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A Thermodynamic Analysis and Comparison of an Organic Rankine Cycled (ORC) System with Six Different Wet, Dry and Isentropic Working Fluids

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Abstract

Organic rankine cycle (ORC) is environment friendly waste low heat energy recovery system, utilizing organic working fluid instead of steam utilized in classic rankine cycle. Different types of organic working fluids, which are mainly wet,dry and isentropic, can be used in ORC systems. Isentropic fluids are highly usable, also freons and their alternatives demonstrate similar system responses in ORC system. Thus, organic fluid selection is an important case in terms of not only efficiency, energy and exergy but also safety and environmental concerns. In this study, an organic rankine cycled system with different organic working fluids, which are R134a, R245fa, R152a, R11, R113 and R32 was simulated via a simulation software. After simulations, the results were analyzed thermodynamically and compared mathematically. According to these results, the highest system thermal efficiency value as 0,26 was gained with the R11 working fluid. Then, the system thermal efficiency with R113 is 0,21, and then it is 0,20 with R245fa, then the system thermal efficiency with R134a is 0,14, and then it is 0,13 with R152a, and lastly the lowest thermal efficiency is 0,05 with R32, respectively, under same working conditions. Moreover, the biggest generator work is supplied with R11 as 826 kW, then with R152a as 600 kW, then with R113 as 516 kW, then with R245fa as 509 kW, then with R134a as 397 kW, then with R32 the lowest generator work value as 191 kW. Accordingly, as a result, R11, and then R113 supplied the best performance values for this ORC system, respectively. Further future studies on this subject area is on spot and continuing.

Keywords: ORC, Organic working fluids, energy efficiency, energy recovery system, working fluid selection, thermodynamic analysis.

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Altı Farklı Islak, Kuru ve İzentropik Çalışma Akışkanıyla Organik Rankin Çevrimli (ORÇ) Bir Sistemin Termodinamik Analizi ve Karşılaştırılması

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Özet

Organik rankine çevrimi (ORÇ), klasik rankine çevriminde kullanılan buhar yerine organik çalışma sıvısı kullanan çevre dostu atık düşük ısı enerjisi geri kazanım sistemidir. ORÇ sistemlerinde ağırlıklı olarak yaş, kuru ve izentropik olmak üzere farklı tipte organik çalışma sıvıları kullanılabilir. İzentropik akışkanlar oldukça kullanışlıdır, ayrıca freonlar ve alternatifleri ORÇ sisteminde benzer sistem tepkileri gösterir. Bu nedenle organik sıvı seçimi sadece verimlilik, enerji ve ekserji açısından değil, aynı zamanda güvenlik ve çevresel kaygılar açısından da önemli bir durumdur. Bu çalışmada, R134a, R245fa, R152a, R11, R113 ve R32 olmak üzere farklı organik çalışma akışkanlarına sahip bir organik rankine çevrimli sistem bir simülasyon yazılımı ile simüle edilmiştir. Simülasyonlardan sonra sonuçlar termodinamik açıdan analiz edildi ve matematiksel olarak karşılaştırıldı. Bu sonuçlara göre 0,26 ile en yüksek sistem ısıl verim değeri R11 çalışma akışkanı ile elde edilmiştir. Ardından, R113 ile sistem termal verimliliği 0,21 ve ardından R245fa ile 0,20, ardından R134a ile sistem termal verimliliği 0,14 ve ardından R152a ile 0,13 ve son olarak en düşük termal verim verimlilik, aynı çalışma koşullarında R32 ile sırasıyla 0,05'tir. Ayrıca en büyük jeneratör işi 826 kW olarak R11, ardından 600 kW olarak R152a, ardından 516 kW olarak R113, daha sonra 509 kW olarak R245fa, ardından 397 kW olarak R134a, daha sonra en düşük jeneratör çalışma değeri R32 ile sağlanmaktadır. 191 kW olarak. Buna göre, sonuç olarak, R11 ve ardından R113, sırasıyla bu ORÇ sistemi için en iyi performans değerlerini sağladı. Bu konu ile ilgili gelecekte yapılacak çalışmalar yerinde ve devam etmektedir.

