Expansion of organic Rankine cycle working fluid in a cylinder of a low-speed two-stroke ship engine

Ulrik Larsen

Chalmers University of Technology

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Introduction

Background and motivation
Background and motivation

Emissions and fuel economy ($\text{CO}_2$)

Important ship emission factors: $\text{CO}_2$, $\text{NO}_x$, $\text{SO}_x$ and PM.

(freedigitalphotos.net)
Background and motivation
Emissions and fuel economy

Stricter regulations $\rightarrow$ increased fuel prices
50+ % of operational costs

(freedigitalphotos.net)
Background and motivation

The increasing interest in emission reduction, ship operating costs reduction, and the newly adapted IMO EEDI rules calls for measures that ensure optimal utilisation of the fuel used for main engines on board ships.

Main engine exhaust gas energy is by far the most attractive among the waste heat sources of a ship because of the heat flow and temperature. It is possible to generate an electrical output of up to 11% of the main engine power by utilising this exhaust gas energy in a waste heat recovery system consisting both steam and power turbines, and combined with utilising scavenge air energy for exhaust boiler feed-water heating.

This paper describes the technology behind waste heat recovery and the potential for shipowners to lower fuel costs, cut emissions, and the effect on the EEDI of the ship.

Introduction

Following the trend of a required higher overall ship efficiency since the first oil crisis in 1973, the efficiency of main engines has increased, and today the fuel energy efficiency is about 50%. This high efficiency has, among other things, led to low SFOC values, but also a correspondingly lower exhaust gas temperature after the turbochargers.

Even though a main engine fuel energy efficiency of 50% is relatively high, the primary objective for the shipowner is still to lower ship operational costs further, as the total fuel consumption of the ship is still the main target. This may lead to a further reduction of CO2 emissions – a task, which is getting even more important with the new IMO EEDI rules in place from 2013.

The primary source of waste heat of a main engine is the exhaust gas heat dissipation, which accounts for about half of the total waste heat, i.e., about 25% of the total fuel energy. In the standard high-efficiency engine version, the exhaust gas temperature is relatively low after the turbocharger, and just high enough for producing the necessary steam for the heating purposes of the ship by means of a standard exhaust gas-fired boiler of the smoke tube design.

However, the MAN B&W two-stroke ME main engine optimised for WHRS will increase the possibilities of producing electricity from the exhaust gas. The result will be an improvement in total efficiency but a slightly reduction of the efficiency of the main engine will be seen.

![Fig. 1: Heat balance for large-bore MAN B&W engine types without and with WHRS](MAN Diesel - Waste Heat Recovery Systems)
Background and motivation

Steam based WHR is well known

Photo by Francesco Baldi.
Background and motivation

Innovation! The new Still engine!

NEW BRITISH ENGINE SURPASSES DIESEL

Still’s Invention Recovers More Than 50 Per Cent. of Lost Fuel Energy.

INCREASES ENGINE POWER

(The New York Times 1919)
Background and motivation

Innovations

(Prater, SAE 2000-01-3070)
Background and motivation

Cost-effectiveness

For a WHR to be successful:

1. Minimize loss and degradation of the residual exhaust energy en route to the conversion apparatus
2. Provide for efficient expansion of vapor formed using the rejected heat
3. Limit the number and complexity of components to be added to the engine

(Prater, SAE 2000-01-3070)
Background and motivation

Innovations
Introduction

Objectives
Objectives

Perform a design point steady-state analysis of the concept
- to determine the potential power that can be produced
- identify the optimised process conditions (fluid, pressures, timings)
Methodology

Case
## Methodology

### Table 1
Diesel engine specifications.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
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<tbody>
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<td>Stroke (m)</td>
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<td>Specified MCR (MW)</td>
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<td>Turbochargers (-)</td>
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<tr>
<td>Turbochargers type (-)</td>
<td>High efficiency</td>
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<td>Mean effective pressure (bar)</td>
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Methodology

The expansion process
Methodology

Process
Methodology

The diesel cylinders engine model
Methodology

A marine low-speed two-stroke engine

A zero-dimensional type model:

- thermodynamic properties, Gyftopoulus and Baretta;
- heat losses, Woschni;
- Redlich-Kwong corrections to the ideal gas law;
- combustion heat release, Wiebe (Miyamoto version);
- friction model, Chen and Flynn, and Winterbone;
- a two-zone combustion model;
- combustion products, Rakapoulus, and;
- NOx, the extended Zeldovich mechanisms + Kilpinen corrections.
Methodology

The fluid expander model
Methodology

The fluid expander model

- energy balance;
- friction losses (as for the diesel cylinders);
- heat losses (as for the diesel cylinders);
- valve opening and flow models;
- Coolprop fluid models.
Methodology

Boilers and pump
Methodology
The fluid expander model

- energy balances;
- UA log mean temperature model;
- Coolprop fluid models.
Methodology

Optimisation
Methodology

Optimisation

- Particle swarm;
- Pattern search.

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Optimisation variables.</th>
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<td>ORC evaporation pressure (bar)</td>
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<td>Superheating approach ($^\circ$ C)</td>
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<tr>
<td>Temperature difference $T_f - T_2$ ($^\circ$ C)</td>
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<td>Exhaust valve closing time (CAD)</td>
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<td>Condensing temperature ($^\circ$ C)</td>
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<td>End of injection time (CAD)</td>
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<td>Exhaust valve opening time (CAD)</td>
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<td>Geometrical expansion ratio (-)</td>
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Methodology

Models validity
Methodology

Validity

Table 4
Comparison with dynamic model.

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<th>Fluid</th>
<th>Mass flow (kg/s)</th>
<th>Power, relative (%)</th>
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Results

Fluids and power potential
Results
Results

![Graph showing the relationship between cylinder power (MW) and cylinder inlet exergy flow (MJ/s). The graph depicts a positive correlation with scattered data points and a linear trend line.]
Results

**Regular diesel cycle**

**Cyclopropane expansion**

![Graphs showing cylinder pressure and volume for diesel and cyclopropane cycles.](image-url)
Results

Regular diesel cycle vs Cyclopropane expansion

Power (MW)

Crank angle (°)
Results

Optimised parameters
## Results

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<th>$EVO$ (°)</th>
<th>$T_1$ (°C)</th>
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Results

Sensitivity to parameters
Results

![Graph showing power in kW as a function of maximum UA value in kW/K for different substances: R245fa (blue), Cyclopropane (red), R1234ze(z) (brown).]
Results

![Graph showing power (kW) vs. maximum expansion ratio (-) for different refrigerants. The graph compares R245fa, Cyclopropane, and R1234ze(z).]
Results

Graph showing the power (kW) for different working fluid temperatures (°C).

- **R245fa**
- **Cyclopropane**
- **R1234ze(z)**
Results
Discussion

Future work

- part-load performance;
- dynamic problems;
- power the entire engine by vapor expansion (external combustion);
- expansion under the pistons;
- experimental work.
The

End