2017 DOE Vehicle Technologies Office Review

Affordable Rankine Cycle (ARC) Waste Heat Recovery for Heavy Duty Trucks

Principal Investigator: Swami Nathan Subramanian

Eaton

June 8, 2017

Project ID # ACS097

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Overview

Timeline

- Project Start Date: 11/25/2015
- Project End Date: 03/31/2017
- Phase 1 Percent Complete: 100%

Budget Period	Start Date	End Date	% Complete
Phase 1	11/25/2015	06/30/2017	100
Phase 2	07/01/2017	06/30/2018	Not Approved

Budget

Total Project Funding: $ 4,027,142

DOE (Eaton): $1,813,571
DOE (FFRDC) : $ 200,000
Eaton Cost Share:$2,013,571

DOE Funding BP1: $1,018,011
DOE Funding BP2: $ 795,560

Barriers

- **Performance:** Improve Heavy Duty engine efficiency (improvement ≥ 5 %) through WHR systems
- **Emissions:** Engine efficiency improvement without NOx and PM penalty
- **Cost:** Cost effective Rankine Cycle WHR system

Partners

- Project lead: Eaton Corporation
- Collaborations:
  - PACCAR Inc.
  - Modine Manufacturing Company
  - Purdue University
  - Mississippi State University
  - Kettering University
  - Argonne National Laboratory
  - Shell Global Solutions
  - AVL Powertrain Engineering
  - Torad Engineering

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Relevance
Objectives of This Study

Program Objectives

- Demonstrate heavy-duty diesel engine fuel economy improvement through "Roots Expander based Rankine Cycle Waste Heat Recovery Systems ":
  - Using engine coolant as the working fluid for WHR loop
  - 5% Fuel Economy (FE) improvement
- Demonstrate that other pollutants, such as NOx, HC, CO and PM will not increase as part of the overall engine/WHR/exhaust after treatment optimization
- Demonstrate a plan for 50% cost reduction by incorporation of ARC system

Phase 1 Objectives

- Study the feasibility of engine coolant as WHR working fluid
- Analyze exhaust heat energy availability in a heavy duty diesel engine through experiments and quantify the FE improvement from baseline experimental data
- Design WHR system components (Roots expander, heat exchangers) for Rankine cycle based on available exhaust energy
- Analytically predict 5% fuel economy improvement

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Milestones

Month/Year	Milestone	Status
Feb 2016	Kick off Meeting	Completed
March 2016	Engine Baseline	Completed
Nov 2017	WHR Architectures Evaluation	Completed
March 2017	Go/ No Go Review	Completed

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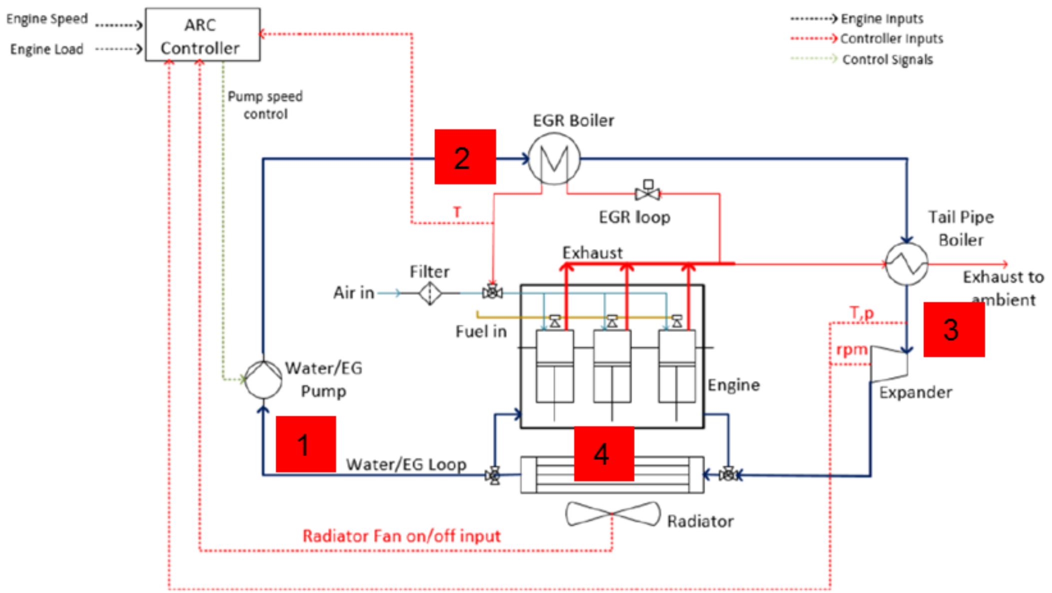
Approach/Strategy