Anahtar Kelimeler : ORÇ, organik çalışma sıvıları, enerji verimliliği, enerji geri kazanım sistemi, çalışma sıvısı seçimi, termodinamik analiz.

1. Introduction

ORC system utilization in energy systems is rather eligible for environment as it recovers low waste heat and produces electrical energy back. The low-temperature energy sources of ORC systems are mainly at temperatures of 80 ◦C to 150 ◦C. ORC system consists of condenser, pump, evaporator and generator parts as seen in Figure 2, for low heat energy recovery and electricity production [1-3].

The first ORCs were utilized in 19th century, and then gained attention in the 21st century power industry. In 1904, Willsie designed two solar ORC engines with capacities of 4.5 kW and 11 kW, utilizing sulfur dioxide as the working fluid. After that, D'Amelio constructed a geothermal plant using ethylene as the working fluid and acted until 1950 [3-5]. Taking into consideration the commercial ORC plants, Ormat and Turboden guide the ORC industry. Ormat has built more than 3000 units up to 4 kW and more than 500 units of 1–25 MW [5-7].

Organic fluid selection is important for the efficiency, availability and safety of the ORC as being organic fluid utilized system. Mainly, a fine working fluid should reveal not only low toxicity, good material compatibility and fluid stability limits, low flammability, corrosion, and fouling characteristics but also high system performance [7,8]. Working fluids can generally be classified as dry, wet and isentropic fluids based on their slope of saturated vapour phase in T-s curves. Vapor saturation curve of wet fluid (e.g., R134a, R152a, R32,) has a negative slope, resulting in a two-phase mixture upon isentropic expansion. A dry fluid (e.g., R113) has a positive slope, while an isentropic (e.g., R245fa, R11) has an infinitely large slope, the fact that the vapor saturation line on a T-s diagram is vertical for these fluids as seen in Figure 1 [8,9].

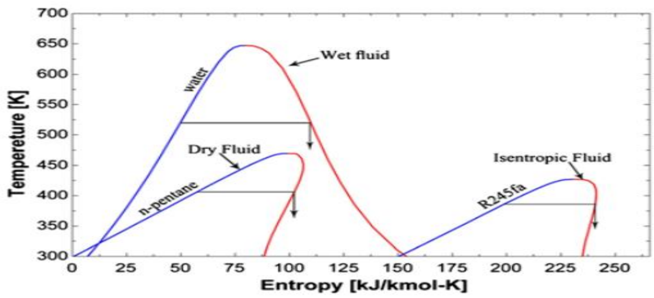

Figure 1. Three types of working fluids: dry, isentropic and wet

Since optimum working fluid selection is a significant phenomenon for ORC systems, there are related studies about ORC working fluids. Although, water, the main Rankine cycle fluid, is in the wet classification; dry and isentropic fluids are offered more valid for ORC applications by research [9-11]. Various review research about ORC systems and working fluids [11-13] propose different analogies from the first and second law efficiency, work output, total irreversibility, exergy efficiency and net work output. The results are tabulated and shown in Table 1 [4,13,14].

Table 1. Working fluid selection for different temperature ranges by different researches

Evaporation Temperature (⁰C)	Fluid Suggestion by various researches and summarized by [4]
50 - 100	R134a, R245fa, R227ea, Hexane, R123, Butane and R141b
100 - 150	R236ea, Solkatherm, R245fa, R11, R114, R245fa, R601a, R601, R141b and R113
150 - 200	R245fa, Benzene and Ethanol
200 - 300	Butylbenzene and R123
250 - 500	n-hexane, n-pentane, toluene, n-octane, toluene and n-dodecane

