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

Ulrik Larsen

Chalmers University of Technology

MOSES, Sion, October 2017

Introduction

Background and motivation

Background and motivation

Emissions and fuel economy (CO_2)

Important ship emission factors: CO_2, NO_x, SO_x and PM.

(freedigitalphotos.net)

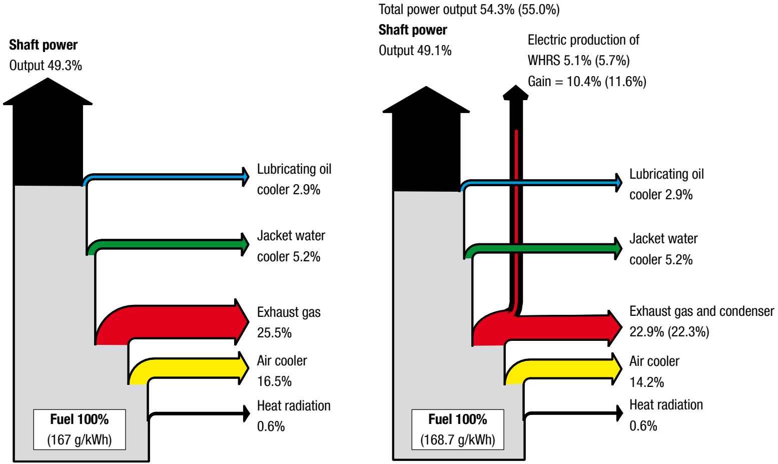
Background and motivation

Emissions and fuel economy

Stricter regulations → increased fuel prices
50+ % of operational costs

(freedigitalphotos.net)

Background and motivation



(MAN Diesel - Waste Heat Recovery Systems)

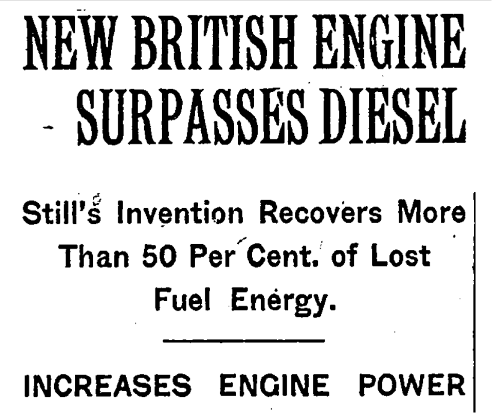
Background and motivation

Steam based WHR is well known

Photo by Francesco Baldi.

Background and motivation

Innovation! The new Still engine!



NEW BRITISH ENGINE SURPASSES DIESEL

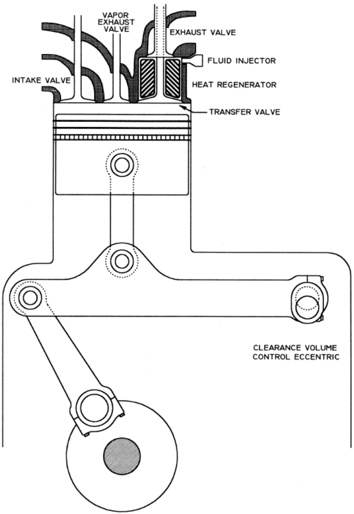
Still's Invention Recovers More Than 50 Per Cent. of Lost Fuel Energy.

INCREASES ENGINE POWER

(The New York Times 1919)

Background and motivation

Innovations



(Prater, SAE 2000-01-3070)

Background and motivation

Cost-effectiveness

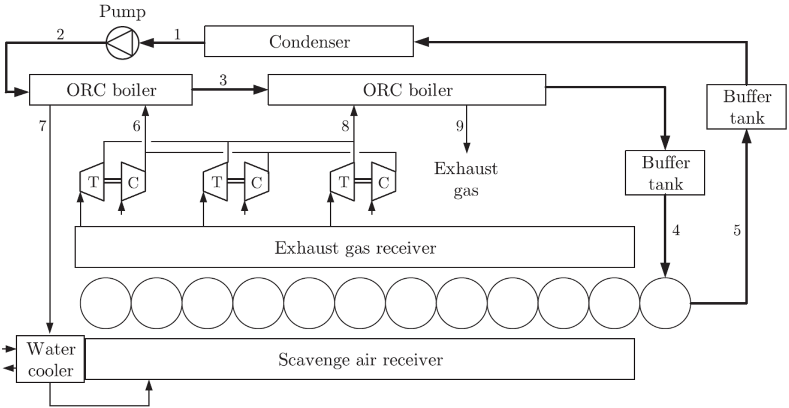
For a WHR to be successful:

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.

