

# A Review of Working Fluids for Organic Rankine Cycle (ORC) Applications

Babatunde, A. Fakeye<sup>1</sup> and <sup>1</sup>\*Sunday, O. Oyedepo<sup>1</sup>

<sup>1</sup>Mechanical Engineering Department, Covenant University, Ota

E-mail address: [Sunday.oyedepo@covenantuniversity.edu.ng](mailto:Sunday.oyedepo@covenantuniversity.edu.ng)

**Abstract.** The organic Rankine cycle (ORC) systems are commercially employed for small scale and large scale thermal conversion to electricity of a large variety of abundant heat sources such as exhaust waste heat and some renewable energy sources where conventional steam Rankine and open-gas cycle turbine cycles cannot provide any viable, sustainable, techno-economic solution for power generation. The ORC operates the conventional steam Rankine cycle in subcritical level but can as well operate trans critical cycle while employing heavy molecular organic fluids in place of steam which makes the ORC suitable for medium and low grade heat conversion into electricity. No singular ideal fluid exists for any application and hence over 600 pure and zeotropic mixtures have been investigated by various researches for their best suitability for different applications and operating conditions based on performance characteristics such as efficiency, cost and environmental impacts. In this study a review of working fluids selection for different applications has been conducted. This study helps in identifying the possible most suitable organic fluids for various ORC applications depending on the operating conditions.

Keywords: risk assessment; failure mode

## 1. Introduction

Organic Rankine Cycles (ORCs) are the most prevalent low-grade waste heat recovery cycles largely because of their simplicity and readily available components [1]. ORC characteristically performs better than the conventional steam Rankine cycle at the low operating temperatures due to the five factors explained by [2] as highlighted below:

- favourable thermodynamic cycle modification/architecture
- practical enthalpy drop and volume flow rate in the turbine
- favourable operating condition of the turbine
- possibility of lower maximum operating pressure and consequently, reduced costs of associated components
- the possibility of selecting positive gauge condensing pressure, hence, avoiding air infiltration.

Designing the best system configuration alongside selecting the best appropriate choice of working fluid for the viable operating condition is therefore the most essential requirement for any ORC system design for any application [3, 4]. An essential advantage of ORC systems is however, the utilization of organic working fluids that can simply employ a single stage expander hence offering advantages of simple design, low cost capital cost and low maintenance [3].

Because of relatively low specific enthalpy drop of organic vapours in turbine compared to water vapour, efficient ORC systems as small as 25 kW utilizing single stage turbo-expanders with reasonable tip speed have been possible. Whereas, water vapour process in most cases require three or four stage turbine with practical minimum size limited to 2 MW [5]. On the whole, the Organic Rankine Cycle units are most appropriate and most widely used for medium and low grade heat sources with wider flexibilities of reconfiguring and modifying the primary cycle to adapt it to the peculiarities of the heat sources [6].

However, the optimal cycle performance and system architecture primarily depends on the selection of the best appropriate working fluid [7]. The use of optimally mixed zeotropic fluids in place of customary pure fluids is a remarkable development to further improve the cycle performance but rather increases the complexity of the system. Pure organic fluids have fixed boiling temperatures and this gives rise to an incompatibility between the temperature profile of the working fluid and that of the heat source [3]. Two pure organic fluids with sufficient difference in their boiling points when optimally mixed produces a temperature glide at phase change which provides a better temperature compatibilities in aimed at either



the condenser or the evaporator [8]. Such zeotropic mixtures have advantages of safety, environmental compatibility, and volumetric flow rate [9] but exhibit reduced heat transfer characteristics compared to pure fluids [10, 11].

## 2 ORC Working Fluids and Applications

The core task in ORC systems design primarily involves the selection of the best appropriate working fluid for the operation condition in either subcritical or supercritical level. This is supreme to obtain optimal performance indexes, simple cycle structure, small components sizes, and in general, safe operation of the system [12, 13]. Suitable working fluids permit proper volume flow rates which is essential for optimum sizing of the turbine for any power level [14], and also determines the proper type and size of the pump, heat exchangers and regeneration in advanced cycles. Xi et al., [15] projected based on the experimental data and environmental factors that Hydrocarbons (HCs) are generally the best choice as working fluids for ORCs because of high energy efficiency, low cost and good environmental compatibility, especially the high molecular weight alkanes, which are always stable and their flammability and explosive characteristics suppressible by adding fire retardant.

The choice of organic working fluids are primarily influenced by the heat source temperature, the cooling medium or ambient temperature, and also the ORC performance assessment criterion employed for the optimization [16, 17]. Chintala et al. [18] summarized the essential considerations for selecting an appropriate organic working fluid. These include:

- Ability to dissolve in lubricant oils
- Safety and Ecological factors
- Ease of handling
- Abundant availability, and
- Economic considerations.

However, there are conflicting stances imposed by some of the desired features of the organic fluid on the efficiency of the ORC, safe operation, system performance and component sizing [19]. For example, high molecular weights and compressibility of working fluids enhance turbine efficiency [17] and reduces the number of stages for axial turbines, but however, high molecular weights fluids with high critical pressures require high rate of heat transfers and consequently, require bigger heat exchangers [20]. Hence, there is need for trade-offs in optimizing the ORC systems configuration and architecture for the best overall performance of the system.

Guo et al., [9], investigated the effects of different pure fluids and their zeotropic mixtures considering the vital operation parameters such as expander intake temperature, degree of superheat, mass flow rate, volumetric flow, exergy destruction, as well as the effect of recuperation on the performance characteristics of an ORC utilizing the exhaust heat of a 240 MW boiler of a pulverized coal-fired power plant. They explained that there is no optimal working fluid satisfying all the indicators and recommended from their findings that:

- Working fluids with high critical temperature showed better thermal efficiencies for the same operating condition,
- Insufficiently large temperature difference between the critical temperature of the constituent working fluids will result into minor temperature glide which will be unable to coherently match neither heat source nor sink.
- Mixture with the matching the heat sink indicates best efficiency and should be considered first when selecting working fluid, while mixture matching the heat source will yield the least total exergy destruction and reduced heat exchange area in the evaporator.

