Tsinghua University
Engine Fluids and Turbo Laboratory

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Heat-storage ORC System of Vehicle ICE Exhaust Heat Recovery with the Capacity of Reducing Heat Fluctuation

Tao CHEN, Lei ZHANG, Weilin ZHUGE, Yangjun ZHANG
State Key Laboratory of Automotive Safety and Energy
Tsinghua University, Beijing, China

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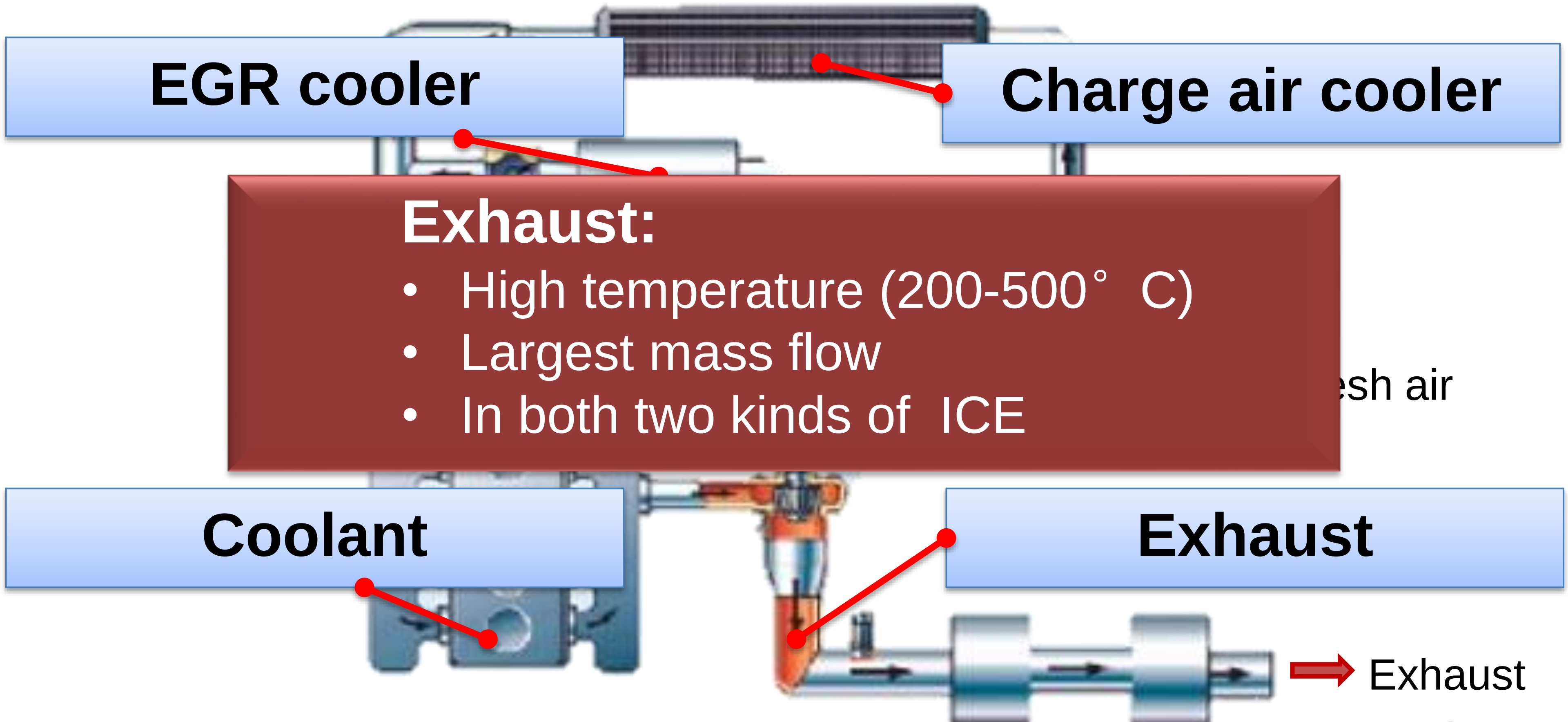
Introduction

Organic Rankine Cycle(ORC) waste heat recovery system in internal combustion engine(ICE)



