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Design Investigation of 5 kW Organic Rankine Cycle (ORC) System Using Diffusion Absorption Refrigeration (DAR) for Cooling and Power Generation for India

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Abstract: A country like India has great potential for the conversion of waste heat into power through Organic Rankine Cycle (ORC). This paper focuses on the design feasibility of a method to produce combined power and cooling effect through ORC, which is environment friendly as it adds no emission for the environment. The organic fluid R123 has been selected for organic Rankine cycle. The working fluid R123 has very low ODP (ozone depletion potential of 0.02) and GWP (global warming potential of 77). The electrical power output and power output of expander are 5 kW and 5.26 kW respectively. The source temperature for ORC is 130. At the outlet of the evaporator the temperature of heat transfer fluid is 110. This available heat at the evaporator outlet act as heat input for diffusion absorption refrigeration (DAR) system. The working fluid for this system is selected as NH_3-$LiNO_3$-He, which operates at lower generator temperature. The evaporator temperature of DAR system is achieved around 5 also the cooling capacity produced around 2.5 kW.

This combined system satisfies both cooling and power requirement simultaneously and make a system in uncoupled form. Further, the analysis of the efficiency of ORC system in variable condensing temperature has been done under Indian climatic conditions. The study reveals that with the increment in the ambient temperature condensing temperature increases. The performance of ORC degrades with the increment in condensing temperature. The cooling water from cooling tower passes from the evaporator of DAR system. This leads to decrease in the cooling water temperature from 23.5 to 15.5. The condensing temperature decreases from 35 to 32 due to the temperature reduction of cooling water. In turn, the efficiency of ORC system increases by approximately 7%. This combined system meets the demand of both power production and cooling effect with no emission of pollutants to the environment.

Key words: Thermal efficiency, organic Rankine cycle, condenser, diffusion absorption chiller.

Introduction

The increment in the global warming effect (GWE) leads to the rise in the temperature of the earth. The greenhouse gases (GHG) are the main factor for this, which are emitted from the human activities (Kokic et al., 2014). The environment pollution increases due to enormous consumption of electricity. To overcome this problem the renewable energy resources are the best alternative option (Aljundi, 2011). Around 25% energy of the fuel is converted into work and as heat; more than 40% energy of fuel being wasted (Hasanuzzaman et al., 2011).

The conversion of waste heat into the power can reduce the greenhouse gases emission and make a healthy environment (Ziviani et al., 2014). ORC is

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propitious technology for utilization of heat energy of low-grade into the useful power. The different type heat sources of low-temperature like geothermal, solar, and biomass energy has been used for the ORC (Tchanche et al., 2011). The environmental temperature and climatic conditions vary drastically throughout India. The performance investigation of ORC system under such conditions is also challenging (Sarkar et al., 2016).

An experiment has been conducted by Feng et al. (2017) to find out the operation characteristics of organic Rankine cycle. The working fluid was selected R123, and source temperature varies from 383.15-413.15 K. The highest electrical power and expander power production are 2.01 and 2.78 kW. Yang et al. (2017) investigated the operation of ORC with various parameters like superheating temperature and temperature of condensation. Results indicate that the increment in the condensing temperature leads to decrease in shaft power output and thermal performance of the cycle.

Liu et al. (2013) investigated the performance of geothermal ORC for dissimilar hydrocarbon fluids. The hot source temperature was from 100-150°C. The analysis found that the decrease in the condensation temperature increases the net power production. For the maximum power output, the optimum condensation temperature was 29.45°C to 29.75°C. Shu et al. (2016) investigated the performance comparison of the two organic fluids R245fa and R123 experimentally for waste heat of engine. Results show that organic fluid R245fa is well suited for the city bus and R123 is suitable for heavy-duty truck.

A comparison study was conducted between wet cooling towers and air cooled condensers for ORC with the geothermal heat source. The study reveals that wet cooling towers are economical than the air-cooled condensers (Walraven et al., 2015). To enhance the performance of ORC system a new design for heat exchangers has been developed. The simulation result shows that the maximum increase in the thermal performance is around 9% (Mastrullo et al., 2015). Also for increment in the efficiency of ORC with reducing temperature of condensation, condensing temperature design for different expander configuration were done (Wei et al., 2017).