Zeotropic mixtures have severally been established to provide improved first efficiency and second law efficiencies as well as significant increase in work output as a result of better matching with the source and sink temperatures. The cycle performance however, depends on the proportion of the pure fluids and can be optimally extended to cover a wide range of selection requirements [21]. The thermo-physical properties of zeotropic mixtures hence depends primarily on the composition and the varying concentrations of the constituents, however, Abadi & Kim, [10] identified four major concerns about the use of azeotropic mixtures as follows:

- the conventional means of determining the thermodynamics properties of zeotropes are not sufficiently accurate,
- heat transfer coefficients of the designated optimized zeotropes from studies are unreliable if at all available,
- heat transfer coefficients of zeotropic mixtures typically get degraded and as a result of relatively lower heat transfer coefficients require bigger evaporator and condenser sizes compared to those of pure fluids, and
- composition shift (or separation) and fractionating of the zeotropic mixture during heat transfer compel a limit on the allowable temperature glide which in a way, reduces the deliverable power and first law efficiency of the system.

Additionally, composition shift hinders azeotropic mixtures from having stable thermodynamic properties in both the evaporator and condenser. Also, steeper attention must be paid to make the system leak-proof, especially the evaporator and condenser, in order to forestall undesirable composition shift [22]. Comparative study by Liu et al., [23] who investigated the influence reheat on ORC utilizing pure and zeotropic mixtures showed that zeotropic mixtures can commendably improve the net power output and also enhance the enthalpy drop between the turbine intake and exit of a reheat ORC system when the mixture's constituents and component ratio are both appropriate. However, uncertainty about the mixture stability under different working conditions, coupled with all of the above mentioned concerns limit the use and study of zeotropic mixtures [9]. Nonetheless, zeotropic mixtures have demonstrated wide prospective applications in both subcritical and supercritical ORCs [24].

## 2.1 Classification and Application of ORC Working Fluids

Recent literatures generally classify fluids as wet, isentropic, or dry as shown in Figure 1 below. Dry fluids are high molecular mass organic fluids exhibiting positive slope on the T-s diagram. Wet fluids are low molecular mass organic fluids exhibiting negative slopes on the T-s diagram. Isentropic fluids are generally of medium molecular mass, exhibiting infinite or nearly vertical on the T-s diagram [24 – 26]. Hence, wet fluids normally require superheating [27]. Liu et al., [23] attributed the presence of hydrogen bond in the molecules of some organic working fluids like water, ammonia, and ethanol, as a probable cause of some fluids being wet as a result of larger vaporizing enthalpies which is considered inappropriate for ORC systems. The measure of wetness or dryness of a fluid is measured by the inverse of the slope, defined as  $\xi = ds/dT$ . Therefore, the value of  $\xi > 0$  implies a dry fluid,  $\xi \approx 0$  implies an isentropic fluid and  $\xi < 0$  implies a wet fluid [28].

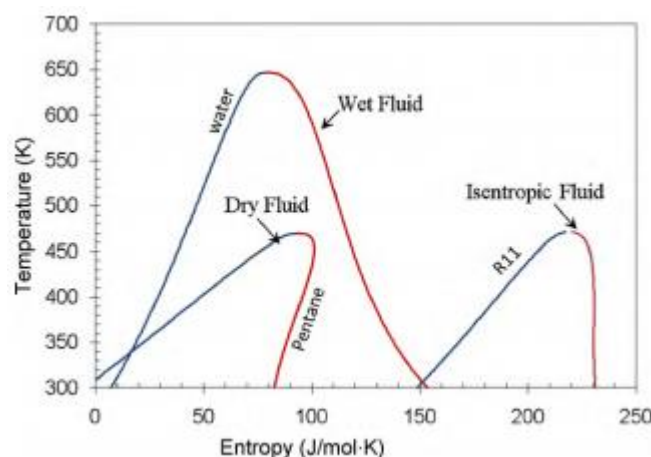


Figure 1: Dry, wet and isentropic working fluids

Isentropic and dry fluids have been widely proposed for subcritical ORC basically to avoid formation of liquid droplet. Nevertheless, if the saturated vapour curve of the dry fluid sharply deflects inwards, the vapor will wastefully exit from the turbine with significant degree of superheat thereby unnecessarily adding to the condenser cooling load. The exiting superheated vapour can however be better utilized for regeneration between the feed pump and the boiler/evaporator to improve the efficiency of the system.

For supercritical Rankine cycles utilizing wet or dry fluids, the turbine intake temperature must be sufficiently high to avoid the double phase region as shown in Figure 2 by propyne, a dry fluid, pentane, a wet fluid [13]. If the temperatures are sufficiently high, the expansion process does not go through the double phase state represented by the dashed lines in figures 2a & b. On the contrary, wet fluids are less affected by superheating after the expansion.

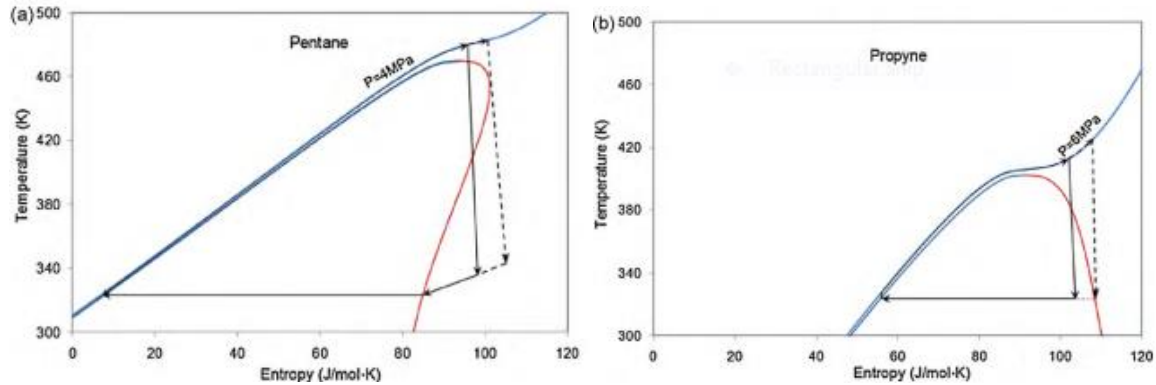


Fig. 2: T-s diagram of working fluids at supercritical levels for a dry and a wet fluid. (a) Pentane. (b) Propyne [13]

Patrick et al. [29] in Chen [13] was mentioned to discover that wet fluids subcool and nucleate in rapid succession to form a double phase fluid, which characteristically delimits the performance and life of the turbine. On the contrary however, dry fluids passing through the two-phase region as referenced, was established by Shu et al. [30] to have inconsequential effect on the performance and life of the turbine.

