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WORKING FLUID SELECTION OF RANKINE-HIRN CYCLE ACCORDING TO THE HEAT SOURCE

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Abstract:

This paper presents our simulation model of Rankine-Hirn cycle. This model is developed for sizing and for working fluid choice of a test bench of Rankine-Hirn cycle for engine waste heat recovery. The heat source characteristics were measured on a diesel tractor engine during work in field. The simulation tool allows to us study some of static operating points. An iterative calculation was used to find the best parameters as pressure and working fluid flow rate according to some constraints such as heat exchanger surface or maximum pressure. We identify that each fluid is adapted for a limited range of the heat source temperature. For our application, ethanol and water are the adapted working fluids. These results defined the future control laws of the waste heat recovery system.

Keywords: *Rankine – Hirn cycle, waste heat recovery, simulation*

1. Introduction

This paper presents a preliminary study of a conception of Rankine-Hirn waste heat recovery (WHR) system. The purpose of this system is the reduction of engines fuel consumption. An analysis of the heat source showed us the best operating range for heat recovery. The Rankin-Hirn cycle model allows finding the best operating parameters and working fluid according to our heat source and pressure and temperature constraints. It appears that each fluid has a preferred heat source temperature range of use. However this difference between fluids is not significant when the heat exchanger achieves a critical size which depends on the heat source power. Finally this model provides the best control parameters of the Rankin-Hirn system to maximize the recovery efficiency.

2. The heat source

The heat source studied is a tractor engine exhaust system. It is a 6.6 liter six cylinder diesel engine with maximum output power of 110 kW. The data used were measured on a diesel tractor engine during work in field. This engine application promises a better performance than passenger's cars engines due to tractors operates most of the time at high load. Our data coupled with simulation showed that approximately 30% of fuel energy is rejected with exhaust gases. The exhaust gases temperature is essentially between 350°C and 450°C. Punov *et. al*. [1] showed that this enthalpy contains 40% to 55% of exergy. The most frequent heat power of exhaust gases is about 70kW, so we can hope an exergy of 30kW for this point. In practice any thermal engine can recover all of this exergy but this study shows the interest and the potential of waste heat recovery.

3. Model of thermodynamic cycle

The model simulates a theoretic endo-reversible Rankine – Hirn cycle, with or without super-heating. Only sub-critical cycles are simulated. A calculation code was developed in Python [2] as the CoolProp database was used for fluids properties [3].

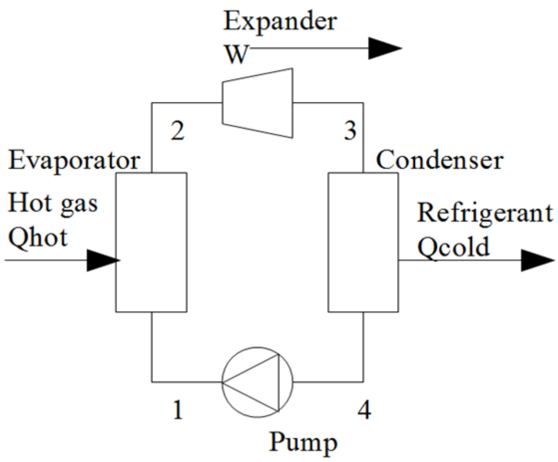

Fig. 1 Waste heat recovery system

This system consists of an evaporator, an expander, a condenser and a pump. The waste heat is absorbed through the evaporator to vaporize the pressurized working fluid. Vapor energy is mechanized in the expander then the expanded vapor is condensed. The low pressure liquid working fluid is pumped and the cycle starts again. The model was developed as it was considered a counter flow heat exchanger is used.

