Review on Selection of Optimum Working Fluid for Organic Rankine Cycle.

Nikhil Pakhale[a], SunayanaNerkar[a], Dr.J.G. Gujar[b]
[a]UG Student,[b]Associate Professor.
[a,b]Department of Chemical Engineering, Sinhgad College of Engineering, Pune, India.

Abstract—The whole universe is facing several major challenges that are caused by some anthropogenic activities. Organic Rankine Cycle (ORC) is commonly accepted as a viable technology to convert low temperature heat to useful work. To prerequisite for achieving the goal of sustainable energy is to create a flexible and agile power system. The organic Rankine Cycle is a green energy technology that utilizes low grade heat. The organic Rankine cycle (ORC) is widely recognized as a viable method for converting low-temperature waste heat to electricity. Several ORC waste heat recovery plants are already in operation as a result of these excellent characteristics. Despite the fact that the basic ORC is gradually being adopted by industry, there is still a need for application of new generation of working fluid with almost null ozone layer depletion potential (ODP)and significantly less Global Warming potential (GWP) compared to currently used working fluids.Waste energy is rejected at different temperatures depending on the industrial process, therefore selecting the best working fluid is vital. This cycle programme allows for the use of a variety of organic working fluids. The current article looks at ORC with a focus on the working fluid and how it can be used in ORC for various applications.

Index Terms—Organic Rankine Cycle, Rankine cycle, waste heat recovery,organic working fluid, renewable energy technology, energy recovery, Energy crisis.

1 Introduction

Energy is a "Golden Link" that connect the environmental and social domains. Because the nonrenewable primary energy resources are finite. The environment suffers greatly by the tremendous use of fossil fuels for daily energy purposes, Therefore,the prerequisite for achieving the goal of sustainable environment lies in creating a flexible and agile power system. Here the organic Rankine cycle(ORC) comes into play. Although it almost identical to the classicalwater/steamRankinecycle,ORCcanconvertheatatlowtemperaturetoelectricitybycarefulselectionofaworkingfluid(WF).It has benefitsover a traditional cycle like maintenance cost is low,favorableoperatingpressures and autonomous operation. So, over the last decade the ORChas become a mature technology.

Therearefivemainfocuspointsconsidered for optimizinganORC:

The heat source type, the selection of the working fluid, the hardwarecomponents, the control strategy and the component layout andsizing.Theheatsourcecanbewasteheat,solarenergy,geothermalheat [1]. Fluid selection criteria were initially based on simple thermodynamic performance criteria. But now due to environmental scenario we should go with eco-friendly working fluid.Besidestheselectionoftheoptimalworkingfluid,the developmentofnew andpromising working fluid with low low Ozone Layer Depletion Potential (ODP) and Global Warming Potential (GWP) value.

2 Organic Rankine Cycle

Alot of thermal energy is required in the chemical industry, including in the production of steel, cement, and other chemicals. During production tremendous amount of waste heat is generated. The conversion of waste heat to electricity may be an option for subsequent processes. Converting waste heat to electricity could be a viable option. The Organic Rankine Cycle (ORC) is a technology that can convert thermal energy to electricity at relatively low temperatures and can thus help to improve the energy efficiency of new or existing applications. Alternative heat sources, such as solar and geothermal energy, as well as biomass, can be used in addition to industrial waste heat. The process of a simple conventional steam power plant was used to understand the Organic Rankine Cycle. As water passes through a series of components, there is changes in a state of water in a steam power plant, then thermal energy is converted to electricity. Components such as a turbine with generator, condenser, feed pump, and boiler are required to implement these state changes.

3 Comparisons between Organic Rankine Cycle and Traditional Rankine Cycle-

The Organic Rankine Cycle works on the same principles as the Steam Rankine Cycle and has the same main components (evaporator, condenser, expander, and pump). Nonetheless, there are some significant differences between the two cycles. The differences are primarily due to the type of working fluid used in the cycle, the thermo-physical properties of the working fluid, the heat source temperature, and the cycle architecture. Compared to the traditional Rankine cycle, the Organic Rankine Cycle can extract energy and generate power from a much lower temperatureheat source. Several important aspects of the comparison between the Organic Rankine Cycle and the traditional Rankine Cycle are highlighted below.

