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

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Overview

- Context & Objective
- Experimental campaign
  - Test rig
  - Experiment results
- Modeling
  - Steady state modeling
  - Dynamic modeling
- Dynamic validation
- Conclusions

Context and Objective

- **High potential of small-capacity ORC power plants** for waste heat recovery applications (Verneau, 1979)
- **Dynamic modeling** represents an **important tool** in particular when control issues are considered (Casella, 2013)

- **Dynamic model** of an **ORC system validated** in both **steady-state and transient conditions** via experimental data from a **10 kWe** waste heat recovery ORC unit with a **screw expander**

F. Casella, T. Mathijssen, P. Colonna, and J. van Buijtenen. Dynamic modeling of organic rankine cycle power systems. Journal of Engineering for Gas Turbines and Power, 135, 2013

A. Verneau. Waste heat recovery by organic uid rankine cycle. In Proceedings from the First Industrial Energy Technology Conference Houston, 1979.

Experimental campaign

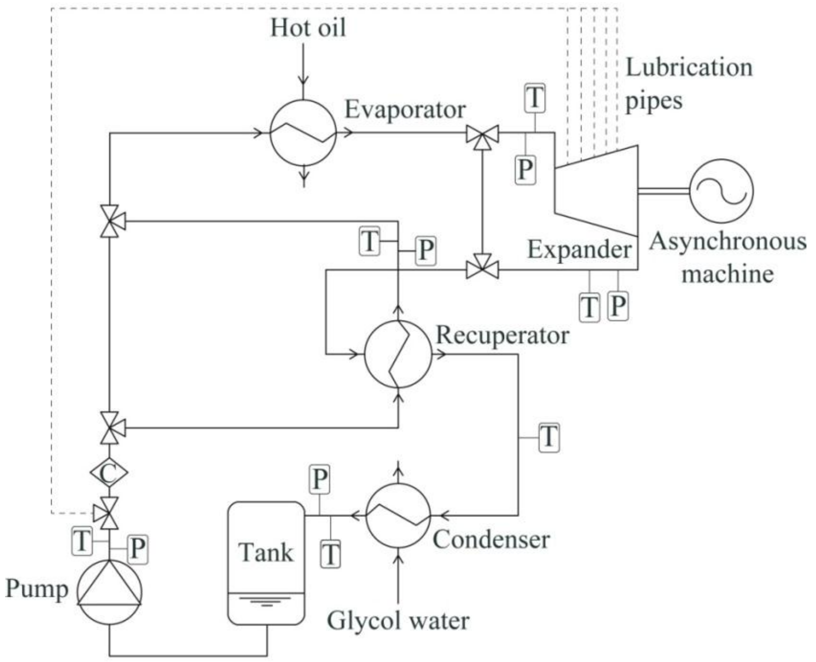
❖ Test Rig

Side view of the ORC test bench

- $P_{el,nom}$ = 10 kWe
- Working fluid: Solkatherm (SES36, Tcrit = 176.85 °C, Pcrit = 28.49 bar).
- Expander: Single screw
- Lubricating oil: MOBIL EAL ARCTIC 68 (3.23% of total mass).
- Heat exchangers: Rec - Cond-Eva all identical brazed plate type.
- Pump: variable speed multistage centrifugal pump.
- No control system
- Heat source: Therminol66 (electrical resistances)
- Cooling system: Ethylen Glycol (34% in Vol)