The exiting part of waste heat for an ORC can be further used to run the absorption chillers for cooling demand (Li et al., 2014). Marin et al. (2013) analysed the performance of solar assisted combined ORC and absorption chillers. They concluded that this type of arrangement could satisfy power generation and cooling demand of a building. Sun et al. (2017) analyzed the second law for combined ORC and an absorption chiller. The analysis result finds that the combined system can be used as uncoupled form as well as coupled form. They also found that with the increment in the source temperature the exergy efficiency of both systems decreases.

An energy and exergy analysis has been conducted for combined ORC and ejector refrigeration system to produce output power and cooling effect simultaneously. Parametric study shows that decrease in condensing temperature increases the thermal efficiency. The increment in ejector mass entrainment ratio leads to increase in thermal as well as exergetic efficiency (Hadi et al., 2017). A feasibility study of combined absorption chillers and power generation (ORC) system has been done. The results show that decrease in cooling water inlet temperature leads to gain in the ORC thermal efficiency. Also levelized electricity cost of new system was more than the previous system (Nattaporn, 2015).

The above literature review shows that many experiments have been carried out to know the performance of the ORC with different parameters. Also, performance improvement with different organic fluid has also been reported. Some researchers focus on to reduce condensing temperature with different heat exchanger design, to increase the performance. A very less attention is given to enhance the ORC efficiency with absorption chillers. A diffusion absorption refrigeration system has not been reported in the literature to gain the thermal performance of ORC.

A novel idea is proposed to reduce condensing temperature of organic Rankine cycle with DAR system. To know the design feasibility for such combined system a mathematical model is developed in the computer software Engineering Equation Solver (EES).

Material and Methods

System Description

The working fluid selection is most important criteria for ORC. Organic fluid has different properties than the water. The water as a working fluid needs to be superheated which is not desirable for ORC. The organic working fluid for the ORC is selected as R123 which is environment friendly fluid. The working principle of organic Rankine cycle is described in Figure 1. The temperature of heat transfer fluid around 140-150 °C enters in the evaporator from point 7. In the evaporator, the working fluid boils when it comes into contact with heat transfer fluid. At point 1 the refrigerant is in vapour

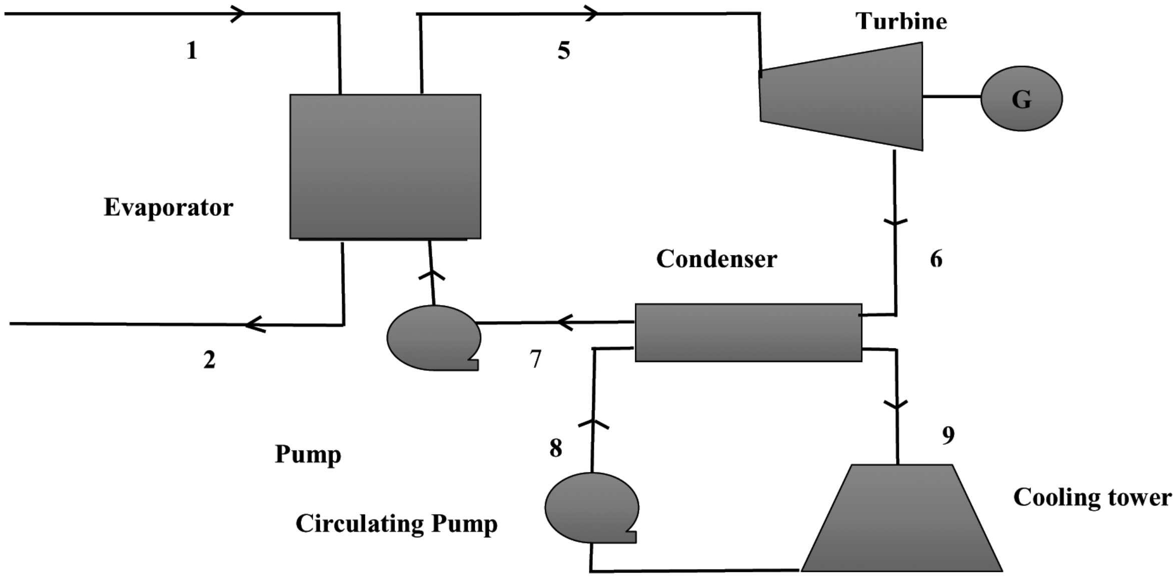

Figure 1: Block diagram of organic Rankine cycle (ORC).

