6th International Seminar on ORC Power Systems

ECONOMIC MODEL PREDICTIVE CONTROL ON A WASTE HEAT RECOVERY MICRO-ORC

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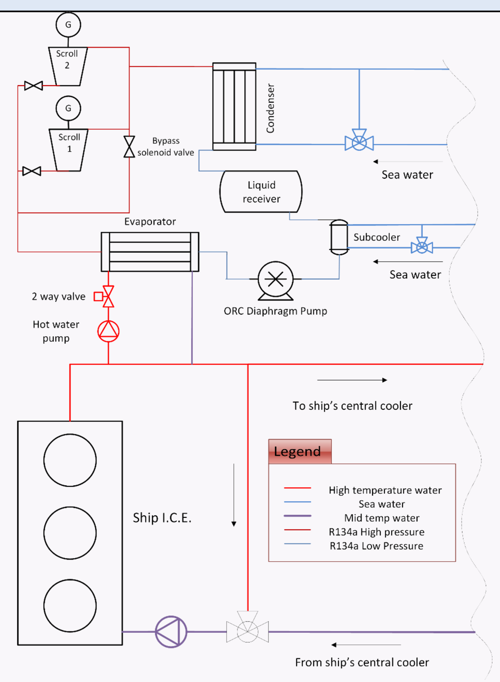
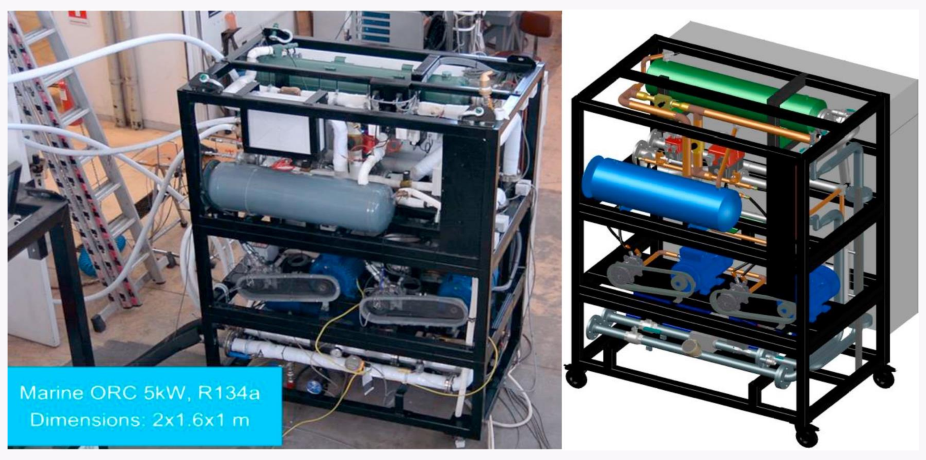
Introduction

- μORC prototype especially designed for waste heat recovery from marine ICE's jacket cooling circuit using R134a[1]
- Dynamic modeling of the ORC in Dymola using the open source Thermocycle library[2]
- Linearized step response models derived from the detailed dynamic model of the setup
- Benchmarking of an Economic MPC control strategy based on the well-known DMC methodology versus conventional PID control





Dynamic Modelling

Brazed Plate Heat Exchangers: Standard 1D Thermocycle Finite Volume model:

- 21 Control Volumes
- Geometrical characteristics based on real HEX data
- Heat Transfer Coef. -> correlations fitted on experimental data

Diaphragm Pump:

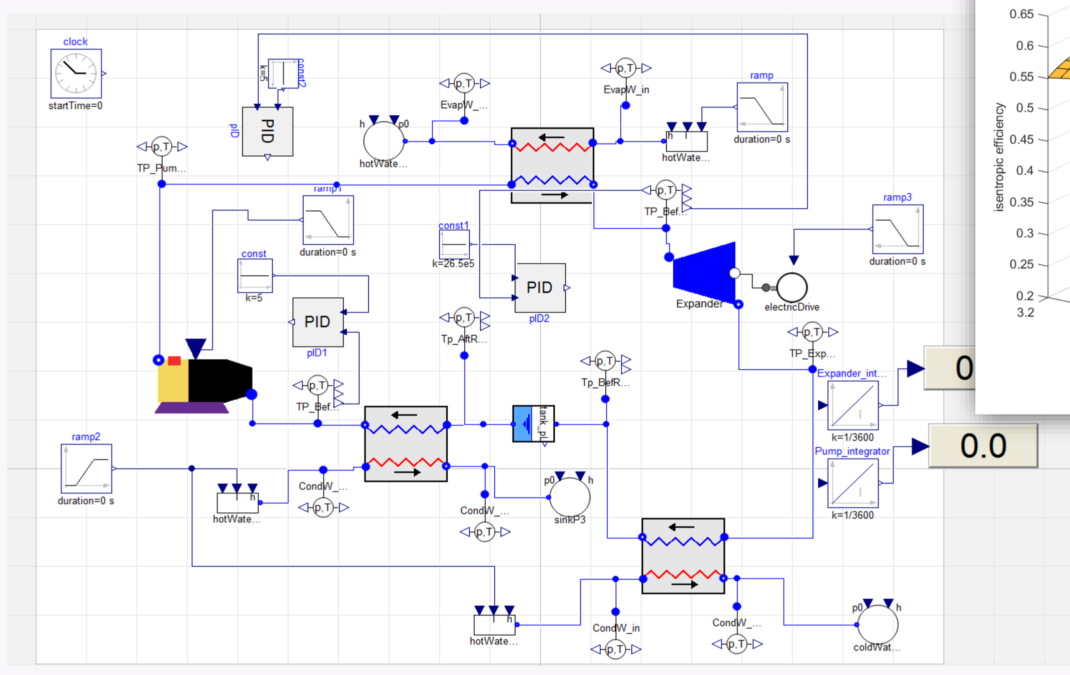
Model based on manufacturer data for

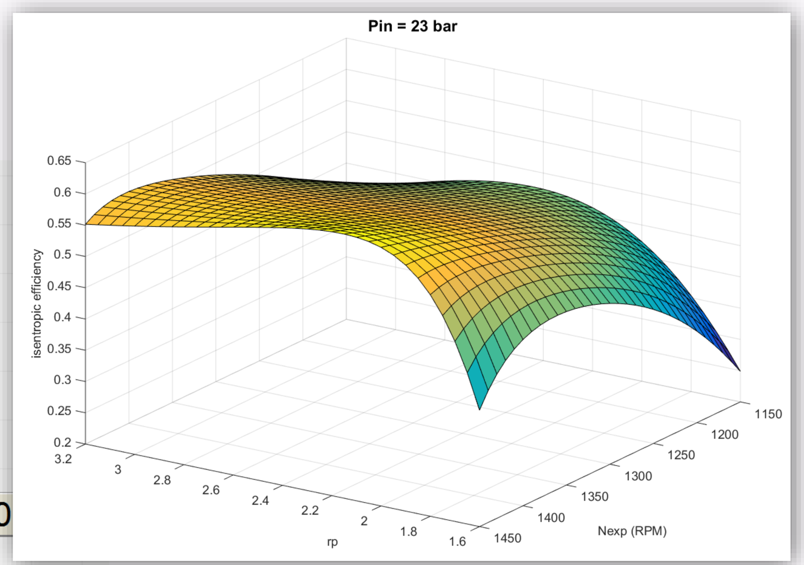
- Volume flow rate vs speed
- Power consumption versus hydraulic energy
- Motor efficiency versus load

Open Drive Scroll Expanders: Calibrated empirical model using Pajecka's equation fitted on acquired experimental data for the isentropic efficiency (e_{is}) and the filling factor (ff)[3]

- $e_{is} = e_{is}\,(p_{in}, r_p, N_{exp})$
- $ff = ff(p_{in}, r_p, N_{exp})$

Liquid Receiver: Standard Thermocycle lumped parameter model





Conventional PID control

Two separate PID control loops:

- **Controller 1:** Maintain superheating at a constant value using the ORC pump speed as a control variable (T_{SH}^{SP} = 5 K)
- **Controller 2:** Maintain the evaporation pressure on a constant value using the expander speed as a control variable ($P_{evap}^{SP} = 25\ bar$)
- **Gains calculated using the IMC Method based on Dymola simulations**

Two control alternates:

- **Alternate A:** Both Controller #1 and Controller #2 acting on the system
- **Alternate B:** Only Controller #1 acting on the system – expander fixed to max speed for enhanced efficiency

Model Predictive Control methodology

Method based on the classic Dynamic Matrix Control approach:

- System output prediction ($\hat{y}$) using step response models derived from Dymola simulations for inputs/disturbances with sampling time $\Delta t_s = 5$ sec
- Minimization of a cost function $J(x)$ over a prediction horizon of N=21 samples leads to the control law $u(t+1)$
- **In each time step t:** new prediction according to the measured variables $y(t)$, disturbances kept constant at $d(t)$

Control variables (scaled):

- Expander speed: u_1
- Pump speed: u_2

Disturbances (scaled):

- Evaporator hot water flow rate : d_1
- Sea water temperature: d_2

Measured variables (scaled):

- Evap. pressure: y_1
- Evap. Out temperature: y_2
- Cond. pressure : y_3
- Subcooler Out temperature: y_4
- Expander elec. Power: y_5

Formulation of the optimization problem (Economic MPC):

"Goal is to maximize the net produced energy over the control horizon N, with the minimum control effort and subject to a set of constraints"

Let:

$$\min(J) \quad i = 1 \dots N$$

$$J = W_e \cdot J_E + W_c \cdot J_C + W_u \cdot J_u, \qquad 0 \le W_e, W_c, W_u \le 1$$

$$J_E = -\sum_{i=1}^{N} \hat{P}_{net}, \quad J_C = \sum_{i=1}^{N}\sum_{k=1}^{5}(w_i \cdot \|e_{k,i}\|), \quad J_u = r_1 \cdot \|u_1\| + r_2 \cdot \|u_2\|$$

Subject to:

- **The model predictions must follow the DMC formulation:**

$$\boldsymbol{\hat{y}_j = A_{j1} \cdot u_1 + A_{j2} \cdot u_2 + F_{j1} \cdot x_1 + + F_{j2} \cdot x_2 + D_{j1} \cdot d_1 + D_{j2} \cdot d_2}$$

- **Operational constraints on:**

Superhating: $\hat{T}_{SH,i} = f(\hat{y}_{1,i}, \hat{y}_{2,i}) + e_{1,i} \ge \mathbf{5\ K}$

Subcooling: $\hat{T}_{SC,i} = f(\hat{y}_{4,i}, \hat{y}_{5,i}) + e_{2,i} \ge \mathbf{5\ K}$

Evaporation pressure: $\hat{p}_{evap,i} = f(y_{2,i}) \le \mathbf{26.5\ bar} + e_{3,i}$

Condensing pressure: $6.5\ bar + e_{4,i} \le \hat{p}_{cond,i} = f(y_{4,i}) \le 9\ bar + e_{5,i}$

Control Variables' Limitations

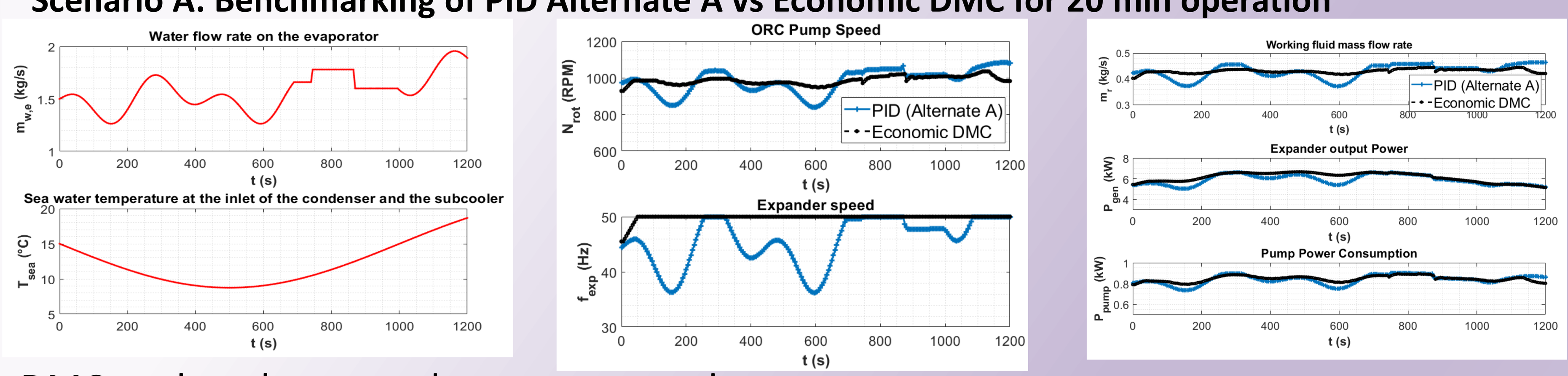
$$\begin{cases} -3 \le u_{1,i} \le 1 \\ -4 \le u_{2,i} \le 2 \\ du_{1,i} = u_{1,i} - u_{1,i-1} < 0.5 \\ du_{2,i} = u_{2,i} - u_{2,i-1} < 0.5 \end{cases}$$