Bahrami et al. [31] projected the suitable thermo-physical characteristics for good organic working fluids and using all of them as the criteria for the selection of the best appropriate fluid in their work, they concluded that the procedure was a rather complicated one. Chen et al. [13] in his review referring to the proposition of Galloni et al. [32] that working fluids with high latent heat, low specific heat and high density are expected to deliver higher turbine work output with smaller equipment setup for fixed operating conditions. Chen et al. [13] however stated that Richard et al. [33] differed that low latent heat fluids were otherwise more desirable; reasoning that saturated vapor condition at the turbine intake presented best operating condition. Chen et al. [13] hence showed a theoretical inquiry by combining Clausius–Clapayron relation,  $\frac{dP}{dT} = \frac{L}{T\Delta V}$ , ideal gas law,  $V_{gas} = \frac{RT}{P}$ , and the widely accepted equation of enthalpy drop,

$$\Delta h_{isentropic} = C_p T_{in} \left[ 1 - \left( \frac{p_{dis}}{p_{in}} \right)^{\gamma-1/\gamma} \right] \quad (1)$$

to arrive at:

$$\Delta h_{isentropic} = C_p \left[ 1 - e^{\frac{L}{C_p} \left( \frac{1}{T_1} - \frac{1}{T_2} \right)} \right] \quad (2)$$

He showed that substituting the ideal gas equation into Clausius–Clapayron equation and then integrating yields:

$$\ln \frac{P_2}{P_1} = \frac{L}{R} \left( \frac{1}{T_1} - \frac{1}{T_2} \right) \quad (3)$$

This in fact depicts that for  $T_1$  and  $T_2$  fixed by the temperature of the heat source and ambient temperature respectively, the pressure ratio is a function of only the latent heat. Chen [13] however supported that from the equation of enthalpy drop, working fluids with higher latent heat gave higher unit work output but on the contrary, from the said equation, higher heat capacity rather the high latent heat fluids appear to correspond to higher unit work output. Borsukiewicz-gozdur & Nowak, [34] in their studies on the contrary recommended that to maintain the low latent heat criterion for the working fluid, a working fluid with critical point mildly above the heat source temperature should selected for a subcritical cycle in order to maintain the smallest possible latent heat of vapourization.

According to their studies, the critical temperature of working fluids has a vital effect on the effectiveness of operation of ORC cycle and the power output in particular. They maintained that low latent heat of evaporation is however the most desirable feature which is sustained by the fact that the latent heat of evaporation reduces when the critical point is approached. How closely from a practical point of view can

the critical point be approached for evaporation to occur of is therefore an advantage. This was afterwards corroborated by Zhang, [26]. Bao & Zhao, [35] held that when using waste heat as the heat source, working fluids having lower latent heats are preferred because the reduced vaporization heat of the organic fluids enables bulk of the heat exchange in the evaporator to result in sensible heat as shown in Figure 3.

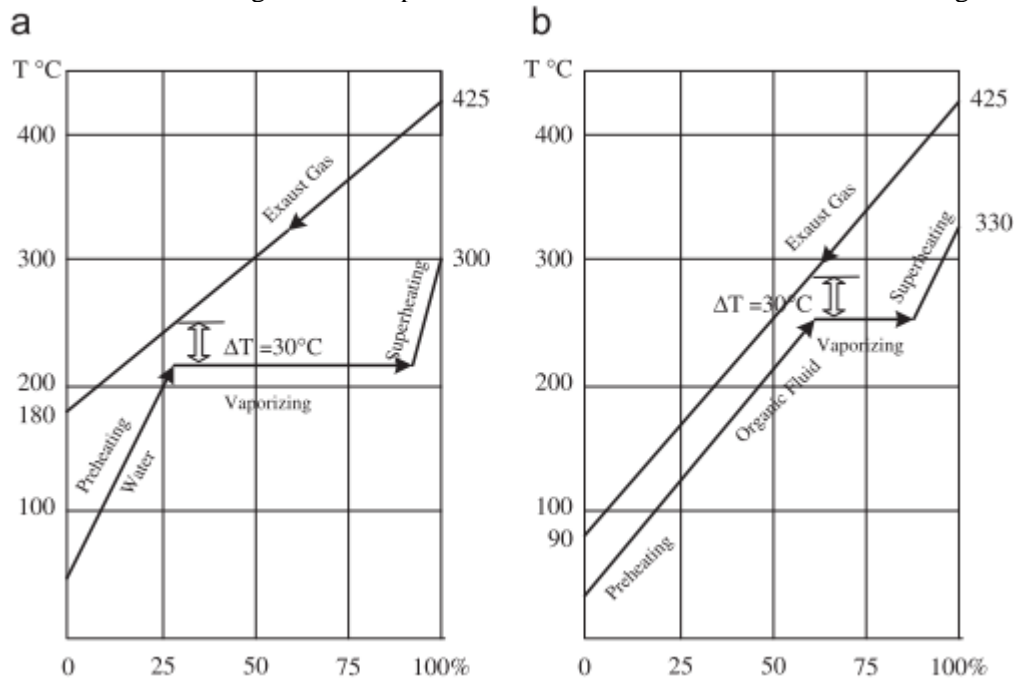


Fig. 3: Influence of latent heat of vaporization on the irreversibility during heat transfer [35].