form impacts on the expander, and it starts rotating. The expansion from high pressure to low pressure is shown by point 1 to 2. The rotation of expander produces useful power which is converted into electricity through the generator. The maximum output power of expander is around 5.26 kW. After the expansion through the expander, the organic fluid goes to the condenser from 2, here it converts into the liquid form and reach at point 3. The condenser is cooled by cold water coming from the cooling tower (process 5-6). After the condensation, the liquid working fluid flows towards pump; here the pressure of fluid increases up to the evaporator pressure at point 4, and again a new cycle starts.

Figure 2 shows the combined system of ORC and DAR system. The temperature of heat transfer fluid at evaporator inlet is around 140-150 °C. After it passes through the evaporator, its temperature decreases around 100-110 °C. At the exit of evaporator available heat acts as source heat for generator of DAR system. Some quantity of this heat is used as input heat to the generator of DAR system. The working fluid for a three fluid system (DAR) is selected as NH_3-$LiNO_3$-He, as it operates at low temperatures. The exhaust heat of ORC around 110 °C is used to boil off the binary mixture of NH_3 and $LiNO_3$. The ammonia is used as refrigerant and lithium nitrate as absorbent. When the refrigerant converts into vapour form, it goes to the rectifier as it reduces the absorbent presence. The remainder solution goes back to the generator. The pure refrigerant passes through the condenser where it converts into liquid form. The liquid refrigerant reaches at hydraulic trap where it meets the inert gas He.

The presence of inert gas decreases the refrigerant pressure and temperature. The mixture then passes through the evaporator, and cooling effect produces at the evaporator. The evaporator temperature is achieved around 5 °C. Then the mixture of gases goes through the heat exchanger (EHX) where the inert gas coming from the absorber removes heat. The temperature of the inert gas decreases before reaching the hydraulic trap. After that, the inert gas and refrigerant mixture passes through absorber. At absorber, the absorbent absorb the refrigerant. The inert gas is not absorbed in the absorber and directed towards EHX. The mixture refrigerant of high concentration passes through the AHX (Auxiliary heat exchanger), where it exchanges the heat with the low concentration of refrigerant mixture; this reduces the heat supply in the generator. Now the inlet cooling water of cooling tower passes through the evaporator of DAR. Due to this, the temperature of cooling water decreases from 23.5 °C to 15.5 °C. This reduces the condensing temperature of ORC unit.

Mathematical Model

Organic Rankine Cycle Energy Analysis

The source temperature for ORC unit is around 130 °C. The power output of expander is assumed around to be 5.26 kW. The m_w is the working fluid mass flow rate, h is the working fluid enthalpy at various points, Q_{in} is heat input to the evaporator, Q_{out} is heat rejected into the atmosphere, W_{exp} is the power output from the expander, W_p is the power consumed by pump, Q_{ct} is the heat gain in cooling tower and n_{th} is the thermal