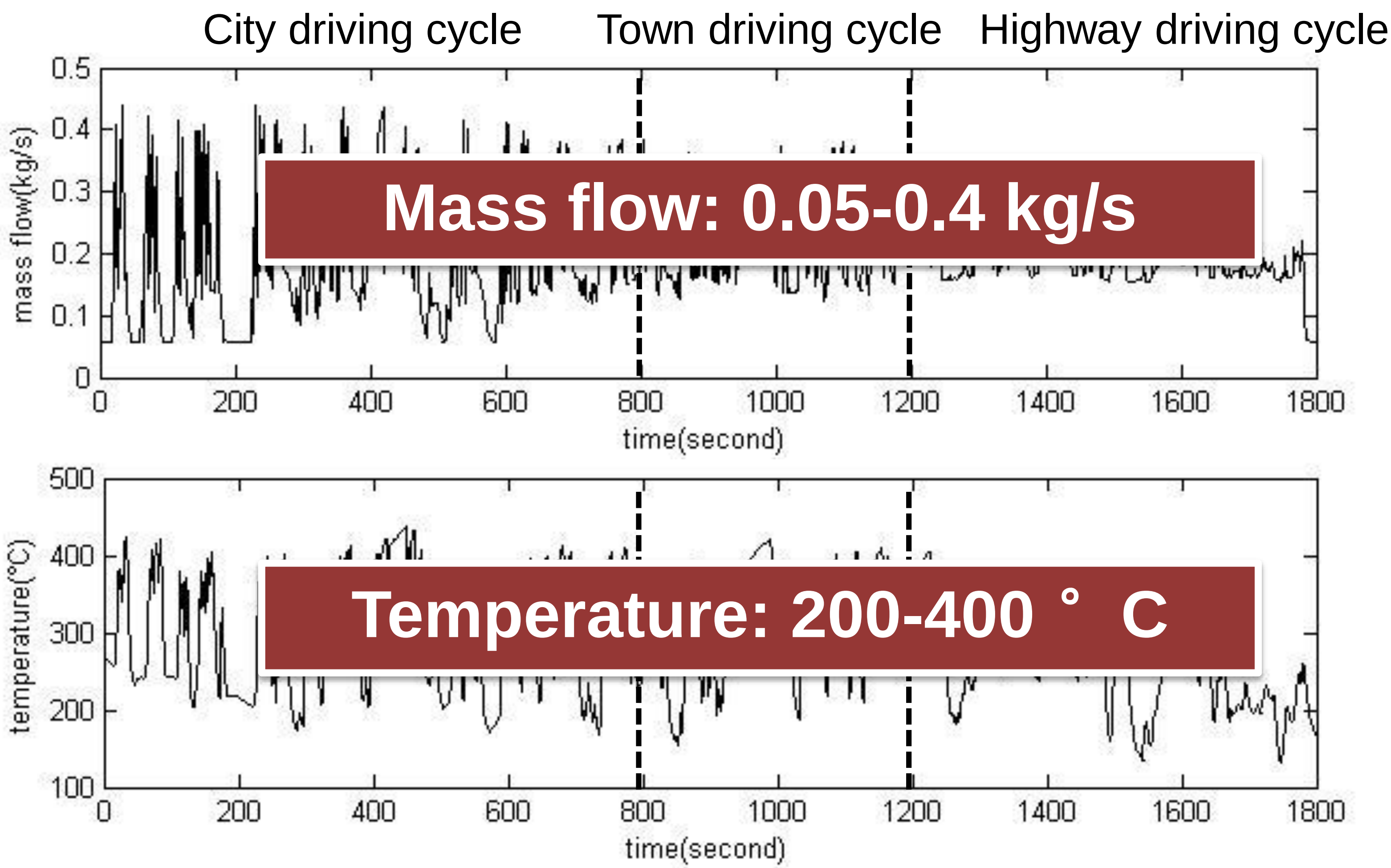
Exhaust:

- High temperature (200-500° C)
- Largest mass flow
- In both two kinds of ICE

Diesel engine

Introduction

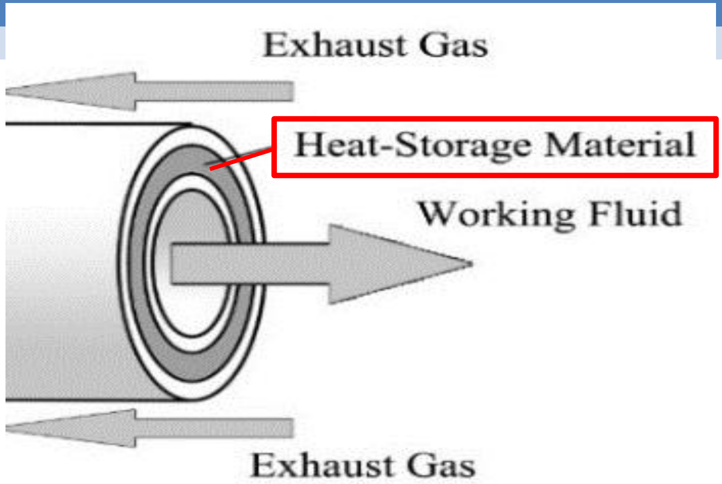
Heat fluctuation of ICE exhaust



Experiment data of engine exhaust in the ETC cycle

Introduction

Heat-storage ORC system



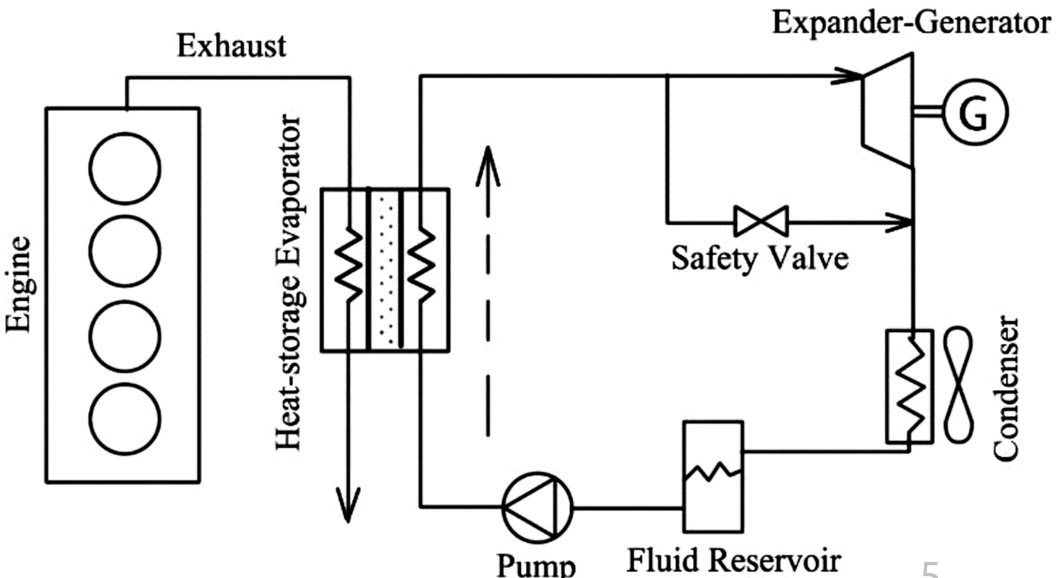
Principle diagram of heat-storage evaporator pipes

Methods to reduce impact of heat fluctuation:

- Active control
- Increase ORC system thermal inertia

Heat-storage ORC system:

- Heat-storage evaporator
- Safety valve



Conceptual scheme of heat-storage ORC system

Introduction

Highlights in this paper

- Propose a heat-storage ORC system to recover waste heat of ICE and to reduce the heat fluctuation with R245fa as working fluid.
- Establish system dynamic model and simulate the performance of the heat-storage ORC system using the experimental data of engine exhaust.
- Analyze main effects (Heat resistance effect & Heat capacity effect) of the heat-storage evaporator, and discuss the selection of heat-storage materials.

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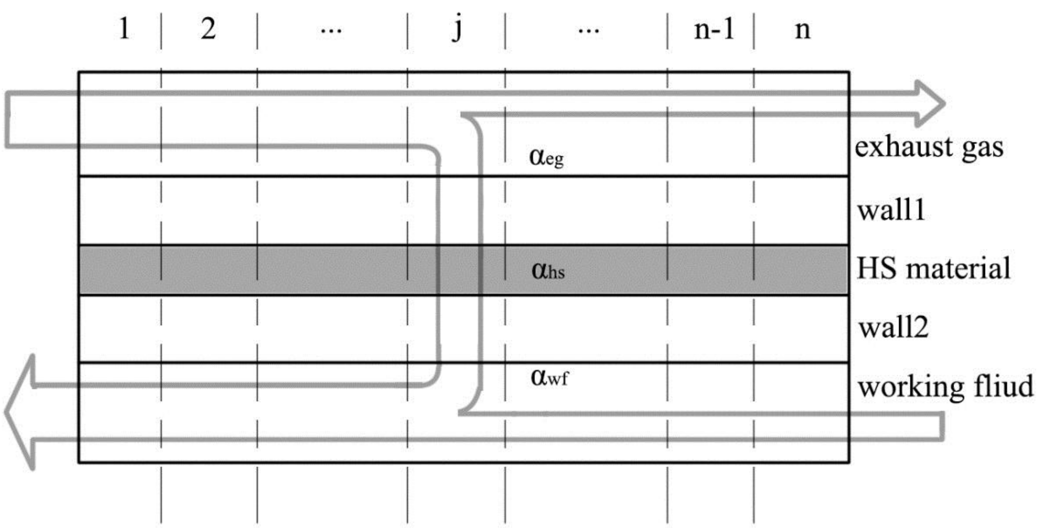
- Methodology
- Results and Discussion
- Conclusions

Methodology

Dynamic model-----Evaporator



One dimensional finite difference model

Assumption

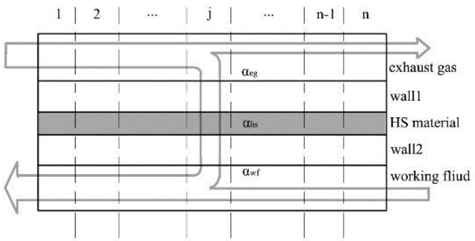
- Shape of transverse section is constant;
- Pressure is constant in the whole flow field;
- inviscid fluid;

Energy conservation equation

$$\int_v (\rho \frac{\partial H}{\partial t} - \rho \cdot u \frac{\partial H}{\partial x}) \mathrm{d}v = \int_A \dot{q} \cdot \mathrm{d}A$$

Methodology

Dynamic model-----Evaporator



Energy conservation equation in fluids ---- exhaust gas, working fluid

$$\overline{\rho_{exh,j}} V_{exh,i} \frac{\partial H_{exh,j}}{\partial t} = \dot{M}_{exh} \frac{H_{exh,j+1} - H_{exh,j}}{2} - A_i \dot{q}_{exh,j}$$

$$\overline{\rho_{wf,j}} V_{wf,i} \frac{\partial H_{wf,j}}{\partial t} = -\dot{M}_{wf,j} \frac{H_{wf,j} - H_{wf,j-1}}{2} + A_i \dot{q}_{wf,j}$$

Energy conservation equation in static object -----two pipes, heat-storage material