- Using baseline 13 liter PACCAR HD diesel engine, characterize and quantify the potential waste energy sources for construction of thermodynamic analysis models – **June 2016** (**Completed**)
- Evaluate different ARC WHR system architectures theoretically and finalize optimized system (assess working fluid composition, heat exchanger layouts, expander size) – **Nov 2016** (**Completed**)
- Predict ARC system performance through analytical investigation – **Jan 2017** (**Completed**)

Technical Accomplishments and Progress

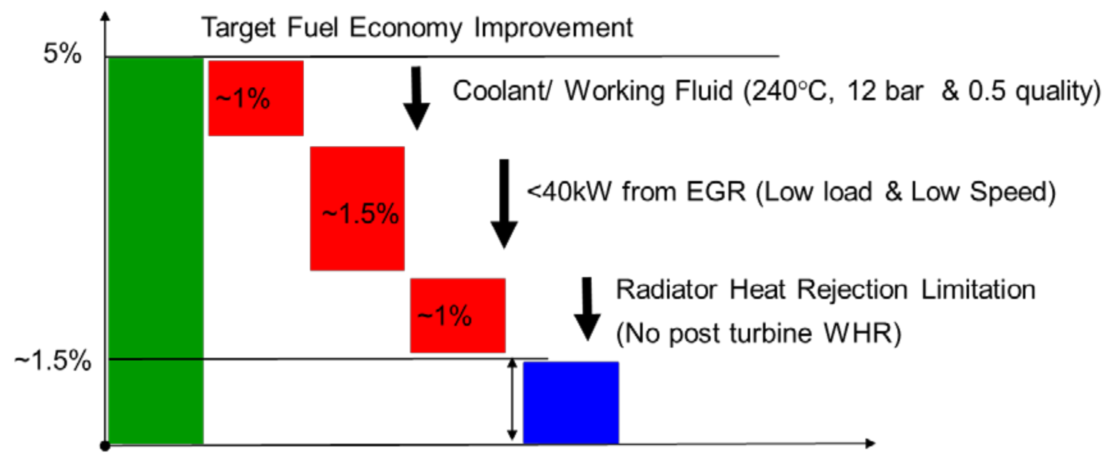
- Baseline engine calibration and experimental data collection
- Coolant feasibility analysis
- Two phase CFD analysis with two component engine coolant
- Analytical investigation of ARC WHR architectures
- WHR components design and development (analytical work)
- Analytical investigation of ARC performance

Technical Accomplishments
WHR Analysis



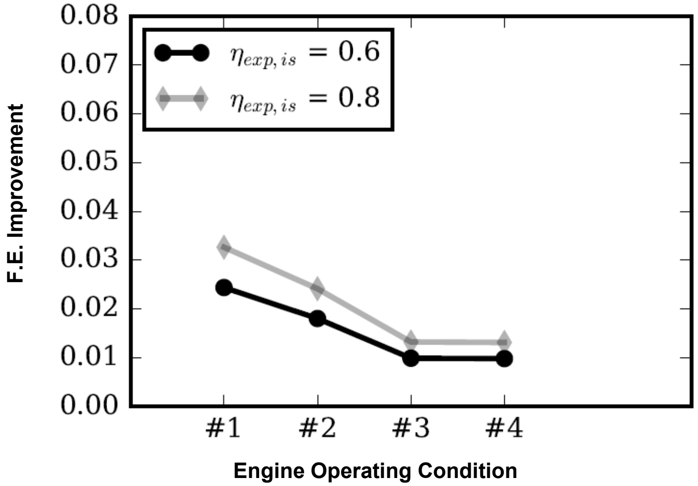
System performance constrained by:

1. Not recovering coolant energy from engine block
2. Max EGR inlet temperature limit
3. Working fluid: 240ºC max temperature, 12 bar max pressure & 0.5 max quality
4. Radiator heat rejection limitation