There are this study related literature such as, Wang et al. assayed the efficiency of nine pure organic fluids at particular actuating districts and attained that R11, R141b, R113 and R123 demonstrated barely higher thermodynamic performances than the others, and that R245fa and R245ca were the most environmental friendly working fluids for engine waste heat-recovery adhibitions [15]. Qiu collated and rectified the eight most generally used working fluids and evolved a efficiency echelon with the help of the spinal point method [16]. Chen et al. [17] resumed pure working fluids for subcritical and supercritical organic Rankine cycle; Tchanche et al. [18] and Fredy et al. [19] also reviewed all kinds of ORC applications; Qiu et al. [20] summarized several expansion machines and picked an expander implemented in micro CHP systems. Hun Kang experimentally and theoretically inspected an ORC for generating electric power utilizing a low-temperature heat origin and R245fa as a working fluid [21]. Quoilin et al. defined ORC practices, markets and costs, working fluid selection, and expansion part matters [22].

2. Materials and Methods

Within this study, a thermodynamic analysis of a ORC system working with six different organic fluids was performed with a simulation software and then performances of the ORC system was compared accordingly. This paper was based on its first version published in the ICEANS 2022 proceedings [6]. These six different working fluids were wet fluids R134a, R32, R152a, isentropic fluids R11, R245fa and dry fluid R113. Each simulation was performed on the same ORC system the schematic of which is demonstrated in Figure 2.

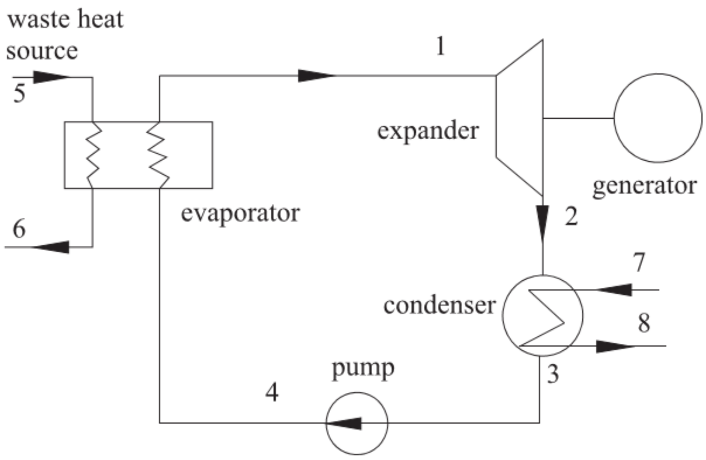

Figure 2. Schematic diagram of the ORC

As shown in Figure 2, between points 1-2 expansion, between points 2-3 condensing, between points 3-4 pumping and between points 4-1 evaporating are the elements of this ORC. Accordingly, the related T-s diagram of this ORC system can be observed from Figure 3 [22-24].

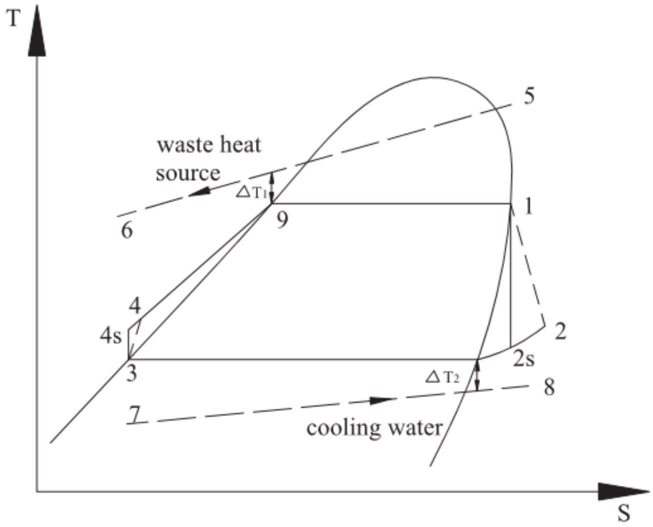

Figure 3. T-s diagram of the ORC

From this T-s diagram seen in Figure 3, the ORC temperature and entropy values related points are shown. In order to conduct the thermodynamic analysis, the basic energy and exergy equations are applied to the ORC in terms of six different working fluids [24,25].