Experimental campaign

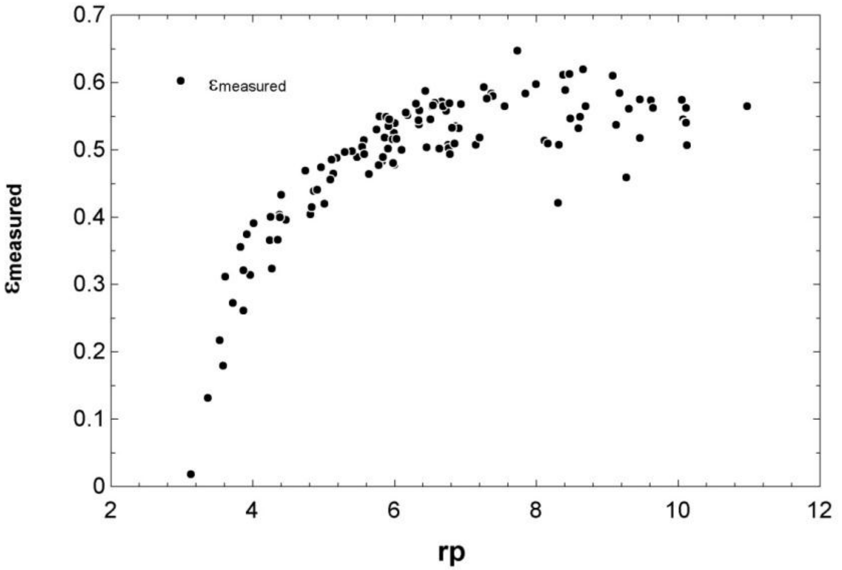
- Sensors



Variable	Device type	Range	Device uncertainty
SES36 flow Rate	Coriolis Flow meter	0 to 1.8kg/s	± 0.1%
T	RTD	-50 to 300°C	± 0.4°C
p	Absolut pressure transmitter	0 to 16bar	± 0.09bar
El. Power	Wattmeter	0 to 100GW	± 0.5%

Experimental campaign

- Experimental results
  - 120 steady-state set point
  - Wide range of operating conditons



Isentropic eficiency vs pressure ratio

Performance	η_{cycle} (%)	η_{exp} (%)	η_{pump} (%)	T_{eva} (°C)	ΔT_{sc} (°C)	ΔT_{sh} (°C)	PP_{ev} (°C)	ΔP_{LP} (bar)	ΔP_{HP} (bar)
Min	2.2	27.3	12.3	119.3	9	1	0.1	0.06	$0.4 \cdot 10^{-3}$
Max	11.3	56.35	20	125	26	29	0.7	0.17	0.09

Steady-state model

- *Engineering Equation Solver (EES)* coupled to ***Coolprop***
- *Expander*
  - Isentropic efficiency - Pacejka equation → f(p_{su}, N_{rot}, r_p) (R^2=91.3%):
    - Parameters identified based on the experiments

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

  - Filling factor (R^2= 94.22 %).

$$\Phi = \frac{\dot{m}}{\rho_{su,exp} \cdot (V_s N_{rot})}$$

Steady-state model

- Heat exchangers
  - Over-dimensioned → Too small pinch point
  - No possibility to have any validated model

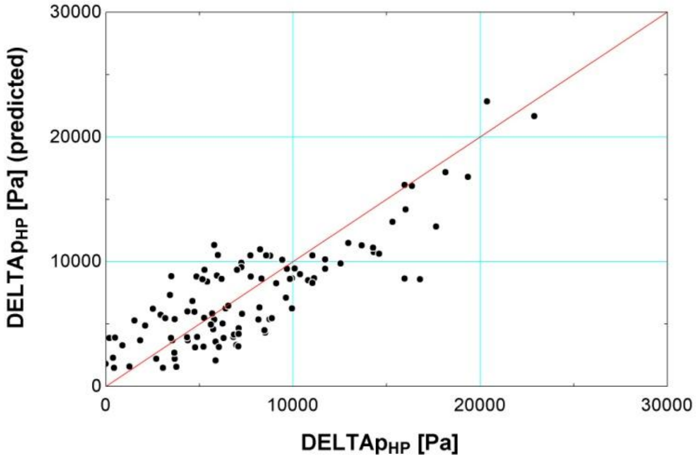
- Pump
  - Empirical correlation for isentropic efficiency (R^2= 32.3 %) and mass flow (R^2= 83.05 %)