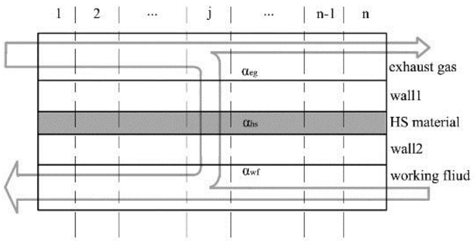
$$Cv_{wall1} M_{wall1,i} \cdot \frac{\mathrm{d}T_{wall1,j}}{\mathrm{d}t} = A_i (\dot{q}_{exh,j} - \dot{q}_{sto1,j})$$

$$M_{sto,i} \cdot \frac{\mathrm{d}E_{sto,j}}{\mathrm{d}t} = A_i (\dot{q}_{sto1,j} - \dot{q}_{sto2,j})$$

$$Cv_{wall2} M_{wall2,i} \cdot \frac{\mathrm{d}T_{wall2,j}}{\mathrm{d}t} = A_i (\dot{q}_{sto2,j} - \dot{q}_{wf,j})$$

Methodology

Dynamic model-----Evaporator



Heat transfer equation

$$\dot{q} = \alpha (T_{up} - T_{down})$$

Heat transfer coefficient of exhaust gas, heat storage materials and working fluids in monophasic region is considered as constant.

$$\alpha_{sto}, \alpha_{exh}, \alpha_{wf,liq}, \alpha_{wf,vap}$$

Heat transfer coefficient of evaporation stage $\alpha_{wf,ev}$ is calculated by [1]:

$$\frac{\alpha_{wf,ev}}{\alpha_{wf,bub}} = \left((1-x)^{0.01} \left((1-x)^{1.5} + 1.9x^{0.6} \left(\frac{\rho_{wf,bub}}{\rho_{wf,dew}} \right)^{0.35} \right)^{-2.2} + x^{0.01} \left(\frac{\alpha_{wf,dew}}{\alpha_{wf,bub}} \left(1 + 8(1-x)^{0.7} \left(\frac{\rho_{wf,bub}}{\rho_{wf,dew}} \right)^{0.67} \right) \right)^{-2} \right)^{-0.5}$$

[1] Horst T., Rottengruber H., Seifert M., Ringler J., 2013, Dynamic heat exchanger model for performance prediction and control system design of automotive waste heat recovery system, Applied Energy, Vol. 105, p. 293–303.

Methodology

Dynamic model-----Evaporator

Reference properties of the heat storage material

Parameters	Reference value	Range
Density	1667 kg/m^3	1400-2200 kg/m3
Heat capacity	1.6 kJ/kg	1.5-1.8 kJ/kg
Thermal conductivity	0.8 W/(m*K)	0.5-2 W/(m*K)

Main parameters of the heat-storage evaporator [1]

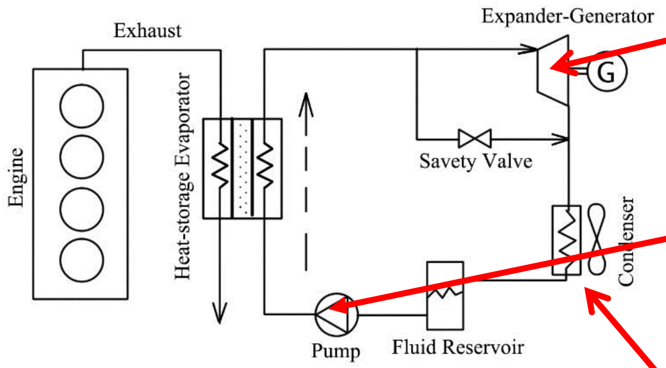
Parameters	Value	Parameters	Value
Area	3 m^2	α_{exh}	1000 W/m^2K
V_{exh}	0.04 m^3	$\alpha_{wf,liquid}$	260 W/m^2K
V_{wf}	0.009 m^3	$\alpha_{wf,evapor}$	360 W/m^2K
M_{wall1}	10 kg	n	40
M_{wall2}	10 kg	M_{sto}	5 kg
Cv_{wall}	4600 J/kg	α_{sto}	800 W/m^2K

Software REFPROP® is used to provide the properties of R245fa

Quoilin S., Aumann R., Grill A., Schuster A., Lemort V., Spliethoff H.,2011, Dynamic modeling and optimal control strategy of waste heat recovery Organic Rankine Cycles, Applied Energy,Vol. 88, no.6: p. 2183–2190.

Methodology

Dynamic model-----Other components



Turbine isentropic efficiency

$$\eta_{turbine} = 0.75$$

Pump isentropic efficiency

$$\eta_{pump} = 0.7$$

Condenser

The ambient temperature in this work is 25° C, and the outlet temperature is set to 40° C.