2.1. Working Fluid Selection

Working fluid selection is one of the most significant concerns for designing ORC system, and accordingly Table 2 demonstrates the general organic working fluids utilized in ORCs [25]. Working fluid selection of ORC system is tougher than other thermodynamic cycles, such as Kalina cycle and compression refrigeration cycle, due to not only rather various heat source types and working conditions, but also hundreds of substances including hydrocarbons, aromatic hydrocarbons, ethers, perfluorocarbons, CFCs, alcohols, siloxanes and inorganics etc. utilizable as working fluid applicants of ORC [25,26].

ORC working fluids can be categorized as Hydrocarbons and aromatic hydrocarbons having favourable thermodynamic properties and flammability concerns; Perfluorocarbons which are intensely stable with intense molecular complexity and thermodynamically unfavourable; Siloxanes which are conspicuous for low toxicity and flammability level; high molecular mass; extended utilization as a high temperature heat transporter and often existing as mixtures rather than as pure fluids, Isobaric condensation and evaporation are not isothermal and indicate a certain shift; Partially flouro-substituted straight chain hydrocarbons mainly zero ODP fluids; Ethers and fluorinated ether which have flammability and toxicity concerns are thermodynamically unfavourable; Alcohols, which have flammability concerns, are soluble in water and thermodynamically unfavourable; Inorganics, which are wide and inexpensive, cause little environmental effect and some operation matters [4,25-27].

Table 2. General working fluids for ORCs and their properties [25]

Substance		Physical data				Safety data	Environmental data			Type
		Molecular Mass(kg/kmol)	T_{bp} (°C)	T_{crit} (°C)	P_{crit} (MPa)	ASHRAE 34 safety group	ALT(yr)	ODP	GWP (100yr)	
1	R717	17.03	-33.33	132.25	11.333	B2	0.01	0	<1	wet
2	R600	58.12	-0.55	151.98	3.796	A3	0.02	0	~20	dry
3	R600a	58.12	-11.67	134.67	3.640	A3	0.02	0	~20	dry
4	R290	44.10	-42.09	96.68	4.247	A3	0.04	0	~20	wet
5	R1270	42.08	-47.69	92.42	4.665	A3	~0	0	~20	wet
6	R11	137.37	23.71	197.96	4.408	A1	45	1	4750	i
7	R12	120.91	-29.75	111.97	4.136	A1	100	1	10890	wet, i
8	R22	86.47	-40.81	96.15	4.990	A1	12	0.05	1810	wet
9	R32	52.02	-51.65	78.11	5.782	A2	4.9	0	675	wet
10	R113	187.38	47.59	214.06	3.392	A1	85	1	6130	dry
11	R114	170.92	3.59	145.68	3.257	A1	300	1	10040	dry
12	R123	152.93	27.82	183.68	3.662	B1	1.3	0.02	77	dry, i
13	R124	136.48	-11.96	122.28	3.624	A1	5.8	0.02	609	i
14	R134a	102.03	-26.07	101.06	4.059	A1	14	0	1430	i
15	R141b	116.95	32.05	206.81	4.460	n.a.	9.3	0.12	725	dry, i
16	R142b	100.50	-9.15	137.11	4.070	A2	17.9	0.07	2310	i
17	R143a	84.04	-47.24	72.71	3.761	A2	52	0	4470	wet
18	R152a	66.05	-24.02	113.26	4.517	A2	1.4	0	124	wet
19	R218	188.02	-36.83	71.95	2.671	A1	2600	0	8830	dry
20	R227ea	170.03	-16.45	101.65	2.926	A1	42	0	3220	dry
21	R236fa	152.04	-1.44	124.92	3.200	A1	240	0	9810	dry
22	R236ea	152.04	6.19	139.29	3.502	n.a.	8	0	710	dry
23	R245fa	134.05	14.90	154.05	3.640	B1	7.6	0	1030	dry
24	R245ca	134.05	25.13	174.42	3.925	n.a.	62	0	693	dry
25	RC318	200.03	-5.98	115.23	2.778	A1	3200	0	10250	dry
26	R718	18.02	99.97	373.95	22.064	A1	n.a.	0	<1	wet

