Advances and Applications in Mathematical Sciences
Volume 20, Issue 10, August 2021, Pages 2137-2150

ENERGY AND EXERGY ANALYSIS OF AN ORGANIC RANKINE CYCLE INTEGRATED WITH VAPOUR COMPRESSION REFRIGERATION SYSTEM

PRATEEK D. MALWE, BAJIRAO S. GAWALI MAHMADRAFIK S. CHOUDHARI, RUSTAM S. DHALAIT and NANDKISHOR S. DESHMUKH

Mechanical Engineering Department
Walchand College of Engineering
Vishrambag, Sangli-416415
Shivaji University (SUK), Kolhapur
Maharashtra, India
E-mail: prateek.malwe@walchandsangli.ac.in

Abstract

An increase in the consumption of fossil fuels in industries has created some serious environmental issues like ozone layer depletion, air pollution, climate change, etc. In the world, around 50% of energy gets wasted in the form of heat from different resources like biomass, solar radiation, etc. To make reuse of this low and medium temperatures waste heat into useful power output, the most reliable and favorable technology is Organic Rankine Cycle (ORC). The maximum obtainable work from a system at any given state and of a given environment is called as exergy. A study reveals that exergy analysis being adapted by engineers for the optimization of any given system. It involves the application of exergy basics, equation balance, and exergy efficiencies to measure and improve system performances. It also helps in the identification of major areas of exergy destruction, which later on subjected to its minimization. In this paper, modelling is done of a vapour compression refrigeration system combined with an ORC to form integrated refrigeration-ORC. The condenser of the cold storage plant with R450A as a refrigerant rejects heat at 70 0C to 75 0C, which has been utilized by implementing ORC. It is followed by the selection of a proper organic fluid among seven different refrigerants considered. An Engineering Equation Solver is used to have thermodynamic modelling of the system. From the energy and exergy investigations, the best combination of R450A and R123 is selected as a fluid pair for the integrated system. The coefficient of performance increases from 3.17 to 3.88 for simple a vapour compression refrigeration system to an integrated system using R123. A power output of 0.296 kW is gained from ORC with 5.70% and 17.97% as thermal and

2010 Mathematics Subject Classification: 51Axx.

Keywords: Organic Rankine Cycle; exergy analysis; vapour compression refrigeration system, exergy efficiency.

Received February 4, 2021; Accepted April 7, 2021

exergy efficiencies respectively.

Nomenclature

Nomenclature ORC = Organic Rankine Cycle	W_c = work input to the compressor
VCRS = Vapour Compression Refrigeration System	Q_{rej} = heat rejected by an IHX
IHX = Internal Heat Exchanger	COP_{ini} = initial COP
TR = Tons of Refrigeration	Q_s = heat supply to IHX
P_0 = pressure at the dead state	m_f = mass flow rate of organic fluid
T_0 = temperature at dead state	W_p = work input to the pump
EES = Engineering Equation Solver	W_e = power produced by expander
Q_e = refrigeration load on evaporator	W_{net} = net power produced
m_r = mass flow rate of refrigerant	$\eta_{thermal}$ = thermal efficiency
h = specific enthalpy	COP combined = combined COP
s = specific entropy	η_{exergy} = exergy efficiency

Introduction

Agriculture is the main occupation in India as the country's growth directly depends on it. A cold chain is a temperature-controlled supply chain and is used to maintain and extend the life of perishable products like fruits, food items, milk products, etc. It starts right from the farm until it reaches the end-user. It consists of a series of interlinked activities like harvesting, precooling, cold storage plants, distributors to end-users. Small and medium scale farmers face a lot of trouble during the post-harvesting processes of crops grown in their farms. The reason being cold storage plants are ted at farther distances.

This may cause deterioration in the quality and wastage of crops. To overcome this hurdle, a small-scale pre-cooling chamber may be installed nearby the farm’s location, which will take care of crops after the post-harvesting process. This will reduce energy consumption and transportation cost. As a solution to this, an ORC integrated with the vapour compression refrigeration system proved to be a prominent method.

