Energy and Parametric Analysis of Organic Rankine Cycle Combined with a Vapor Compression Refrigeration Cycle (ORC-VCR) System using Natural Refrigerants

Muhammad Faizan Qureshi, Mohammad Waqas Chandio*, Abdul Aleem Memon, Laveet Kumar, Muhammad Daniyal Wahla, Uzair Nagori,

Department of Mechanical Engineering, MUET, Jamshoro, Pakistan.
*Corresponding author: waqas.chandio@faculty.muet.edu.pk

Abstract

The dependency on fossil fuels for power generation can be reduced by enhancing the energy efficiency of power generating systems. The refrigeration systems that typically use electricity consume a significant portion of the electricity supplied to cities. The STAND-ALONE refrigeration system which consists of a combined Organic Rankine Cycle and Vapor Compression (ORC-VCR) system is analyzed using the first law of thermodynamics. Dry natural hydrocarbons such as n-Dodecane is used as the working fluid in Organic Rankine Cycle (ORC) and natural Working fluid such as isobutane (R600a) is utilized in Vapor Compression Refrigeration (VCR) Cycle. The study shows that the system can be driven efficiently with Low-grade waste heat from industries or thermal energy from renewable energy sources typically in the range from 100^0C to 350^0C thus reducing reliance on fossil fuel sources. The results also show that the overall Coefficient of performance $COP_{overall}$ of the system and the energy efficiency of the ORC was greatly affected by the evaporation temperature of ORC, T_{eva_ORC} followed by, the evaporation temperature of VCR, T_{eva_VCR}. The maximum $COP_{overall}$ of the system was found to be 0.558 and the energy efficiency of ORC was found to be 20.69% for T_{eva_ORC} of 315^C and T_{eva_VCR} of -30^0C.

Keywords—Organic Rankine Cycle, Vapor Compression Refrigeration Cycle, Energy Analysis, Natural refrigerants, Overall Coefficient of performance

1 Introduction

The world energy crisis can be overcome by utilizing renewable energy sources and recovering low-grade waste heat, which are also two strategies for easing and addressing the environmental issues brought on by the use of conventional energy sources. The ORC (Organic Rankine cycle) has been widely adopted to convert low-temperature heat resources into power by using low-boiling organic working fluids. The steam-based Rankine cycle and ORC operate on a similar principle. The choice of working fluid is the main difference between them. Low-boiling working fluids such as silicon oil, butane, pentane, and hexane, etc. can be used as working fluids in ORC which have lower boiling temperatures than water. These fluids have various characteristics that set them apart from water, including the ability to evaporate with low-temperature heat like recovered waste heat. The ORC technology is excellent and is under rapid development for producing electricity from low-grade energy sources. Solar energy[1], waste heat [2], geothermal energy [3], and biomass usage [4] have all been extensively studied in the literature and used to generate sizable amounts of electrical energy with ORCs. The traditional working fluids offer a serious impact on the environment because of their high value of GWP (Global warming potential) and ODP (Ozone depletion potential) which causes environmental destruction. Hence, the problem of Environmental destruction caused by traditional and synthetic working fluids can be solved by reconsideration of natural refrigerants. Working fluid selection plays a major role in an ORC, the natural organic working fluids have zero ODP and negligible GWP and are the best possible solution to stop environmental destruction. Sruthi Emani and Kumar Mandal [5] discussed the possibility of switching from synthetic

