ_0 is the critical density and T_c is the critical temperature

Tabular Taylor Series Expansion (TTSE)

Motivation

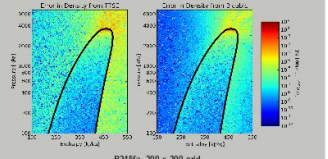
- Pressure enthalpy are common inputs, especially in dynamic modeling in Modica
- Equations of State use T, p as state variables - Need to solve $p, h \rightarrow T, p$
- This solver is very slow, requiring many calls to the equation of state

Implementation

$$T = T_{i,j} + \Delta h \left(\frac{\partial T}{\partial h} \right)_p + \Delta p \left(\frac{\partial T}{\partial p} \right)_h + \frac{\Delta h^2}{2} \left(\frac{\partial^2 T}{\partial h^2} \right)_p + \frac{\Delta p^2}{2} \left(\frac{\partial^2 T}{\partial p^2} \right)_h + \Delta h \Delta p \left(\frac{\partial^2 T}{\partial h \partial p} \right)$$

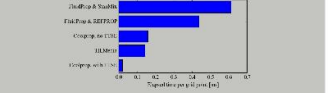
where all derivatives are evaluated at the grid point i, j

- Derivatives are pre-calculated at grid points once (slow)
- Derivatives used to extrapolate from grid point and evaluate $T(p, h)$ for instance (very fast)
- Also possible to use these derivatives with biquadratic interpolation for higher accuracy than TTSE



TTSE Example

Property retrieval in Modica - CoolProp + TTSE is by far the fastest option



Acknowledgements

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ORCNex
The next generation Organic Rankine Cycles

Thank
you!

Experimental study and dynamic modeling of a WHR ORC power system with screw expander

A. Desider¹, M.V.D. Broek^{2,3}, S. Gusev², S. Lecompte³, V. Lemort¹, S. Quoilin¹

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²Department of Industrial System and Product Design, - Ghent University - BELGIUM
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