DESIGN OF A SCROLL EXPANDER FOR AN ORC APPLICABLE TO A PASSENGER CAR FOR FUEL CONSUMPTION IMPROVEMENT

Hyunjin Kim, Jeseung Yu, Department of Mechanical Engineering, University of Incheon, Korea

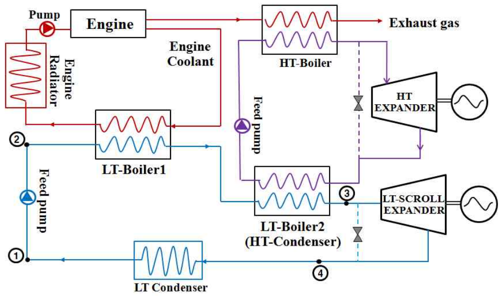
Goal of the study

For automobile engine, about one third of fuel energy is converted into kinetic energy for car operation. Over 60~70% of the fuel energy is thrown a way into the atmosphere as waste heat.

This study aims to improve fuel consumption of a passenger car by applying an organic Rankine cycle to the engine cooling system for recovering waste heat of the engine coolant and converting it to the useful shaft work.

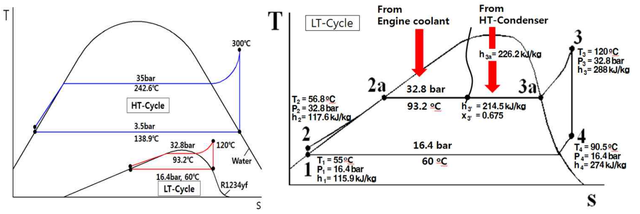
ORC system fo waste heat recovery from automobile engine

Waste heat recovery system from an automobile engine consists of two inter-related Rankine cycles. A high-temperature (HT) cycle is to utilize waste heat of exhaust gas and low-temperature (LT) one is for recovering the engine coolant heat. Heat rejected from HT-condenser is used as an additional heat supply to LT-cycle working fluid. Hence the HT-condenser can be regarded as secondary LT-boiler. (This study only focuses on LT-cycle).



A T-s diagram of the R1234yf Rankine cycle under design operating condition together with that of HT-cycle is presented. Saturation pressures are 32.8 bar and 16.4 bar for Teva=93.2℃ and Tcond.=60℃. respectively for LT-cycle. Theoretical Rankine cycle efficiency is defined by the ratio of the expander output power to the supplied heat as follows.

$$\eta_{R,th} = \frac{(h_3 - h_4) - (h_2 - h_1)}{(h_3 - h_2)} = 7.23\%$$



Scroll expander for an automobile ORC system (LT-cycle)

The shaft output of the expander is to reduce the engine duty via clutch system. since waste of the engine coolant of a passenger car ranges from several to tens kilowatts, the expander shaft output would be at most several kilowatts. So, turbine would not be an appropriate type for the expander in such small capacity, low shaft speed system, but positive displacement type expander would be much better.

For the present Rankine cycle coupled with the engine cooling system, scroll expander was chosen.

Design of scroll expander

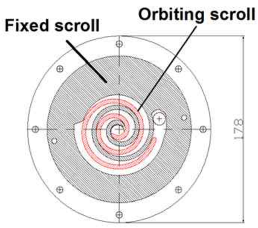
Basic structure of the scroll expander is illustrated. The orbiting scroll is engaged with the fixed scroll from expansion chambers. When the working fluid fo high pressure and temperature enters into the expander inlet at the center of the fixed scroll, it starts to expand in the sealed pockets, making the orbiting scroll to orbit. The orbiting scroll is coupled with the crankshaft eccentric pin at the orbiting scroll hub the so that the orbiting motion of the orbiting scroll may be transmitted to the crankshaft rotation. For lubrication, trochoid oil pump is applied at the rear side of the expander.

Design conditions for LT scroll expander

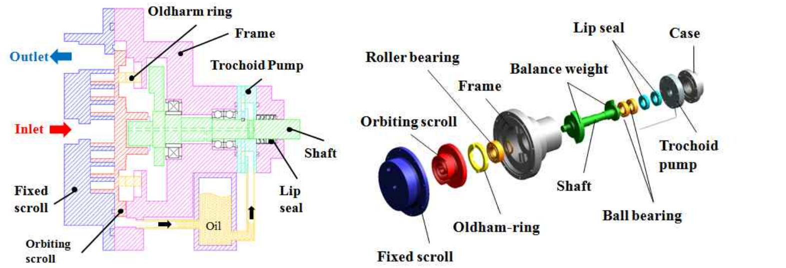
Notation	Description	Values
Q_{in}	Flow rate	145 [LPM]
P_{in}	Inlet pressure	32.8 [bar]
T_{in}	Inlet temperature	120 [℃]
P_{out}	Outlet pressure	16.4 [bar]
N	Shaft speed	4500 [RPM]