~1.5% Predicted F.E. Improvement

Technical Accomplishments
WHR Analysis



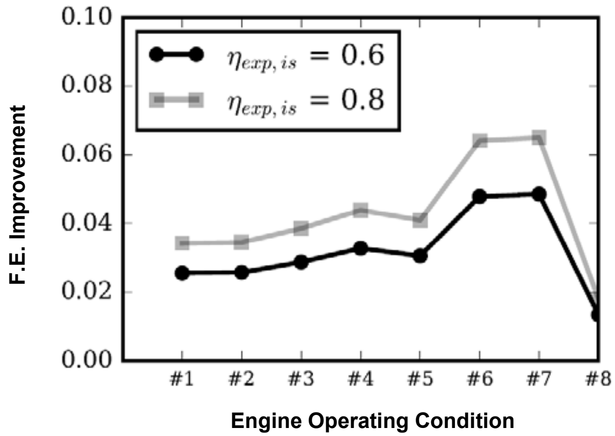
Engine Coolant Limits

240°C max temperature, 12 bar max pressure & 0.5 max quality

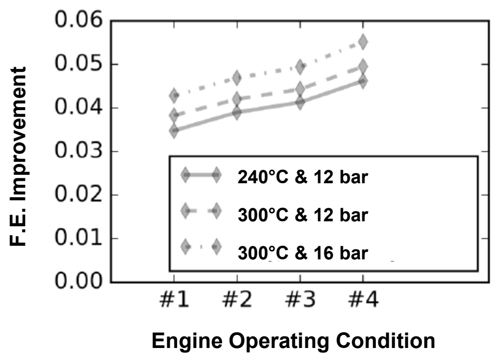
Engine Heat rejection Limitation

Minimum tailpipe (TP) heat recovery at A25 and A50 and no TP at A75 and A100

4% F.E. improvement is possible



With additional heat rejection (larger radiator)



Engine Coolant with increased upper spec (300°C & 16 bar)

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Responses to Previous Year Reviewers' Comments

This project was kicked-off Feb 2016 and the slide deck submitted to AMR team in April 2016. Hence reviewers had no major comments in most of the sections.