Mahumoudi et al. [1] specified that the dependency of humans on the consumption of energy has increased drastically during the last few years. It causes a huge consumption of fossil fuels which creates certain environmental issues. As a remedy to this, two approaches should be as followed:

- To create and increase the usage of renewable energy resources like wind, solar, binary, geothermal, etc.

- To develop technology for the efficient conversion of energy coming out of waste heat sources.

According to the survey of various research papers, about 50% of the earth's energy is available in waste heat form. The various sources of heat energy like internal combustion engines, household waste, geothermal, solar radiation, steam and gas turbines, etc. are available as shown in Figure 1.

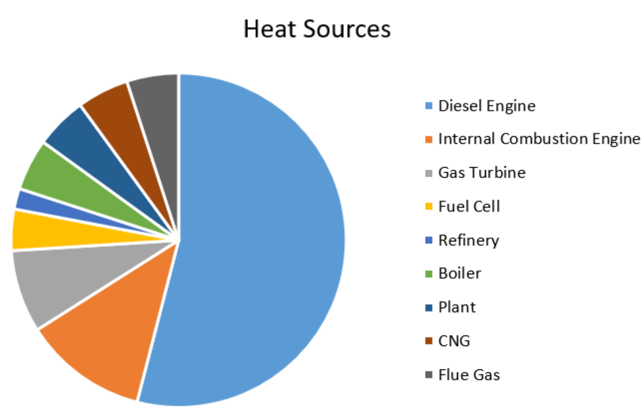

Figure 1. Sources of heat available for waste heat recovery [1].

ORC offers certain advantages over other waste heat recovery systems like no land requirement, ease of manufacture, easy availability of components, flexibility, low maintenance requirement, safe, cheaper, showing better thermal performance, etc. As organic fluids have a lower boiling point than water, this allows recovering lower temperature waste heat resource energy. The thermal efficiency depends upon working fluid temperature, heat sink, and source temperature for an ORC. In general, its value lies between 2% to 19%.

Lakew et al. [2] presented a paper with a prime objective was to classify the working fluids by carrying out an energy balance. The power produced enhances with a rise in heat source temperature due to the corresponding increase in heat source pressure. Franchetti et al. [3] stated a method for organic fluid selection of the ORC system. The objective of this study is to lay down a systematic procedure to forecast the challenges faced in the design of system components. Kaushik et al. [4] introduced a Canopus heat exchanger to increase the COP of the system. A decrease in the inlet and an increase in outlet condenser water temperatures cause an increase in heat recovery and heat removal factor from the condenser. Rajabloo [5] specified that ORC performance improves due to the use of mixture fluids. Oyewumni et al. [6] considered an ORC system with the maximization of power output as an objective function. The system receives heat at 380^0C from the exhaust gases. A rise in the evaporator pressure correspondingly begins growth in the specific investment cost of the components.

Quoilin et al. [7] stated that for small-scale ORC setups, the positive displacement machines and scroll expanders were suited the most. Caceres et al. [8] did the optimization of ORC to select the most suitable organic fluid out of 39 different combinations of working fluids. Bonk et al. [9] presented a paper on designing a micro ORC system of 1 kW power output. 3MTM Novec 649 is considered a novel organic fluid. Dai et al. [10] set the objective function as exergy efficiency. The sizing of the turbine is directly proportionate to the inlet fluid's specific volume.

Tahir et al. [11] built an ORC using R245fa with an objective function of producing lower than 1 kW power. The higher and lower source temperatures are maintained in the temperature in the scale of 60^0C-100^0C and 10^0C-30^0C respectively. It is advised to make use of a highly efficient pump to have positive heat recovery. Quoilin et al. [12] carried numerical modelling for an

ORC using R123 with hot air as a heat source. Scagnolatto et al. [13] simulated a small-scale ORC (10kW) with R123 gives the highest exergy efficiency.