Designed fixed and orbiting scroll

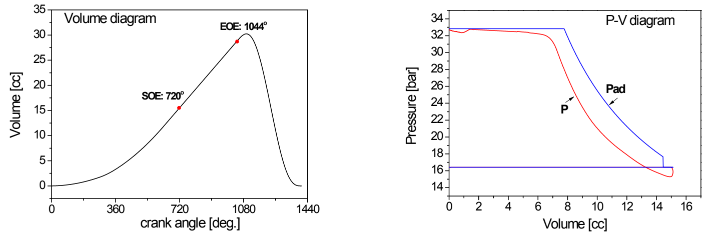
Scroll Wrap Parameters		
Notation	Description	Value
r_s	Orbiting radius	3 [mm]
a	Base circle radius	2.2282 [mm]
t	Wrap thickness	4 [mm]
h	Wrap height	28 [mm]
α	Involute starting angle	51.4 [°]
e	Involute end angle	973.42 [°]
ϕ_d	Cutter angle	288.29 [°]
ϕ_d	Discharge starting angle	325.12 [°]



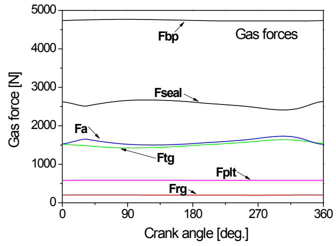
Modeling of expander



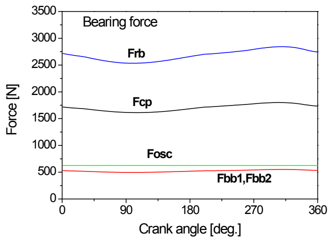
Numerical simulation on the expander performance



Volume diagram   P-V diagram



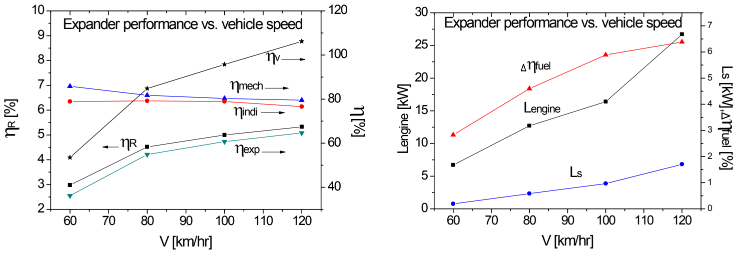
Gas forces



Bearing forces

Notation	Description	Value
L_{th}	Theoretical power [W]	2799.3
L_{indi}	Indicated power [W]	2144.9
ΔL_{mech}	Mechanical loss [W]	440.4
L_{wrap}	Wrap tip [W]	181.4
L_{cp}	Drive bearing [W]	73.2
L_{rb}	Roller bearing [W]	158.1
$L_{bb1,2}$	Ball bearing [W]	12.3
L_{or}	Oldham-ring [W]	3
L_s	Shaft power [W]	1704.5
η_v	Volumetric efficiency [%]	106.2
$\eta_{indi.}$	Indicated efficiency [%]	76.6
η_{mech}	Mechanical efficiency [%]	79.5
η_e	Expander efficiency [%]	64.7

Scroll expander performance at design condition



Expander performance vs. vehicle speed

Conclusion

- Application of an organic Rankine cycle to a passenger car has been considered to improve fuel consumption by recovering engine coolant heat
- The evaporator and condenser temperatures of the ORC were set at T_H=93℃ and T_L=60℃, respectively, for the vehicle speed of 120km/hr. At this temperature condition, theoretical efficiency of the Rankine cycle with R1234yf as the working fluid was 6.4%.
- A scroll expander was designed for energy conversion from thermal energy of the working fluid in the ORC to useful shaft power. For axial compliance, a back pressure chamber was provided on the rear side of the orbiting scroll. Lubrication oil was to be delivered by a positive displacement type oil pump driven by the expander shaft.
- Performance analysis on the designed scroll expander showed that the expander efficiency was 64.7%. It extracts the shaft power of 1.7kW out of engine coolant waste heat (plus some portion of the exhaust gas heat) of 32.1kW
- This amount of the expander output is equivalent to the fuel consumption improvement of about 6.4% for the passenger car under consideration at the vehicle speed of 120km/hr.
- With decreasing vehicle speed, the scroll expander efficiency was calculated to decrease accordingly: it turned out to be 36.2% at 60km/hr, resulting in ab out 2.8% improvement in the fuel consumption.