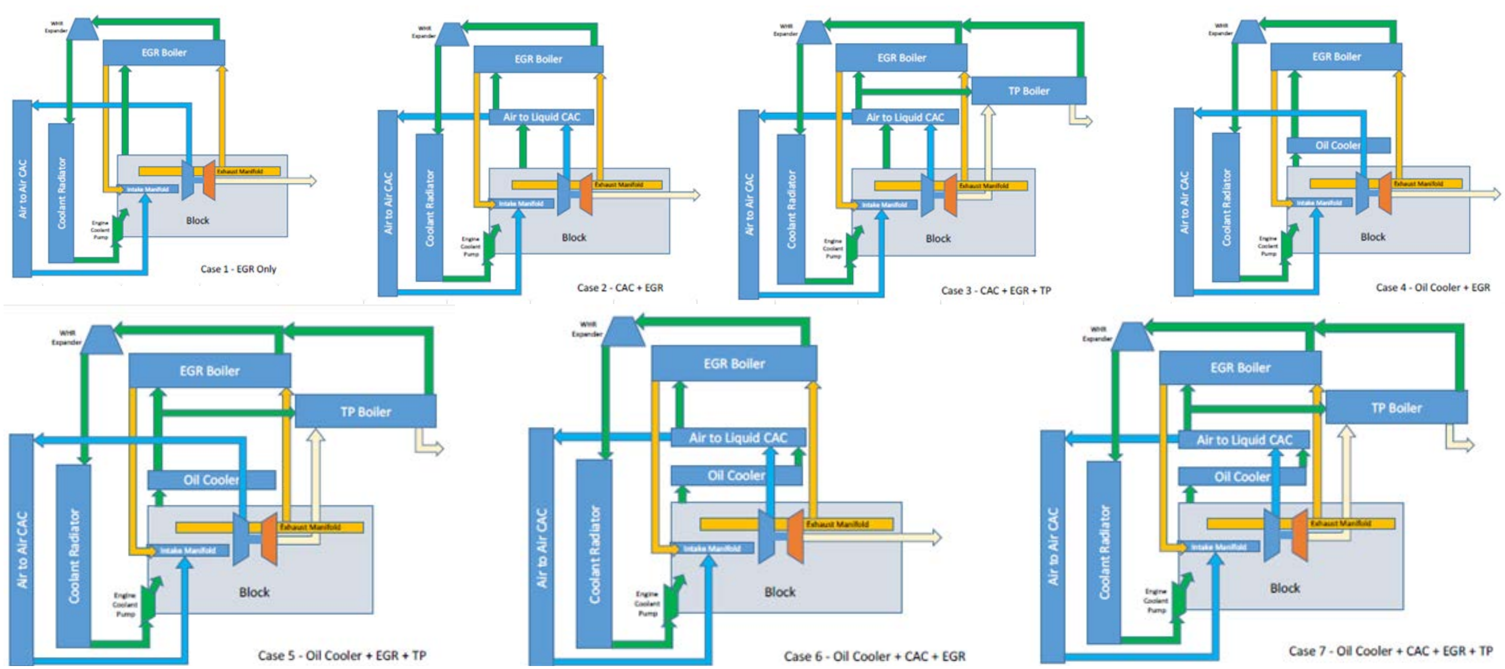
1. Approach to performing the work

Reviewer 1:

The reviewer stated that most of the work is still in progress. The steps presented on the Approach/Strategy slide seem to be in the right direction. Perhaps additional plots and visual representations other than words would help the reader understand the project team's intent faster.

The reviewer remarked that the use of the existing coolant as the working fluid eliminates the driver's burden to buy additional fluids— a feasibility study is in progress. The evaluation of different WHR architectures should include at least a basic schematic/drawing of the main WHR components: pump, boiler, expander, condenser, etc.

Different WHR architectures were analyzed



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Responses to Previous Year Reviewers' Comments

1. Approach to performing the work

Reviewer 2:

The reviewer noted that very early in the program, the plan looks fair. It would go a long way to have had a first-order analysis that would show what it takes to get a 5% fuel economy (FE) improvement—how much heat is needed, what efficiencies are needed, etc.

WHR analysis conducted in phase 1 and a final architecture has been selected based on boundary conditions (coolant degradation, engine EGR inlet temperature, vehicle heat rejection limitation) and results provided in this slide deck.

Reviewer 3:

The reviewer stated that, in the literature, the working fluid for WHR is typically ethanol, and the expected fuel economy benefit in real world driving is around 3%-5%. This project chooses to use the engine coolant as the working fluid with a target 5% FE improvement. If successful, it would represent a significant advance in WHR technology.

WHR analysis shows that a similar level (~4%) of benefit can be achieved with this approach using a larger radiator to address the vehicle's current heat rejection limitation. Results have been provided in this slide deck.

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Responses to Previous Year Reviewers' Comments

1. Approach to performing the work

Reviewer 4:

The reviewer noted that this project is at an early stage and the project team is pursuing an interesting strategy. The reviewer had concerns regarding the 5% FE increase with WHR systems. There were no thermodynamic data supporting this number presented in the presentation, and it seems like an aggressive goal. The reviewer said that it would be good to know the assumptions that go into the projected 5% FE benefit from this project.

Team worked with NIST to obtain proper working fluid properties (glycol-water two phase conditions) in phase 1 and analyzed different WHR architectures. Analytical results show ~4% of F.E. benefit can be achieved by adding radiator heat rejection capacity.

Reviewer 6:

The reviewer commented that using coolant as a working fluid is an excellent idea; however, the performance would be challenging to meet the target due to high-temperature decomposition of the coolant. It is not clear how 5% FE is defined. The reviewer wanted to know if it would be for a single point at 65 mph cruise speed or over the 13 mode composite Supplemental Emission Test point.

Team members agree with the working fluid constraint on glycol decomposition temperature. Selected SET 13 operating conditions based on customer payback weighting factors were used for F.E. improvement calculation.

