Feasibility Study of ICE Bottoming ORC with Water/EG Mixture as Working Fluid

Davide Ziviani\textsuperscript{a}, Donghun Kim\textsuperscript{a}, Swami Nathan Subramanian\textsuperscript{b}, James E. Braun\textsuperscript{a} and Eckhard A. Groll\textsuperscript{a}

\textsuperscript{a} Purdue University, School of Mechanical Engineering, Ray W. Herrick Laboratories, West Lafayette, IN, USA,

\textsuperscript{b} Eaton Corporate Research & Technology, Southfield, MI, USA
Outline

- Introduction
- Affordable Rankine Cycle
- Thermophysical Properties of Water/EG Mixture
- Thermodynamic Cycle Modeling
- Results
- Conclusions
- Future Work
Introduction (1/2)

• Heavy Duty Diesel Engines (HDDEs) reject a considerable amount of energy to the ambient

• In order to meet the U.S. Department of Energy (DOE) break thermal efficiency (BTE) goals, WHR by means of ORCs has been identified by U.S. engine manufacturers as viable solution

• Research on ORC systems applied to passenger and commercial vehicles has flourished in recent years
  - Subcritical and transcritical cycles (e.g., Amicabile et al. 2015)
  - Cascade cycles (e.g., Chen et al. 2017)
Introduction (2/2)

- Cost, complexity, environmental concerns and safety considerations are major issues that hold back OEMs from adopting ORCs in vehicles.

- Return of investment period for the end customer is not highly attractive by using current technology (3 to 4 years payback period).

- An affordable Rankine cycle (ARC) system is proposed in order to obtain real benefits of WHR on the road and reduce the costs by 50% with a targeted payback period of 1.4 to 2 years.

- A novel ORC architecture proposed within the ARC project is based on using the engine coolant as the working fluid.
Affordable Rankine Cycle (1/2)
Limitations arise concerning the maximum heat rejection rate.

To ensure normal operation of the truck engine, the following constraints are taken into account:

- Return temperature of engine recirculating gases
- Maximum engine coolant temperature at expander inlet
- Exhaust tail pipe boiler exit temperature
The working fluid is a binary mixture of water and ethylene glycol.

Few studies are available about thermodynamic and transport properties, e.g., Teja et al. 2003 and Dai et al. 2011.

As the mixture phase-change is an important aspect, VLE conditions need to be obtained to understand the effect of concentration shifting.

Original Water/EG mixture REFPROP file had issues:
Updated Water/EG mixture available within REFPROP 10.0 release
A steady-state cycle model has been developed in EES

Heat inputs are determined from the engine operation

The total heat rate available at the EGR and at the exhaust tail pipe:

\[ \dot{Q} = \epsilon_{HX} \dot{m} \Delta h \]

The heat rejected by the radiator:

\[ \dot{Q}_{\text{cond}} = \dot{m}_{\text{water/EG}} \Delta h_{\text{radiator}} \]

Pump and expander are modeled by assuming the isentropic efficiencies

The cycle performance and the benefits of the ARC system are quantified in terms of ORC thermal efficiency and Break Power (BP) improvement:

\[ \eta_{\text{ORC, net}} = \frac{\dot{W}_{\text{exp}} - \dot{W}_{\text{pump}}}{\dot{Q}_{\text{EGR,in}} - \dot{Q}_{\text{TP,in}}} \]

\[ BP = \frac{\dot{W}_{\text{exp}} - \dot{W}_{\text{pump}}}{\dot{W}_{\text{engine}}} \]
Cycle model assumptions:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixture concentration (mass fraction)</td>
<td>[0.5-0.5]</td>
<td>Engine coolant concentrations</td>
</tr>
<tr>
<td>T_{water-EG,max}, °C</td>
<td>220-300</td>
<td>Issues with thermal stability above 200 °C</td>
</tr>
<tr>
<td>p_{max}, kPa</td>
<td>2000</td>
<td>Expander limitations</td>
</tr>
<tr>
<td>Tail pipe HEX ΔT_{PP}, °C</td>
<td>5</td>
<td>Design choice</td>
</tr>
<tr>
<td>p_{cond}, kPa</td>
<td>variable</td>
<td>Related to radiator operating conditions</td>
</tr>
<tr>
<td>Tail pipe HEX ΔT_{PP}, °C</td>
<td>5</td>
<td>Design choice</td>
</tr>
<tr>
<td>Minimum expander inlet quality, -</td>
<td>0.5</td>
<td>Design choice</td>
</tr>
<tr>
<td>η_{is,exp}, -</td>
<td>0.6-0.8</td>
<td>Typical range for expanders [9]</td>
</tr>
<tr>
<td>η_{is,pump}, -</td>
<td>0.6</td>
<td>Design choice</td>
</tr>
</tbody>
</table>

Engine operating conditions:

<table>
<thead>
<tr>
<th>Parameter</th>
<th># 1</th>
<th># 2</th>
<th># 3</th>
<th># 4</th>
<th># 5</th>
<th># 6</th>
<th># 7</th>
<th># 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>T_{EGR,in}, °C</td>
<td>358.4</td>
<td>464.2</td>
<td>543.0</td>
<td>611.0</td>
<td>437.1</td>
<td>513.2</td>
<td>654.9</td>
<td>428.3</td>
</tr>
<tr>
<td>T_{TP,in}, °C</td>
<td>272.4</td>
<td>326.4</td>
<td>354.7</td>
<td>389.1</td>
<td>298.4</td>
<td>328.5</td>
<td>415.2</td>
<td>296.2</td>
</tr>
</tbody>
</table>
Effect of the Engine Operating Conditions (1/2)

Without heat rejection limitations

With heat rejection limitations

\[ T_{\text{exp, in}} = 220^\circ \text{C} \]
Effect of the Engine Operating Conditions (2/2)

- Variation of the water-EG mixture concentration

- Relaxed constraints on temperature and pressure
Effect of Expander Internal Volume Ratio (1/2)

- PD expanders are characterized by fixed internal volume ratio $r_{v,in}$
- The theoretical internal specific work can be computed as:

$$w_{in,th} = w_{is,exp} + w_{V=const,exp}$$

$$w_{is,exp} = h_{su}(T_{su}, p_{su}) - h_{in}(v_{in}, s_{su})$$

$$w_{V=const,exp} = v_{in}(p_{in} - p_{ex})$$

$$v_{in} = r_{v,in} V_s$$

- In the case of roots expanders:

$$w_{in,th} = w_{V=const,exp} = V_s(p_{in} - p_{ex})$$

- The actual specific work is affected by mechanical losses:

$$w_{in} = w_{in,th} \eta_{mech}$$
To evaluate the influence of the expander volume ratio on the performance of the ARC running with a water/EG (0.5-0.5) mixture:

- $p_{\text{cond}} = 110 \, kPa$; $p_{\text{evap}} = 1000 \, kPa, 1500 \, kPa, 2000 \, kPa$
- $T_{\text{EGR,in}} = 430 \, ^{\circ}C$; $T_{\text{TP}} = 294.4 \, ^{\circ}C$

$4 < r_{v,in} < 6$ would be suitable to optimize the system.
Conclusions

- Water-EG mixture has been proposed as working fluid of an ORC for WHR within heavy-duty trucks.
- A thermodynamic cycle model has been developed to investigate the potential improvements on the engine BTE.
- Simulation results showed that the employment of water-EG is heavily conditioned by engine operating conditions and high temperature limitations.
- The maximum BP improvement obtained was 6.94% for engine operating point #7.
- Although the initial parametric studies showed some potential for ARC architecture, additional work is needed to improve the performance especially under dynamic conditions.
- A dynamic cycle model with different control strategies will be further developed.


Future Work (1/2)

- WHR from a vehicle is a highly transient problem
- The optimization of the ORC during real operation requires a proper control strategy
- The development of a control strategy can be done by employing a dynamic model
- Since HXs influence the transient behavior of an ORC significantly, two dynamic models have developed
  - Moving Boundary Method (MB)
  - Finite Volume Method (FV)
- Challenges: binary-mixture, accuracy vs. computational speed, switching algorithm, numerical instabilities among others
Future Work (2/2)

- Comparison between experimental and numerical results for FVM under dynamic conditions:

  **Evaporator**
  - Pressure $P^E$ [Pa]
  - Enthalpy $h_1$ [kJ/kg]
  - Temperature $T_{C_{Evap}}$ [$^\circ$C]

  **Condenser**
  - Pressure $P^C$ [Pa]
  - Enthalpy $h_3$ [kJ/kg]
  - Temperature $T_{C_{Cond}}$ [$^\circ$C]

9/15/2017
D. Ziviani (dziviani@purdue.edu)
FV method is considered in this presentation

\[
\frac{\partial \rho_j}{\partial p} \frac{\partial \rho_j}{\partial h} \frac{\partial j}{\partial p} = \frac{1}{A dx} (m_{i,j} - m_{e,j})
\]

\[
\left( h_j \frac{\partial \rho_j}{\partial p} - 1 \right) \frac{\partial \rho_j}{\partial h} \frac{\partial j}{\partial h} = \frac{1}{A dx} (m_{i,j} h_{i,j} - m_{e,j} h_j)
\]

\{h_i(t), m_i(t), m_e(t), m_s(t), T_s,i(t)\} \rightarrow \{p(t), h_e(t), T_s,e(t)\}

Numerical comparison between MV and FV
Appendix (2/2)

- Profiles of model inputs ($T_w$: water temperatures, $m_w$: mass flow rates of water)
- Profiles of model outputs and experiments ($m_r$: refrigerant flow rate)