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Thermodynamic Analysis of Combined ORC-VCR Powered by Waste Energy from Diesel Engine

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Abstract: ***To efficiently utilize the waste energy from both exhaust gases and cooling water of a Diesel engine, an organic Rankine cycle-vapor compression refrigeration (ORC-VCR) combined system is employed and a thermodynamic model is developed, analyzed and optimized. Four hydro-carbon working fluids R600 (butane), R600a (isobutane), R601 (pentane), R601a (isopentane) are analyzed and evaluated in order to find a suitable working fluid for the combined system which may yield high system efficiencies for same waste energies from the diesel engine. The overall coefficient of performance (COP) and working fluid mass flow rate of per kW cooling capacity (MKW) are chosen as key performance indicators. The boiler pressure in the sub-critical range, the condenser temperature and evaporator temperature are taken to be the decision variables for optimization. Comparison between selected working fluids for their optimized systems is done on the basis of COP, MKW, condenser pressure, boiler temperature, expansion ratio (EPR) and compression ratio (CMR). The analysis shows that among the selected working fluid, R600 is the best for the ORC-VCR system for waste energy utilization from both exhaust gases and cooling water a diesel engine.***

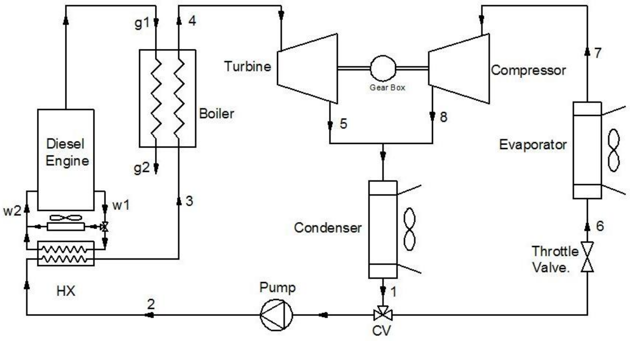
Keywords: Waste Energy Recovery; Organic Rankine cycle; Vapour Compression Refrigeration Cycle, Genetic Optimization

1. Introduction

Diesel engine (DE), that converts energy from heat to work, has vast applications in road vehicles, marine transport, and power plants. diesel engines are preferred for their reliability, low specific cost and high electrical efficiency, especially in the power range of hundreds of kW to few MW [1]–[3]. In a diesel engine, all the energy released during combustion of the fuel cannot be converted into useful work because of some thermodynamic limitations. The balance is released through exhaust gases and cooling systems as low grade energy (heat), and thus it is simply wasted. In this respect, thermally activated cooling technologies as methods to recover the low-grade thermal energy have gained considerable interest [4]. The thermally activated refrigeration can be fulfilled by sorption (adsorption and absorption), thermoelectric and Rankine cycle powered vapour compression refrigeration (VCR) systems. Comparing with the others, the last one has flexibility associated with the mechanical power delivered by an expander, which makes the system to continuously utilize the thermal energy throughout the year [5]. An organic Rankine cycle (ORC) can be used to produce useful work by exploiting such low grade energy sources. In ORCs, organic fluids are preferred to water when the required power is limited and the energy source temperature is low. This is because of the fact that organic fluids often have lower heat of vaporization and they can better follow the heat source to be cooled, and thus temperature differences and irreversibility at the evaporator are reduced [6-8]. Many studies has been carried out on various working fluids that are organic refrigerants for combined ORC-VCR systems [9]-[11]. However refrigerants like chlorofluoro carbons and hydochlorofluoro carbons have negative impact on the environment [12], so various hydrocarbons (natural fluids) are accepted as possible alternatives to these refrigerants [13]. Hydrocarbon refrigerants are natural, nontoxic refrigerants that have excellent thermo-physical properties, no ozone depleting properties and low global warming potential. Hydrocarbons are highly flammable, but with adequate safety precautions and regulations, the flammability will not be a major problem in the usage of hydrocarbons [14-15].

2. System Description

A schematic diagram of ORC-VCR combined system bottoming a diesel Engine is shown in Fig.1.