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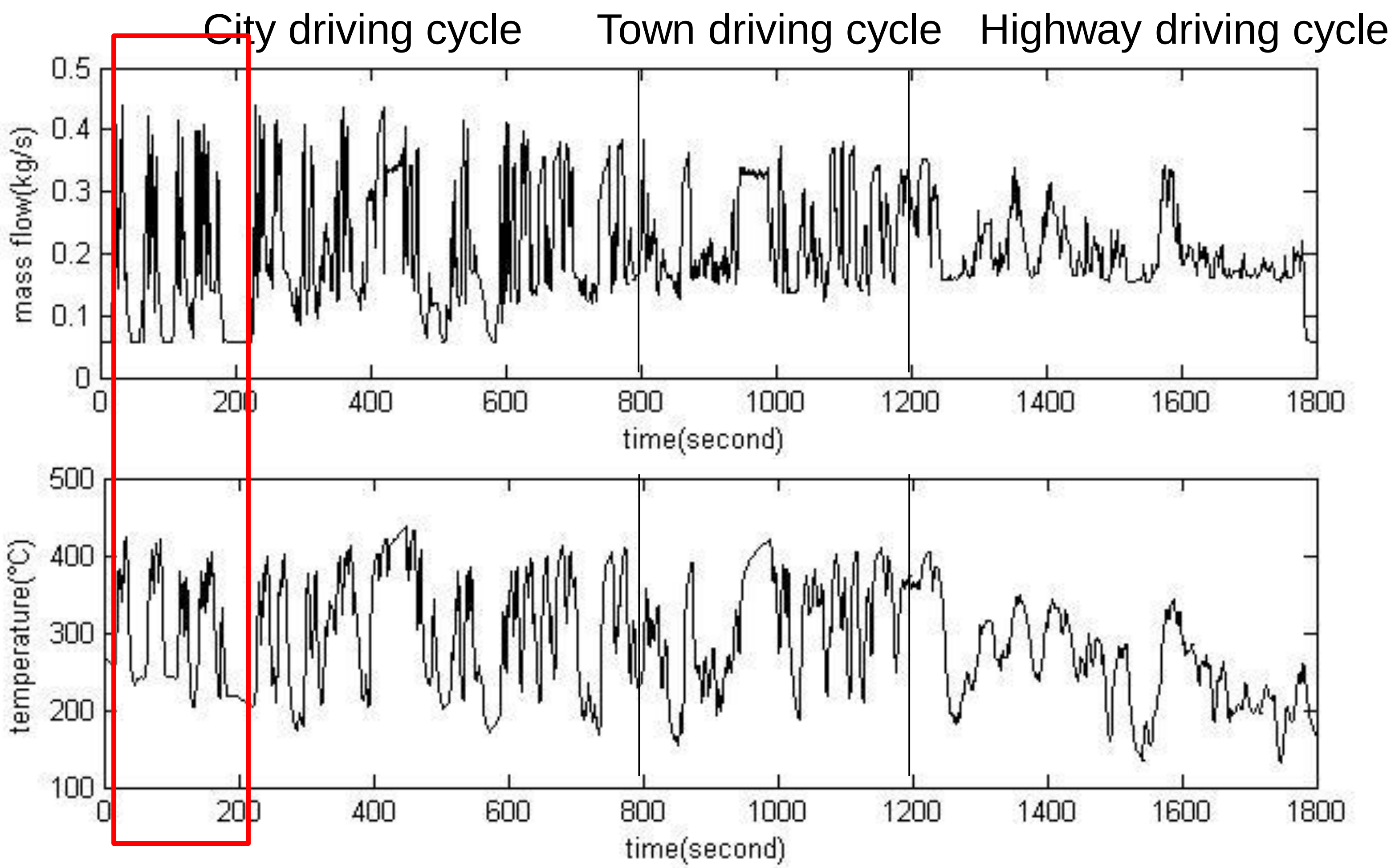
Results and Discussion

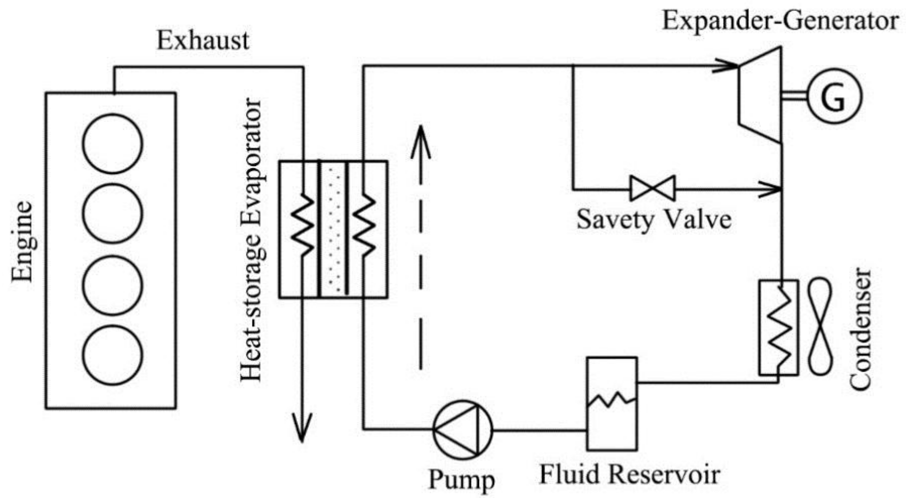
Heat source: 200s of the test data



Experiment data of engine exhaust in the ETC cycle

Results and Discussion

Rules of system performance simulation



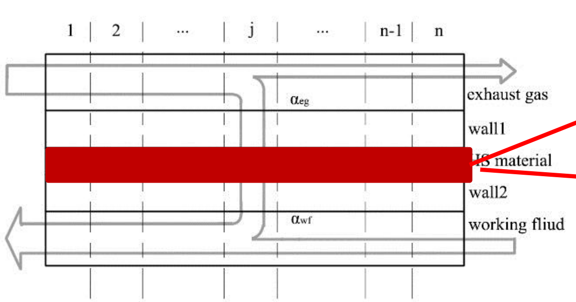
Conceptual scheme of heat-storage ORC system

Assume the system has got to **steady working condition at the start point** where the exhaust temperature is 330 ° C and the exhaust mass flow rate is 0.15 kg/s

If **superheating temperature** at the evaporator outlet is lower than **3 ° C** , the safety valve will open and the output power will be considered as **zero**.

