© 2017 IJSRSET | Volume 3 | Issue 8| Print ISSN: 2395-1990 | Online ISSN : 2394-4099
Themed Section: Engineering and Technology

Working fluids for Organic Rankine Cycle – A Review

K. Srinivasa Rao*1, C. Lakshmi Sindhuja2

[*1]Department of Mechanical Engineering, Vidya Jyothi Institute of Technology, Aziz Nagar, Hyderabad, Telangana, India
[2]Department of Mechanical Engineering, Vidya Jyothi Institute of Technology, Aziz Nagar, Hyderabad, Telangana, India.

ABSTRACT

Waste heat recovery techniques play a major role in reducing the dependency on fossil fuels and in meeting future energy needs. Organic Rankine Systems working on waste heat recovery system are successfully installed and run in many countries in the world. Lower normal boiling point of most of the organic fluids make them use a lower temperature heat source than water to evaporate and hence are finding their use in Organic Rankine cycle for generation of electrical power. This paper aims at presenting selection of working fluid for Organic Rankine cycle.
Keywords: Waste Heat Recovery, Organic Rankine Cycle, Organic Fluids, Electrical Power.

I. INTRODUCTION

Heat recovery and waste heat recovery technologies can be important in reducing the dependency on fossil fuel power. A significant number of solutions have been proposed to generate electricity from alternative heat source, such as low-temperature or low-power heat sources. Among the proposed solutions, the Organic Rankine Cycle (ORC) system is the most extensively used. ORC uses waste heat streams such as exhaust gases from engines or incinerators, low temperature wet steam from industrial processes at just-above atmospheric pressures, hot liquid waste heat etc. This system uses the same components as in a conventional steam power plant (a boiler or evaporator, a work-producing expansion device called turbine, a condenser and a pump).

However there is a considerable difference between the simple and organic rankine cycles in terms of the working fluid used and its properties as well as the cycle architecture. ORC can be simple or non- recuperated and recuperated. For higher temperature waste heat streams, the thermal efficiency of the organic rankine cycle system can for some working fluids be improved significantly by the use of a recuperative preheater.

The recuperated ORC system uses the heat of the turbine exhaust vapor to preheat the cold condensed liquid leaving the pump before being fed to the evaporator.

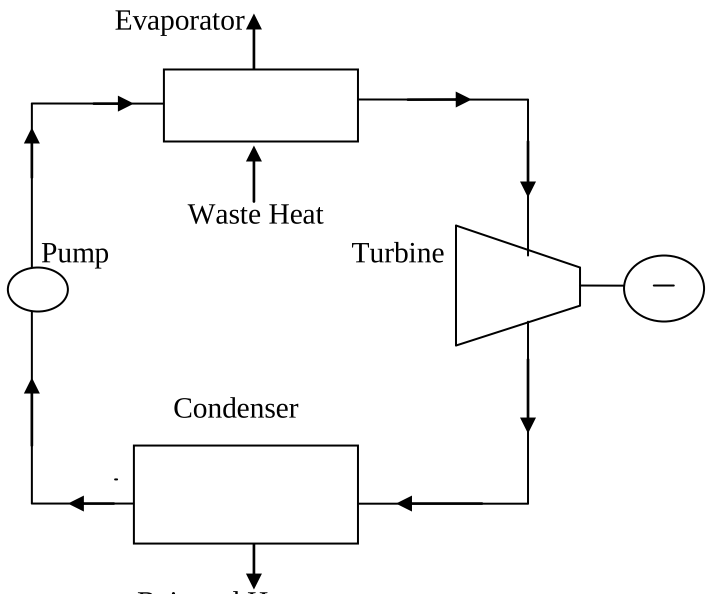

Figure 1. Schematic of Organic Rankine Cycle

However there is a considerable difference between the simple and organic rankine cycles in terms of the working fluid used and its properties as well as the cycle architecture. ORC can be simple or non- recuperated and recuperated. For higher temperature waste heat streams, the thermal efficiency of the organic rankine cycle system can for some working fluids be improved significantly by the use of a recuperative preheater. The recuperated ORC system uses the heat of the turbine exhaust vapor to preheat the cold condensed liquid

leaving the pump before being fed to the evaporator. There are three types of Organic cycles, depending on the pressures at which the four thermodynamic processes (compression, heat addition, expansion and heat rejection) occur.

i) Subcritical Organic Rankine cycle in which all the four processes occur at pressures lower than the critical pressures for the working fluid.
ii) Trans-critical Organic Rankine cycle in which the process of heat addition occurs at a pressure higher than the critical pressure for the working fluid and the heat rejection process occurs at a pressure lower than the critical pressure for the working fluid. The compression and expansion processes occur between the two pressure levels.
iii) Supercritical Organic Rankine Cycle in which all the four processes occur at pressures higher than the critical pressures for the working fluid.

II. WORKING FLUID SELECTION

The selection of the working fluid in Organic Rankine cycle plays an important role, and it depends on the application and the level of heat source. The slope dT/ds of the saturation vapour curve of organic fluid in T-S diagram can be positive, negative or infinite while it is negative for water as shown in the figure 2. The positive and infinite slopes have enormous advantages for turbo machinery expanders. These working fluids leave the expander as superheated vapor and eliminate the risk of corrosion. Furthermore, there is no need for overheating the vapour before entering the expander, and a smaller and cheaper heat exchanger (evaporator) can be used.