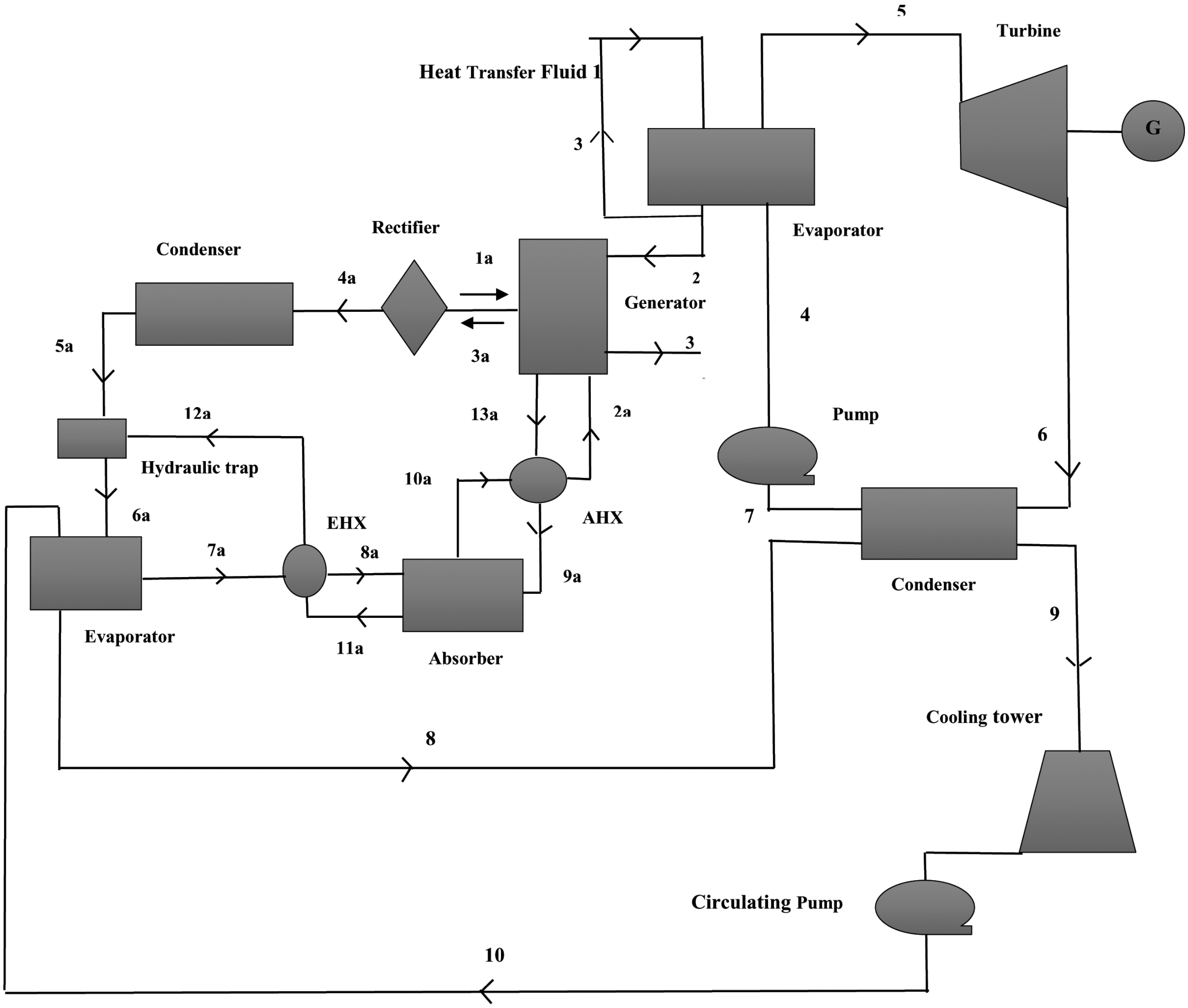

Figure 2: Block diagram of combined organic Rankine cycle (ORC) and diffusion absorption refrigeration (DAR).

efficiency. Energy analysis of ORC is carried out with the following assumptions:

- The expander and pump isentropic efficiency was assumed to be around 75% and 80% respectively.
- The different piping losses are assumed to be negligible.
- Mechanical losses from coupling, turbine, and pumps were assumed to be negligible.

Heat input to the evaporator

$$Q_{in}(\text{kW}) = m_w(h_5 - h_4) \tag{1}$$

Expander power output

$$W_{\text{exp}}(\text{kW}) = m_w(h_6 - h_7) \tag{2}$$

Heat rejected from the condenser.

$$Q_{out}(\text{kW}) = m_w(h_6 - h_7) \tag{3}$$

Pump power consumption

$$W_p(\text{kW}) = m_w(h_4 - h_7) \tag{4}$$

Cooling water heat gain

$$Q_{ct}(\text{kW}) = m_{wat}(h_9 - h_8) \tag{5}$$

$$\text{Net power generation} = \text{Expander power output} - \text{Pump power consumption} \tag{6}$$

$$\text{Thermal efficiency}(\eta_{\text{th}}) = \frac{\text{Net power generation}}{\text{Heat input to the evaporator}} \tag{7}$$

