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Testing of Low-grade Heat Source Organic Rankine Cycle with Small Hot Vapor Reciprocating Engine

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Abstract

Investigating for recovering low-grade heat source (<100°C) by the expansion process of the small hot vapor reciprocating engine has never been studied yet. This research focuses on that one and the organic rankine cycle has been designed for the electric power generation not over 500 W. The organic substance as R-123 has conducted for working fluid of operating the system. Testing of organic rankine cycle has been achieved with the pressure of working fluid not exceeding 7 bars. The results show that the optimal maximum of electric power generation indicates at 5 bars, 270 rpm and 221 W. The tendency of testing organic rankine cycle compared between R-123 and compressed ambient air is agreeable.

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Keywords: Organic Rankine Cycle, low-grade heat source, Small Hot Vapor Reciprocating Engine

1. Introduction

An organic rankine cycle (ORC) is strongly attended [1-7] and intended to improve the thermal efficiency to convert the renewable energy to the electric power. Particularly low-grade thermal source [1] (<370°C) i.e. industrial processes, biomass, solar energy etc., A recovery of waste heat by using small hot vapor reciprocating engine has never been investigated yet.

Feasibility to adapt the rankine cycle and the temperature of heat source does not exceed 100°C to operate the system is focused. By the expansion process conducts small hot vapor reciprocating engine to achieve conversion of thermal energy in superheated steam of working fluid to the electric power. The optimal

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maximum of electricity generation that relates with pressure, engine speed and power output is discussed. Additionally, the comparing between R-123 and compressed ambient air is also presented.

In a few past decades, turbine expander is popularity and exactly belong to the system that is high electricity generation (>1MW). Doherty et al. [8] the development of a small-scale system designed at low temperature heat source such as solar energy to generate electricity was described. The system had been designed and operated using n-pentane as the working fluid. The testing of ORC, it delivered 1.5 kW of electricity with 4.3% for thermal efficiency. For getting the advantaged from a phase change of the working fluid (as high energy density), a new type prototype of ORC that was friendly environmental system which was operated with low-grade heat sources was proposed by Takahisa et al [9] and HCFC-123 also used as working fluid. Numerical modeling and experimental apparatus were conducted for investigations. The results of simulation showed the optimum operating conditions of water, increasing the turbine inlet temperature results high turbine power. Reversing the appearance by the turbine inlet temperature was as low as possible above the boiling point of working fluid; the best operating conditions for HCFC-123 appeared. The standard comparing cycles leading to the studied many standard comparing cycles for the reciprocating steam engines had been established by Bernardello et al [10]. The predicted showed that there were maximum operational points on which depend in some conditions and constructive features. Operating caution of steam engines, the isochoric processes must be aware for they always caused useful energy waste.

Table 1 Thermal property of working fluids

Working fluid	Molecular weight	Boiling point [K]	Density [kg/m^3]	Latent heat [kJ/kg]	Specific heat ratio
Air	60	-	1.14	-	1.4
R-123	152.9	300.85	1462.2 (liquid)	168.41	1.11

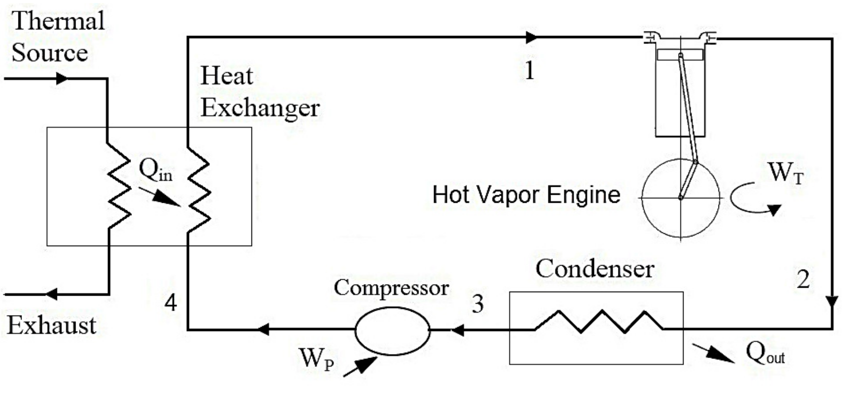

Fig.1. Schematic diagram of ORC system

2. Design of ORC

Design of ORC for low-grade energy source bases on the concept of ideal rankine cycle. The ideal cycle is for vapor power plant of which does not involve any internal irreversibility [11], such as pressure drop, steady state and no heat loss that consists of four processes of as follows:

1-2 isentropic expansion in a hot vapor reciprocating engine
2-3 constant pressure heat rejection in a condenser
3-4 isentropic compression in a compressor
4-1 constant pressure heat addition in an evaporator

The small hot vapor reciprocating engine that is used in this investigation is modified compact three cylinders as depicted in Table 2

Table 2 Hot vapor engine specifications

Engine Specifications	
Engine	3cyl. Daihastu
Displacement (cm^3)	670
Bore x Stroke (mm)	63 x 72

Sequential stages of the system design start with determining the hot vapor engine (stages 1-2): the expander depressurizes the superheated vapor of working fluid after flows passed this one. Then the vapor becomes at lower pressure P2 and low temperature T2. In order to analyze the cycle (Figure 1) at an expansion stage, it need identify some relationship between the volumes of the cylinder such that the cut-off ratio (φ), closure ratio (r_F), volume ratio (ε), pressure ratio (r_P) and the specific heat ratio referring the following [10], respectively. Secondly: condenser (stages 2-3), after that: pump (stages3-4), finally: evaporator (stages 4-1), for calculating such that the condenser load ($\dot{Q}_{out}$), the work pump ($\dot{W}_P$) for recirculating working substance and the quantitative of heat input ($\dot{Q}_{in}$) can be considered by adapting the first's law of thermodynamics as well.

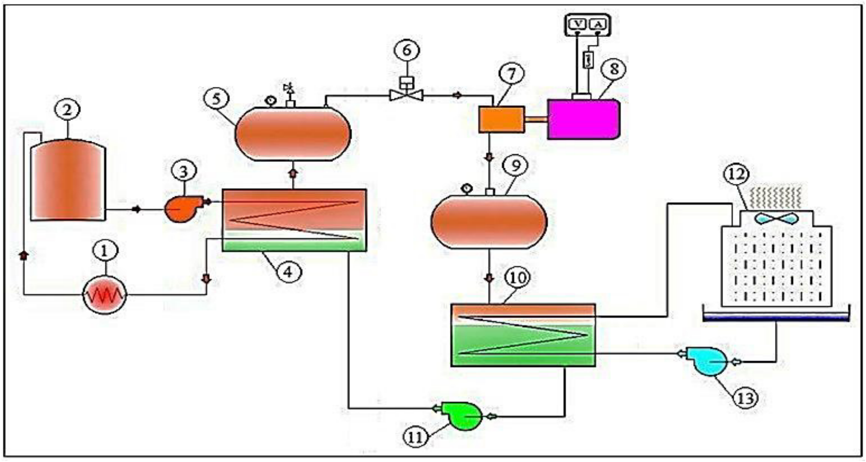

Fig.2. Schematic diagram of testing ORC

3. Experimental apparatus

Figure 2 shows schematic diagram of testing ORC uses R-123 as working fluid. The components of this one consist of four main parts as the following: the first is low-grade heat source at which the temperature and pressure are not exceeding 100ºC and 1 bar (1atm) represented by the number 1, 2 and 3, respectively. Second is the system of organic rankine cycle represented by the number 4, 5, 6, 7, 9, 10 and 11 that working fluid uses R-123. Third is the generating system of electric power represented by the number 8. And finally, heat rejecting system represents by the number 12 and 13 that conducts cooling tower for regaining the working fluid phase change. To operate the system, working fluid (0.06 kg/s) was heated to superheated vapor and contained the pressure reservoir 200 liters (number 5) while pressure control valve (number 6) was closed until reaching anticipated pressure (7 bars). After that the pressure control valve gradually opened for avoiding difference pressure effect and observed the reciprocating engine for smoothly running. The speed of engine must be stable and then the measurements evaluate the performance of the apparatus as the following: Electricity and engine speed were measured by METRAHit 29S and digital tachometer DT-246L. The mass flow rate of working fluid was measured by calibrated flow meter. After the working fluid come out the condenser, the phase change was accomplished to be saturated liquid. Then it was pumped back to the evaporating process once (number 4).