Fluid Stream: 1-2-3-4-5-6-7-8 = Working fluid ; g1-g1 = Exhaust Gas ; w2-w1= Cooling Water

Figure 1:schematic diagram of ORC-VCR

The cooling water of the diesel engine passes through a heat exchanger (HX). It preheats the condensed working fluid from the condenser before entering the boiler. The hot exhaust gases from the diesel engine passes through the boiler. It vaporizes the ORC working fluid in the boiler and the vapor is expanded to produce shaft work. The cooling side is a standard vapor compression cycle. Instead of using an electrical motor to drive the compressor, the compressor is directly coupled to the expander

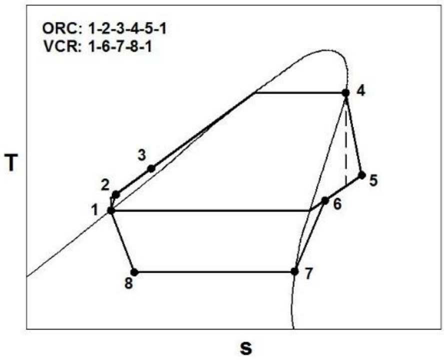


Figure 2: T-s diagram of ORC-VCR

The conversion losses associated with electrical motors are eliminated. The high pressure vapor after compression goes through the standard condensing and evaporating processes before completing the loop. The organic Rankine cycle and vapour compression refrigeration cycle share a common condenser.The T-s diagram of the organic Rankine cycle drive vapour compression refrigeration cycle is shown in Fig. 2. Accordingly, the various processes of the system are presented as follows:

1 → 2 : actual pumping work;
2 → 3 : heat addition in the HX;
3 → 4 : heat addition in the boiler;
4 → 5 : actual expansion in the expander;
5 → 1 : heat rejection (condensation) in the ORC;
1 → 6 : isenthalpic expansion in the throttle valve;
6 → 7 : heat absorption (evaporation) in the VCR cycle;
7 → 8 : actual compression in the compressor;
6 → 1 : heat rejection (condensation) in the VCR cycle;
g1 → g2 : heat rejection by exhaust gases;
w1 → w2 : heat rejection by cooling water;

3. Thermodynamic Analysis

Thermodynamic analysis of ORC-VCR combined system has been carried out in this work. In order to simplify the analysis, some assumptions are made as follows: steady-state conditions are considered in all components; heat and friction losses in the system is neglected; the condenser has a given sub-cooling of 5^{O}C to prevent boiler feed pump cavitation; the condition of vapour entering turbine is dry saturated; the minimum temperature of exit of exhaust gas is constrained 130^{O}C by it dew point to prevent corrosive effects; the working fluid leaving the boiler and evaporator is saturated. The thermo-physical properties of the hydrocarbon refrigerants based on Peng-Robinson equation of state were calculated using a software package called an Engineering Equation Solver (EES). A major feature of EES is the high accuracy thermodynamic and transport property database that is provided for hundreds of substances in a manner that allows it to be used with the equation solving capability [16].

3.1 Mathematical Model

For the organic Rankine cycle (ORC)

Process 1-2: Pump work input

$$\dot{W}_p = \frac{\dot{m}_{orc}\left(h_2 - h_1\right)}{\eta_p} \tag{1}$$

Process 2-3: Heat absorbed in heat exchanger from cooling water (Process w1-w2)

$$\dot{Q}_{cw} = \dot{m}_{orc}\left(h_3 - h_2\right) \tag{2}$$

Process 3-4: Heat absorbed in boiler from exhaust gases (Process g1-g2)

$$\dot{Q}_{eg} = \dot{m}_{orc}\left(h_4 - h_3\right) = \dot{m}_g c_{pg}\left(T_{g1} - T_{g2}\right) \tag{3}$$

Process 4-5: Turbine work output

$$\dot{W}_t = \dot{m}_{orc}\left(h_4 - h_5\right)\eta_e \tag{4}$$

Process 5-1: Heat rejected to condenser

$$\dot{Q}_{c,orc} = \dot{m}_{orc}\left(h_5 - h_1\right) \tag{5}$$

The net work of the ORC is defined as:

$$\dot{W}_{net} = \dot{W}_t - \dot{W}_p \tag{6}$$

The thermal efficiency of the ORC is defined as:

$$\eta_{orc} = \frac{\dot{W}_{net}}{\dot{Q}_{eg} + \dot{Q}_{cw}} \tag{7}$$

For vapour compression refrigeration cycle (VCR)