Shet et al. [14] used an internal heat exchanger, vortex tube, and work recovery turbine in the investigation of a transcritical (CO_2) system. The best performance is shown by the work recovery turbine due to lower entropy generation. Chen et al. [15] carried exergy and energy investigation in the transcritical Rankine cycle using CO_2 and R32 as refrigerants. The thermal efficiency with R32 is slightly higher than that with the carbon dioxide system. Hence, R32 is preferred to use instead of CO_2. Saha [16] stated that a tremendous amount of heat is available as waste energy from the condenser of a refrigeration system by using ORC serves to be a promising solution for the same. With a rise in the evaporator pressure, the thermal performance of the plant increases. Rawat et al. [17] used a united VCRS-ORC configuration. The COP of the united system varies directly with the boiler exit, and inversely with the condenser temperature.

This section involves the basics of waste heat recovery. Further part of the paper includes modelling of integrated VCRS-ORC setup, the methodology followed, results and discussions, conclusion and ends with references.

Configuration of System

This section deals with the description of the experimental setup along with the working fluids selection criteria.

Experimental Setup: As shown in Figure 3, a refrigeration system is combined with a subcritical ORC to form an integrated VCRS-ORC system. The specifications of the system are given in Table 1. A cold storage plant of 1.5 TR capacity runs on VCRS uses R450A as a refrigerant. The heat rejected by the condenser of VCRS is utilized by implementing an IHX, which acts as a condenser for VCRS and as a boiler/evaporator for ORC. This fluid gets vaporized through the evaporator which is then fed to an expander to produce the required power. At last, it then passed through a condenser from which the condensate is sent to the evaporator and the cycle continues.

Table 1. Specifications of Setup.

Name of component	Type
VCRS side	
Compressor	Hermetically sealed
Evaporator	Bare (copper) tube type
Expansion device	Thermostatic expansion valve
Refrigerant	R450A
Capacity	1.5 TR
ORC side (modeled)	
Pump	Positive displacement type
Expander	Scroll type
Condenser	Plate heat exchanger
Cooling medium	Water
Integrated VCRS – ORC side (modeled)	
IHX	Plate heat exchanger

System Description: Figure 2 and Figure 3 shows a diagram and temperature-entropy chart representation respectively of an integrated VCRS-ORC system. This section involves the different configurations of components required along with the ORC classification.

Selection of Working Fluids: The fluids working used in ORC are also called organic fluids are categorized depending on their saturation curve slope as negative, positive, and infinite for wet, dry, and isentropic fluids respectively. Instead of using pure fluids, mixture fluids should be used. Seven dry and isentropic organic fluids (like R123, R141b, R1234ze, R227ea, R245fa, R600, and R152) are selected for the ORC subsystem. Certain desirable properties of an ideal organic fluid are listed as:

- A ratio of 0.93 to 1.02 should be maintained for the organic fluid's critical temperature and the maximum cycle temperature.

• Lower latent heat of vaporization and lower boiling point.

• High molecular weight and low specific volume.

• Fluids with double bonds are highly competent than those with only one bond.

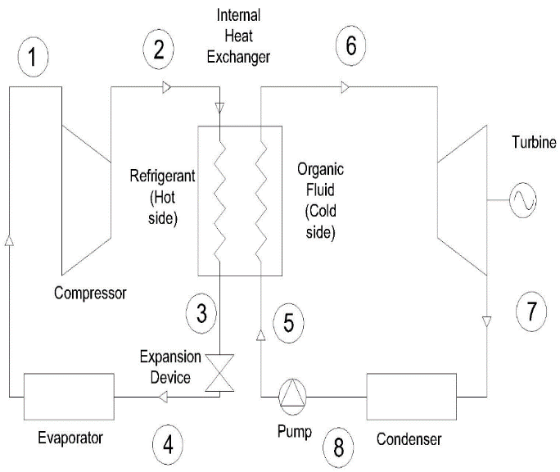

Figure 2. A representation of VCRS-ORC as an integrated system in cold storage.