Optimum working fluid is chosen for related ORC system according to the properties of the working fluid such as critical temperature, critical pressure, global warming potential (GWP), ozone depletion potential (ODP) and safety data values. As these values base the thermodynamic structure of the ORC system in terms of thermal efficiency and generator work value, different working fluids affect the system accordingly. Therefore, six different working fluids are studied. Efficiency of the ORC system changes depending on the used working fluid. In order to analyse and compare the thermal efficiencies of the system, different working fluids are applied. The properties of the fluids R134a, R245fa, R152a, R11, R113 and R32 utilized in this study are seen in Table 2 [25,27-29]. The limitations related this study is that there are limited organic working fluids to choose for ORC systems and their GWP, ODP, safety limits to take into account. Furthermore, the mentioned comparison method is mathematical depending on the thermodynamic analysis of the cycle. The limitations of the comparison method are not only the condensation temperature, the evaporation temperature and pressure but also the efficiency of the pump and turbine.

2.2. Thermodynamic Analysis

The thermodynamic analysis of this studied ORC system was based on the main energy equations. Accordingly, the system of equations for the thermodynamic analysis are below [29,30]:

Pump work input: $\dot{W}_p = \frac{\dot{m}(h_4 - h_3)}{\eta_p}$

Expander work output: $\dot{W}_E = \frac{\dot{m}(h_1 - h_2)}{\eta_E}$

Evaporator heat input: $\dot{Q}_{evap} = \dot{m}(h_1 - h_4)$

Condenser heat output: $\dot{Q}_{cond} = \dot{m}(h_2 - h_3)$

Efficiency: $\eta_{th} = \frac{\dot{W}_E - \dot{W}_P}{\dot{Q}_{evap}}$

In order to explain some system variables to simulate and find the ORC system outputs, the efficiency of the pump and turbine is assumed to be 0.998, which is a reasonable efficiency value. The condensation temperature is varied in the range of 40 to 140 °C. The evaporation pressure is varied in the range of 42,205 to 42,355 bar. The evaporation temperature is varied in the range of 42 to 300 °C. And, the thermodynamic analysis calculations of the ORC system simulations are done according to these energy equations and values [30,31].

3. Results and Discussion

As a result, six different working fluids R134a, R245fa, R152a, R11, R113, R32 were applied to this ORC system explained, via a simulation software, respectively. The thermodynamic outputs of the system were analysed and compared according to each working fluid.

Within the system parameters explained above, when this ORC simulated with R11 working fluid, system thermal efficiency was calculated as 0,26. Then, it was calculated as 0.21 with R113, 0.20 with R245fa, 0.14 with R134a, 0.13 with R152a, and 0.05 with R32 under the same working conditions. In terms of generator works results, R11 working resulted 826 kW generator work output, R152a working gave 600 kW generator work, R113 resulted 516 kW generator output, R245fa working gave 509 kW generator work, R134a resulted 397 kW generator work, and then R32 working gave the lowest generator work value as 191 kW.

4. Conclusions

For this ORC system, the best suited working fluid was founded as R11 according to the simulation results analysed. The safety of R11 is also reasonable to utilize. Thus, R11 is the most efficient working fluid for this ORC in terms of system thermal efficiency and generator work output. Moreover, the second most efficient working fluid was found R113 for this system. The future work is on topic for the application of other working fluids.