Zhang [26] studied the thermodynamic effect of the inflection point of saturated vapour curve for 38 different types of dry and isentropic fluids. He defined the inflection point by a model of near-critical point triangle and investigated performance analysis. The results were in agreement with Borsukiewicz-gozdur & Nowak, [34] by concluding that heptane, cyclohexane, octane, nonane, decane, and dodecane in that they had low latent heats of evaporation at the inflection point to be the suitable working fluids. Furthermore, He et al., [36], proposed organic fluids showing low latent heat but high sensible heat. In the same manner, Liu et al. [23] in He et al., [36] stated that organic fluids found wide applications in waste heat recovery systems because they meet the requirements of low latent heat and high sensible heat. However, the ratio of vapourization latent heat to the sensible heat, described as the vapourization enthalpy ratio, is a close ratio to the thermodynamic index, Jacob Number, which was analytically derived by Mikielewicz & Mikielewicz, [37] by considering twenty pure organic fluids for subcritical and supercritical ORCs. Singh & Pedersen [38] in Bao & Zhao [35] recommended a derivative of the Jacob Number but encompassing condensing and evaporating temperatures, called Figure of merit given as:

$$\text{FOM} = \text{Ja}^{0.1} \left( \frac{T_{\text{cond}}}{T_{\text{evap}}} \right)^{0.8} \quad \text{and} \quad \text{Ja} = C_p \frac{dT}{H_v}, \quad (4)$$

where  $C_p dT$  is the vapourization sensible heat and  $H_v$  is the vapourization latent heat.

Whereas, Mikielewicz, [39] conducted an appraisal on critical performance indicators of ORC. They introduced an evaluation indicator- the Jacob number, recommended by Mikielewicz and Mikielewicz [37] to set up a modified thermodynamic method and model for ORC and to demonstrate interaction between ORC and Carnot cycle as well as the thermodynamic cycle triangle in order to develop a more convenient and simplified alternative for the complex traditional numerical method. The Jacob number, Ja, represents the ratio of sensible heat capacity to the latent heat capacity of the organic working fluid. The preeminence of this parameter consists in the blend of two key factors influencing cycle performance which are the evaporator and condenser temperatures, as well as organic fluid properties such as specific heat  $C_p$  and latent heat  $h_{fg}$ , simultaneously.

$$\text{Jacob number is given by } \text{Ja} = \frac{C_p(T_e - T_c)}{h_{fg}}. \quad (5)$$



The work of Wang et al. [40] however generated more explorable correlations between Ja, the thermal efficiency and exergetic efficiency of the considered cycles and the network output and also with possibility of further modifications to include more parameters. The thermophysical properties of the selected working fluid were in agreement with the work of Borsukiewicz-gozdur & Nowak, [34].

In another study, Amicabile et al., [41] employed thermodynamic analysis to show that the enthalpy of vapourization is inversely proportional to the molecular weight of the fluid and thereby suggested that low molecular weight fluids should be avoided because of their high enthalpy of vapourization. Due to the large amount of working fluid and the diversity of criteria for selecting appropriate working fluids for ORC applications, there is no one single optimal fluid for a given temperature level and a given application. Quoilin et al [42] identified two approaches for fluid selection: the screening method and the operating map method.

Screening method is though the popular approach in the scientific literature but it is impaired by the use of objective function void of influences of fluid properties on the practical design of the cycle. The thermodynamic model developed is limited to optimizing working fluid performances in terms of thermal efficiency, output power or exergy efficiency inherently capable of proffering unrealistic working fluids. The operating map approach proposed by Quoilin et al. [42] integrated the interaction between expander, heat exchangers and the working fluid into a selection process that leads to the selection of appropriate types and sizes of the basic components of the ORC. The approach maps out acceptable conditions and limits on component size as shown in Figures 4 to 7, therefore does not yield impractical working fluids. However, the operating map method is only a pre-selection tool to narrow down the possible choices because the operating maps of some working fluids overlap with some others. The fluid selection process therefore has to be further optimized by a more accurate procedure.

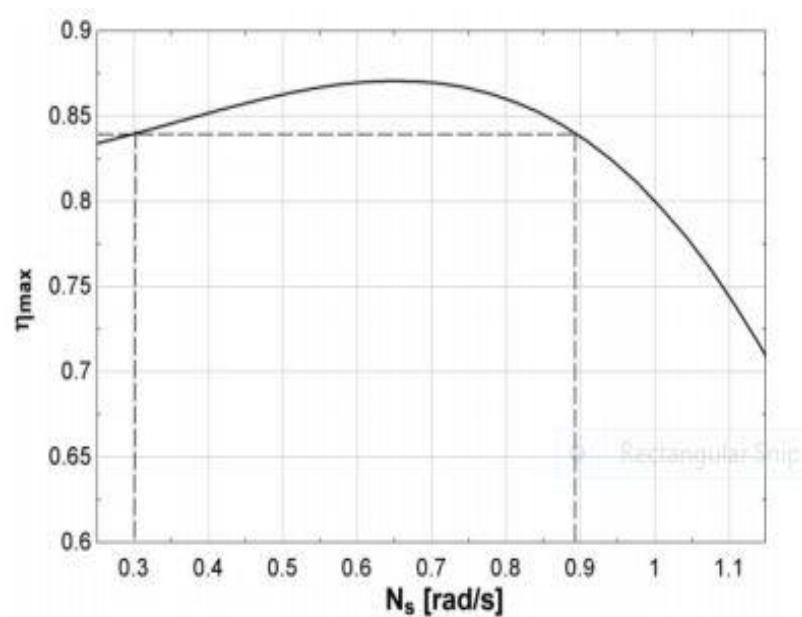


Figure 4: Characteristic maximum efficiency curve as a function of its specific speed for a radial turbine [42]

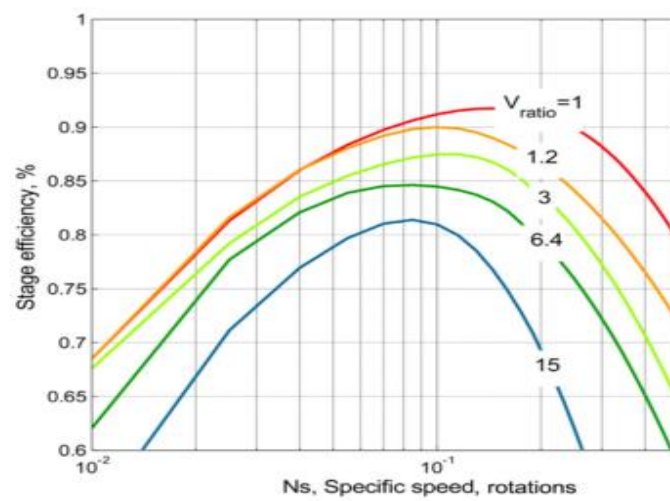


Figure 5: Parametric curves proposed for turbine stage efficiency prediction of axial turbines [2]