Process 1-6: Isenthalpic expansion in throttling valve

$$h_1 = h_6 \tag{8}$$

Process 6-7: Refrigeration effect

$$\dot{Q}_e = \dot{m}_{vcr}\left(h_7 - h_6\right) \tag{9}$$

Process 7-8: Compressor work input

$$\dot{W}_c = \frac{\dot{m}_{vcr}\left(h_8 - h_7\right)}{\eta_c} = \dot{W}_{net} \tag{10}$$

Process 8-1: Heat rejected to condenser

$$\dot{Q}_{c,vcr} = \dot{m}_{vcr}\left(h_8 - h_1\right) \tag{11}$$

The COP of the VCR is defined as:

$$COP_{vcr} = \frac{\dot{Q}_e}{\dot{W}_{net}} \tag{12}$$

The overall COP is defined as:

$$COP_{overall} = \eta_{orc}\, COP_{vcr} \tag{13}$$

The mass flow rate of working fluid per kW of cooling capacity

$$MKW = \frac{\dot{m}_{orc} + \dot{m}_{vcr}}{\dot{Q}_e} \tag{14}$$

The expansion ratio across the expander and the compression ratio across the compressor, which are proportional to the expander and compressor sizes, respectively:

$$EPR = \frac{v_5}{v_4} \tag{15}$$

$$CMR = \frac{p_8}{p_7} \tag{16}$$

3.2 Input Parameters and boundary conditions

In the present study, power output, parameters of exhaust gases and cooling water of a commercial turbocharged diesel engine is employed in the simulations. Then input parameters and boundary conditions are listed in Table.1.

Table 1: Input parameters and boundary conditions

Parameters	Value	Range
Power out of diesel engine	1000 kW	-
Exhaust gas mass flow rate	2.275 kg/s	-
Boiler entry temperature of exhaust gases	220^{O}C	-
Boiler exit temperature of exhaust gases	120^{O}C	-
Cooling water mass flow rate	9.216 kg/s	-
Cooling water temperature from diesel engine	90 ^{O}C	-
Cooling water temperature to diesel engine	80 ^{O}C	-
Expander isentropic efficiency	0.8	-
Compressor isentropic efficiency	0.75	-
Pump isentropic efficiency	0.75	-
Sub-cooling in condenser	5 ^{O}C	-
Superheat in evaporator	5 ^{O}C	-
Boiler pressure	3000 kPa	2000 kPa – P_{crit}
Evaporator temperature	-5 ^{O}C	-15 ^{O}C – 5 ^{O}C
Condenser temperature	45 ^{O}C	30 ^{O}C – 55 ^{O}C

3.3 Working fluids

The working fluids selected for analysis and optimization, on basis of high molecular weight, high critical temperature, dry expansion and low ozone depletion potential, are six hydrocarbons i.e. Propane (R290), Butane (R600), Isobutane (R600a), Pentane (R601), Isopentane (R601a) and Propylene (R1270). The thermodynamic properties are given in table.

Table 2: Properties of working fluids

Desig.	Mol. Wt.	P_{crit} (kPa)	T_{crit} (°C)	ODP	GWP	Ignit. (°C)
R600	58.1	3796	152.01	0	4.0	405
R600a	58.1	3640	134.70	0	3.0	462
R601	72.1	3364	196.58	0	4.0	260
R601a	72.1	3370	187.78	0	4.0	420

3.4 Optimization of ORC-VCR system

The optimization of the ORC-VCR system is performed using the Genetic Algorithm [17]. In the present study, the effects of the boiler pressure (P_{boil}), condenser temperature (T_cond) and evaporator temperature (T_{evap}) on the performances of the system are analysed. The overall COP ($COP_{overall}$) and working fluid mass flow rate of per kW cooling capacity (MKW) are the distinct objective functions for optimization of the ORC-VCR system for each of the selected working fluid. Firstly, the system is optimized separately for each of the objective function. Then multi-objective optimization is done on the system to maximize overall COP and minimize MKW simultaneously. Multi-objective optimization is done using the Weighted Sum Method [18][19].

4. Results and Discussion

The results of the thermodynamics analysis indicates that for all the working fluids, the $COP_{overall}$ increases with increasing P_{boil} and attains a maximum beforetheir P_{crit} are reached (Figures 3).The MKW for all fluids decreases with increasing P_{boil} and attains a minimum before their P_{crit} are reached (Figures 4). For all the working fluids, $COP_{overall}$ monotonically increases and MKW monotonically decreases both with decrease in T_{cond} (Figure 5)and increase in T_{evap} (Figure 6). It is also observed from (Figure 5) that for each working fluid, maximum value of $COP_{overall}$ and minimum value of MKW do not occur at the same value of P_{boil} for specific values of T_{cond} and T_{evap}.

