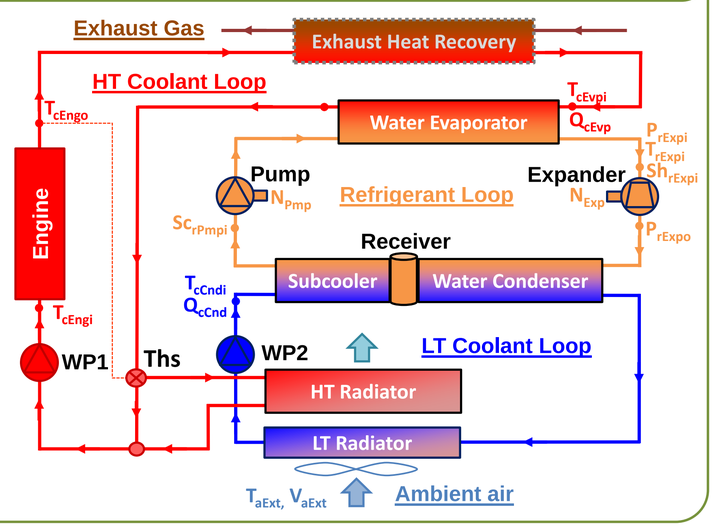
CONTROL STRATEGIES FOR AUTOMOTIVE RANKINE SYSTEM EVALUATION USING A COSIMULATION PLATFORM

Abdelmajid Taklanti*, Jin-Ming Liu, Regine Haller, Samy Hammi

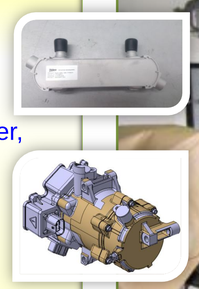
Valeo Thermal Systems

R134a Organic Rankine Cycle Architecture



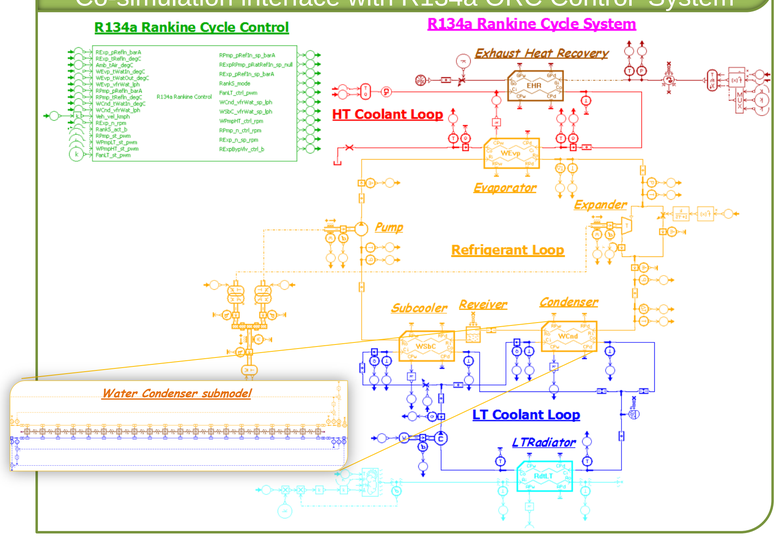
Low Temperature Organic Rankine Cycle

- **Organic Rankine Cycle experimental mockup**
  - R134a working fluid.
  - Boiling by engine coolant with optional overheating by exhaust gas.
  - Condensation by indirect low temperature coolant loop.
  - Valeo brazed tubes and plates exchangers for evaporator, condenser, subcooler, EHR and radiator.
  - Expander derived from a Valeo electrical scroll compressor.
- **Other Organic Rankine Cycle evaluated**
  - Low temperature R245fa Organic Rankine Cycle.
  - High temperature Ethanol and Water Organic Rankine Cycles.