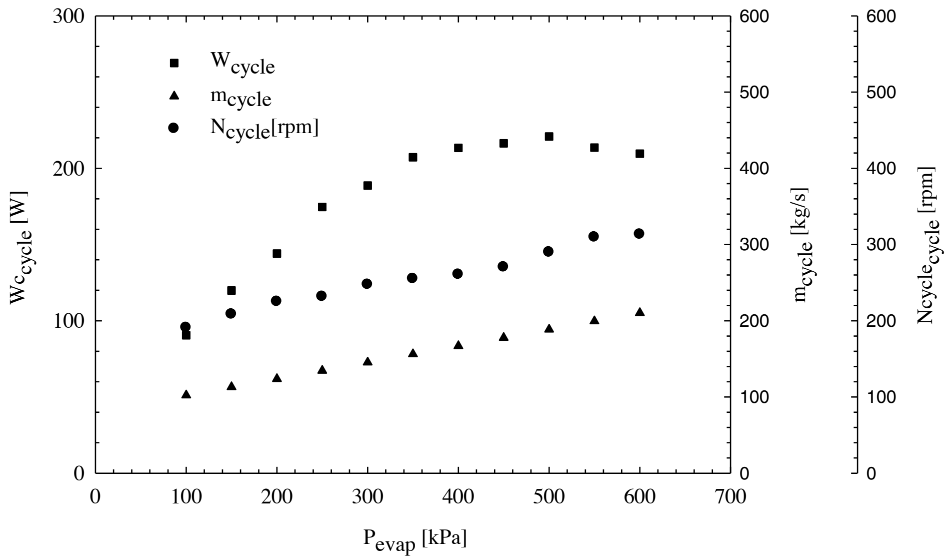

Fig.3. Testing results of ORC with the R-123

4. **Testing results and discussion**

Figure 3 shows work done, mass consumption and engine speed in a cycle as a function of the evaporator pressure. The maximum testing of electric power generation for operating ORC system indicates at about 5 bars, 270 rpm of engine speed and 210 watts of electric power output. The electric power generation trends increasing with raised the engine speed. When it passes the maximum point of the engine performance, the electricity trends decreasing with increased the engine speed even although the mass flow rates of working fluid increases with raised the engine speed. The reason of which the electric power decreases after passing the maximum point is the fluid moving further into the superheat state at the engine exit. Additionally, the mechanical work is function of engine speed and torque as illustrated in equation 1. In the other word, the maximum torque for the small hot vapor reciprocating engine appears at the point of conditions that corresponds to the reported results of Takahisa Y, et al [9].

Figure 4 shows compared work done in a cycle between the compressed air and R-123 as a function of the evaporator pressure. The tendency is agreeable whereas the testing of R-123 results higher the electrical power than the compressed air because at the similar state of substance. R-123 shows the energy content (enthalpy) higher than the air. Furthermore, the R-123 as working fluid also gets more advantage from phase change of working substance during the expansion process of the rankine cycle.

$$\dot{W}_{mech} = \frac{2\pi n}{60} T \tag{1}$$

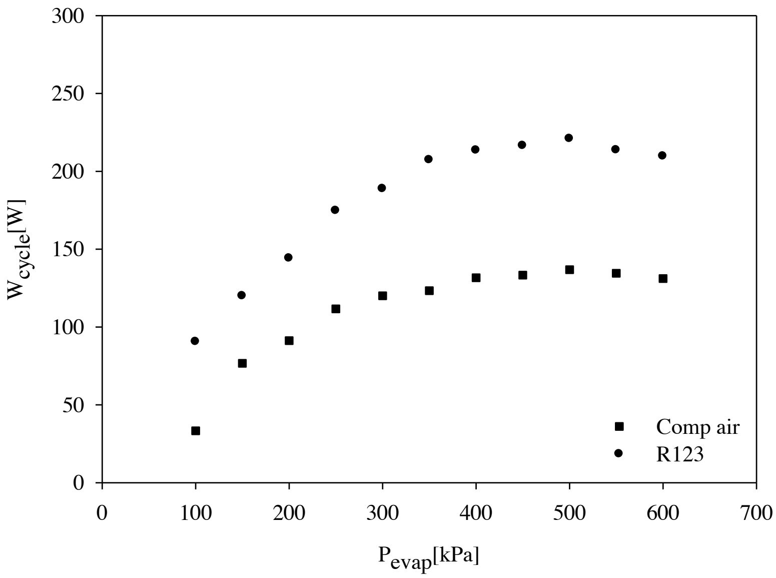

Fig.4. Compared work done in a cycle between compressed ambient air and R-123 as a function of the evaporator pressure

5. Conclusions

Results of testing the system using the compressed ambient air for electric power generation, the optimal maximum appears at about 5 bars, 270 rpm and 137 W. And the testing using R-123 for electric power generation, the optimal maximum appears at about 5 bars, 270 rpm and 210 W, respectively.

The compared work done of ORC that operates with R-123 and the compressed ambient air as working substance trends agreeably while the results R-123 is higher electric power than the compressed ambient air throughout the operating range.

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