$$\epsilon_{s,pp} = f(f_{pp}, r_p) \qquad \dot{m} = f(f_{pp})$$

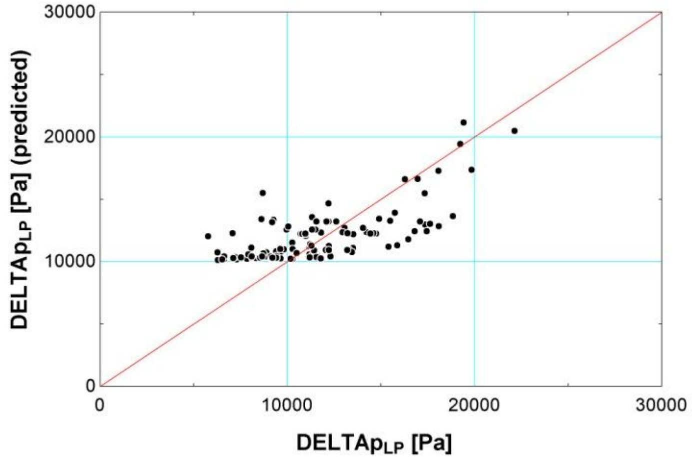
  - Low repeatability of the performance → No accurate empirical model

Steady-state model

- Pressure Drop: Lumped in the high and low pressure lines
  - Linear term : $k \cdot \dot{V}$
  - Quadratic term: $\frac{1}{A^2} \cdot \frac{\dot{m}^2}{2 \cdot \rho}$