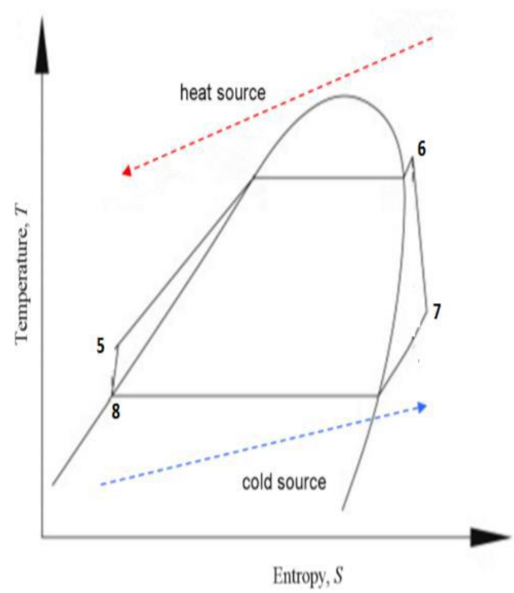

Figure 3. A representation of system on T-s diagram for R123.

Methodology

This section describes energy and exergy analysis followed by assumptions, objectives, procedures, and system modelling using EES.

System Modelling: Thermodynamic investigation including first and second law assessment of integrated VCRS-ORC system is done using programs in EES and the experimental observations are displayed in Table 2.

Table 2. Observations for integrated VCRS-ORC system.

Parameters	Unit	Value
VCRS side		
IHX pressure	bar	9.72
Evaporator pressure	bar	1.86
IHX inlet temperature	^0C	75
IHX outlet temperature	^0C	34
Inlet temperature to the evaporator	^0C	- 8
Outlet temperature to the evaporator	^0C	29
The refrigerant mass flow rate	lph	48
ORC side (modeled)		
IHX pressure	bar	3.29
Condenser pressure	bar	1.54
IHX inlet temperature	^0C	41
IHX outlet temperature	^0C	65
Degree of superheat	^0C	10
Expander inlet temperature	^0C	75
Inlet temperature to the condenser	^0C	57
Outlet temperature to the condenser	^0C	29
The organic fluid mass flow rate	kg/s	0.037

Exergy Analysis. Dincer [18] defines the exergy of any substance as a degree of its quality or the capability to create a difference. It serves as an efficient indicator of the impact of globalization on the environment. The reason being it becomes and an utmost requirement to know the relationship between the energy and exergy. Exergization is the way of utilizing exergy analysis along with their tools in a predefined manner for the improvement of thermal systems in the design, monitoring, and analysis to have a cost-effective, efficient, and environmentally friendly thermal system. The concept of exergization should be used in almost every discipline. It consists of two crucial steps: writing down energy, exergy balance equations, and deciding the performance criteria by calculating the exergy efficiencies.

Energy Analysis. It governs the law of conservation of energy, which deals with balancing net energy input and net energy output. Asim et al. [19] utilized the heat discarded from the air conditioning system via a condenser in ORC using a sharing heat exchanger. R600a and R123 are used as working fluids in VCRS and ORC combination give the highest combined COP and highest maximum exergy efficiency of around 40% for the ORC cycle. Following parameters like compressor power input, evaporator cooling capacity, heat rejected by IHX and initial system COP can be calculated as:

$$Q_s = m_f \times (h_6 - h_5) \tag{1}$$

$$W_p = m_f \times (h_5 - h_8) \tag{2}$$

$$W_e = m_f \times (h_6 - h_7) \tag{3}$$

$$Q_{rej} = m_r \times (h_2 - h_3) \tag{4}$$

$$COP_{ini} = \frac{Q_e}{W_c}. \tag{5}$$

It has been assumed that there is a 100% heat transfer between the heat discarded by the condenser of VCRS and the input heat received by ORC. The other parameters like pump work input, expander power output, net power produced, Carnot and thermal efficiency, and combined COP are given as:

$$Q_s = m_f \times (h_6 - h_5) \tag{5}$$

$$W_p = m_f \times (h_5 - h_8) \tag{6}$$

$$W_e = m_f \times (h_6 - h_7) \tag{7}$$

$$W_{net} = W_e - W_p \tag{8}$$

$$\eta_{\text{thermal}} = \frac{\text{Net power prodcued}}{\text{Heat input to ORC}} = \frac{W_{\text{net}}}{Q_s} \times 100 \tag{9}$$

$$COP_{comb} = \frac{Q_e}{W_{net} - W_c}. \tag{10}$$

The ORC subsystem exergy efficiency is given by:

$$\eta_{ex} = \left(\frac{W_{net}}{m_r \times [(h_2 - h_3) - T_0 \times (s_2 - s_3)]} \right) \times 100 . \tag{11}$$

Results and Discussions

The discrimination and choice of the best appropriate organic fluid are done by maintaining a constant condenser temperature of the VCRS subsystem at 55^0C. The first and second law assessment of the system along with the integrated VCRS-ORC considering all seven organic fluids are tabulated as presented in Table 3, which signifies to use and prefer R123 over R141b (being wet fluid).

Table 3. Thermal performance of fluids considered.

ORC Fluid	COPi	COPcomb	Wnet (kW)	η (%)	η (%)
R123	3.17	3.88	0.296	5.70	17.97
R141b	3.17	3.89	0.302	5.76	18.29
R1234ze	3.17	3.80	0.269	5.32	16.31
R227ea	3.17	3.85	0.286	5.05	17.35
R245fa	3.17	3.87	0.291	5.58	17.68
R600	3.17	3.86	0.290	5.23	17.56
R152a	3.17	3.85	0.286	5.54	17.37

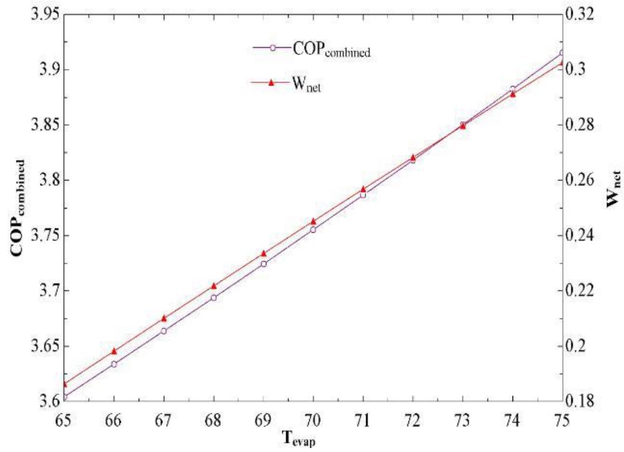

Figure 4. Variation of combined COP and network output with an evaporator temperature.

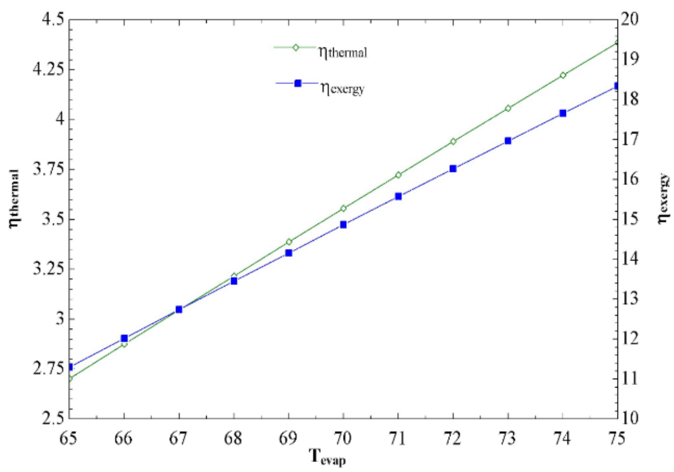

Figure 5. Change of the integrated system's exergy efficiency and ORC's thermal efficiency subsystem with the evaporator temperature.