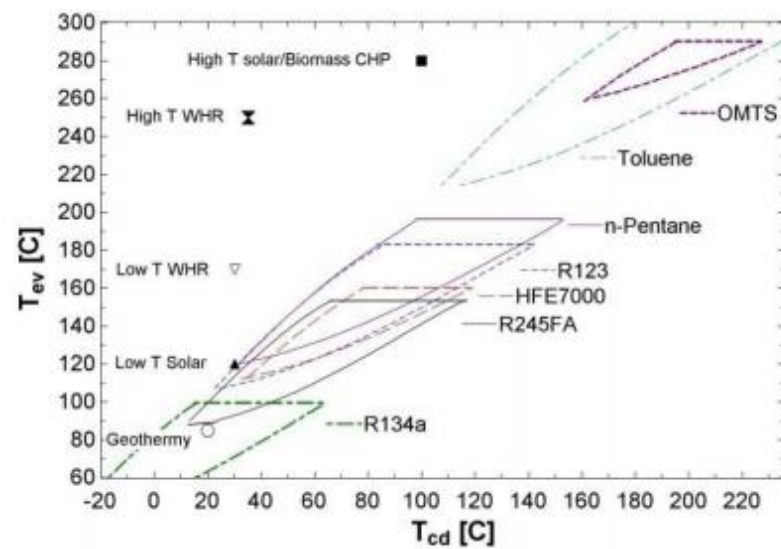


Figure 6: Screw expander operating map [42]

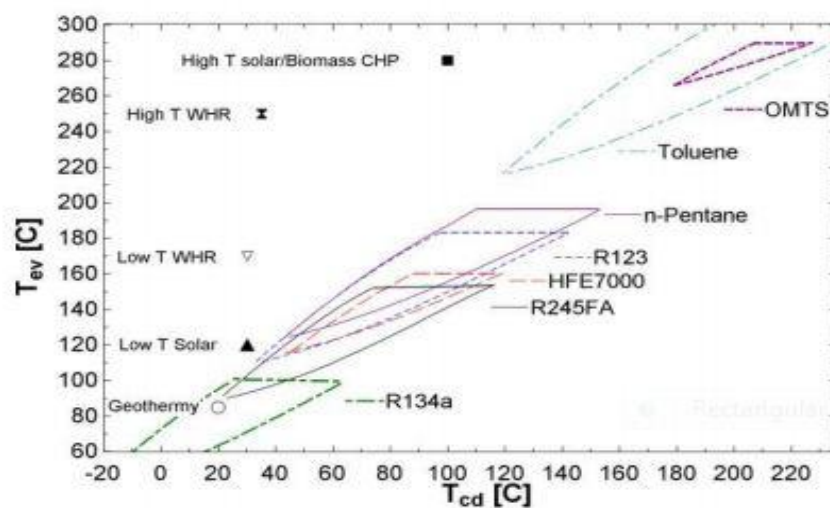


Figure 7: Scroll expander operating map [42]

The top left-hand corner in Figure 7 above shows the region of excessively large expansion ratio while the down right-hand corner is the region of too high volume flow rate.

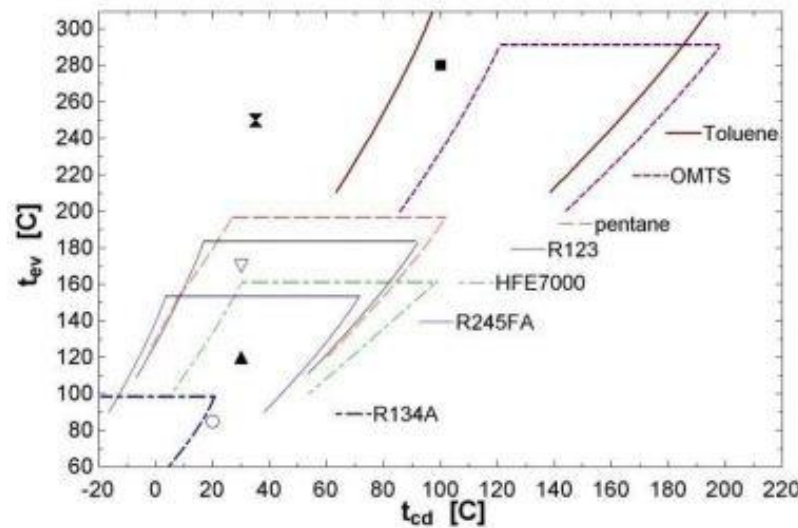


Figure 8: Radial inflow turbine operating map [42]

Of all the fluids investigated, only R123 and R245fa showed capacity to achieve desirable cycle performances. R245fa operates at superatmospheric pressure at condenser temperature of 40°C eliminating the possibility of infiltration of non-condensable gases into the condenser [31] and it is the most utilized working fluid in ORC experiments and the most considered for waste heat recovery applications [43].

### 3 Effects of Critical Temperature on Working Fluids Pre-selection

The critical temperature is a function of the strength of the intermolecular interactions that binds the molecules of a substance together as a liquid but it sets a limit on the evaporation temperature in subcritical cycles and also determines the temperature glide in zeotropic mixtures. According to [44], the comparatively high critical temperature, high thermal stability and low vapour pressure characterize the suitability of organic fluids for ORC applications. High critical temperature working fluids have been found to be essential to maintain ORC systems within the subcritical range and to avoid disintegration of the organic working fluids at the elevated temperatures of waste exhaust gases [45]. Low critical temperature fluids perform better for supercritical cycles [46], however, the chemical stability of organic working fluids operating on supercritical cycle also depends on their critical temperatures because of the tendency to degenerate with high degree of superheat. High critical temperature permits high turbine inlet temperature fluids to expand to lower pressures at the turbine exit, hence larger enthalpy difference to deliver more power [47] but are however, subatmospheric at ambient temperature [42] which exposes the condenser to the possibility of infiltration of non-condensable gases.