The pump work and the pressure drop in the circuit were neglected. Thermal capacity of exhaust gases was considered constant, $cp_{gaz} = 1{,}157 kJ/kg.K$. The pinch point method is used to calculate the results. Input parameters of the model are the followings:
- Hot source temperature and gas mass flow
- Cold source temperature
- Surface A and heat exchange coefficients U of the hot heat exchanger
- Maximum and minimum pressure of the cycle

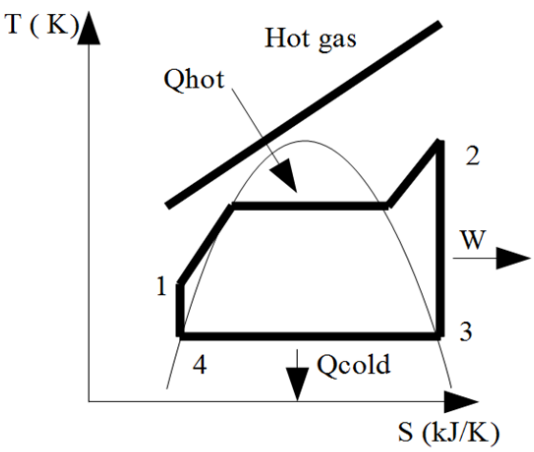

Fig. 2 T-S diagram of the Hirn cycle

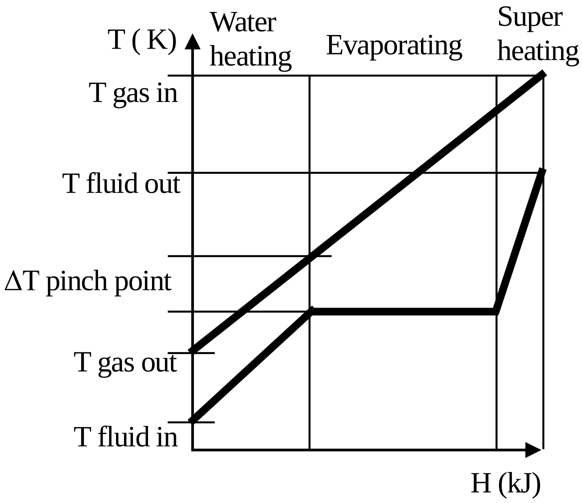

Fig. 3 Fluid and gas temperature variation into the heat exchanger.

- Super-heating temperature

An iterative calculation links the pinch point and the surface of the heat exchanger. ΔTln at each area of the exchanger (fig. 3) is used for total surface A calculation.

$$\Delta Tln = \frac{(\Delta T_x - \Delta T_0)}{\ln\left(\frac{\Delta T_x}{\Delta T_0}\right)} \quad (1)$$

$$\dot{Q}_{exchange} = U.A.\Delta Tln \quad (2)$$

$$\dot{Q}_{exchange} = \dot{m}_{gas}.cp_{gas}.\Delta T_{gas} \quad (3)$$

$$\dot{Q}_{exchange} = \dot{m}_{workingfluid}.\Delta h_{workingfluid} \quad (4)$$

The power on the expander shaft is:

$$\dot{W} = \dot{m}_{workingfluid}.\Delta h_{workingfluid} \quad (5)$$

Most interesting results to find the best operating point parameters are maximum power and global exergetic efficiency. The thermal power available is calculate with ambient temperature T_0 as reference.

$$\dot{Q} = \dot{m}_{gas}.cp_{gas}.(T_{gas} - T_0) \quad (6)$$

The second law of thermodynamics allows obtaining the maximum useful energy of exhaust gases.

$$\dot{E}x = \Delta\dot{H} - T_0.\Delta\dot{S} \quad (7)$$

$$\dot{E}x_{gas} = \dot{m}_{gas}.cp_{gas}.(T_{gaz} - T_0).\left(1 - \frac{T_0.\ln\frac{T_{gas}}{T_0}}{T_{gas} - T_0}\right) \quad (8)$$

The global efficiencies are:

$$\eta_{II} = \frac{\dot{W}}{\dot{E}x_{gas}} \quad (9)$$

Heat transfer efficiencies:

$$\eta = \frac{\dot{Q}_{workingfluid}}{\dot{Q}_{gas}} \quad (10)$$

The best exergetic efficiency is searched for each hot source temperature by an iterative method. Control parameters are working fluid mass flow, pressure and the super heating temperature.

4. Results

Three fluids are analyzed, water, ethanol and R245fa. These fluids are the most commonly studied and used for Rankine – Hirn and organic Rankine cycle (ORC) [4-7]. The first objective is to find the best working fluid for the hot source temperature range. This study is conducted with no limit in pressure and super heating. The heat exchanger surface is considered infinite.

