Thermodynamic Vehicle Integration of a Rankine Waste Heat Recovery System

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• Main focus of project
• GT Suite model with simplified WHR representation
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Vehicle Energy Balance (example)

**conventional**
- Engine: 100%
- Fuel: 100%
- Cooling System: 39%
- Exhaust: 30%
- EGR: 11%
- Net Engine Output: 42%

**with WHR system**
- Engine: 100%
- Fuel: 100%
- Cooling System: 48%
- Exhaust: 30%
- EGR: 11%
- Exh: 13%
- Net Engine Output: 45%

**Comparison**
- Increase with WHR system:
  - Cooling System: +23%
  - Net Engine Output: +7%
Principal layout of system

- EGR Evaporator substitutes today’s EGR cooler
- Main exhaust gas evaporator added behind exhaust aftertreatment
- Superheated working fluid drives expansion machine
- WHR condenser connected to main cooling system
Main focus of project

- Investigation of cooling system layouts for a (given) Rankine WHR system
  - Implementation of WHR condenser in cooling concept
  - Investigation of temperature levels for coolant side of WHR condenser
  - Secure cooling capacity for critical operating points
  - Evaluate function in operating points typical for WHR operation
- Proposal of control strategies
  - How to deal with lack of cooling capacity while preserving energy as much as possible
- Vehicle route analysis
  - Which amount of potential WHR energy can be used during a real drive cycle?
GT Suite Model

Overview: Model with simplified WHR representation

Medium Temperature Coolant Circuit

High Temperature Coolant Circuit

Rankine WHR (exhaust)
GT Suite Model

Details: Cooling module (Cool3D)

- Calibrated with dyno measurements and 3D-CFD
- Various configurations investigated and optimized

conventional

with WHR system

High Temperature Radiator
Medium Temperature Radiator
Charge Air Cooler
AC Condenser
**Details: Modelling of Rankine heat input and control strategy**

1. Exhaust gas maps (engine speed, engine load) for EGR and main exhaust gas
2. Evaporator performance (T<sub>out</sub> dependent on working fluid temp. and pressure)
3. Main exhaust gas can (partly) be bypassed to decrease heat load
4. Sum of heat load from WHR system dependent on expander efficiency

**Control strategy:** Main exhaust bypass ratio, fan speed and flow rates such that

- all temperatures and gradients within specifications
- Maximum of: Expander power – Fan power
Simulation results

Result: System behaviour for highway drive (example)

- Constant engine speed
- Increasing engine load
Simulation results

Result: System behaviour for highway drive (example)

- Constant engine load (100%)
- Increasing engine speed
Simulation results

Result: Energy balance for route profile (example)

Route histogram (example)

Utilization of potential WHR system power
- Potential power based on given evaporators
- 100 % → no exhaust bypass, fan power not increased compared to conventional vehicle

Weighting and integration of operating points according to route frequency
Complete GT Suite Model

Outlook: Detailed evaporator model

TheSys prototype: EGR evaporator

Component performance test bench

1-phase + 2-phase performance map measurements

TheSim two-stage regression method

1. Phase
2. Phase

1. Phase
2. Phase

TheSim 1-ph.
TheSim 2-ph.
TheSim 1-ph.

Superheater (gas to gas HX)
Boiler
Preheater (gas to liquid HX)

Working fluid (vapor)

Working fluid (liquid)

Exhaust inlet

Exhaust outlet
Complete GT Suite Model

Outlook: Detailed evaporator model

TheSim calculation with individual dataset

2-stage regression result

Direct implementation of TheSim correlation (HxNuCorr / UserModel)
Complete GT Suite Model

Outlook: Model with fully detailed Rankine WHR circuit
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