Responses to Previous Year Reviewers' Comments

2. Technical accomplishments and progress
   - No major comments
3. Collaboration & coordination
   - No major comments
4. Proposed future work
   - No major comments
5. Does it support petroleum displacement goal
   - No major comments
6. Resources
   - No major comments

Collaborations and Coordination

Team Member	Responsibility
Eaton (Prime)	Design, develop, characterize, and deliver ARC system – HDDE exhaust waste heat recovery application
Torad	Design, develop, prototype, and deliver expander
Paccar	Perform engine baseline testing and provide inputs for basic WHR analysis, ARC system architecture optimization, HDDE performance predictions, and commercialization
Modine	Design, develop, characterize, and deliver Heat exchangers for ARC system – (EGR cooler, Post turbine boiler, Radiator which accommodates two phase condition and liquid to liquid condenser for testing purpose)
ANL	Perform two-phase heat transfer testing and develop correlations for analytical model predictions
MSU	Conduct experiments for working fluid feasibility in engine ORC system and final demonstration
Kettering University	Perform CFD analysis of the Roots expander design as well as inlet and outlet optimization for mixed-phase working fluid
Purdue University	Plant model development and WHR system analysis
AVL	Perform system analysis, optimization and support commercialization analysis
Shell Global Solutions	Conduct coolant analysis, support the project in an advisory role and provide expertise on engine coolant technology (formulations) and physical, chemical, and bench performance testing

Summary

- The baseline PACCAR engine provides an excellent platform for WHR demonstration
- 50/50 glycol-water mixture has been used as the working fluid (no secondary working fluid circuit)
- Original system architecture does not meet the 5% F.E. target and is constrained by the engine coolant upper specification and vehicle's heat rejection limit (based on WHR analysis for specific operating conditions)
- **Decision to stop ARC when Budget Period 1 ends 31 March 2017**

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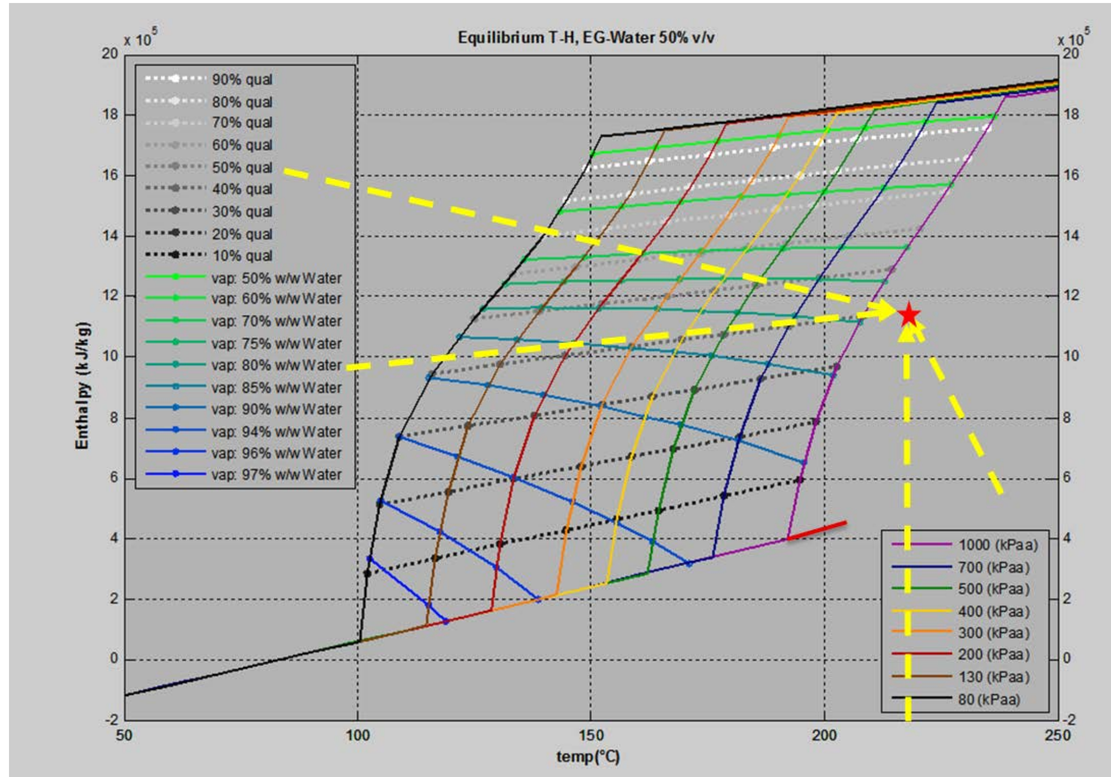
Technical Back-Up