Mass flow rate is steady.

Influence of heat storage materials



Heat storage evaporator

Heat resistance effect

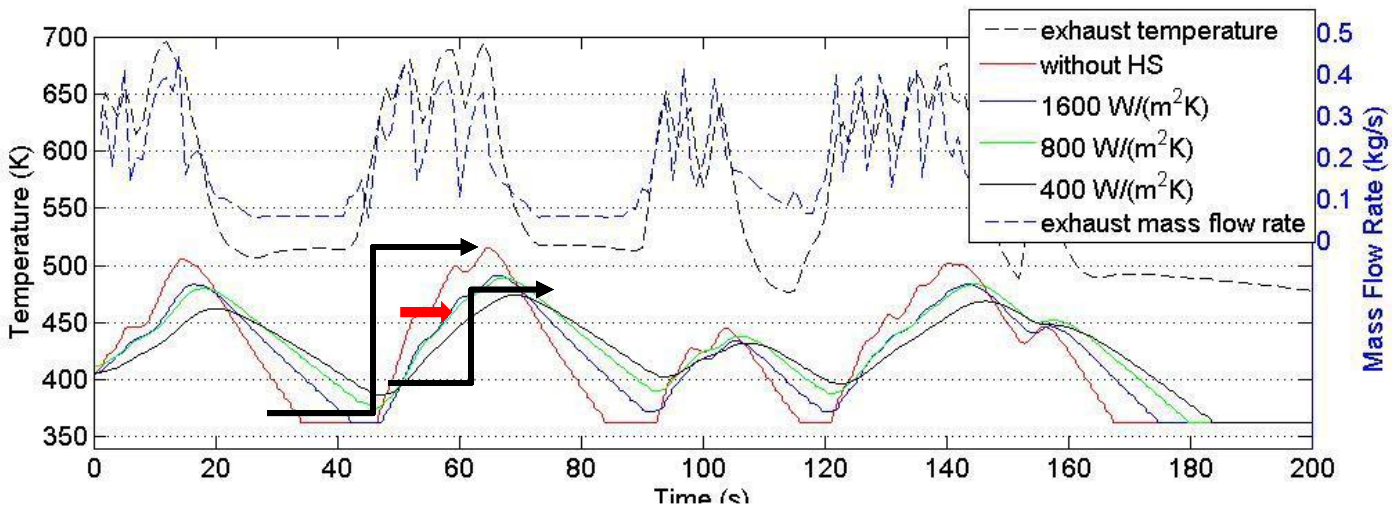
- resist heat transfer

Heat capacity effect

- increase heat capacity of evaporator

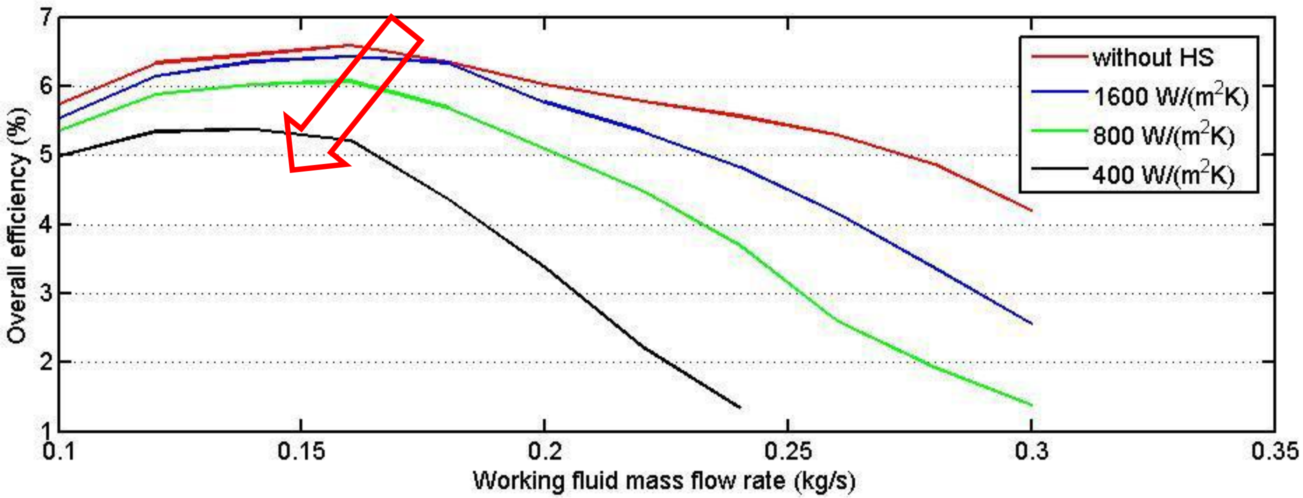
Results and Discussion

Heat resistance effect



Fluctuation of the evaporator outlet temperature

As the heat resistance increasing, temperature fluctuation is reduced.