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to natural refrigerants. According to the research, the pure natural hydrocarbons R290 and R600a are suitable for air conditioning and refrigeration systems, respectively, in place of R22 and R134a, respectively. As the pure hydrocarbons and their derivatives are naturally occurring, have very low GWP and ODP, and have a low boiling point, thus they can also be employed as working fluids for the power generation and refrigeration cycle. Siddiqi and Atakan [6] investigated the behavior of alkanes in ORCs operating at various temperatures at which the waste heat is accessible in comparison to water, benzene, and toluene, and concluded that for low-temperature n-pentane and n-hexane are promising, for higher temperature n-dodecane, benzene and toluene are suitable and for intermediate temperature octane, heptane and water are suitable. In worldwide electricity production, Refrigeration systems use approximately 15% of the total electricity produced globally, which is primarily derived from fossil fuels (coal, oil, and gas)[7]. To reduce the electricity consumption for refrigeration, the ORC-powered Vapor Compression Cycle (ORC-VCR) can reduce the electricity consumption at the residential and industrial levels. Khatoon et al. [8] focused on the thermal performance analysis of an ORC-VCR using a common shaft. Three working fluids (R245fa, R123, and R134a,) were chosen for the refrigeration cycle, and two (R245fa and Propane) were picked for the ORC. R123 in the VCR cycle with propane in the ORC showed the highest efficiency of 16.48% with the highest COP (Coefficient of performance) value of 2.85 at 40 °C. Li et al. [9] examined an ORC-powered VCR that used hydrocarbon refrigerants and low-grade thermal energy for boiler exit temperatures ranging from 60^0 C to 90^0 C, condenser temperatures from 30^0 C to 50^0 C, and evaporation temperatures from -15^0 C to 15^0 C. Butane was found to be showing the best results with an overall COP of 0.47 for an evaporation temperature of 5^0 C. Mole et al. [10] combined ORC and vapor compression cycle (ORC-VCR) system utilizing low GWP working fluids and low-temperature heat sources was studied. The ORC-VCR system's calculated COP ranged from 0.30 to 1.10 for evaporation temperatures between -13^0 C to 7^0 C. Hu, B et al. [11] established the thermodynamic model of combined (ORC–VCR) for air conditioning in the ship. To efficiently utilize cooling water and transport flue gas waste heat. The system performance was analyzed by using five commonly used working fluids. Calculations proved that R601 was the most suitable working fluid. The system's performance is significantly impacted by the system's condensing temperature and heat source temperature. A major portion of the energy used by tractive diesel engines, marine engines, and electrical generators is lost as heat in the cooling water and exhaust. at temperatures high enough to produce electricity. Alklaibi, A.M. and N. Lior [12] evaluated the waste heat recovery of the engine by ORC resulted in a reduction of its specific fuel consumption from 5 to 11.3% and an increase of about 5% of the engines' thermal efficiency. Saleh et al. [13] investigate the performance and refrigerant selection for single and two stages vapor compression refrigeration cycles. Several pure hydrocarbons, hydrofluorocarbons, and hydrofluoroolefins are proposed as alternative refrigerants to substitute R22 and R134a due to their environmental impacts. The two-stage cycle presents a gain in COP of 5.1% compared with the single-stage cycle based on the used refrigerant. Among all investigated refrigerants, cyclopentane is the most suitable refrigerant for the two cycles from the viewpoint of thermal efficiency. Sanchez D. et al. [14] investigated experimentally the performance of R600a, R290, R1234ze (E), R1234yf, and R152a as possible substitutes for R134a in VCR. Based on the experimental results, they concluded that R1234yf and R152a can be the possible replacement options for R134a. Ghanbarpour et. al. [15] investigated the energetic and exergetic performance, as well as the environmental impact, of three vapor compression system configurations using R290, R600a, and R1270 as R134a replacements. A single-stage cycle, a cycle with an internal heat exchanger, and a two-stage cycle with vapor injection are three configurations used for investigation. According to the results, alternative hydrocarbon refrigerants may be able to match R134a's system performance. According to the exergy analysis, the two-stage refrigeration cycle with vapor injection was the most efficient option.

Based on the aforementioned review, there is little or no agreement on the use of an environmentally friendly working fluid suitable for the combined ORC-VCR system. This paper presents the energy analysis of the combined Organic Rankine cycle and Vapor Compression Refrigeration cycle (ORC-VCR) system. The performance of the system was evaluated using dry natural hydrocarbon such as n-Dodecane as the working fluid in ORC and natural working fluid isobutane (R600a) in VCR. The properties of the working fluids selected for study are mentioned in table 1. In addition, the effects of condenser and evaporator temperature on the COP and efficiency of the system were also examined.