Engine Coolant – WHR Working Fluid

	Scientific
Autoignition Temperature	427°C
Critical Pressure	8,200 kPa
Critical Specific Volume	0.191 L/gmol
Critical Temperature	446.85°C
Dielectric Constant at 25°C	37.7
Electrical Conductivity at 20°C	1.07×10^{-6} mhos/cm
Evaporation Rate (Butyl Acetate = 1)	0.01
Flash Point, Closed Cup (Pensky-Martens Closed Cup ASTM D93)	126.7°C
Flash Point, Open Cup (Cleveland Open Cup ASTM D92)	137.8°C
Heat of Combustion at 25°C	-1,053 kJ/gmol
Heat of Formation at 25°C	-460 kJ/gmol
Heat of Fusion	9.96 kJ/gmol
Heat of Vaporization at 1 atm	53.2 kJ/gmol
Molecular Weight	62.07 g/mol
Normal Boiling Point	197.1°C
BP/ P (750 to 770 mm Hg)	0.337°C/kPa
Normal Freezing Point	-13°C
Onset of Initial Decomposition	240°C



Engine Coolant Limits

<240°C max temperature (Team selected 220°C as the operating temperature)

<0.5 max quality (Team selected 0.47 as the operating quality)

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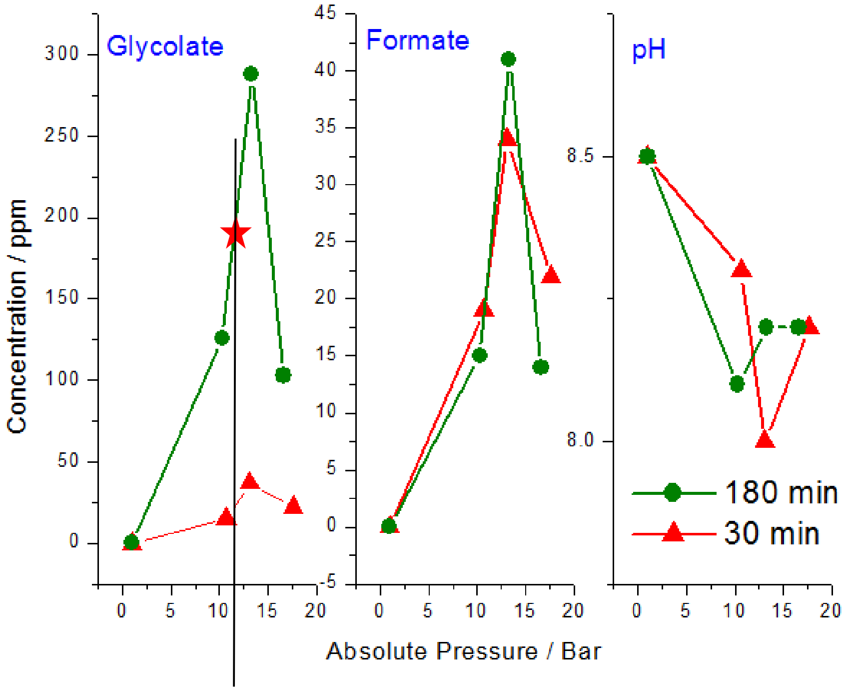
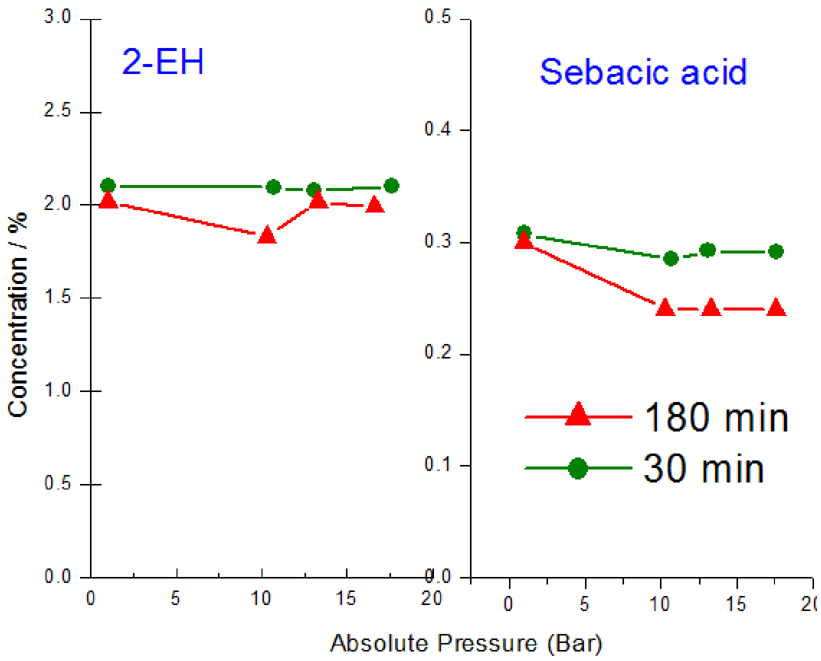
Engine Coolant – WHR Working Fluid