Saadatfar et al., [48] from similar investigation of a number of working fluids based on the correlation between critical temperature of working fluids and the cycle efficiency likewise reported that higher critical temperature produces higher efficiency but lower condensing pressure and hence proposed classification of working fluids as a function of their critical temperature by means of acentric factor and molecular complexity parameters. High critical temperature organic fluids, generally with low condensing pressures, exhibit volume ratio (ratio of the specific volume at the turbine outlet to the specific volume at the inlet during an isentropic expansion) as high as 200 to 300. The specific volume range is undesirable for the cycle architecture because the high volume flow rates require bigger size turbine resulting in low rotational speeds well below 300 rpm and thus require multi-pole generator [2].

Also, working fluid with higher critical temperature exhibits lesser optimal evaporating pinch point and greater optimal condensing pinch point [49]. The optimal evaporating temperatures of different working fluids was observed to display an increasing relationship with increasing critical temperature, but on the other hand, the optimal condensing temperatures had no significant effect. This accordingly was an



indication that condensing temperature does not respond to cost-effective performance and hence, according to Li et al [49], this further corroborates the choice of parameters optimization at a given condensing temperature in many studies. Henrik & Per [50] hence clearly stated that higher critical temperature fluids provide superior performance and are less susceptible to changes in condenser temperature and pressure.

Henrik Ö & Per [50] also demonstrated that there is a direct positive correlation between increase in expansion ratio and increased critical temperature of fluids. The fluids with higher critical temperatures showed greater expansion ratio potentials and hence, greater work output potential. They also demonstrated that:

- (i) fluids with higher critical points offers higher expander enthalpy drop, and consequently greater work output, and
- (ii) for a fluid expanding between two fixed pressures, the volume expansion ratio decreases with increasing maximum cycle temperature but gives rise to increase in enthalpy drop.

Similarly, Wang et al. [40], based their investigation of the performance of ORC systems for WHR solely on the critical temperature criterion, proposed that the critical temperature can be a singular factor for fluid selection. The authors proposed based on their finding that thermal efficiencies have dispersed distribution against every other physical parameter other except for the critical temperature alone. In the investigation, five organic fluids were employed; R245fa, R123, R601, isohexane and hexane, with critical temperatures from low to high.

Their results showed correlation between thermal efficiency increase and increase in critical temperature while R601 provided the maximum efficiency because of the closeness between the critical temperature and the heat source temperature. It was in a similar trend discovered by Agromayor & Nord [51] that transcritical-recuperated cycle architecture employing either dry or isentropic organic fluids exhibited optimal performance when the critical temperature of the working fluid was slightly lower than the temperature of the heat source. Conversely, no common relationship was established for the optimal cycle architecture for heat source temperatures higher than the critical temperatures of the organic fluids. Bianchi et al., [52] also reported from studies that specific pumping work reduces as the critical temperature of organic working fluids increases, especially when the critical temperature is greater than 150°C, but no direct relationship with liquid specific heat.

#### 4. Guidelines for Screening of Working Fluids

Since the efficiency of the Organic Rankine Cycle for a fixed working condition and the life of the turbine as well significantly depends on the selected dry working fluid [53], it therefore requires an optimization process for the probable working fluids in order to determine the most suitable working fluid in concurrently with the expander selection and the ORC architecture. [42] hence identified thirteen basic guidelines for screening of working fluids highlighted below:

- Thermodynamic performance
- Positive or isentropic saturation vapor curve
- High vapor density
- Low viscosity
- High conductivity
- Acceptable evaporating pressure
- Positive condensing gauge pressure
- High stability temperature
- Melting point
- High safety level

#### 5. Conclusion

In this study, comprehensive review of working fluids selection for ORC applications has been carried out. Pure and azeotropic fluids have been discussed. The thermo-physical properties, stability, environmental effects, safety and compatibility, and availability and cost which are essential factors to be considered when

making a choice of the most appropriate organic working fluids and appropriate trade-off are discussed comprehensively.