3.1 Working fluid

Working fluid used in cycle is the main difference between the two cycles. The Steam Rankine Cycle uses only water as a working fluid, whereas Organic Rankine Cycles can use hundreds of different working fluids. The process of developing and discovering new working fluids is never-ending. The thermo-physical properties of the chosen working fluid have a significant impact on the cycle architecture, component size and shape, and economics. Working fluids have different thermophysical, safety, and environmental properties. For many working fluids, environmental and safety data are unavailable. The right working fluid selection is very important for cycle efficiency, Net Work Out, and other factors.

3.2 Normal Boiling Point and T-S diagram

The normal boiling point of most organic fluids is lower than that of water. Organic fluids, as a result of this property, require a lower heat source temperature than water in order to evaporate and recover thermal energy from low-grade heat sources. The T-S diagram for water and some other working fluids that can be used in Organic Rankine Cycles is shown in Fig. 1.[3]. A notable difference in Fig. 1 is the entropy difference between the saturation liquid line and the saturation vapor line.

As compared to water, organic working fluids have a very low entropy change. Water, as a working fluid, requires more thermal energy to transition from saturated liquid to saturated vapour and can transport more thermal energy per kilogram of water.

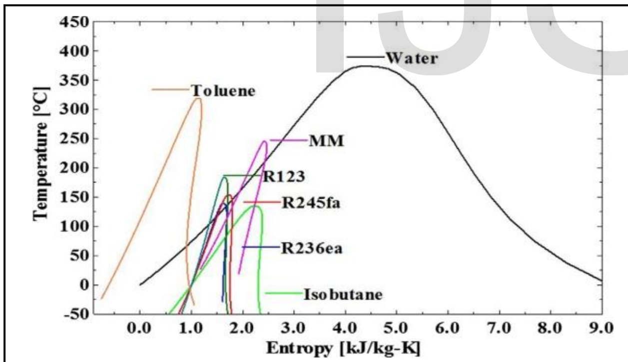

Fig:1: The diagram of entropy temperature of water and some public organic working Fluids

3.3 Cycle architecture

Organic fluid density, which is highly dependent on Volumetric flow rate is an important parameter for sizing a cycle. Higher density results in a lower specific volume, a lower volumetric flow rate, and a smaller component size.

Drop formation at the end of expansion stages is a very common and typical problem in Steam cycles. These droplets harmturbine blades and degrade the life and effectiveness of the expander. Superheat is therefore required to solve this problem. In the Rankine Cycle, the boiler is normally made up of three distinct heat exchangers (preheater, evaporator and superheater). While the boiler in the Organic Rankine Cycle is made up of one or two heat exchangers only.

Generally, ORC cycles use dry or isentropic fluids so there is no requirement for superheat. Working fluids leave the expander as superheated vapour, and the expansion process can begin right from the saturation vapour line. At the completion of the expansion process, there is no need to worry about vapour quality. When the working fluid leaves the expander at a temperature substantially lower than the temperature at the pump outlet, the recuperator or Internal Heat Exchanger IHE is required sometimes.

3.4 Condenser Pressure

In many ORCS, the condenser pressure is higher than the atmospheric pressure. This is a desirable property because condensing pressures lower than atmospheric pressure cause air infiltration issues in the cycle, lowering cycle efficiency[4]. At 298 K, the water condensing pressure is 3.15 kPa, while R11 condensing pressure is 105.49 kPa and Isobutane condensing pressure is 349.14 kPa.

3.5 Environmental and Safety Aspects

Water is an environmentally friendly working fluid that is non-flammable, non-toxic, and has no ozone depletion potential (ODP) or global warming potential (GWP). Many organic fluids have a significant negative impact on greenhouse gas emissions and ozone depletion issues. These organic fluids can be both flammable and toxic at the same time.

4 Organic Rankine Cycle and Working Principle

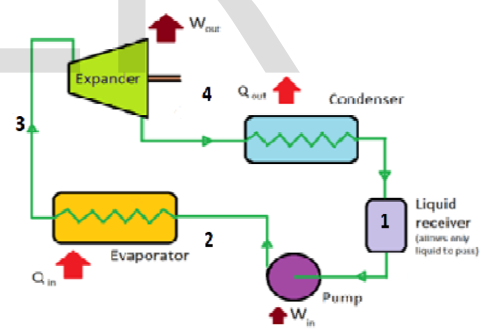

Fig. 2. Schematic block diagram of ORC.