The initial COP of 3.17 is calculated by considering the VCRS system alone. Later on, ORC is coupled that yields a power output of 0.296kW at 5.70% thermal efficiency, which can be used partially to reimburse electricity needed for running VCRS. Consequently, the integrated system's combined COP enhances to 3.88 with a 17.97% overall system's exergy efficiency. The combined COP and network output increase with an increase in the evaporator temperature as shown in Figure 4. It is because the heat-carrying capacity of an organic fluid increases correspondingly evaporator temperature that causes a rise in the combined COP of the system. Following Figure 4, for a given heat input, the system's thermal efficiency varies proportionately with the network output of the system. Thus, Figure 5 depicts, the ORC thermal efficiency enhances with a rise in the evaporator temperature. Hence, the quality of energy of the integrated system improves because of a rise in the evaporator temperature.

Conclusions

This paper has analyzed an integrated VCRS-ORC system for waste heat recovery using an IHX using Engineering Equation Solver. Seven different refrigerants consisting of dry and isentropic fluids were considered as organic fluids for the ORC subsystem. Depending on the outcomes of energy and exergy investigation, the conclusions can be summarized as follows:

- Working fluids perform a crucial part in the ORC system's progressing and functioning in case of waste heat of low-grade temperature.

- The organic fluid of the integrated VCRS-ORC system gets influenced by the outcome of VCRS. Hence, a VCRS with better performance signifies the overall performance of an integrated system. R450A is selected as a refrigerant for VCRS as it has low global warming potential, lower flammability and thus it's safe to use.

- The objective function of the ORC design is the maximization of exergy efficiency. The highest (18.29%) exergy efficiency is found with R141b, but still, it's not selected being a wet fluid. Next, to R141b, R123 is chosen as an optimal fluid for ORC with 17.95% exergy efficiency.

Acknowledgment

The authors would like to thank the Director, TEQIP-III and HoD-Mechanical Engineering of Walchand College of Engineering, Vishrambag Sangli for giving moral support and providing funding to publish this paper.

References

[1] A. Mahmoudi, M. Fazli and M. R. Morad, A recent review of waste heat recovery by organic rankine cycle, Applied Thermal Engineering 143 (2018), 660-675, https://doi.org/10.1016/j.applthermaleng.2018.07.136.

[2] A. Lakew and O. Bolland, Working fluids for a low-temperature heat source, Applied Thermal Engineering 30 (2010), 1262-1268, https://doi.org/10.1016/j.applthermaleng.2010.02.009.

[3] B. Franchetti, A. Pesiridis, I. Pesmazoglou, E. Sciubba and L. Tocci, Thermodynamic and technical criteria for the optimal selection of the working fluid in a mini-ORC, 29th International Conference on efficiency, cost, optimization, simulation, and environmental impact of energy systems. Portoroz: Brunel University Research Archive. (2016).

[4] S. C. Kaushik, N. L. Panwar and V. S. Reddy, Thermodynamic evaluation of heat recovery through a canopus heat exchanger for VCRS, Journal of Thermal Analysis and Calorimetry 110(3) (2011), 1493-1499, https://doi.org/10.1007/s10973-011-2111-7.

[5] T. Rajabloo, Thermodynamic study of ORC at different working and peripheral conditions, IV International Seminar on ORC Power Systems. 129 (2017), 90-96. Milano: Elsevier. https://doi.org/10.1016/j.egypro.2017.09.165.

[6] O. A. Oyewunmi, S. Lecompte, M. D. Paepe and C. N. Markides, Thermoeconomic analysis of recuperative sub-and transcritical organic rankine cycle systems, IV International Seminar on ORC Power Systems. 129 (2017), 58-65. Milano: Elsevier. https://doi.org/10.1016/j.egypro.2017.09.187.