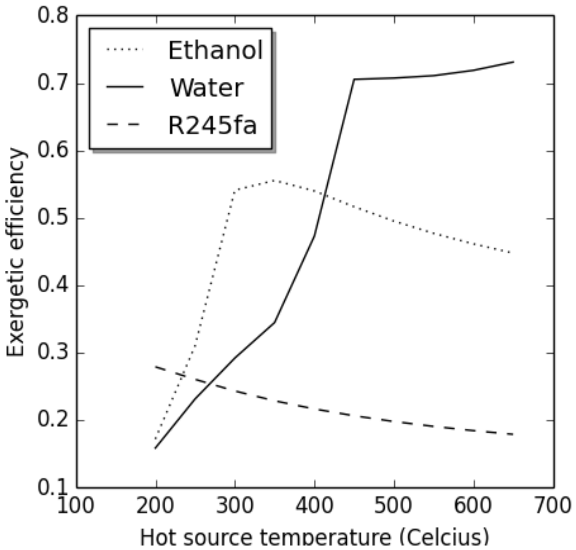

Fig. 4 Exergetic efficiency (η_{II}) of Hirn cycle without constraints. Cycle with super-heating.

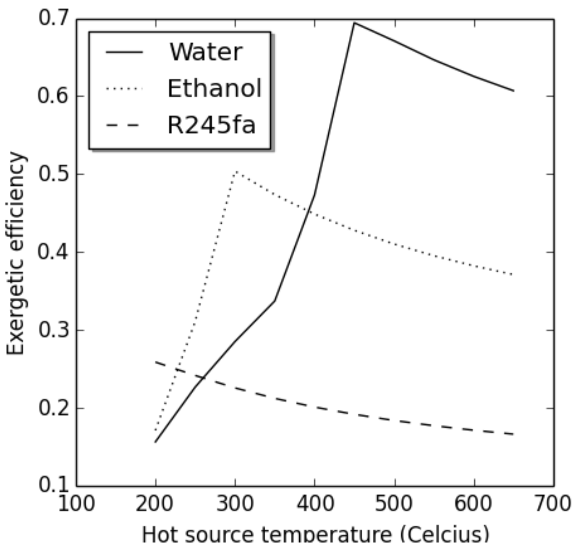

Fig. 5 Exergetic efficiency (η_{II}) for Rankine cycle without constraints. Cycle without super-heating.

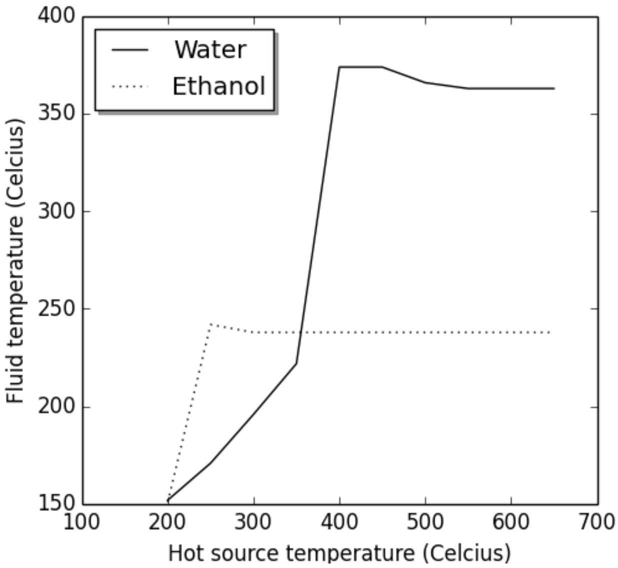

Fig. 6 The best evaporating temperature of Rankine cycle

The cold source is fixed at 100°C. This temperature was chosen because it is a value compatible with the engine coolant temperature and it is not necessary to depressurize condenser for water. Others fluids are studied with the same cold source temperature.

A first simulation is released for Hirn cycle, i.e. super-heating. Each fluid provides a better performance than others for a limited range of hot source temperature (fig. 4). R245fa is better for a temperature lower than 200°C, ethanol is better within the range of 200°C to 400°C and water is preferable for temperature higher than 400°C. R245fa seems to be not enough efficient for the studied temperature range, which is from 300°C to 500°C. Ethanol efficiency increases rapidly until a maximum and decreases after that. On the other hand, water efficiency increases slowly after an important increase.