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### References

- [1] Ziviani, D., Dickes, R., Quoilin, S., & Lemort, V. Organic Rankine cycle modelling and the ORCmKit library : analysis of R1234ze (Z) as drop-in replacement of R245fa for low-grade waste heat recovery. *The 29th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems*, 2016, 1–13
- [2] Astolfi, M., Romano, M. C., Bombarda, P., & Macchi, E. Binary ORC (Organic Rankine Cycles) power plants for the exploitation of medium-low temperature geothermal sources - Part B: Techno-economic optimization. *Energy*, 2014, 66, 435–446. <https://doi.org/10.1016/j.energy.2013.11.057>
- [3] Chen, H., Yogi Goswami, D., Rahman, M. M., & Stefanakos, E. K. Energetic and exergetic analysis of CO<sub>2</sub>- and R32-based transcritical Rankine cycles for low-grade heat conversion. *Applied Energy*, 2011, 88(8), 2802–2808. <https://doi.org/10.1016/j.apenergy.2011.01.029>
- [4] Habeeb, A. Low-Grade Waste Heat Recovery-To- Power Generation Low-Grade Waste Heat Recovery-To-, (October), 2014.
- [5] Larjola, J., Uusitalo, A., & Turunen-saaresti, T. Background and Summary of Commercial ORC Development and Exploitation, 2011.
- [6] Mocarsk, S., & Borsukiewicz-Gozdur, A. Selected aspects of operation of supercritical (transcritical) organic Rankine cycle. *Archives of Thermodynamics*, 2015, 36(2), 85–103. <https://doi.org/10.1515/aoter-2015-0017>
- [7] Simone L, Constantine N. M, Ioannis V & Rodolfo T. A thermodynamic feasibility study of an Organic Rankine Cycle (ORC) for heavy-duty diesel engine waste heat recovery in off-highway applications, *Int J Energy Environ Eng* 2017, 8:81–98
- [8] Heberle, F., Preißinger, M., & Brüggemann, D. Zeotropic mixtures as working fluids in Organic Rankine Cycles for low-enthalpy geothermal resources. *Renewable Energy*, 2012, 37(1), 364–370. <https://doi.org/10.1016/j.renene.2011.06.044>
- [9] Guo, C., Du, X., Yang, L., & Yang, Y. Organic Rankine cycle for power recovery of exhaust flue gas. *Applied Thermal Engineering*, 2015, 75, 135–144. <https://doi.org/10.1016/j.applthermaleng.2014.09.080>
- [10] Abadi, B.G., & Kim, K. C. Investigation of organic Rankine cycles with zeotropic mixtures as a working fluid: Advantages and issues. *Renewable and Sustainable Energy Reviews*, 2017, 73(February), 1000–1013. <https://doi.org/10.1016/j.rser.2017.02.020>
- [11] Weith, T., Heberle, F., Preißinger, M., & Brüggemann, D. Performance of siloxane mixtures in a high-temperature organic rankine cycle considering the heat transfer characteristics during evaporation. *Energies*, 2014, 7(9), 5548–5565. <https://doi.org/10.3390/en7095548>
- [12] Bândeian, D. C., Smolen, S., & Cieslinski, J. T. Working fluid selection for Organic Rankine Cycle applied to heat recovery systems. *World Renewable Energy Congress 2011*, 772–779.
- [13] Chen, H., Goswami, D. Y., & Stefanakos, E. K. A review of thermodynamic cycles and working fluids for the conversion of low-grade heat. *Renewable and Sustainable Energy Reviews*, 2010, 14(9), 3059–3067. <https://doi.org/10.1016/j.rser.2010.07.006>
- [14] Angelino, G. A review of italian activities in the field of organic rankine cycle.pdf. *VDI BERICHTE*, 1984.
- [15] Xi, X., Zhou, Y., Guo, C., Yang, L., & Du, X. Characteristics of Organic Rankine Cycles with Zeotropic Mixture for Heat Recovery of Exhaust Gas of Boiler. *Energy Procedia*, 2015, 75, 1093–1101. <https://doi.org/10.1016/j.egypro.2015.07.496>
- [16] Shengjun, Z., Huaixin, W., & Tao, G. Performance comparison and parametric optimization of subcritical Organic Rankine Cycle (ORC) and transcritical power cycle system for low-temperature geothermal power generation. *Applied Energy*, 2011, 88(8), 2740–2754. <https://doi.org/10.1016/j.apenergy.2011.02.034>
- [17] Stijepovic, M. Z., Linke, P., Papadopoulos, A. I., & Grujic, A. S. On the role of working fluid properties in Organic Rankine Cycle performance. *Applied Thermal Engineering*, 2012, 36(1), 406–413. <https://doi.org/10.1016/j.applthermaleng.2011.10.057>
- [18] Chintala, V., Kumar, S., & Pandey, J. K. A technical review on waste heat recovery from compression ignition engines using organic Rankine cycle. *Renewable and Sustainable Energy Reviews*, 2017, 81, 493–509. <https://doi.org/10.1016/j.rser.2017.08.016>

- [19] Hettiarachchi, M. H. D., Golubovic, M., Worek, W. M., & Ikegami, Y. Optimum design criteria for an Organic Rankine cycle using low-temperature geothermal heat sources. *Energy*, 2007, 32(9), 1698–1706. <https://doi.org/10.1016/j.energy.2007.01.005>
- [20] Saadatfar, B., Fakhrai, R., & Fransson, T. The Journal of MacroTrends in Energy and Sustainability Waste heat recovery Organic Rankine cycles in sustainable energy conversion: A state-of-the-art review. *Jmes*, 2013, 1(1), 161–188.
- [21] Andreasen, J. G., Pierobon, L., Larsen, U., Haglind, F., & Author, C. Multi-Objective Optimization of Organic Rankine Cycle Power Plants Using Pure and Mixed Working Fluids. *Proceedings of the 3rd International Seminar on ORC Power Systems*, 2015, 1–11. <https://doi.org/10.3390/en9050322>
- [22] Liu, C., Gao, T., Xu, J., Zhu, J., & Xu, X. Analysis of Pure Fluid and Zeotropic Mixtures Used in Low-Temperature Reheating Organic Rankine Cycles. *Proceedings of the 3rd International Seminar on ORC Power Systems*, 2015, 1–10.
- [23] Nouman, J. Comparative studies and analyses of working fluids for Organic Rankine Cycles -ORC. 2012, Retrieved from <https://www.diva-portal.org/smash/get/diva2:555314/FULLTEXT01.pdf>
- [24] Habibzadeh, A., & Rashidi, M. M. Thermodynamic analysis of different working fluids used in organic rankine cycle for recovering waste heat from GT-MHR. *Journal of Engineering Science and Technology*, 11(1), 2016, 121–135
- [25] Zhang, X. Thermodynamic Study of Inflection Point of Saturated Vapor Curve for Dry and Isentropic Working Fluids. *Proceedings of the 3rd International Seminar on ORC Power Systems*, 2015, 1–10.
- [26] Kandathil, A. K. A Guide to working fluid selection for Organic Rankine Cycle ORC generators. *Genixx, HEATCATCHER*. Retrieved from <http://www.heatcatcher.com/guide-working-fluid-selection-organic-rankine-cycle-orc-generators/>, 2016.
- [27] Liu, B. T., Chien, K. H., & Wang, C. C. Effect of working fluids on organic Rankine cycle for waste heat recovery. *Energy*, 2004, 29(8), 1207–1217. <https://doi.org/10.1016/j.energy.2004.01.004>
- [28] Dhar, H., Kumar, S., & Kumar, R. A review on organic waste to energy systems in India. *Bioresource Technology*, (August), 2017, <https://doi.org/10.1016/j.biortech.2017.08.159>
- [29] Patrick L, Athanasios I. P & Panos S. Systematic Methods for Working Fluid Selection and the Design, Integration and Control of Organic Rankine Cycles—A Review, *Energies* **2015**, 8, 4755 - 4801
- [30] Shu, G, Liu, L, Tian, H, Wei, H & Yu, G. Parametric and working fluid analysis of a dual-loop organic Rankine cycle (DORC) used in engine waste heat recovery, *Applied Energy* 113: 2014: 1188 – 1198
- [31] Bahrami, M., Hamidi, A. A., & Porkhial, S. Investigation of the effect of organic working fluids on thermodynamic performance of combined cycle Stirling-ORC. *International Journal of Energy and Environmental Engineering*, 2013, 4(12), 1–9. <https://doi.org/10.1186/2251-6832-4-12>
- [32] Galloni, E, Fontana, G & Staccone, S. Design and experimental analysis of a mini ORC (organic Rankine cycle) power plant based on R245fa working fluid, *Energy* 90: 2015: 768 – 775
- [33] Richard L, Adam H & David R. A knowledge-based system for low-grade waste heat recovery in the process industries, *Applied Thermal Engineering* 94: 2016: 590–599
- [34] Borsukiewicz-gozdur, A., & Nowak, W. Desirable Thermophysical Properties of Working Fluids in Organic Rankine Cycle. *European Geothermal Congress 2007*, (June), 1–5.
- [35] Bao, J., & Zhao, L. A review of working fluid and expander selections for organic Rankine cycle. *Renewable and Sustainable Energy Reviews*, 2013, 24, 325–342. <https://doi.org/10.1016/j.rser.2013.03.040>
- [36] He, M., Zhang, X., Zeng, K., & Gao, K. A combined thermodynamic cycle used for waste heat recovery of internal combustion engine. *Energy*, 2011, 36(12), 6821–6829. <https://doi.org/10.1016/j.energy.2011.10.014>
- [37] Mikielewicz, D., & Mikielewicz, J. A thermodynamic criterion for selection of working fluid for subcritical and supercritical domestic micro CHP. *Applied Thermal Engineering*, 2010, 30(16), 2357–2362. <https://doi.org/10.1016/j.applthermaleng.2010.05.035>
- [38] Singh, D.V & Pedersen, E. A review of waste heat recovery technologies for maritime applications, *Energy Conversion and Management* 111, 2016: 315–328
- [39] Mikielewicz, D. M.. A thermodynamic criterion for selection of working fluid for subcritical and supercritical domestic micro CHP. *Applied Thermal Engineering, Elsevier*, 105(10.1016/j.applthermaleng.2010.05.035), 2356. <https://doi.org/10.1016/j.egypro.2017.03.330>
- [40] Wang, H., Xu, J., Yang, X., Miao, Z., & Yu, C. (2015). Organic Rankine cycle saves energy and reduces gas emissions for cement production. *Energy*, 86, 59–73. <https://doi.org/10.1016/j.energy.2015.03.112>