System overall efficiency vs. working fluid mass flow rate

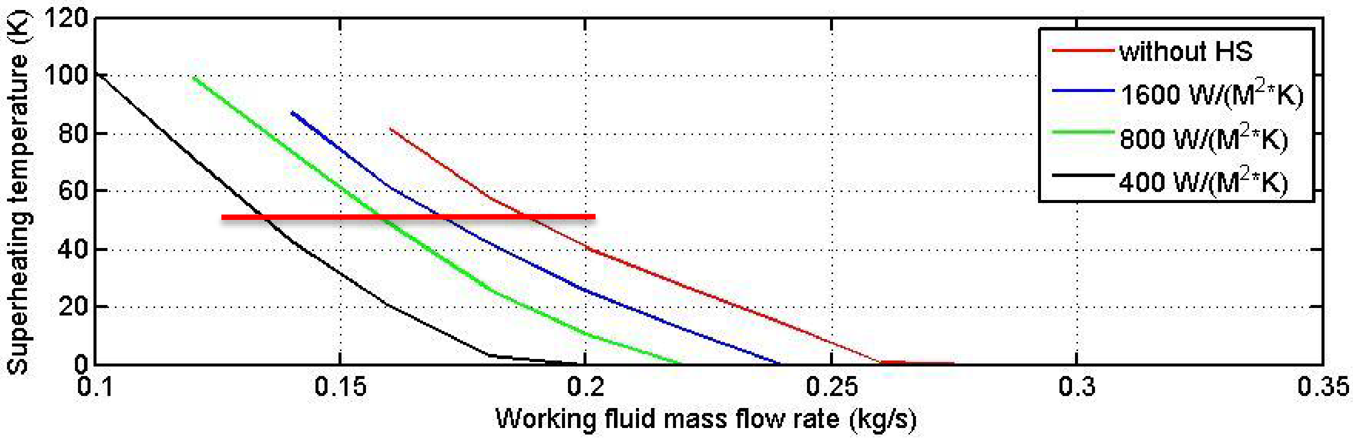
As the heat resistance increasing, maximum overall efficiency decreases.

Results and Discussion

Heat resistance effect-Analysis

High heat resistance means working fluid mass flow rate should be lower to get the same superheating temperature. So the overall efficiency will decrease.

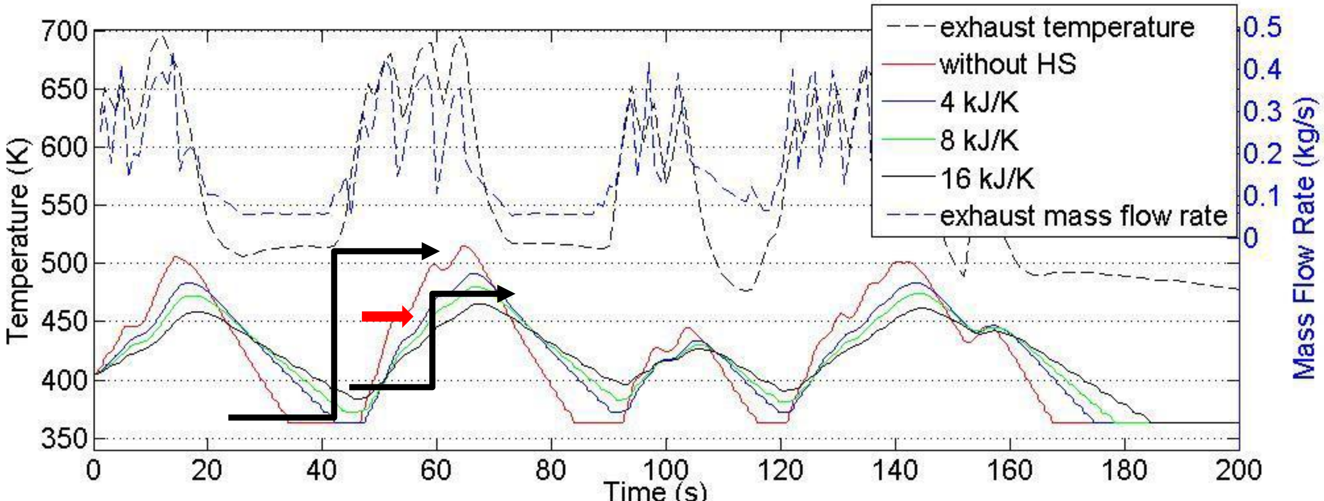
High heat resistance means lower thermal energy will be conducted to working fluids, so the influence of exhaust fluctuation is reduced as well.