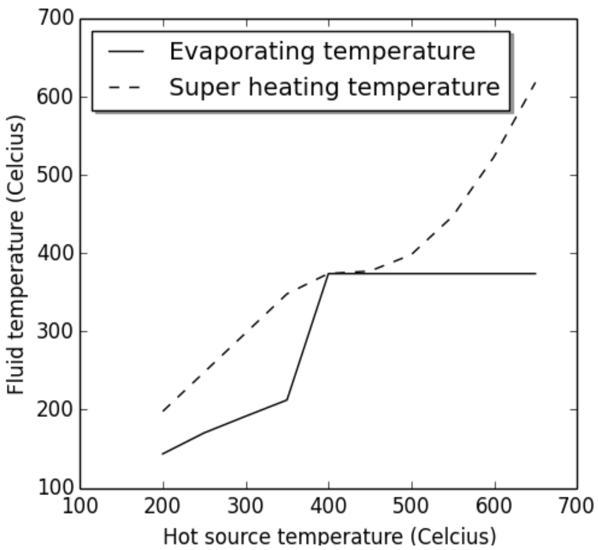

Fig. 7 Evolution of evaporating temperature and super-heating temperature with water as working fluid.

Significant increasing of efficiency occurs when the hot source temperature exceeds the critical temperature of the working fluid. Critical temperatures are 241.56°C for ethanol and 373.946°C for water.

A second simulation (fig. 5) studies the Rankine cycle without constraints, but unlike the previous simulation the fluid is not super-heated. The maximum efficiency is slightly lower than with super-heating but the main difference concerns the water that efficiency decreases after the maximum. This decreasing is more important for ethanol than with super-heating. R245fa is a dry fluid. The super heating does not allow a benefit [4] for dry and isentropic fluids, so the results are the same. Water and ethanol are wet fluids, thus the super-heating gets a profit.

The optimal evaporating temperature of the Rankine cycle (fig. 6) reaches a maximum which is the critical temperature before a weak decrease for highest hot source temperatures. This comportment was described by Chambadal [9].

Immediately after the fast efficiency increase (fig.7) the optimal super-heating temperature is reduced to a minimum. The temperature at this point corresponds to the critical temperature of the fluid. The super heating temperature increases anew when the gas temperature exceeds the critical temperature of the fluid. So when the gas temperature is slightly higher than the critical temperature of the fluid, Rankine cycle is better but for higher or lower temperature Hirn cycle is preferable. The temperature evolution according to the heat exchange shows (fig. 8) that an optimal choice of fluid and working fluid temperature can limit the difference between the hot and cold fluids and reduce the exergetic destruction.

For a gas temperature higher than the critical temperature of the fluid, the evolution of the fluid liquid phase temperature follows the gas temperature evolution shape. In this case, the exergetic efficiency is very high because all amount of the heat is transferred to the working fluid with the minimal exergetic

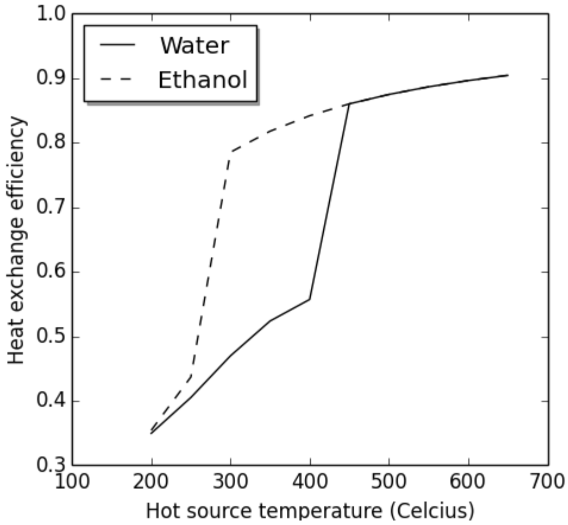

Fig. 9 Heat exchange efficiency for infinite heat exchanger in Hirn cycle

destruction. These examples need an infinite heat exchanger but it shows that even if the heat exchanger is infinite an efficiency of 100% is impossible due to the non-constant heat capacity of the fluid. The fig. 9 shows the evolution of the heat transfer efficiency to the working fluid. In case of an infinite heat exchanger, the global efficiency mainly depends on the heat exchange efficiency which depends on the fluid characteristics. Ethanol and water are studied here but each fluid offered a preferred range of use of hot source temperatures.