Diffusion Absorption Refrigeration Energy Analysis

Von platen and Munters (1928) developed the Diffusion Absorption Refrigeration (DAR) system. For the analysis of cooling system with capacity of 2.5 kW, a mathematical model was generated. The evaporator and generator temperature was 5 °C and 100 °C respectively. The thermodynamic properties of mixture NH_3-$LiNO_3$ are calculated from the work of Sun (1998). The Q_{gen} denotes generator heat input, Q_r rectifier heat rejected, Q_c condenser heat rejected, Q_{abs} heat rejected through absorber, Q_{evap} heat absorbed by evaporator, m is the mass flow rate, and suffix He denotes the helium. COP is the coefficient of performance of DAR system. The following assumptions were assumed for the energy analysis of DAR system:

- Along the pipes pressure drops are neglected.
- The thermal losses from the pipes are assumed to be zero.
- The absorber and condenser assumed to be at same temperature.

Generator

$$m_{2a}h_{2a} + m_{1a}h_{1a} + Q_{gen} = m_{3a}h_{3a} + m_{13a}h_{13a} \quad (8)$$

$$m_{2a} + m_{1a} = m_{3a} + m_{13a} \quad (9)$$

Rectifier

$$m_{3a}h_{3a} = m_{1a}h_{1a} + m_{4a}h_{4a} + Q_r \quad (10)$$

$$m_{3a} = m_{1a} + m_{4a} \quad (11)$$

Condenser

$$m_{4a}h_{4a} = Q_c + m_{5a}h_{5a} \quad (12)$$

$$m_{4a} = m_{5a} \quad (13)$$

Hydraulic trap

$$m_{5a}h_{5a} + m_{he12a}h_{he12a} = m_{6a}h_{6a} + m_{he6a}h_{he6a} \quad (14)$$

$$m_{he12a} = m_{he6a} \quad (15)$$

$$m_{5a} = m_{6a} \quad (16)$$

Evaporator

$$m_{6a}h_{6a} + m_{he6a}h_{he6a} + Q_{evap} = m_{7a}h_{7a} + m_{he7a}h_{he7a} \quad (17)$$

$$m_{6a} = m_{7a} \quad (18)$$

$$m_{he6a} = m_{he7a} \quad (19)$$

Heat exchanger (EHX)

$$m_{7a}h_{7a} + m_{he7a}h_{he7a} + m_{he11a}h_{he11a} = m_{8a}h_{8a} + m_{he8a}h_{he8a} + m_{he12a}h_{he12a} \quad (20)$$

$$m_{he7a} + m_{he11a} = m_{he8a} + m_{he12a} \quad (21)$$

$$m_{7a} = m_{8a} \quad (22)$$

Absorber

$$m_{8a}h_{8a} + m_{he8a}h_{he8a} + m_{9a}h_{9a} = m_{10a}h_{10a} + m_{he11a}h_{he11a} + Q_{abs} \quad (23)$$

$$m_{he8a} = m_{he11a} \quad (24)$$

$$m_{8a} + m_{9a} = m_{10a} \quad (25)$$

Heat exchanger (AHX)

$$m_{10a}h_{10a} + m_{13a}h_{13a} = m_{9a}h_{9a} + m_{2a}h_{2a} \quad (26)$$

$$m_{13a} = m_{2a} \quad (27)$$

$$m_{10a} = m_{9a} \quad (28)$$

$$\text{COP} = \frac{Q_{evap}}{Q_{gen}} \quad (29)$$

Based on the above mathematical model the simulation study was carried out for different condensing temperature and cooling water temperatures.

Results and Discussion

In this section the effect of ambient temperature, cooling water inlet temperature, and condensing temperature on the performance of organic Rankine cycle is presented. Also, the effect of integrating of DAR in ORC is discussed. The COP of DAR system is found to be 0.46 with the above mathematical model. These results can be compared with the findings from Acuna et al. (2016).