Superheating temperature at the evaporator outlet vs. working fluid mass flow rate

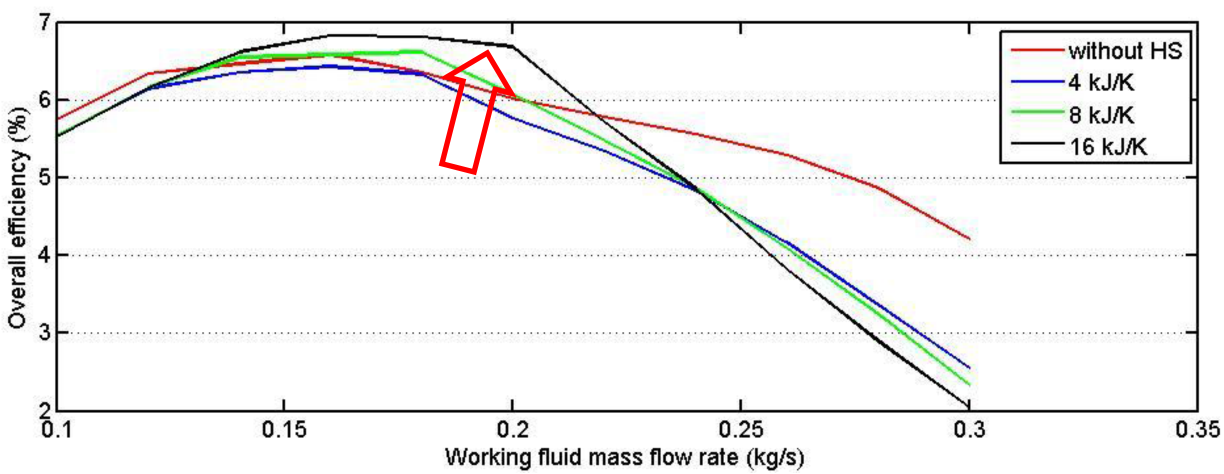
Results and Discussion

Heat capacity effect



Fluctuation of the evaporator outlet temperature

As the heat capacity increasing, temperature fluctuation at evaporator outlet is reduced



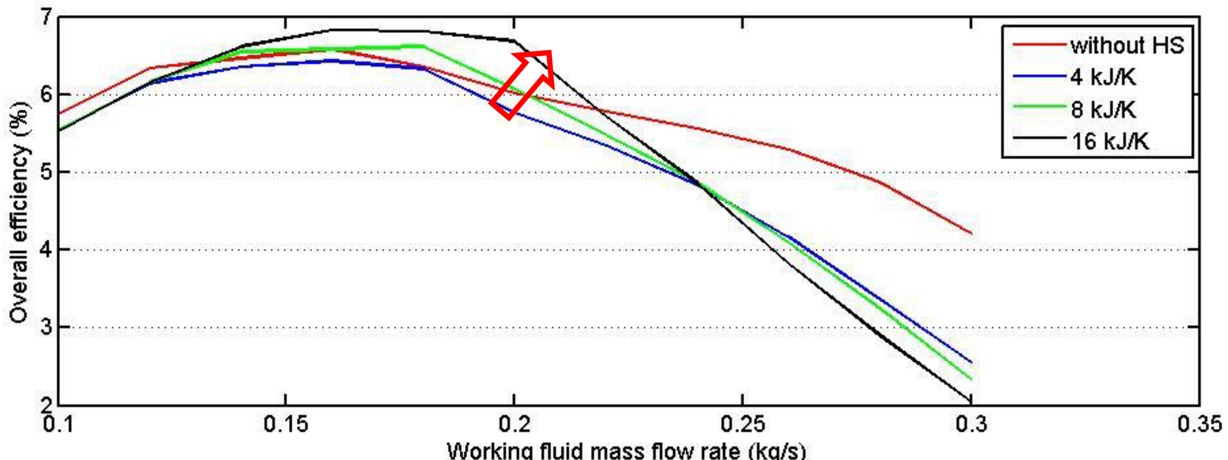
System overall efficiency vs. working fluid mass flow rate

As the heat capacity increasing, maximum overall efficiency increases.

Results and Discussion

Heat capacity effect-Analysis

High heat capacity leads to a low temperature fluctuation obviously, it also means the safety-open time decreases. So the overall efficiency raises with the heat capacity increasing.



System overall efficiency vs. working fluid mass flow rate

Heat capacity effect ≷ Heat resistance effect

Lower efficiency

Results and Discussion

Heat storage materials & thickness

How to raise heat resistance as well as lessen heat capacity?

Heat transfer coefficient

$$\alpha_{sto} = 2\frac{\lambda_{sto}}{h_{sto}}$$

Heat capacity

$$C_{sto} = c_{v,sto} \cdot V_{sto}$$

Geometry relation

$$A = \frac{V_{sto}}{h_{sto}}$$

Change geometry parameter: thickness

- Thickness ⇧
- Heat capacity effect ⇧
- Heat resistance effect ⇧

Change heat conductivity & volumetric heat capacity

- Better storage material
- Heat capacity effect ⇧
- Heat resistance effect ⇩

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Conclusions

- The heat storage ORC system can reduce the heat fluctuation of the exhaust significantly, and in the cases of this paper overall efficiency can be increased from 7.3 % to 8 %;
- When the heat capacity effect is stronger than the heat resistance effect, the overall efficiency can be increased;
- The thickness of the heat storage is an important geometry parameter.
- Selecting the heat storage material with high volumetric heat capacity and heat conductivity can increase the system performance

Thank you for your attention

Q&A

Email: t-chen14@mails.tsinghua.edu.cn