In the second study a constraint of heat exchanger surface is introduced. Only ethanol and water are studied. Due to R245fa provides lower performances the fluid was not studied in this case. The pressure is limited to 30bar and the super-heating is fixed at 30°C higher than the evaporation temperature. The role of super heating is not only for the efficiency improvement but also for protection of the expander which can be damaged by droplets appearance during the expansion. Fig. 10 shows the results obtained for both fluids with a heat exchanger surface in range of 1 to 12 m².

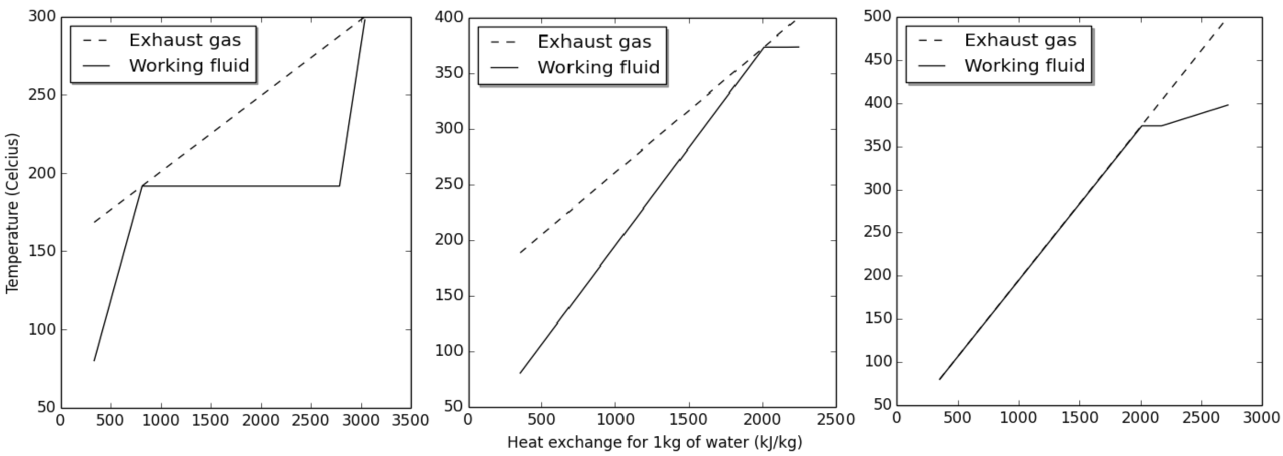

Fig. 8 Temperatures profiles of water and gas in the infinite heat exchanger for gas inlet temperature of 300, 400 and 500°C

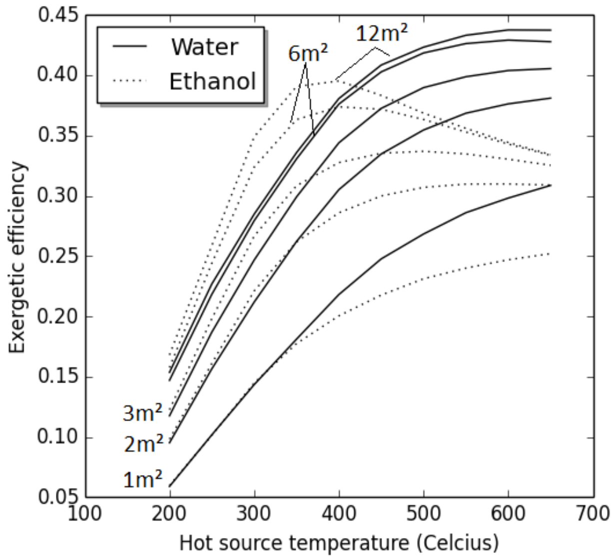

Fig. 10 WHR system global efficiency (η_{II}) for different size of heat exchanger.