- DMC algorithm implemented in Matlab, using the Gurobi optimizer and the YAL-MIP toolbox.
- **Computational cost / time step:** ~0,5sec on a quad core desktop processor

Simulation Results

- Simulation for DMC where ran on Dymola by feeding the controller outputs from MATLAB back to the model, while for PID ran exclusively in Dymola.

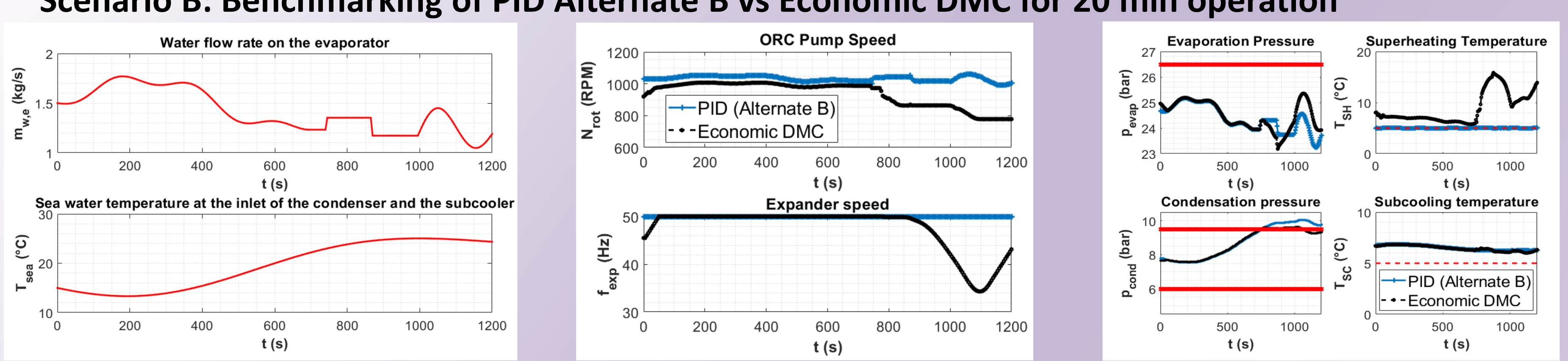
Scenario A: Benchmarking of PID Alternate A vs Economic DMC for 20 min operation



DMC pushes the expander to max speed:

- Higher pump consumption and expander production
- Enhanced net energy output by ~4.5% compared to PID

Scenario B: Benchmarking of PID Alternate B vs Economic DMC for 20 min operation



Similar in terms of power consumption but DMC manages to avoid condenser overpressure constraint violation by combined expander/pump control

Conclusions

- Successful evaluation of a linear Economic Model Predictive Controller on a μORC leading to enhanced power production and constraint satisfaction compared to conventional control techniques at low computational cost.
- DMC methodology is mature, easy to implement (using just experimental data for the formulation of the step response models) and commercially available.

References: ***[1]*** P. Pallis et al. "Development, experimental testing and techno-economic assessment of a fully automated marine organic rankine cycle prototype for jacket cooling water heat recovery," Energy, vol. 228, ***[2]*** S. Quoilycle: A Modelica library for the simulation of thermodynamic systems," in Proceedings of the 10th International Modelica Conference, 2014, ***[3]*** S. Declaye et al., "Experimental study on an open-drive scroll expander integrated into an ORC (Organic Rankine Cycle) system with R245fa as working fluid," Energy, vol 55.