5. References

[1]R. Loni, G. Najafi, E. Bellos, F. Rajaee, Z. Said, M. Mazlan, “A review of industrial waste heat recovery system for power generation with Organic Rankine Cycle: Recent challenges and future outlook,” Journal of Cleaner Production, vol. 287, 125070, 2021.

[2]A. Kumar, D. Rakshit, “A critical review on waste heat recovery utilization with special focus on Organic Rankine Cycle applications,” Cleaner Engineering and Technology, vol. 5, 100292, December 2021.

[3]H.M.D.P. Herath, M.A. Wijewardane, R.A.C.P. Ranasinghe, J.G.A.S. Jayasekera, “Working fluid selection of Organic Rankine Cycles,” Energy Reports, vol. 6, pp. 680-686, 2020.

[4]J. Bao and L. Zhao, “A review of working fluid and expander selections for organic rankine cycle,” Renewable and Sustainable Energy Reviews, vol. 24, pp. 325-342, 2013.

[5]M. Bahrami, A. A. Hamidi and S. Porkhial, “Investigation of the effect of organic working fluids on thermodynamic performance of combined cycle Stirling-ORC,” International Journal of Energy and Environmental Engineering, pp. 4-12, 2013.

[6]O. Boydak, “A Thermodynamic Analysis And Comparison Of An Organic Rankine Cycled (ORC) System With Different Organic Working Fluids,” ICEANS 2022 proceeding, May 2022.

[7]O. Boydak, I. Ekmekci, M. Yılmaz, and H. Koten, “Thermodynamic investigation of organic rankine cycle energy recovery system and recent studies,” Thermal Science, vol. 22, no. 6A, pp. 2679-2690, 2018.

[8]K. Darvish, M. A. Ehyaei, F. Atabi and M. A. Rosen, “Selection of Optimum Working Fluid for Organic Rankine Cycles by Exergy and Exergy-Economic Analyses,” Sustainability, vol. 7, pp. 15362-15383, 2015.

[9]K. Thurairaja, A. Wijewardane, S. Jayasekara, C. Ranasinghe, “Working fluid selection and performance evaluation of ORC,” Energy Procedia, vol. 156, pp. 244-248, 2019.

[10] L. E. Méndez-Cruz, M. Á. Gutiérrez-Limón, H. Lugo-Méndez, R. Lugo-Leyte, T. Lopez-Arenas and M. Sales-Cruz, “Comparative Thermodynamic Analysis of the Performance of an Organic Rankine Cycle Using Different Working Fluids,” Energies, vol. 15, 2588, 2022.

[11] A. F. Babatunde and O. O. Sunday, “A Review of Working Fluids for Organic Rankine Cycle (ORC) Applications,” 2018 IOP Conf. Ser.: Mater. Sci. Eng. vol. 413, 012019, 2018.

[12] S. Hu, Z. Yang, J. Li and Y. Duan, “A Review of Multi-Objective Optimization in Organic Rankine Cycle (ORC) System Design,” Energies, vol. 14, 6492, 2021.

[13] A. Mahmoudi, M. Fazli, M. R. Morad, “A recent review of waste heat recovery by Organic Rankine Cycle,” Applied Thermal Engineering, vol. 143, pp. 660-675, October 2018.

[14] T. Guo, H. Wang, S. Zhang, “Fluid Selection for a Low-Temperature Geothermal Organic Rankine Cycle by Energy and Exergy,” 2010 Asia-Pacific Power and Energy Engineering Conference, March 28, 2010.

[15] X. Zhang, Y. Zhang, J. Wang, “Evaluation and selection of dry and isentropic working fluids based on their pump performance in small-scale organic Rankine cycle,” Applied Thermal Engineering, vol. 191, 116919, 5 June 2021.

[16] G. Qiu, “Selection of working fluids for micro-CHP systems with ORC,” Renew. Energy 2012, 45, pp. 565–570, 2012.