The ideal Organic Rankine Cycle is similar to the ideal Rankine Cycle in terms of working principles. The working fluid for the condensate is pumped from the low-pressure condenser to the high-pressure evaporator. The process occurs at constant entropy. The high-pressure liquid enters the evaporator at a constant pressure and absorbs thermal energy from the heat source. The refrigerant changes phase from saturated liquid to saturated or superheated vapour in this process. External heat sources include industrial waste heat, geothermal heat, solar heat, biomass, and others. The saturated or superheated vapour exits the evaporator and expands at constant entropy through an expander to produce mechanical work. During the expansion process significantpressure drop take place. Depending on the working conditions and the type of working fluid used, the working fluid leaves the expander and enters the condenser as unsaturated, saturated, or superheated vapour. The working fluid condenses in the condenser and, with the help of a heat sink, phase changes to saturated or undercooled liquid, before the cycle is repeated.

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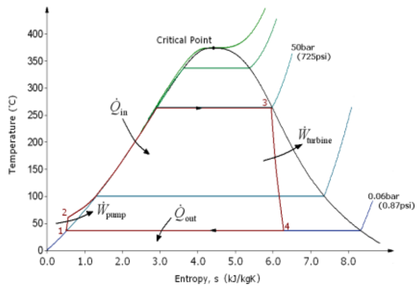

Fig. 3. Temperature vs. specific entropy diagram of ORC.

4 WORKING FLUIDS FOR ORC-

The organic Rankine is a potential method for using low-temperataurewaste heat. The working fluid has a significant impact on operation of an ORC system. As a result, selection of working fluid is acritical step in designing an ORC for a given waste heat recovery background process.
The slope of satururationvapour line in T-S diagram is an important factor to consider while selecting a working fluid. Working fluids can be classified into three types when it comes to the saturation vapour line.
Fluids with positive ds/dt slope are dry working fluids such asDecane, Nonane, Octane, Toulene, Heptane, Cyclohexane, hexane, R113, R365mfc, and other are included in this category.

$$\frac{dS}{dt}>0.$$

Wet working fluid have negative ds/dt slope. Heavy water, ethanol, methanol, R1, sulphurdioxide, DME and other common working fluids fall into this category.

$$\frac{dS}{dt}< 0$$

Fluids with infinite ds/dt deviation are isentropic R142b, Cis-butane, R11, R4b, acetone, and other popular working fluids are the examples of isentropic fluids.

4.1 Wet working fluids

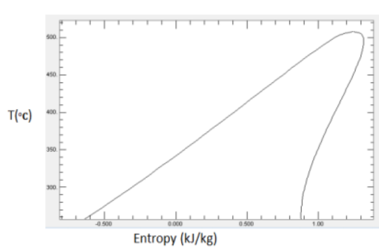

Fig:4 Temperature vs. specific entropy diagram of a ORC for wet working fluid

In case of wet working fluid (for example H2O, NH3, etc) vapour expansion in turbine begins at a saturated level due to which condensation will occure i.e., during expansion.
These liquid droplets will strike the blades of turbine and can cause potential harm to the blades of turbine. This as result will reduce isentropic efficiency of turbine, so wet fluids are typically superheated to avoide such difficulties, ensuring tht the working fluid remains dry during expansion and that condensation does not form in turbine.

4.2 Dry working fluids

Dry fluids have a positive slope and are the best choice for ORC systems that use low-grade heat sources. Due to the small temperature difference between the hot and cold sides, superheating dry fluids is not recommended because it reduces ORC efficiency. When dry working fluid is used (e.g., pentane, R-245fa, toluene, etc.) the turbine's vapour expansion begins at a saturated condition, expansion will continue in the dry region. As a result, there will be no condensation in the turbine and no need for a super-heater.

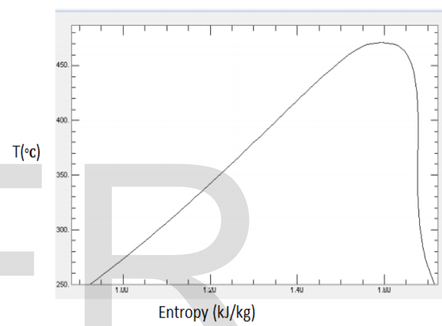

Fig:5 Temperature vs. specific entropy diagram of a ORC for dry working fluid

4.3 Isentropic working fluids

Isentropic working fluids have an infinite slope, which means that expansion causes no phase transition or change in the superheating of fluid.