HP - R^2 = 65.12%



LP - R^2 = 20.95%

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Dynamic model

- *Modelica/Dymola*

MODELICA

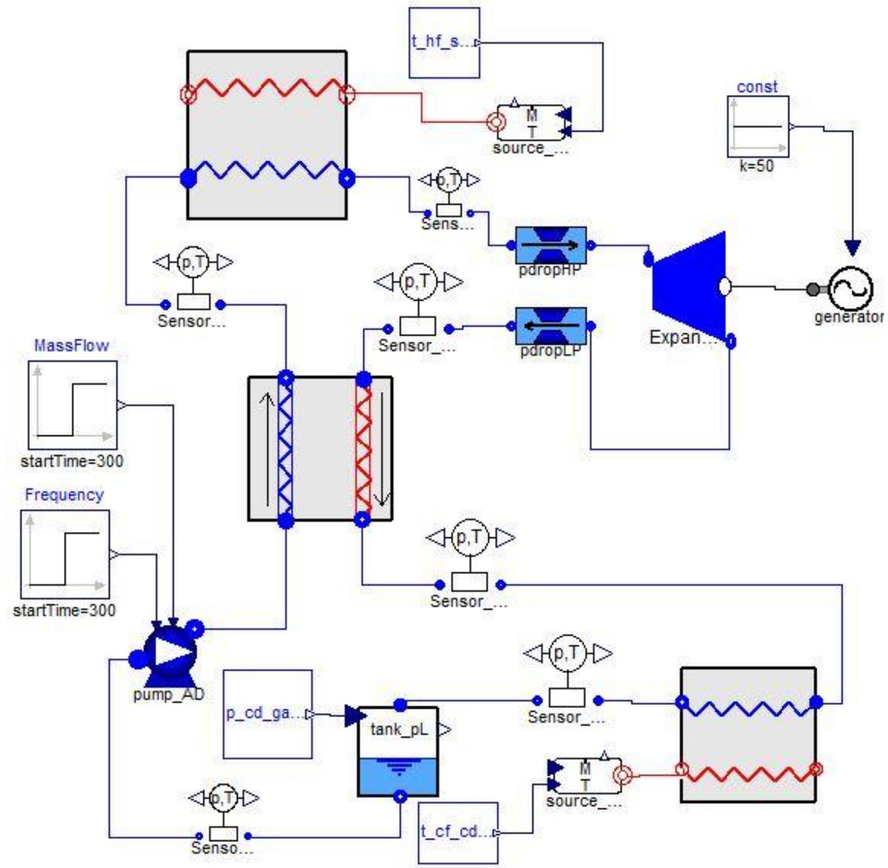
- *Coolprop*

CoolProp

- *ThermoCycle* library

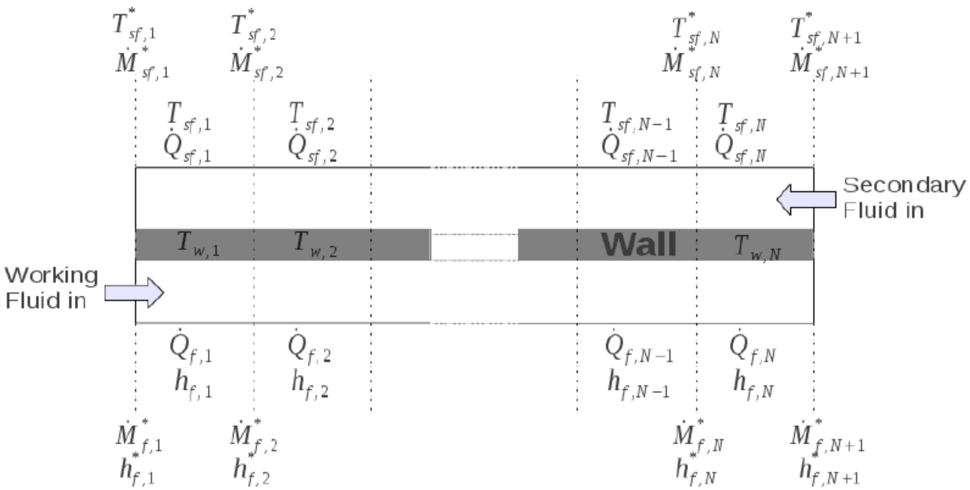
Thermo Cycle THE MODELICA LIBRARY

www.thermocycle.net



Dynamic modeling

- Heat exchangers



- ✓ 1-D discretized model
- ✓ No Pressure drop

✓ Conservation of energy:

$$V_i \cdot \rho_i \cdot \frac{\partial h_i}{\partial t} = \dot{M}^*_{i-1} \cdot (h^*_{i-1} - h_i) - \dot{M}^*_i \cdot (h^*_i - h_i) + \dot{Q}_i + V_i \cdot \frac{dp}{dt}$$

✓ Conservation of mass:

$$\frac{dM_i}{dt} = V_i \cdot \left(\frac{\partial \rho}{\partial h} \cdot \frac{dh}{dt} + \frac{\partial \rho}{\partial p} \cdot \frac{dp}{dt} \right) = \dot{M}^*_i - \dot{M}^*_{i-1}$$

✓ Metal wall:

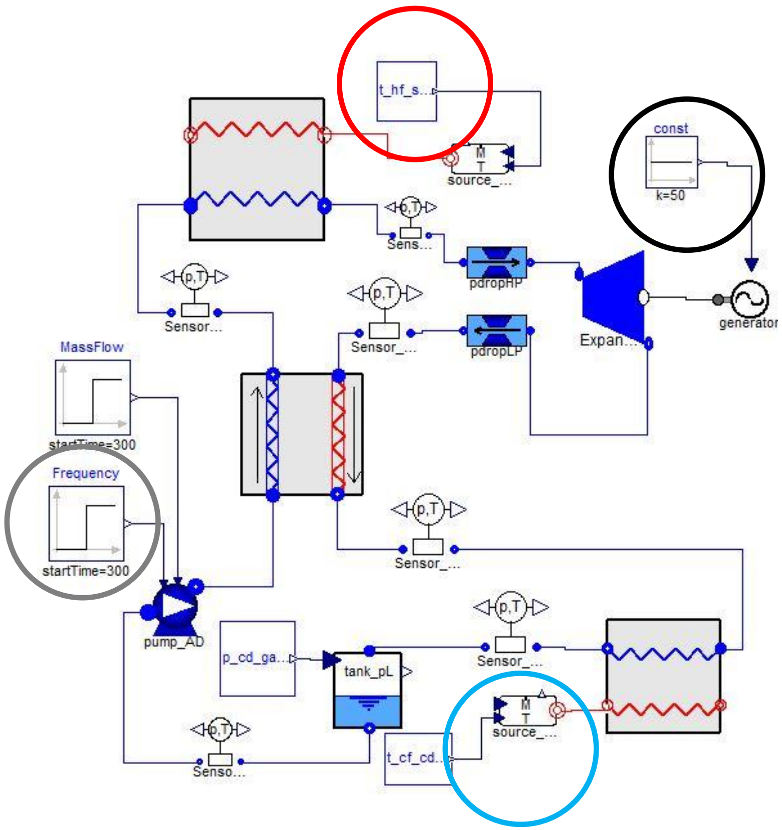
$$c_w \cdot M_{w,i} \cdot \frac{dT_{w,i}}{dt} = \dot{Q}_{sf,i} - \dot{Q}_{f,i}$$