TABLE 1: Working Fluid properties [16],[17]

Working fluid	Critical Temperature	Critical Pressure (bar)	GWP	ODP
n-Dodecane	385	18.17	NA	0
isobutane	134.7	36.29	3	0

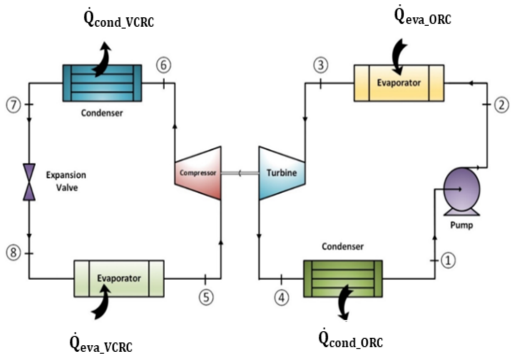

Fig. 1: Schematic diagram of Combined ORC-VCR system

2 COMBINED ORC-VCR SYSTEM DESCRIPTION

The system considered for energy analysis consists of two sub-systems which comprise of combined ORC-VCR system as shown in Fig.1. The ORC identified as (1-2-3-4-1) with n-dodecane as the working fluid and a VCR System identified as (5-6-7-8-5) with isobutane (R600a) as the working fluid. The turbine shaft of ORC is directly coupled with the compressors of VCR. The whole assembly is recognized as a Combined ORC-VCR system.

The Simple ORC subsystem as shown in Fig.1 has four essential components: pump, turbine, condenser, and evaporator. In the evaporator (process 2-3), the working fluid is initially heated and vaporized to the temperature (T_{eva_ORC}) due to the heat that is absorbed from the heat source $\dot{Q}_{eva\_ORC}$, then the high-pressure Vapors enter the turbine, and the high enthalpy of those vapors is turned into mechanical shaft work. $\dot{W}_{turbine}$ i.e process (3-4) after passing through the turbine, the low-pressure vapors enter the condenser (Process 4-1) where the condensation occurs at the temperature T_{cond} due to the heat being rejected ($\dot{Q}_{Cond\_ORC}$) to the external medium at the temperature of (T_0). As a result of the fluid being pumped (Process 1-2) to the evaporator, the heat from the heat source is now absorbed. In this way the cycle completes. The net power delivered from ORC ($\dot{W}_{net} = \dot{W}_{turbine} - \dot{W}_{pump}$) is used to drive the compressors of the VCR ($\dot{W}_{Comp}$).

To create a low-temperature environment, a vapor compression refrigeration subsystem is used as shown in fig.1. The subsystem consists of a condenser, a compressor, an evaporator, and a throttle valve. The heat is absorbed by the refrigerant in the evaporator. ($\dot{Q}_{eva\_VCR}$) from the refrigeration space at evaporation temperature (T_{eva_VCR}) and totally converts into vapors (process 8-5). The vapors are now compressed (process 5-6) in a compressor and then in the condensed the heat ($\dot{Q}_{cond\_VCR}$) is released at (T_{cond_VCR}) to the condensing medium (process 6-7) whose temperature is (T_0). Finally, the cycle is completed when it expands in the throttle valve (process 7-8).
The following assumptions served as the foundation for the computations.

2.1 Assumptions for ORC

- The cycle is operated in steady-state circumstances.
- There are barely any pressure drops in the tube and other components.
- At the ORC evaporator's exit, the working fluid is saturated vapor.
- To prevent cavitation in the boiler feed pump, the working fluid is subcooled to 3°C at the ORC condenser's exit.
- The pump and expander's isentropic efficiency measures at a value of 80%.