[7] S. Quoilin, M. V. Broek, S. Declaye, P. Dewallef and V. Lemort, Techno-economic survey of organic rankine cycle (orc) systems, Renewable and Sustainable Energy Reviews 22 (2013), 168-186, https://doi.org/10.1016/j.rser.2013.01.028.

[8] I. E. Caceres, R. Agromayor and L. O. Nord, Thermodynamic Optimization of an Organic Rankine Cycle for Power Generation from a Low Temperature Geothermal Heat Source, Proceedings of the 58th on Simulation and Modelling, 138 (2017), 251-262. Reykjavik: Linkoping University Electronic Press, Linkopings university, https://doi.org/10.3384/ecp17138251.

[9] C. D. Bonk, C. Laux, M. Rodder and M. Neef, Design of a 1 kW Organic Rankine Cycle for Teaching and Research Issues, IV International Seminar on ORC Power Systems, 129 (2017), 931-938. Milano: Elsevier Ltd. https://doi.org/10.1016/j.egypro.2017.09.117.

[10] Y. Dai, J. Wang and L. Gao, Parametric optimization and comparative study of organic rankine cycle (ORC) for low grade waste heat recovery, Energy Conversion and Management 50 (2008), 576-582, https://dx.doi.org/10.1016/j.enconman.2008.10.018.

[11] M. M. Tahir and N. Yamada, Characteristics of small orc system for low-temperature waste heat recovery, Journal of Environment and Engineering 4(2) (2009), 375-385, https://doi.org/10.1299/jee.4.375.

[12] S. Quiolin, V. Lemort and J. Lebrun, Experimental study and modelling of an organic rankine cycle using scroll expander, Applied Energy 87 (2010), 1260-1268, https://doi.org/10.1016/j.apenergy.2009.06.026.

[13] G. Scagnolatto, R. L. Nunes, L. C. Gómez and C. B. Tibirica, Simulation of a Small Organic Rankine Cycle, 17th Brazilian Congress of Thermal Sciences and Engineering (pp. 1-12). Brazil: ABCM (2018). https://doi.org/10.26678/ABCM.ENCIT2018.CIT18-0554.

[14] S. Shet, O. Patil and N. Agrawal, Energetic and exergetic studies of modified CO_2 transcritical refrigeration cycles, 12th IIR Gustav Lorentzen Conference on Natural Refrigerants (pp. 1-8). Edimbourg: (2016). IIF-IIR. https://doi.org/10.18462/iir.gl.2016.1026.

[15] H. Chen, D. Y. Goswami and E. K. Stefanakos, Energetic and exergetic analysis of CO_2 and R32 based transcritical rankine cycles, Applied Energy 88 (2011), 2802-2808, https://doi.org/10.1016/j.apenergy.2011.01.029.

[16] A. Saha, Energy and Exergy Analysis of Waste Heat Recovery Systems using Organic Rankine Cycle, Master of Science, Bangladesh University of Engineering and Technology (BUET), Department of Mechanical Engineering, Dhaka (2016).

[17] K. S. Rawat, H. Khulve and A. K. Pratihar, Thermodynamic analysis of combined ORC-VCR system using low grade thermal energy, International Journal for Research in Applied Science and Engineering Technology 3 (7) (2015), 515-522.

[18] I. Dincer, Exergization, International Journal of Energy Research 40 (2016), 1887-1889, https://doi.org/10.1002/er.3606.

[19] M. Asim, M. K. Leung, Z. Shan, Y. Li, D. Y. Leung and M. Ni, Thermodynamic and Thermo-economic Analysis of Integrated ORC for Waste Heat Recovery from Vapor Compression Refrigeration System, World Engineers Summit-Applied Energy Symposium and Forum: Low Carbon Cities and Urban Energy Joint Conference 143 (2017), 192-198. Singapore: Elsevier. https://doi.org/10.1016/j.egypro.2017.12.670