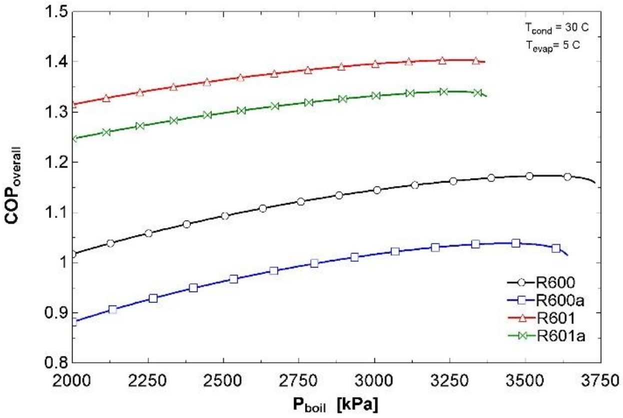


Figure 3 : Variation of overall COP with boiler pressure

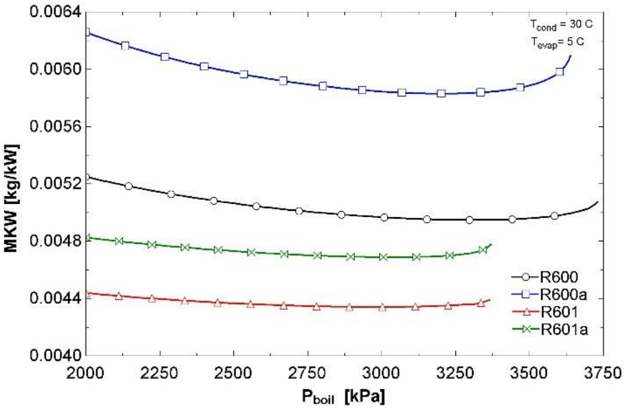


Figure 4 : Variation of MKW with boiler pressure

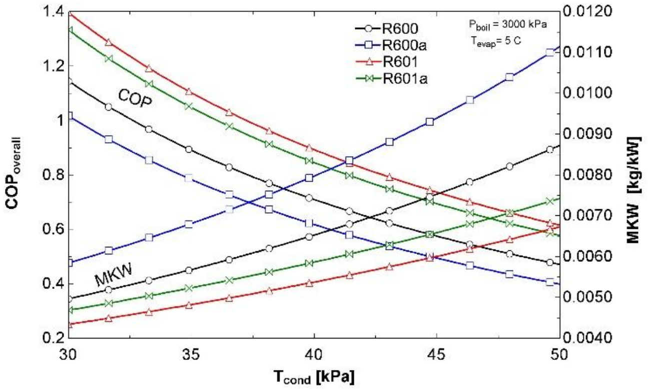


Figure 5: Variation of overall COP, MKW, with condenser temperature

It is also seen that for a specific value of P_{boil}, the maximum value of $COP_{overall}$ and minimum value of MKW will occur at the lower limit of T_{cond} range and higher limit of T_{evap} range.By multi-objective optimization, a single value of P_{boil} is obtained as a compromise between the maximum $COP_{overall}$ and minimum MKW for the specified value of lower limit of T_{cond} and upper limit of T_{evap} as shown in Table 4

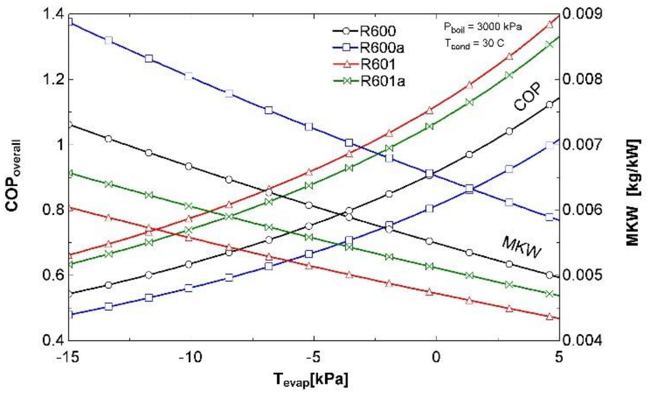


Figure 6: Variation of overall COP, MKW, with evaporator temperature

Table 4: Optimum values

Working Fluid	P_{boil} (kPa)	T_{cond} (℃)	T_{evap} (℃)	$COP_{overall}$	MKW (kg/kW)
n-butane (R600)	3441	35	-5	0.623	0.00719
Isobutane (R600a)	3329	35	-5	0.544	0.00883
n-pentane (R601)	3175	35	-5	0.753	0.00596
Isopentane (R601a)	3160	35	-5	1.035	0.00546