The effect of inlet temperature of cooling water on the condensing temperature is shown in Figure 3. In the figure, it is evident that when the inlet temperature of cooling water from wet cooling tower is increased, the condensing temperature is also increased. For the mathematical simulation, the inlet temperature of cooling water is increased from 15.5 °C to 22.5 °C, the increment in the condensing temperature is from 32 °C to 35 °C. The condenser of ORC unit is cooled by wet cooling tower, so inlet cooling water temperature has to be as low as possible. As the temperature of cooling water is low, the refrigerant R123 condenses at low temperature, which leads to being beneficial for the performance of organic Rankine cycle (ORC). But high condensing temperature is the result of water temperature increases which are not favourable for ORC performance.

Figure 4 shows the effect of ambient conditions on the cooling water inlet temperature of ORC system. The

Table 1: Input parameters of organic Rankine cycle

Component and parameters	*Value*
Evaporator capacity (kW)	53
Expander power output (kW)	5.01
Pump power consumption (kW)	0.213
Source temperature (°C)	130
Working fluid mass flow rate (kg/sec)	0.260

Table 2: Input parameters of diffusion absorption refrigeration system

Component	*Value*
Generator (kW)	5.2
Condenser (kW)	2.8
Absorber (kW)	4.3
Evaporator (kW)	2.5
Generator temperature (°C)	100
Evaporator temperature (°C)	5

performance of wet cooling tower strongly depends on the ambient conditions. When the unsaturated air comes into contact with spray water, the evaporative cooling takes place, so the water cools. The maximum water can be cooled up to the wet bulb temperature of the ambient air. As the wet bulb temperature of ambient air increased from 14 °C to 23 °C, the cooling water temperature is increased from 18 to 25 °C. The reason is that when the wet bulb temperature increases the efficiency of the cooling tower decreases. This leads to the reduction in the cooling water inlet temperature. As the cooling water temperature increases the condensing temperature increases which degrades the performance of ORC system.

The effect of condensing temperature on the performance of expander is shown in Figure 5. For the simulation purpose, the condensing temperature varies from 30 °C to 38 °C, which is higher for the Indian climatic conditions. As the condensation temperature increases the expander work is reduced. Because the enthalpy of organic fluid increases at the outlet of the expander, so enthalpy drop across the expander decreases. When the ORC system is integrated with DAR system, the condensing temperature of the organic fluid is decreased, because of the reduction in the inlet cooling water temperature as it passes through the evaporator of DAR system. Due to this, there is an increment in the expander work. The expander work increases as shown in Figure 5.

The main reason for the increment in the expander work is: at the lower condensing temperature the enthalpy of the working fluid is low, so expansion is done at a lower temperature; this leads to increment in the enthalpy difference. So the power production by expander is more in the combined system. The expander power output produced at condensing temperature around 35 °C is 3.7 kW, when the whole system is used as the combined system then the condensing temperature is decreased around 3 °C; so power production increases up to 4 kW. This increase in the shaft work with the reduction in the condensation temperature can be compared with the works from Yang et al. (2017).

The ORC efficiency variation with the condensing temperature is shown in Figure 6. The simulation result shows that when the condensing temperature increases the thermal efficiency is reduced as the expander work is decreased. When the combined system is studied as a whole, the temperature of cooling water from

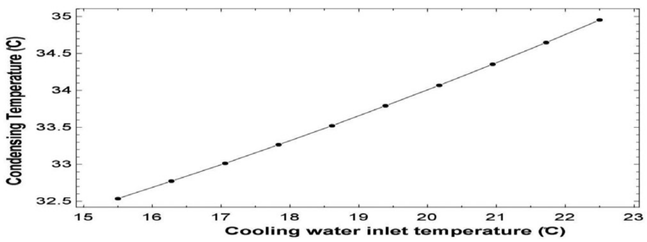

Figure 3: Effect of inlet temperature of cooling water on condensing temperature of ORC.

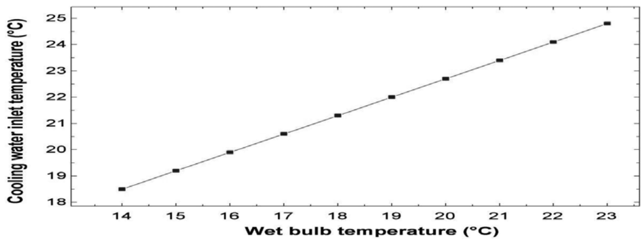

Figure 4: Effect of wet bulb temperature on cooling water inlet temperature of ORC system.