2.2 Assumptions for VCR

- The cycle is operated in steady-state circumstances.
- There are negligible Pressure drops in the tubing and other components.
- At the evaporator's exit, the working fluid is in the saturated vapor state.
- Working fluid is subcooled at 10^0 C at the outlet of the condenser.
- The net power produced by the ORC is the power consumed by the compressor of the VCR.
- The cooling load $\dot{Q}_{eva\_VCR}$ is 1 kW.
- The compressor's isentropic efficiency registers a value of 80%.

Components	Energy Balance Equation
Organic Rankine Cycle	
Evaporator	$\dot{m}_{ORC}h_2 + \dot{Q}_{eva\_ORC} = \dot{m}_{ORC}h_3$
Turbine	$\dot{m}_{ORC}h_3 + \dot{W}_{turbine} = \dot{m}_{ORC}h_4$
Pump	$\dot{m}_{ORC}h_1 - \dot{W}_{pump} = \dot{m}_{ORC}h_2$
Condenser	$\dot{m}_{ORC}h_4 - \dot{Q}_{cond\_ORC} = \dot{m}_{ORC}h_1$
Vapor Compression Refrigeration Cycle	
Evaporator	$\dot{m}_{VCR}h_8 + \dot{Q}_{eva\_VCR} = \dot{m}_{VCR}h_5$
Compressor	$\dot{m}_{VCR}h_5 + \dot{W}_{comp} = \dot{m}_{VCR}h_6$
Condenser	$\dot{m}_{VCR}h_6 - \dot{Q}_{cond\_ORC} = \dot{m}_{VCR}h_7$
Expansion valve	$\dot{m}_{VCR}h_7 = \dot{m}_{VCR}h_8$

3 THERMODYNAMIC MODEL

After applying the First law of thermodynamics to various components of a combined ORC-VCR system, the following mathematical model was constructed [18].

The actual power required for the pump and compressors will be

$$\dot{W}_{actual} = \frac{\dot{W}_{isentropic}}{\eta_s}$$

COP of Vapor Compression Refrigeration system

$$COP_{VCR} = \frac{\dot{Q}_{eva\_VCR}}{\dot{W}_{Comp}}$$

The efficiency of the ORC system

$$\eta = \frac{\dot{W}_{net}}{\dot{Q}_{eva\_ORC}}$$

The Overall COP of the ORC-VCR system

$$COP_{overall} = \frac{\dot{Q}_{eva\_VCR}}{\dot{Q}_{eva\_ORC}}$$

4 RESULTS AND DISCUSSION

The flow parameters at each state point in the ORC-VCR system are specified in table 2. Table 4 shows the performance parameters determined using energy analysis. Since the coefficient of performance of combined ORC-VCR system COP Overall and the efficiency (η_{ORC}) of the ORC can be expressed as the functions of many variables such that T_{eva_ORC}, T_{Cond}, T_{eva_VCR}, etc. thus, a parametric analysis has been carried out to check the dependency of these variables on the $COP_{Overall}$ and η_{ORC}. The temperature range has been taken between the triple point temperature and critical point temperature of the working fluid used. Moreover, the range of operating parameters required is mentioned in table 3.

TABLE 2: Flow parameters of ORC-VCR System

State Point	$T(^0C)$	P(kPa)	h(kJ/kg)	(kg/s)
1	27	0.02682	4.336	0.00183
2	27.04	673.9	5.06	0.00183
3	315	673.9	984.3	0.00183
4	226.7	0.02682	780.9	0.00183
5	-30	46.37	515.2	0.003733
6	40.39	404.5	614.6	0.003733
7	20	404.5	247.3	0.003733
8	-30	46.37	247.3	0.003733

TABLE 3: Operating parameters

Parameters	Value range
T_{eva_ORC} (^0C)	85-325
T_{cond} (^0C)	30, 35, 40, 45, 50
T_{eva_VCR} (^0C)	-30, -35, -40, -45, -50