For each working fluid , based on their optimum values of P_{cond} , T_{cond} and T_{evap} the values of all parameters i.e. Boiler Pressure P_{boil} ; Condenser Pressure P_{cond} ; Evaporator PressureP_{evap} ; Boiler Temperature T_{boil} ; Condenser Temperature T_{cond} ; Evaporation Temperature T_{evap} ; Heat from exhaust gas $\dot{Q}_{eg}$; Heat from cooling water $\dot{Q}_{cw}$; Heat to condenser $\dot{Q}_{c}$; Refrigeration effect $\dot{Q}_{e}$; Mass flow of water in HX $\dot{m}_{cw}$; Mass flow rate in ORC$\dot{m}_{orc}$; Mass flow rate in VCR $\dot{m}_{vcr}$; Mass flow per kW of cooling MKW ; Efficiency of ORC η_{orc} ; COP of VCR COP_{vcr} ; Overall COP $COP_{overall}$; Compression ratio CMR ; Expansion ratio EPR are shown in table 5

Table 5: Values of all parameters

Parameters		R600	R600a	R601	R601a
P_{boil}	kPa	3441	3329	3175	3160
P_{cond}	kPa	329	464	98	129
P_{evap}	kPa	85	131	20	43
T_{boil}	℃	146.0	129.4	192.4	183.0
T_{cond}	℃	35	35	35	35
T_{evap}	℃	-5	-5	-5	-5
$\dot{Q}_{eg}$	kW	469.3	469.3	469.3	469.3
$\dot{Q}_{cw}$	kW	123.3	151.5	90.47	95.45
$\dot{Q}_{c}$	kW	962.1	958.7	981.3	1149.0
$\dot{Q}_{e}$	kW	369.4	337.8	421.5	584.4
$\dot{m}_{cw}$	kg/s	2.946	3.619	2.161	2.280
$\dot{m}_{orc}$	kg/s	1.343	1.637	1.035	1.108
$\dot{m}_{vcr}$	kg/s	1.315	1.345	1.476	2.083
MKW	kg/kJ	0.00719	0.00883	0.00596	0.00546
η_{orc}	–	0.097	0.091	0.108	0.105
COP_{vcr}	–	4.062	3.959	4.153	5.935
COP_{overa}	–	0.623	0.544	0.753	1.035
CMR	–	3.862	3.555	5.028	3.018
EPR	–	17.083	11.662	62.041	46.217

From the point of view of thermodynamic performance R601a is the best working with highest value of $COP_{overall}$ and lowest value of MKW as indicated in table 5. For practicality of the overall system, it is required that the pressure in the condenser be close to and above atmospheric pressure; boiler temperature to be well below the self-ignition temperature of working fluid; CMR and EPR to be low for economic sizing of compressor and turbine. Considering all these parameters as indicated in table 5, R600 is the suitable working fluid with condenser pressure above atmospheric, high self-ignition temperature and moderate CMR and EPR.

5. Conclusion

Thermodynamic analysis is necessary to find the independent variables that affect the performance of a combined ORC-VCR system. These variables need to be optimized to obtain the best performance. In this effort, thermodynamic analysis and optimization is done to compare the performance of hydro-carbon working fluids R600, R600a, R601and R601a in the combined ORC-VCR system. The inferences derived for are combined ORC-VCR system: Overall COP increases to a maximum and then decrease with increase in boiler pressure within the sub-critical limit Overall COP monotonically decreases with increase in condenser temperature and decrease in evaporator temperature MKW deceases to a minimum and then increase with increase in boiler pressure within the sub-critical limit. MKW monotonically increases with increase in condenser temperature and decrease in evaporator temperature. The maximum overall COP and minimum MKW does concur at the same boiler pressure.

Though R601 (n-pentane) is the best from view point of thermodynamic performances, R600 (n-butane) is the appropriate working fluid from practicality point of view.

The further scope is to perform an exergoeconomic analysis of the system in order to evaluate it based on an exergy analysis with economic principles.

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