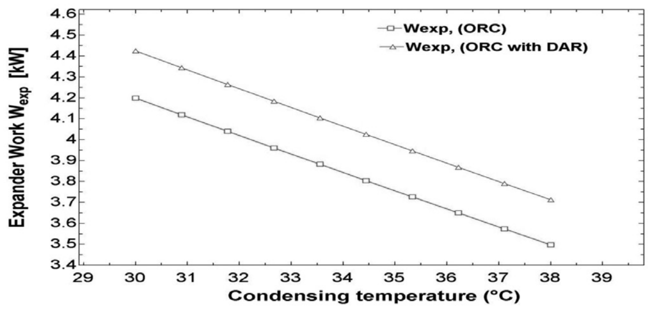

Figure 5: Effect of condensation temperature on the expander work of ORC system.

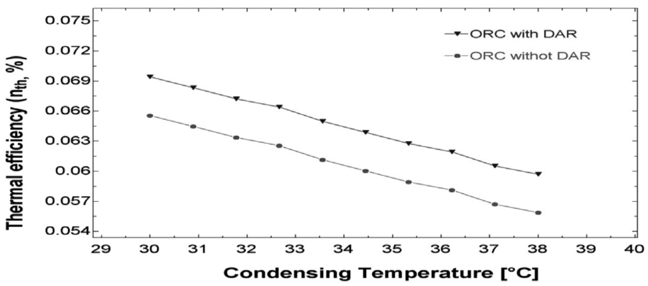

Figure 6: Effect of condensation temperature on the performance of ORC with and without DAR.

cooling tower reduces when it goes to the evaporator of DAR system. The temperature of the evaporator is around 5 °C. For the present study, the reduction in the temperature of cooling water is from 22.5 °C to 15.5 °C. Due to this, the condensing temperature decreases around 35 °C to 32 °C. This reduction in the condensing temperature results into increase in the expander work, which turns into the increase in the efficiency from 5.8% to 6.2%. So the maximum increase in the thermal efficiency is around 7% for the simulated data. These results can be compared with the findings from Yang et al. (2017) and Wei et al. (2007).

The results show that the condensing temperature reduction leads the gain in efficiency of the cycle. This system will be very beneficial for the places where the condensing temperature is high throughout the year. In India the climates are very diverse so the system performance affects with different environment condition. The Diffusion Absorption Refrigeration system does not need power input, so this system can be effective for the places where the electricity supply is very less. Various industries can be integrated this system to utilize the waste heat to generate the power and cooling simultaneously. This small scale combined ORC and DAR system also can satisfy the power needs and cooling demand of a building.

Conclusion

It is concluded from the above study that a design investigation of combined ORC (organic Rankine cycle) and DAR (diffusion absorption refrigeration) system to produce power and cooling was feasible. A numerical simulation study was conducted to analyse the effect of cooling water temperature, and condensing temperature on the performance of the system. The high condensation temperature has a negative impact on the performance of the ORC. Also, study finds that combining ORC system with DAR system can improve the thermal efficiency of ORC system. The reduction in the cooling water temperature from 23.5 °C to 15.5 °C leads to a reduction in the condensing temperature around 3 °C. So the thermal efficiency increases around 7%.

The organic fluid R123 is suitable for the ORC with a very low value of ODP and GWP. This is one more step towards the green and clean technology. For the future study the economic analysis and effect of environment parameters like ambient temperature and relative humidity on the combined system to know the performance of ORC and DAR system will be conducted. In India at the various places the environmental parameters vary drastically throughout year. So this study will be helpful to find the suitable places for the implementation of this combined system**.**

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References

Acuña, A., Velázquez, N., Sauceda, D., Rosales, P., Suastegui, A. and A. Ortiz (2016). Influence of a compound parabolic concentrator in the performance of a solar diffusion absorption cooling system. *Applied Thermal Engineering*, **102:** 1374-1383.

Aljundi, I.H. (2011). Effect of dry hydrocarbons and critical point temperature on the efficiencies of organic rankine cycle. *Renewable Energy*, **36:** 1196-1202.