R134a Organic Rankine Cycle Mockup

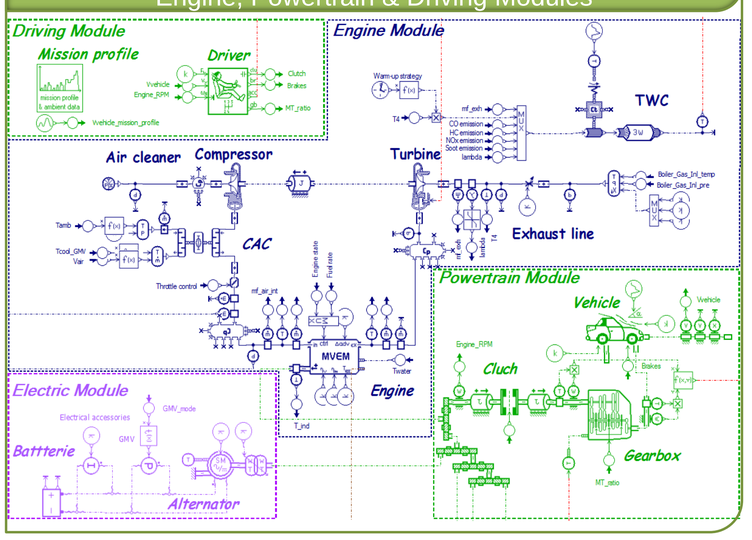
R134a ORC Simulation Model and Co-simulation interface with R134a ORC Control System



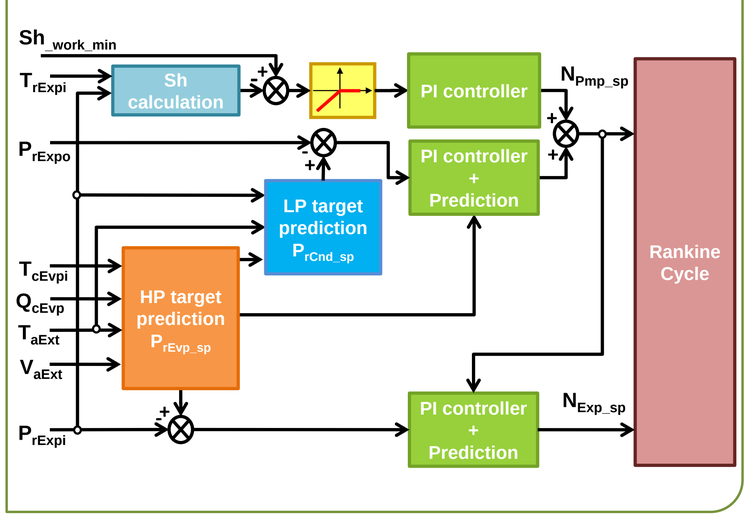
Organic Rankine Cycle Simulation models

- **Organic Rankine Cycle simulation model**
  - Transient multi-physics models developed in AMESim simulation tool.
  - Multi-zones models for heat exchangers (Up to 20 zones by exchanger).
  - Steady state efficiencies models for expander and pump.
- **Model validation**
  - Components characterization, correlation parameters calibration and system validation based on R134a ORC mockup experimental results.
- **Vehicle Energy and Thermal Management simulation Platform**
  - Driving module with driver and mission profile.
  - Engine module with 2 liters turbocharged gasoline engine, air intake line and exhaust gas line.
  - Powertrain module with vehicle, gearbox and transmission.
  - Electric module with battery, alternator and electrical accessories.
  - Engine thermal module with cooling loop and components, lubrication loop and components, engine thermal capacities, underhood and fan.
- **Co-simulation AMESim / Simulink**
  - Co-simulation with ORC control system developed on Simulink tool.