[17] H. Chen, D. Y. Goswami, E. K. Stefanakos, “A review of thermodynamic cycles and working fluids for the conversion of low-grade heat,” Renewable and Sustainable Energy Reviews, 14(9), pp. 3059–67, 2010.
[18] B. F. Tchanche, G. Lambrinos, A. Frangoudakis, G. Papadakis, “Low-grade heat conversion into power using organic Rankine cycles—A review of various applications,” Renewable and Sustainable Energy Reviews, 15(8), pp. 3963–79, 2011.
[19] F. Vélez, J. J. Segovia, M. C. Martín, G. Antolín, F. Chejne, A. Quijano, “A technical, economical and market review of organic Rankine cycles for the conversion of low-grade heat for power generation,” Renewable and Sustainable Energy Reviews, 16(6), pp. 4175–89, 2012.
[20] G. Qiu G, Liu H, Riffat S. Expanders for micro-CHP systems with organic Rankine cycle,” Applied Thermal Engineering, 31(16), pp. 3301–7, 2011.
[21] S. H. Kang, “Design and experimental study of ORC (organic Rankine cycle) and radial turbine using R245fa working fluid. Energy,” vol. 41, pp. 514–524, 2012.
[22] S. Quoilin, S. Declaye, B. Tchanche, V. Lemort, “Techno-economic survey of Organic Rankine Cycle (ORC) systems,” Renew. Sustain. Energy Rev., vol. 22, pp. 168–186, 2013.
[23] M. Hijriawan, N. A. Pambudi, D. S. Wijayanto, M. K. Biddinika, L. H. Saw, “Experimental analysis of R134a working fluid on Organic Rankine Cycle (ORC) systems with scroll-expander,” Engineering Science and Technology, an International Journal, vol. 29, 101036, May 2022.
[24] N. B. Desai, S. Bandyopadhyay, “Thermo-economic analysis and selection of working fluid for solar organic Rankine cycle,” Applied Thermal Engineering, vol. 95, pp. 471-481, 25 February 2016.
[25] C. Liu, C. He, H. Gao, X. Xu and J. Xu, “The Optimal Evaporation Temperature of Subcritical ORC Based on Second Law Efficiency for Waste Heat Recovery,” Entropy, vol. 14, pp. 491-504, 2012.
[26] E. H. Wang, H. G. Zhang, B. Y. Fan, M.G. Ouyang, H. Zhao, H. Q. Mu, “Study of working fluid selection of organic Rankine cycle (ORC) for engine waste heat recovery,” Energy 2011, 12, pp. 3406–3418, 2011.
[27] A. Toffolo, A. Lazzaretto, G. Manente, M. Paci, “A multi-criteria approach for the optimal selection of working fluid and design parameters in Organic Rankine Cycle systems,” Applied Energy vol. 121, pp. 219-232, 15 May 2014.
[28] S. Thangavel, V. Verma, Rahul Tarodiya, P. Kaliyaperumal, “Comparative analysis and evaluation of different working fluids for the organic rankine cycle performance,” materialstoday:Proceedings, vol. 47, Part 10, pp. 2580-2584, 2021.
[29] M. Bahrami, F. Pourfayaz, “Low global warming potential (GWP) working fluids (WFs) for Organic Rankine Cycle (ORC) applications,” Energy Reports, vol. 8, pp. 2976-2988, November 2022.
[30] S. Wang, C. Liu, S. Zhang, Q. Li, E. Huo, “Multi-objective optimization and fluid selection of organic Rankine cycle (ORC) system based on economic-environmental-sustainable analysis,” Energy Conversion and Management, vol. 254, 115238, 15 February 2022.
[31] B. Turkoglu, S. A. Uymaz, E. Kaya, “Binary Artificial Algae Algorithm for feature selection,” Applied Soft Computing. vol. 120, 108630, pp. 1-19, May 2022.