4.1 Effect of T_{eva_ORC} and T_{cond} on ORC Efficiency

The effect of variation of Evaporation and condensation Temperature of ORC on the Efficiency of ORC has been investigated using n-Dodecane as the working fluid in ORC. Fig.2 shows the variation of the Efficiency of ORC η_{ORC} corresponding to the Evaporation and condensation Temperatures of ORC T_{eva_ORC} and T_{cond} respectively. while maintaining the other variables unchanged. It can be observed from Fig.2 that the lower value of T_{eva_ORC} led to a lower value of η_{ORC}. and as the evaporation temperature increased the efficiency also increased. This is due to the decrease in latent heat of vaporization of n-Dodecane as the temperature rises. And hence $\dot{Q}_{eva\_ORC}$ decreases in result efficiency increases. For a fixed value of T_{eva_ORC} the decrease in efficiency from $T_{cond} = 30 - 50^0$ C registered a value of 33.708

TABLE 4: Performance parameters

Vapor Compression Refrigeration System	
$\dot{Q}_{eva\_VCR}$ (kw)	1
$\dot{Q}_{cond\_VCR}$ (kw)	1.371
$\dot{W}_{comp}$ (kw)	0.3709
COP_{System}	2.696
$\dot{m}_{VCR}$ (kg/s)	0.003733
Organic Rankine Cycle	
$\dot{W}_{net}$ (kW)	0.3709
$\dot{m}_{ORC}$ (kg/s)	0.00183
$\dot{Q}_{eva\_ORC}$ (kW)	1.792
$\dot{W}_{turbine}$ (kW)	0.3722
$\dot{Q}_{cond\_ORC}$ (kW)	1.421
$\dot{W}_{pump}$ (kW)	0.001326
$\eta_{ORC}(\%)$	20.69
Combined ORC-VCR system	
$COP_{overall}$	0.558

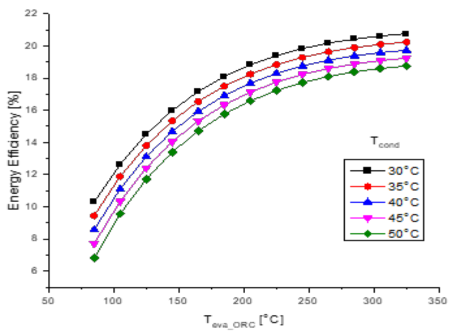

Fig. 2: Efficiency η_{ORC} as a function of T_{eva_ORC} and T_{cond}

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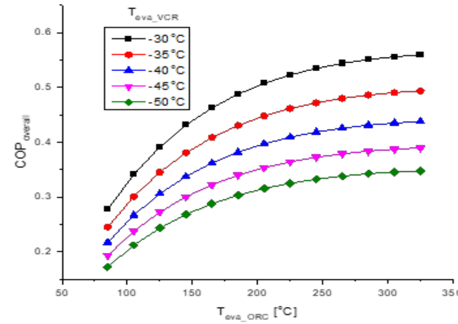

Fig. 3: $COP_{overall}$ as a function of T_{eva_ORC} and T_{eva_VCR}

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% however, with a constant value T_{cond} an increase of 50.385% was observed in the efficiency for the entire range of T_{cond}.

4.2 Effect of T_{eva_ORC} and T_{eva_VCR} on $COP_{Overall}$

The effect of variation of evaporation Temperatures of ORC and VCR on the COP Overall of the Combined ORC-VCR system has been investigated using n-Dodecane as the working fluid in ORC and isobutane in VCR. The Fig.3. shows the variation of the COP Overall corresponding to the evaporation Temperature of ORC T_{eva_ORC} and VCR T_{eva_VCR} While keeping the other parameters constant. It can be observed from fig.3 that the lower value of T_{eva_ORC} led to a lower value of $COP_{Overall}$ and as T_{eva_ORC} increased the COP Overall also increased. This is because when the temperature rises the latent heat of vaporization decreases accompanied by the decrease in $\dot{Q}_{eva\_ORC}$. which causes COP Overall to increase. For a fixed value of T_{eva_ORC} the increase in COP Overall from $T_{eva\_VCR} = -50^0 C to - 30^0 C$ registered a value of 37.796% on the other hand for a fixed value of T_{eva_VCR} an increase of 50.357% was noticed in the COP Overall for the entire range of T_{eva_VCR}.