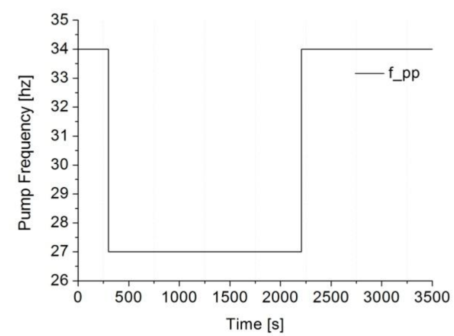
Dynamic modeling

- Expander and pump
  - Small time constant → No dynamic implemented
  - Based on steady-state performance curves
- Liquid receiver
  - Thermodynamic equilibrium between sat. vapor and sat. liquid
- Sub-cooling
  - Not possible to extract an accurate model to describe the trend.
  - Use partial pressure of non-cond gases as input to tank model

Dynamic Validation

- Dynamic response
  - Rectangular function imposed to pump rotational speed.

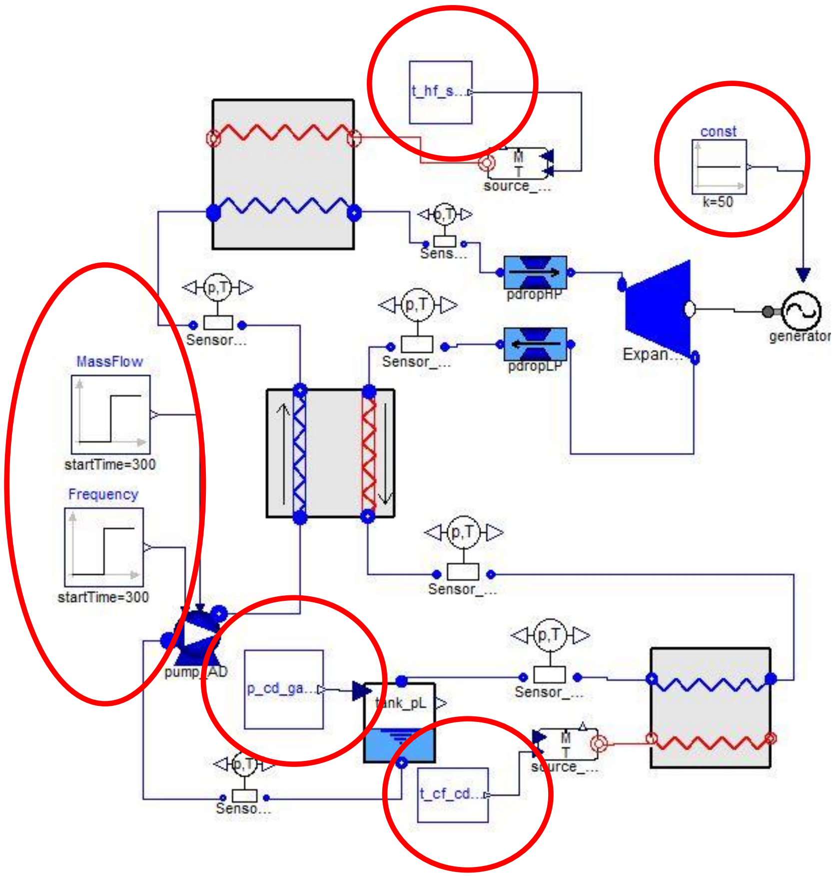




- ✓ $N_{rot,exp}$ = const.
- ✓ $T_{hf,ev,su}$ = const.
- ✓ $M_{hf,ev,su}$ = const.
- ✓ $M_{cf,cd,su}$ = const.

Dynamic Validation

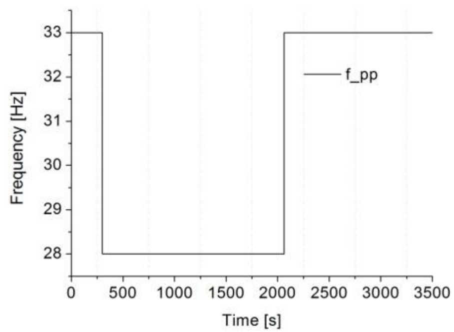
- Inputs to the model

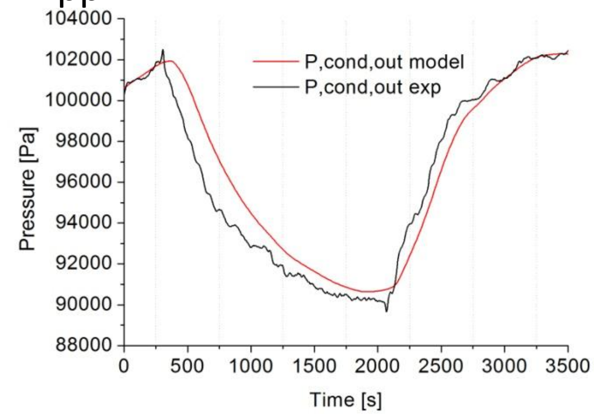


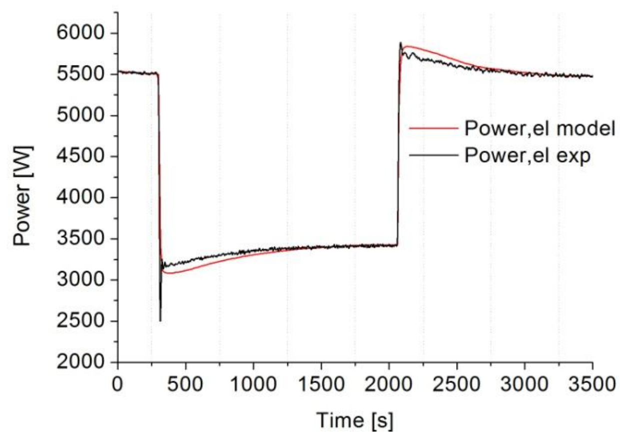
- ✓ Pump frequency
- ✓ Mass flow rate
- ✓ Expander Rotational speed
- ✓ Temperature hot side evaporator inlet
- ✓ Temperature cold side condenser inlet
- ✓ Non-condensable gases partial pressure