- [42] Amicabile, S., Lee, J. I., & Kum, D. A comprehensive design methodology of organic Rankine cycles for the waste heat recovery of automotive heavy-duty diesel engines. *Applied Thermal Engineering*, 2015, 87, 574–585. <https://doi.org/10.1016/j.applthermaleng.2015.04.034>
- [43] Quoilin, S., Declaye, S., Legros, A., & Guillaume, L. Working fluid selection and operating maps for Organic Rankine Cycle expansion machines. *International Compressor Engineering Conference*, 2012, 1–10.
- [44] Quoilin, S., Broek, M. Van Den, Declaye, S., Dewallef, P., & Lemort, V. Techno-economic survey of organic rankine cycle (ORC) systems. *Renewable and Sustainable Energy Reviews*, 2013, 22, 168–186. <https://doi.org/10.1016/j.rser.2013.01.028>
- [44] Ziviani, D., Beyene, A., & Venturini, M. Advances and challenges in ORC systems modeling for low grade thermal energy recovery. *Applied Energy*, 2014, 121, 79–95. <https://doi.org/10.1016/j.apenergy.2014.01.074>
- [45] Song, J., & Gu, C. W. Analysis of ORC (Organic Rankine Cycle) systems with pure hydrocarbons and mixtures of hydrocarbon and retardant for engine waste heat recovery. *Applied Thermal Engineering*, 2015, 89, 693–702. <https://doi.org/10.1016/j.applthermaleng.2015.06.055>
- [46] Jumel, S., & Feidt, M. Working fluid selection and performance comparison of subcritical and supercritical organic Rankine cycle (ORC) for low- temperature waste heat recovery, 2011(Iea 2011), 2012, 559–569.
- [47] Rusev, T. M. (2014). Comparative Study of Different Organic Rankine Cycle Models: Simulations and Thermo-Economic Analysis for a Gas Engine Waste Heat Recovery Application, 1–77.
- [48] Saadatfar, B., Fakhrai, R., & Fransson, T. The Journal of MacroTrends in Energy and Sustainability Waste heat recovery Organic Rankine cycles in sustainable energy conversion: A state-of-the-art review. *Jmes*, 2013, 1(1), 161–188.
- [49] Li, Y. R., Du, M. T., Wu, C. M., Wu, S. Y., Liu, C., & Xu, J. L. Economical evaluation and optimization of subcritical organic Rankine cycle based on temperature matching analysis. *Energy*, 2014, 68, 238–247. <https://doi.org/10.1016/j.energy.2014.02.038>
- [50] Henrik Ö & Per L, Comparison and analysis of performance using Low Temperature Power Cycles, *Applied Thermal Engineering* 52 (2013) 160 – 169
- [51] Agromayor, R., & Nord, L. O. Fluid selection and thermodynamic optimization of organic Rankine cycles for waste heat recovery applications. *Energy Procedia*, 2017, 129, 527–534. <https://doi.org/10.1016/j.egypro.2017.09.180>
- [52] Bianchi, G., Fatigati, F., Murgia, S., Cipollone, R., & Contaldi, G. Modeling and Experimental Activities on a Small-scale Sliding Vane Pump for ORC-based Waste heat Recovery Applications. *Energy Procedia*, 2016, 101(September), 1240–1247. <https://doi.org/10.1016/j.egypro.2016.11.139>
- [53] Algieri, A., & Morrone, P. Energy analysis of organic rankine cycles for biomass applications. *Thermal Science*, 19(1), 2015, 193–205. <https://doi.org/10.2298/TSCI120706030A>