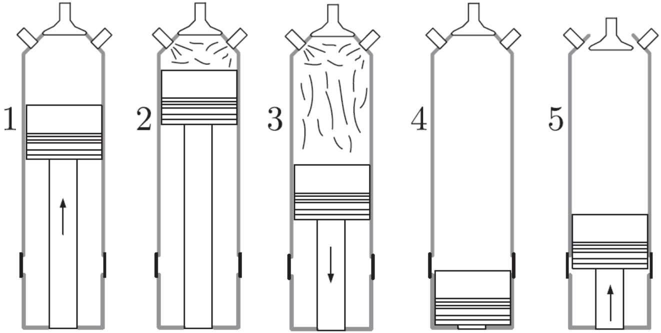
Type	12K98ME-C6
Cylinders (-)	12
Bore (m)	0.98
Stroke (m)	2.66
Engine speed MCR (rpm)	104
Specified MCR (MW)	68.52
Turbochargers (-)	3
Turbochargers type (-)	High efficiency
Mean effective pressure (bar)	18.2

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 3
Optimisation variables.

	Limits
ORC evaporation pressure (bar)	5-p_c
Superheating approach (° C)	1–150
Temperature difference T_7–T_2 (° C)	5–100
Exhaust valve closing time (CAD)	90–179
Condensing temperature (° C)	40–120
End of injection time (CAD)	185–359
Exhaust valve opening time (CAD)	361–500
Inlet valve radius (m)	0.005–0.18
Geometrical expansion ratio (-)	2–50

Methodology

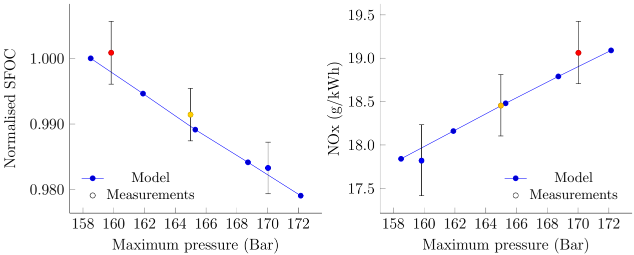
Models validity

Methodology

Validity

Table 4
Comparison with dynamic model.

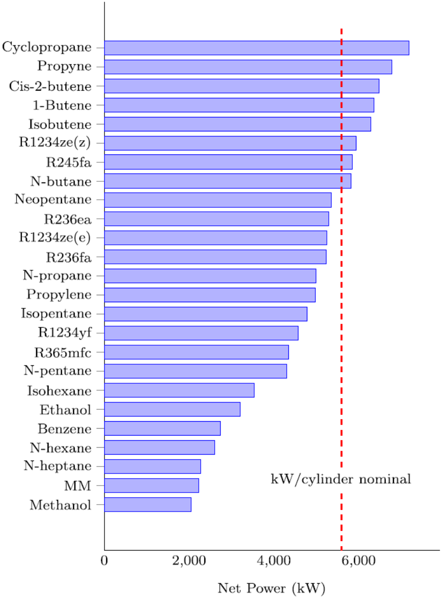
Fluid	Mass flow (kg/s)	Power, relative (%)
Cyclopropane	70	−2.2
Isobutene	67	−1.1
R245fa	125	−8.4
R1234ze(z)	132	−4.8
Cis-2-butene	57	−7.0