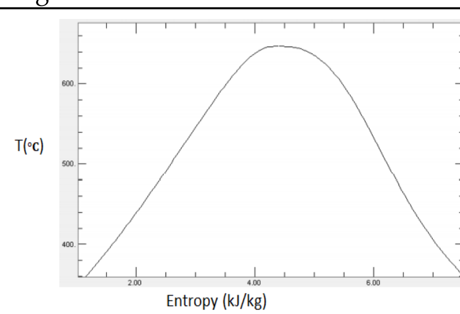

Fig:6 Temperature vs. specific entropy diagram of a ORC for isentropic working fluid

5 WORKING FLUID SELECTION CRITERIA

The working fluid is mainly determined by the temperature of the heat source and the heat sink. There are a variety of options for any heat temperature level that exhibit a good match between heat source and heat sink temperatures as well as cycle boundary conditions. But There is no such thing as the "best" fluid for the Organic Rankine Cycle because the choice of fluid is very dependent on the application and cycle circumstances. Choosing the correct working fluid is a difficult task. The fluid selection procedure involves a trade-off between thermodynamics and fluid properties.

In choosing the most appropriate Working fluid, the following factors should be considered [5]

5.1 Thermodynamic Properties

Thermodynamic characteristics of working fluid are essential for the design of Organic Rankine Cycles when it comes to maximising energy efficiency and minimising exergy losses. Some essential thermodynamic properties for working fluids are as follows:

- The Net Power Out, thermal efficiency, and second law efficiency for a given heat sink and heat source should all be as high as feasible.
- To avoid leakage, the condensing pressure should be higher than the atmospheric pressure.
- The lower the specific volume and volumetric flow rate, the higher the density. To achieve smaller components and more compact machines, low volumetric flow is desirable. So, the density of Working Fluid should always be higher

  Because low density fluids have a large specific volume, larger components (heat exchangers and expanders) are required.More expensive units and systems result from larger component sizes.
- To maintain high heat transfer coefficients and minimal friction losses in heat exchangers, low viscosity is necessary in both the liquid and vapour phases.
- Working fluid chosen should be chemically and thermodynamically stable.
- The liquid's heat capacity (C_P) should be high, because it allows good energy recovery from the heat source and lowers the working fluid's bulk flow rate.
- between the heat source, the heat sink, and the working fluid is enhanced by a higher convective heat coefficient and high thermal conductivity.
- The fluid's freezing point must be greater than the cycle's lowest temperature.
- convective heat Transfer coefficient and thermal conductivity should be as high as possible for the heat transfer process

5.2 Heat transfer properties

Working fluid with a high C_P value absorbs thermal energy from the heat source efficiently. High C_P enhances efficiency by allowing improved temperature profile in heat exchangers. The heat transfer process is influenced by a variety of factors. The cycle architecture is affected by a variety of elements, including pipe design, flow rates (Reynolds number), and material choices. Other parameters have to do with the characteristics of the working fluid and have an impact on the total heat transfer potential.[6]

5.3 Environmental and Safety Criteria

Ozone Depletion Potential (ODP), Global Warming Potential (GWP), and ASHRAE safety groups are three key environmental factors for the choosing of Organic Working Fluids, according to several studies. While selecting Working fluid according to environmental and safety factors many of them are being phased in or out or are on their way out. Working fluids that are being phased out have a high ozone depletion potential ODP and a high global warming potential GWP. While some working fluids have good thermodynamic properties, they also have negative environmental and safety consequences.[7]

5.4 Global Warming Potential

The quantity of Global Warming Potential (GWP) indicates the amount of global warming induced by a certain working fluid in comparison to CO2 during a 100-year period. To put it another way, the GWP is the ratio of a substance's warming to that induced by an equivalent mass of carbon dioxide.

5.5 Ozone Deplection Potential

In comparison to R11, the Ozone Depletion Potential (ODP) refers to the ability of refrigerants and other compounds to degrade stratospheric ozone. According to the United States EPA the ODP is defined as "The ratio of a chemical's influence on ozone compared to that of a similar mass of CFC-11."[8]Since non-null ODP fluids are gradually being phased out under the Montreal Protocol, the ODP of contemporary refrigerants is either null or extremely near to zero.