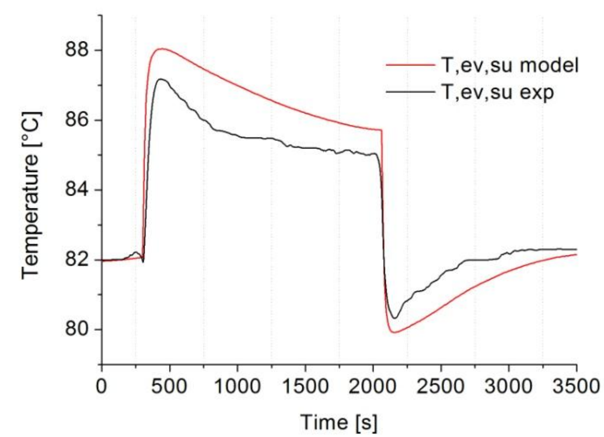
Dynamic Validation

- Results: 5Hz step down and up in N_{pp}
  - Step down at 300s step up at 2062s



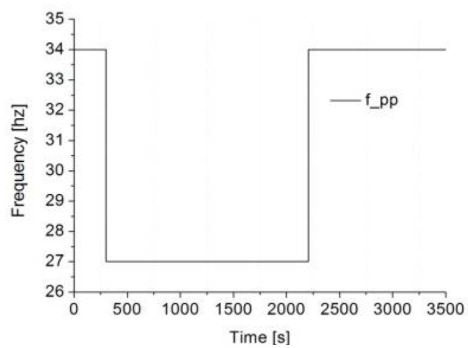


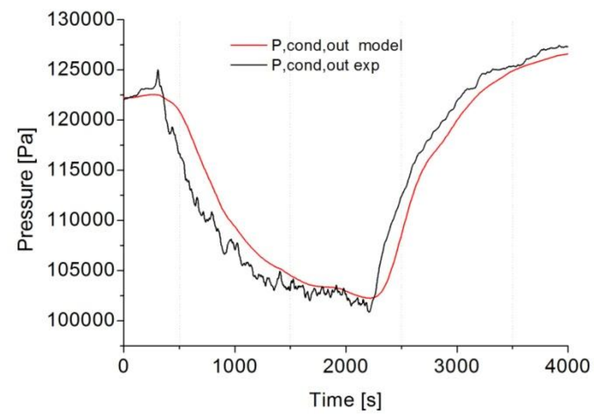


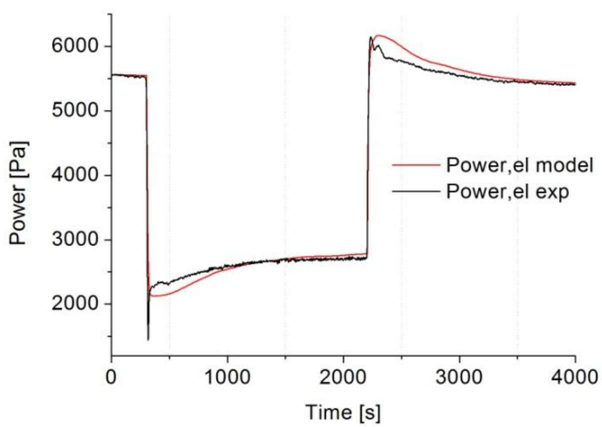


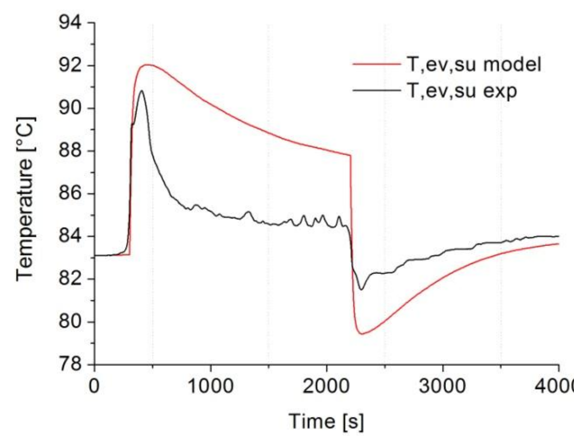
Dynamic Validation

- Results 7Hz step down and up in N_{pp}
  - Step down at 300s up at 2205s









Conclusions

- Development and validation of a steady-state model based on experimental tests
- Robust and fast dynamic model developed with the *ThermoCycle* library
- Preliminary validation of the dynamic model

Future work

- Test rig improvements - more experiments
- Validating components separately

THANK you!

Questions?