Vehicle Energy Management Simulation Platform Engine, Powertrain & Driving Modules



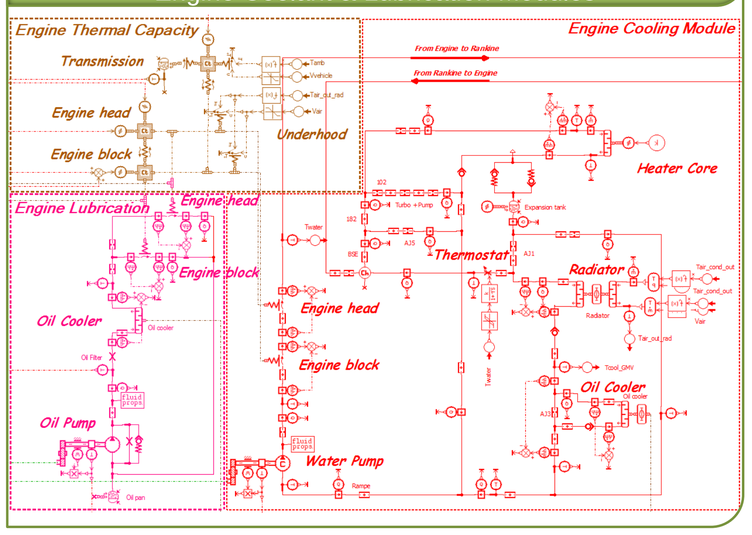
R134a ORC Control Diagram



Organic Rankine Cycle Control System

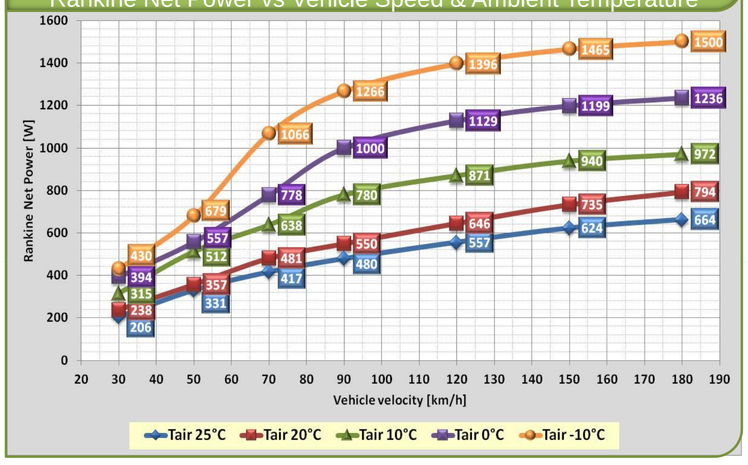
- **Control objective**
  - Maximize Rankine recovered mechanical net power
    $Pw_{mNet} = Pw_{mExp} – Pw_{mPmp} – Pw_{mFan}$
  - Ensure a minimal superheat at expander inlet: Sh_{rExpi_min}
  - Ensure a minimal subcooling at pump inlet: Sc_{rPmpi_min}
  - Avoid high pressure exceeds a maximal limit: P_{rEvp_max}
  - Avoid coolant return temperature below a minimal limit: T_{cEvpo_min}
- **Optimal operating conditions prediction**
  - From ORC sensors acquisition data : T_{cEvpi}, T_{rExpi}, P_{rExpi}, P_{rExpo}
  - From Vehicle acquisition data : T_{aExt}, V_{aExt}, N_{Eng}, Q_{cEvp}, Q_{cCnd}
  - Estimation of optimal high pressure and low pressure targets:
    $P_{rEvp\_sp} = f(T_{cEvpi}, T_{aExt}, Q_{cEvp}, Q_{cCnd}, V_{aExt})$
    $P_{rCnd\_sp} = g(P_{rEvpo\_sp}, T_{aExt})$
- **Expander and Pump speeds control**
  - Expander speed controlled to satisfy estimated high pressure P_{rEvp_sp} and high pressure limitation P_{rEvp_max}
  - Pump speed controlled to satisfy estimated low pressure P_{rCnd_sp} and expander superheat limitation Sh_{rExpi_min}

Vehicle Thermal Management Simulation Platform Engine Coolant & Lubrication Modules