Degraded EG Products



Corrosion Inhibitors (OAT)



- Thermal degradation experiment was conducted at 165 ºC under various pressures

<u>Engine Coolant Limits</u>

<15 bar max pressure ; Team selected 12 bar as the operating pressure

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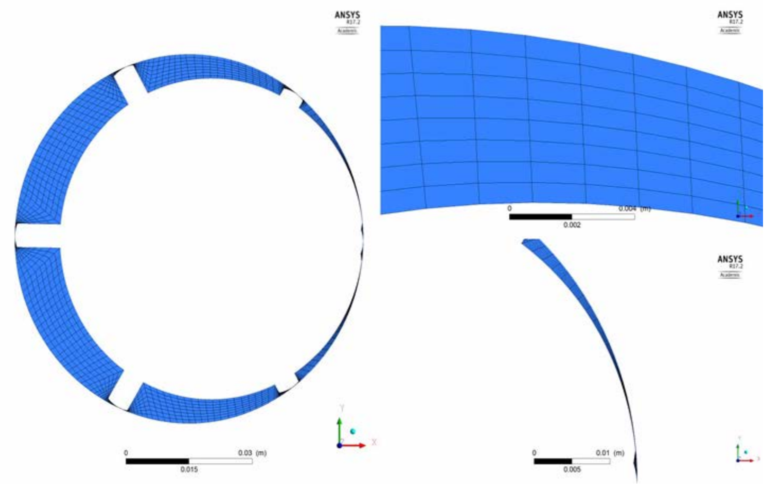
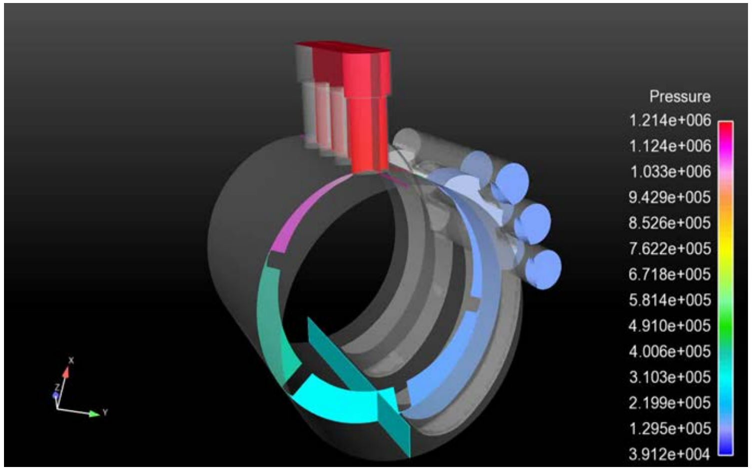
Torad Expander CFD Analysis



Operating Condition	Case 1	Case2
Speed (RPM)	2326	2326
Inlet Pressure (bar)	12	12
Outlet Pressure (bar)	1.5	1.5
Inlet Quality	0.37	0.46
Inlet Mass Flowrate (g/s)	33.2	28.0
Inlet density (kg/m3)	18.0	14.5
Volume flowrate (cc/s)	1844	1931
Average Torque (N.m)	18.21	17.48
Average Power (W)	4436	4257
Isentropic change in Enthalpy (J/g)	142.3	166.4
Isentropic Efficiency (%)	93.9	91.4



Theoretical analysis with the following assumptions

- Fluid frictional losses been included but mechanical losses (such as losses in gears and bearings) are not included
- Leakages around the tip of the vanes been included
- No heat transfer to the housing

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