5.6 ASHRAE safety group

The American Society for Heating, Refrigeration, and Air-conditioning Engineers (ASHRAE) refrigerant safety classification, focuses on important qualities such as non-corrosive, non-flamm

able, and non-toxic, has also been recognised as a good indicator of how harmful a fluid is deemed. ASHRAE classifies refrigerants according to their toxicity and flammability, using a two-character system:

The letters A and B stand for "lower" and "higher" toxicity, respectively. Flame propagation is represented by the digits 1,2, and 3. Number 1 indicates no flame propagation, number 2 indicates lesser flammability, and number 3 indicates higher flammability. The abbreviation "wwf" standsfor "worse case fraction of flammability" or "worse case formulation," and it denotes that the working fluid is flammable in both the vapour and liquid phases. In some circumstances, group 2 is denoted by the letter L (for example, A2L and B2L), and the letter L denotes that the group is more difficult to ignite [8]

	Lower Toxicity	Higher Toxicity
Higher flammability	A3	B3
Lower flammability	A2	B2
No Flame Propagation	A1	B1

6 APPLICATION OF ORC -

The Organic Rankine Cycle can be utilised to generate mechanical work or electrical power in a variety of applications, including the ones listed below.

6.1 Waste heat recovery

Waste heat recovery is a method of extracting energy from waste heat generated by a variety of activities, particularly in industrial applications. Waste heat boilers, recuperators, and regenerators are utilised in some applications to recover and redirect heat straight to the process [9]. When the temperature of the wasted heat is low, that cannot be used in steam cycles. But Organic Rankine Cycle can be employed to generate electricity from low grade waste heat

6.2 Solar thermal power

Thermal power is a tried-and-true technology. Three different technologies are utilised to extract power from solar thermal: the parabolic dish, the solar tower, and the parabolic though. The parabolic tower can operate at temperatures ranging from 300 to 400 degrees Celsius. For a long time, this technology was associated with the classic Steam Rankine Cycle, which was used to generate electricity. But Organic Rankine Cycle is amore promising technology. The Steam Rankine Cycle, on the other hand, requires a greater temperature and installed power to be viable. When compared to steam cycles, the Organic Rankine Cycle can operate at lower temperatures, has a smaller component size, and requires a cheaper initial investment. The installed power can be scaled down to kilowatts (kW) [10].

6.3 Geothermal power plants

Geothermal energy has the ability to provide renewable energy to a huge number of people. In 2007, geothermal energy provided 1% of the world's electricity. This energy source is clean and renewable, and it can be produced in a very efficient manner. Three main technologies are employed to extract power in geothermal power plants: dry steam power plants, flash steam power plants, and binary cycle power plants. [11]

7 CHALLENGES TO IMPLEMENTATION OF ORC -

7.1 Optimum Working Fluid

TheORC requires anoptimum working fluid to function properly. It determines the system's efficiency and economics.The main challenge in term of working fluid is its commercial availability and choice/selection.Today, the majority of fluids are phased, it is important to follow international protocols as well as it is important look for properties that are environmentally friendly for working fluid. Appropriate critical parameters, positive or large slope, high thermal stability and compatibility with materials, low environmental impact, high safety level, good availability and low cost, high performance, and so on are some of the criteria for suitable fluids. Despite several methods available in the literature, combining these criteria to find a suitable fluid in a set is always a difficult task.[12]

7.2 Environmental Impact of ORC

Typically, ORC plant environmental impacts of ORC plant on environmentare expressed in terms of working fluid’s effect(ODP, GWP, and atmospheric lifetime). However, this is insufficient; the entire chain should be examined. There are few works available [13], and more research on various technologies and applications is needed.

8 CONCLUSION

It is a critical task to choose the best working fluid for the Organic Rankine Cycle. There are many different types of working fluids to choose from, and many factors should be considered. Some working fluids have excellent thermodynamic properties but have unfavourable environmental and safety characteristics. Other fluids have good environmental and safety records, but they are not thermodynamically efficient. The fluid selection process is a trade-off between thermodynamic, environmental, and safety properties. There is no ideal working fluid that can meet all of the desired criteria. From a thermodynamic standpoint, the best working fluid is determined by the temperatures of the heat source and the heat sink. There are several working fluid candidates for each heat source and heat sink temperature. Working fluids with good thermodynamic properties, such as high thermal efficiency, second law efficiency, and Net Work Out, should be chosen. Another important factor to consider during the working fluid selection process is the thermal conductivity of the working fluid.

1. Working fluids with a lower critical temperature result in more efficient ORC cycle systems (100 percent turbine and pump efficiency and no piping losses)
2. The development of safe and environmentally acceptable working fluids with lower ODP and GWP value than those currently available could benefit future ORC systems.

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