4.3 Effect of T_{eva_ORC} and T_{cond} on $COP_{Overall}$

The effect of condensation temperature and Evaporation Temperature of ORC on the overall COP of the Combined ORC-VCR system has been shown for different values of the condensation temperature of the VCR. It has been observed that for a fixed value of T_{eva_ORC} very low condensation temperature in VCR say $T_{cond} = 30^0 C$ results in the highest value of the $COP_{Overall}$. And for $T_{cond} = 50^0 C$ the COP Overall is the lowest among all temperature ranges. And for the

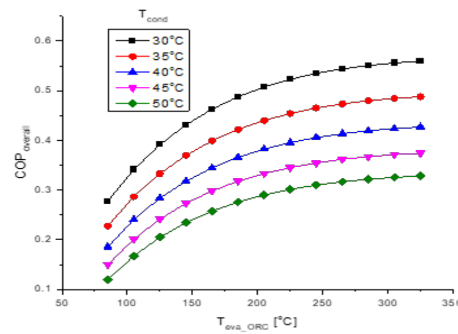

Fig. 4: $COP_{Overall}$ as a function of T_{eva_ORC} and T_{cond}

entire range of T_{cond} the increase in the COP Overall was 56.983% And for a fixed value of T_{cond}. The overall COP also rises as the ORC's evaporation temperature rises. with a 50.357% increase in $COP_{Overall}$ as shown in Fig. 4. Additionally, it has been shown that this system can be driven by heat sources with a temperature range of $(100 - 350^0 C)$.

5 Conclusions

A novel STAND-ALONE refrigeration system comprising a Combined ORC -VCR system has been modeled for various operating conditions for applications requiring very low evaporation temperatures. Natural refrigerants have been reconsidered as working fluids utilizing low-grade waste heat or renewable thermal energy resources. following are some conclusions.

- The most important variable for the ORC-VCR system was T_{eva_ORC} followed by T_{eva_VCR} and T_{cond}.
- T_{eva_ORC} had a significant impact on the system's total COP and ORC Efficiency, followed by T_{eva_VCR} and T_{cond}.

TABLE 5: Nomenclature, Subscripts, Greek Symbols

Nomenclature	
GWP	Global Warming Potential
ODP	Ozone Depletion Potential
COP	Coefficient of performance
T	Temperature (^0C)
P	Pressure (kPa)
Q	Rate of heat transfer (kW)
W	Mechanical Power (kW)
m	Mass flow rate (kg/s)
h	Specific enthalpy (kJ/kg)
Subscripts	
Comp	Compressor
Cond	Condenser
Eva	Evaporator
ORC	Organic Rankine Cycle
VCR	Vapor compression refrigeration
Sub	Subcooled
s	Isentropic
Greek Symbols	
η	efficiency

- Low-grade waste heat or Thermal renewable energy (i.e., geothermal, solar, waste heat, etc.) in the range of $100 - 350^0C$ can be used for driving the system. Hence dependency on traditional fossil-energy sources can be reduced.
- The overall Coefficient of performance $COP_{overall}$ of the system and the energy efficiency of the ORC was greatly affected by the evaporation temperature of ORC, T_{eva_ORC} followed by, the evaporation temperature of VCR, T_{eva_VCR}. The maximum $COP_{overall}$ of the system was found to be 0.558 and the energy efficiency of ORC was found to be 20.69% for T_{eva_ORC} of 315^0C and T_{eva_VCR} of -30^0C.
- The use of natural working fluids reduces the risk of GWP and ODP thus reducing environmental destruction.

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