Feng, Y.-Q., Hung, T.-C., Wu, S.-L., Lin, C.-H., Li, B.-X., Huang, K.-C. and J. Qin (2017). Operation characteristic of a R123-based organic Rankine cycle depending on working fluid mass flow rates and heat source temperatures. *Energy Conversion and Management*, **131:** 55-68.

Hadi, R., Mohammad, E., Hadi, G., Majid, A. and K. Reza (2017). Energy and Exergy analysis of novel combined cooling and power (CCP) cycles. S1359-4311(16)34471-4.

Hasanuzzaman, M., Rahim, N.A., Saidur, R. and S.N. Kazi (2011). Energy savings and emissions reductions for rewinding and replacement of industrial motor. *Energy*, **36:** 233-240.

Kokic, P., Crimp, S. and M. Howden (2014). A probabilistic analysis of human influence on recent Record global mean temperature changes. *Clim Risk Manage*, **3:** 1-12.

Li, J., Pei, G., Ji, J., Bai, X., Li, P. and L. Xia (2014). Design of the ORC (organic Rankine cycle) condensation temperature with respect to the expander characteristics for domestic CHP (combined heat and power) applications. *Energy*, **77:** 579-590.

Liu, Q., Duan, Y. and Z. Yang (2013). Performance analyses of geothermal organic Rankine cycles with selected hydrocarbon working fluids. *Energy*, **63:** 123-132.

Marin, A., Untea, A., Grosu, L., Dobrovicescu, A. and D. Queiros-Conde (2013). Performance evaluation of a combined organic Rankine cycle and an absorption refrigeration system. *Termotehnica*, **1:** 81-90.

Mastrullo, R., Mauro, A.W., Revellin, R. and L. Viscito (2015). Modeling and optimization of a shell and louvered fin mini-tubes heat exchanger in an ORC powered by an internal combustion engine. *Energy Convers Manage*, **101:** 697-712.

Nattaporn, C. and Tanongkiat (2015). Analysis of combined cooling, heating and power generation from organic Rankine cycle and absorption system. *Energy*, **91:** 363-370.

Sarkar, J. and S. Bhattacharyya (2015). Potential of organic Rankine cycle technology in India: Working fluid selection and feasibility study. *Energy*, **90:** 1618-1625.

Shu, G., Zhao, M., Tian, H., Huo, Y. and W. Zhu (2016). Experimental comparison of R123 and R245fa as working fluids for waste heat recovery from heavy-duty diesel engine. *Energy*, **115:** 756-769.

Sun, D.W. (1998). Comparison of the performances of NH_3-H_2O, NH_3-$LiNO_3$ and NH_3-NaSCN absorption refrigeration systems. *Energy Convers. Mgmt*, **39(5/6):** 357-367.

Sun, W., Yue, X. and Y. Wang (2017). Exergy efficiency analysis of ORC (organic Rankine cycle) and ORC based combined cycles driven by low-temperature waste heat. *Energy Conversion and Management*, **135:** 63-73.

Tchanche, B.F., Lambrinos, G., Frangoudakis, A. and G. Papadakis (2011). Low-grade heat conversion into power using organic Rankine cycles – A review of various applications. *Renew. Sustain. Energy Rev.*, **15:** 3963-3979.

Von Platen, B.C. and C.G. Munters (1928). Refrigerator, US Patent 1,685,764.

Walraven, D., Laenenb, B. and W. D'haeselee (2015). Minimizing the levelized cost of electricity production from low-temperature geothermal heat sources with ORCs: Water or air cooled. *Appl Energy*, **142:** 144-153.

Wei, D., Lu, X., Lu, Z. and J. Gu (2007). Performance analysis and optimization of organic Rankine cycle (ORC) for waste heat recovery. *Energy Conversion and Management*, **48:** 1113-1119.

Yang, S.-C., Hung, T.-C., Feng, Y.-Q., Wu, C.-J., Wong, K.-W. and K.-C. Huang (2017). Experimental investigation on a 3 kW organic Rankine cycle for low grade waste heat under different operation parameters. *Applied Thermal Engineering*, **113:** 756-764.

Ziviani, D., Beyene, A. and M. Venturini (2014). Advances and challenges in ORC systems modelling for low grade thermal energy recovery. *Appl. Energy*, **121:** 79-95.