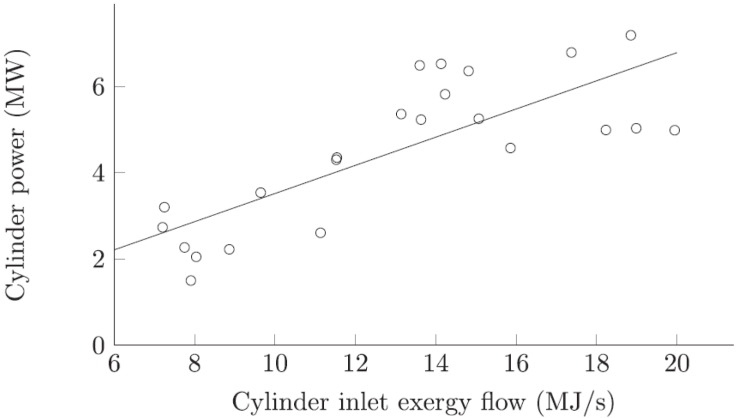
Results

Fluids and power potential

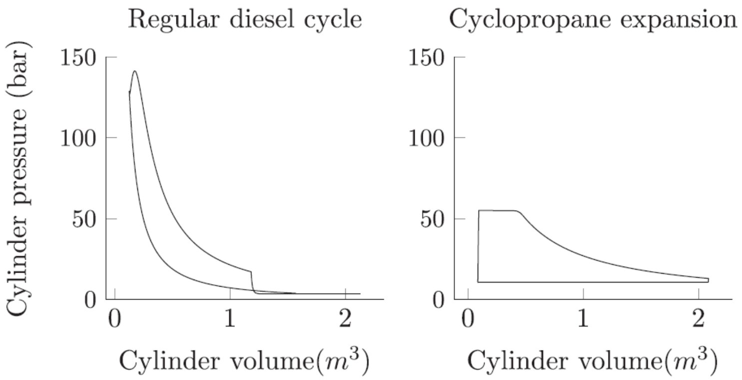
Results


Cyclopropane
Propyne
Cis-2-butene
1-Butene
Isobutene
R1234ze(z)
R245fa
N-butane
Neopentane
R236ea
R1234ze(e)
R236fa
N-propane
Propylene
Isopentane
R1234yf
R365mfc
N-pentane
Isohexane
Ethanol
Benzene
N-hexane
N-heptane
MM
Methanol
kW/cylinder nominal
0
2,000
4,000
6,000
Net Power (kW)

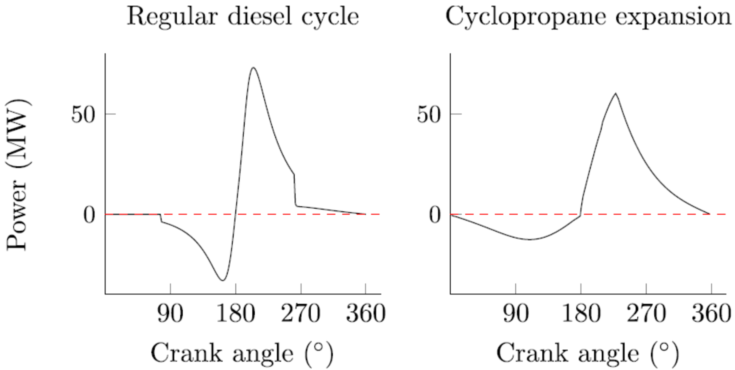
Results


Cylinder power (MW)
0
2
4
6
6
8
10
12
14
16
18
20
Cylinder inlet exergy flow (MJ/s)

Results


Regular diesel cycle
Cyclopropane expansion
Cylinder pressure (bar)
150
100
50
0
0
1
2
Cylinder volume(m^3)
Cylinder volume(m^3)

Results


Regular diesel cycle
Cyclopropane expansion
Power (MW)
50
0
90
180
270
360
Crank angle (°)
50
0
90
180
270
360
Crank angle (°)

Results

Optimised parameters

Results

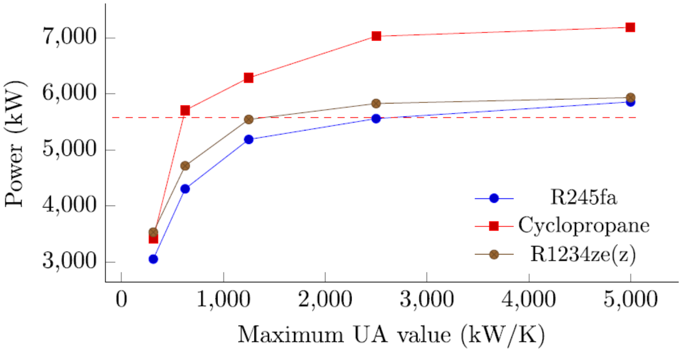
Table 5
Optimised parameters.

Fluid	γ (-)	T_4 (° C)	Δ_i (-)	EVO (°)	T_1 (° C)	α (-)	r (m)	ΔT (° C)	$\dot{m}_1$ (kg/s)	$\overline{UA}_1$ (kW/K)	$\overline{UA}_2$ (kW/K)
Cyclopropane	0.998	200	177–231	361	40	44.3	0.13	6	70	3474	385
Propyne	1.000	229	177–230	384	50	39.5	0.14	8	57	2947	574
Cis-2-butene	0.946	242	177–230	361	40	49.0	0.16	24	57	2506	1586
1-Butene	0.999	207	177–232	362	40	49.8	0.18	9	71	2658	533
Isobutene	0.998	220	177–232	361	40	49.4	0.15	9	67	3314	634
R1234ze(z)	0.997	205	175–232	361	40	43.1	0.10	6	133	3793	570
R245fa	0.999	224	175–230	361	40	47.2	0.09	7	125	4021	817
N-butane	0.998	230	180–232	363	40	50.0	0.11	11	61	4146	926
Neopentane	0.999	204	176–230	361	40	49.1	0.16	5	75	3321	1034
R236ea	0.897	210	177–236	366	40	49.9	0.18	6	148	2654	460
R1234ze(e)	1.000	214	177–238	361	40	50.0	0.18	5	131	1996	462
R236fa	1.000	224	177–236	361	40	49.3	0.18	6	143	2715	639
N-propane	0.997	172	182–243	362	40	49.0	0.16	5	80	1452	255
Propylene	1.000	192	184–244	375	40	43.9	0.18	6	76	1409	303
Isopentane	0.905	200	177–221	361	40	50.0	0.16	32	66	813	2476
R1234yf	1.000	180	177–245	361	40	37.1	0.18	5	163	1380	278
R365mfc	0.611	194	176–243	361	40	49.9	0.17	5	129	3865	923
N-pentane	0.550	193	177–250	362	40	50.0	0.16	9	70	3903	927
Isohexane	0.574	201	175–234	361	40	47.4	0.12	57	55	410	3381
Ethanol	0.260	244	179–235	362	59	49.8	0.16	99	20	82	1801
Benzene	0.235	197	180–249	361	57	49.9	0.16	100	40	69	3332
N-hexane	0.295	213	177–288	361	42	36.3	0.18	23	59	3754	4178
N-heptane	0.356	209	179–242	362	40	49.7	0.16	99	40	117	1882
MM	0.519	215	176–238	361	48	49.9	0.17	72	62	221	2875
Methanol	0.081	247	184–333	361	40	4.2	0.16	70	22	406	438