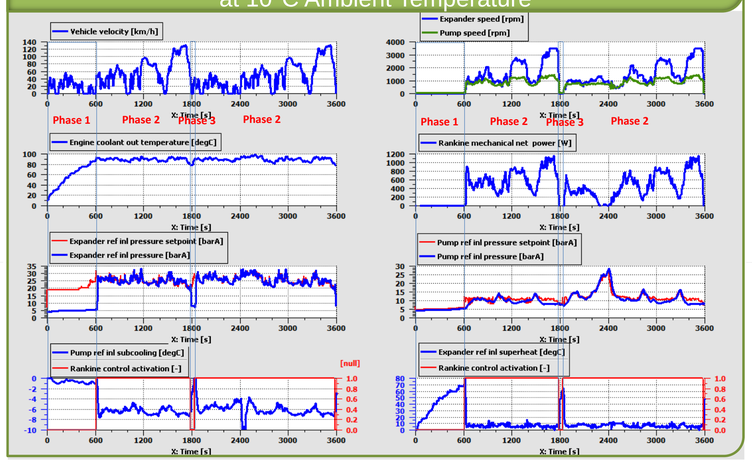


Rankine without EHR

Rankine Net Power vs Vehicle Speed & Ambient Temperature



Rankine with HER operation during WLTC Driving Cycle at 10°C Ambient Temperature

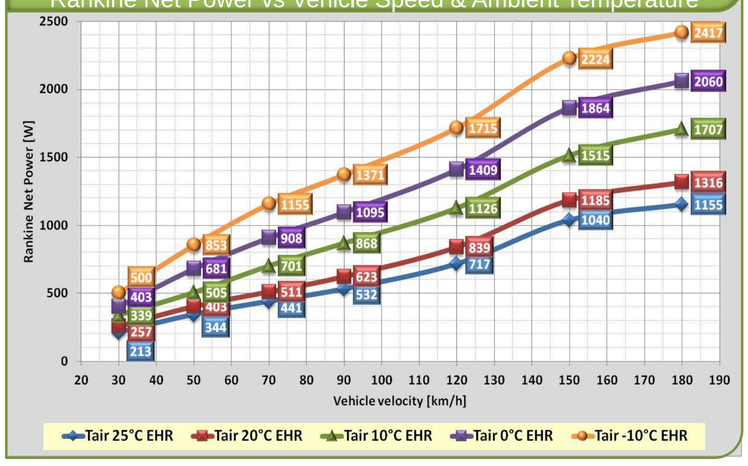


ORC Performances at constant vehicle velocity driving cycles

- **Mechanical net power for Rankine without EHR**
  - 200 W at 30 km/h to 660 W at 180 km/h at 25°C ambient temperature.
  - 300 W at 30 km/h to 1000 W at 180 km/h at 10°C ambient temperature.
  - 400 W at 30 km/h to 1500 W at 180 km/h at -10°C ambient temperature.
- **Mechanical net power for Rankine with EHR**
  - 200 W at 30 km/h to 1150 W at 180 km/h at 25°C ambient temperature.
  - 300 W at 30 km/h to 1700 W at 180 km/h at 10°C ambient temperature.
  - 500 W at 30 km/h to 2400 W at 180 km/h at -10°C ambient temperature.

Rankine with EHR

Rankine Net Power vs Vehicle Speed & Ambient Temperature



ORC Performances at transient WLTC cycles

- **Rankine system control phases**
  - Phase I : Rankine Off during engine heat up.
  - Phase II : Rankine On when engine is warm.
  - Phase III : Rankine switch off to avoid engine cool down.
- **WLTC cycle average mechanical net power for Rankine without EHR**
  - 270 W at 25°C ambient temperature to 660 W at -10°C for WLTC cycle.
  - WLTC cycle average power is ~ 50 W lower than for 46 km/h cycle.
- **WLTC cycle average mechanical net power for Rankine with EHR**
  - 300 W at 25°C ambient temperature to 750 W at -10°C for WLTC cycle.
  - WLTC cycle average power is ~ 50 W lower than for 46 km/h cycle.

WLTC Driving Cycle and 46 km/h Driving Cycle

Rankine Net Power vs Ambient Temperature