The hot source power is 40kW. For another power these surfaces reveals different results. The result for a heat exchanger of 12m² is very close to the infinite exchanger and the best range of efficiency is clearly different for ethanol and water. In the case of a reduced heat exchanger surface, the exergetic efficiency for both fluids cannot be distinguished for low temperatures but the efficiency with water as working fluid remains higher at higher temperature.

If the heat transfer is relatively low compared to hot source power, the advantage of each fluid for a limited range of hot source temperatures disappears. The fluid which presents the higher critical temperature becomes then the most interesting fluid for the entire range of hot source temperature. In our application the temperature range extends from 300°C to 500°C such that with a large heat exchanger ethanol and water are interesting. Ethanol provides a better efficiency between 300°C and 400°C and water is better for a higher range. But in practice we are limited by the size

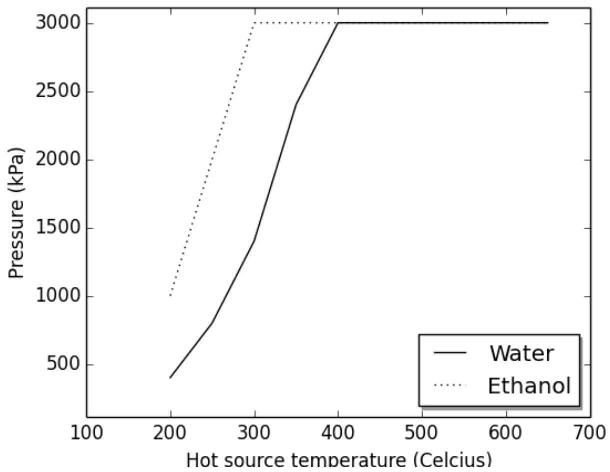

Fig. 11 Optimal pressure in function of heat source temperature

and the price of the heat exchanger. The size will be between 2 and 3m². For this size, ethanol offers same performances as water below 350°C and lower performances above this temperature.

The pressure (fig.11) evolution of limited 30 bar and 30°C super-heating cycle case revealed that the pressure should not be always 30 bar. Therefore, to optimize the system in varying conditions, it is necessary to control these parameters.

5. Conclusions

The effect of the fluid properties and the heat exchanger size on the WHR efficiency has been studied in this paper. We observed that each fluid presents a preferred temperature range of use. The optimal temperature of Rankine-Hirn cycle depends on the critical temperature of the working fluid.

With these considerations ethanol and water present advantages respectively in the range from 300°C to 400°C and from 400°C to 500°C. These two fluids are interesting for hot source studied. However, these first results have been obtained with an infinite heat exchanger. When we consider a limited heat exchanger surface, performance decreases with the surface. This decreasing is not constant: the maximum efficiency of each fluid tends to the same limit when the temperature is inferior to the lowest critical temperature of all fluids. But the efficiency of the fluid which presents the lowest critical temperature decreases below its critical temperature. With the constraint of heat exchanger surface, water seems to be a better working fluid for the studied application.

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ИЗБОР НА РАБОТЕН ФЛУИД В СИСТЕМА ЗА РЕКУПЕРИРАНЕ НА ЕНЕРГИЯ ЧРЕЗ ЦИКЪЛ НА РАНКИН В ЗАВИСИМОСТ ОТ ИЗТОЧНИКА НА ТОПЛИНА

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Abstract:

Тази публикация представя симулационен модел на цикъл на Ранкин за рекуипериарне на енергия. Моделът е разработен с цел оптимизиране на елементите от цикъла на Ранкин и избор на работен флуид в стендови условия при изследване на рекуперирането на енергия от отработилите газове на ДВГ. Параметрите на отработилите газове бяха измерени по време на реална експлоатация на дизелов двигател за трактор. Изчислителната програма позволява изследване на цикъла на Ранкин в установени режими. Итеративен метод е използван за оптимизиране на определени параметри, като налягането и дебита на работния флуид при ограничителни условия за изменение топлообменната повърхност. В следствие на получените резултати се установи, че за всеки от изследваните флуиди е подходящ за опреден диапазон на изменение на температурата на източника на топлина. За нашите бъдещи изследвания се предвижда използване на вода и етанол като работен флуид. Получените резултати определят начина на управление на системата за рекупериране на енергия от отработилите газове.

Keywords: *цикъл на Ранкин, рекупериране на енергия, симулация*