Results

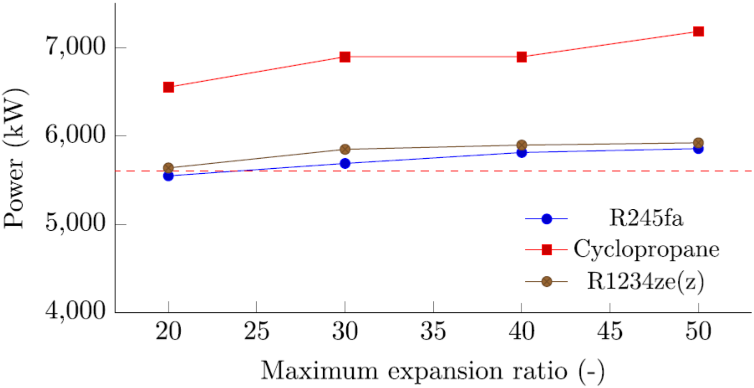
Sensitivity to parameters

Results

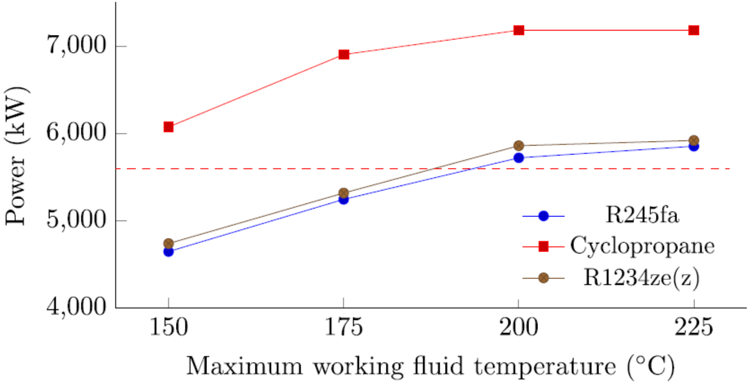


Power (kW)
7,000
6,000
5,000
4,000
3,000
0
1,000
2,000
3,000
4,000
5,000
Maximum UA value (kW/K)
R245fa
Cyclopropane
R1234ze(z)

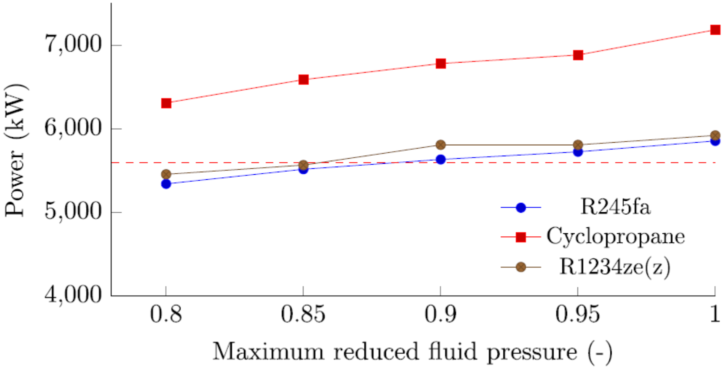
Results


Power (kW)
7,000
6,000
5,000
4,000
20
25
30
35
40
45
50
Maximum expansion ratio (-)
R245fa
Cyclopropane
R1234ze(z)

Results


7,000
6,000
5,000
4,000
Power (kW)
150
175
200
225
Maximum working fluid temperature (°C)
R245fa
Cyclopropane
R1234ze(z)

Results


7,000
6,000
5,000
4,000
Power (kW)
R245fa
Cyclopropane
R1234ze(z)
0.8
0.85
0.9
0.95
1
Maximum reduced fluid pressure (-)

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