ASHRAE Code	Substance	Type of the fluid
R600	Butane	Dry
R601	Pentane	Dry
R152a	1,1-Difluoroethane	Wet
R170	Ethane	Wet
R134a	1,1,1,2-Tetrafluoroethane	Isentropic
R12	Dichlorodifluoro methane	Isentropic

Table 2. Some commonly used working fluids in ORC system

A significant difference in figure is the entropy difference between the saturation liquid line and the saturation vapor line. Organic working fluids have a very low entropy change compared with water. Water as working fluid needs more thermal energy to change phase from saturated liquid to saturated vapor and can carry out more thermal energy per kg of water. The advantage of this property is that water needs a much lower mass flow rate than organic fluids to absorb the same amount of thermal power from a certain heat source.

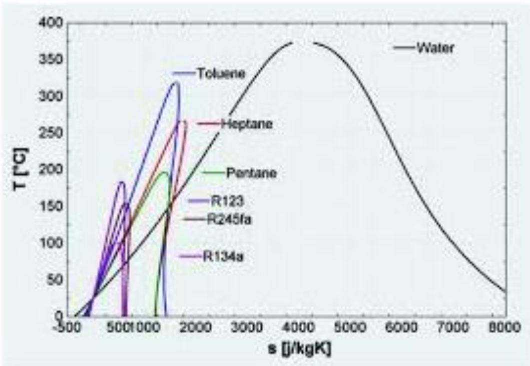

Figure 2. T-S diagram for different working fluids

A higher mass flow rate leads to higher power consumption by pump and a higher piping system diameter should be used to overcome pressure losses related to high Reynolds number. A higher mass flow means also higher components size and pressure losses. Some organic fluids have a very low freezing temperature (due to low triple point) and the freezing problem in the condenser is eliminated even at extremely low ambient temperatures. In addition, the fluid must have optimum thermodynamic properties at the lowest possible pressures and temperatures, as well as fulfil several criteria, such as being economical, non toxic, non flammable, environmentally friendly, etc. The choice of right working fluid is not an easy process. The fluid selection process is a trade-off between thermodynamic specifications, safety, environmental and economy aspects.

A. Thermodynamic properties

The following are some important thermodynamic properties for the working fluids

- ✓ The Net Power Output, the thermal efficiency and the second law efficiency should be as high as possible for a certain heat sink and heat source.

- ✓ The condensing pressure should be higher than the atmospheric pressure to avoid leakage issues.
- ✓ In sub-critical cycles the critical pressure for the working fluid must be higher than the pressure in the evaporator.
- ✓ Vapor density: The higher the density, the lower the specific volume and volumetric flow rate. Low volumetric flow is desirable to achieve smaller component and more compact machines. Low density fluids have high specific volume and need bigger components (heat exchangers and expander). A bigger component size leads to more expensive units and more costly systems. Furthermore, a high specific volume increases the pressure drop in the heat exchangers and needs higher pump work.
- ✓ Saturation Vapour line: Regarding saturation vapour line, there are three kinds of working fluids which are dry, isentropic and wet working fluids. Using wet fluid may lead to drop formation at the end of expansion process. The drop formation can lead to serious damages in turbo machinery expanders. To avoid drop formation, superheat is necessary but it needs a bigger and more expensive evaporator. By using dry or isentropic fluids, the problems associated to drop formation can be eliminated.
- ✓ Large enthalpy variation in the turbine leads to high Net Work Out.
- ✓ Higher convective heat coefficient and high-thermal conductivity increases the heat transfer process between the heat source, the heat sink and the working fluid.
- ✓ The working fluid must have higher latent heat which provides higher unit work output during expansion.
- ✓ The working fluid should be thermally and chemically stable.

B. Heat transfer Properties

Heat transfer properties are very important parameters in sizing heat exchangers. High C_P value makes working fluid absorbs efficiently the thermal energy from heat source. High C_P allows a better temperature profile approaches in the heat exchangers and improves efficiencies. There are many factors affecting the heat transfer process. Some factors are related to the cycle architecture including piping design, flow rates (Reynolds number) and material selection. Other factors are related to the working fluid properties and affect the overall heat transfer capability. The working fluid thermal conductivity (k), specific heat (C_P) and viscosity (μ) are three key properties used to calculate Prandtl number ($Pr = \mu * C_P/k$) which is widely used in heat exchanger design. It is desirable to have a working fluid with a viscosity as low as possible, and a specific heat and thermal conductivity as high as possible.

C. Environmental, safety, and stability

According to the Montreal Protocol, some fluids are being restricted depending on their Ozone Depleting Potential (ODP). In addition, Kyoto Protocol put some limitation regarding the Greenhouse Warming Potential (GWP) to avoid the greenhouse effect of gas emissions. Some of organic fluids such as R-11, R-12, R-113, R-114, and R-115 have been phased out, while some others such as R-21, R-22, R-123, R-124, R-141b and R-142b are being phased out in 2020 or 2030. The security classification of the ASHRE can be used as an indicator for the other characteristics like non-corrosive to avoid higher maintenance costs, non-flammable (a problem in particular for longer alkanes at temperatures above 200°C.), and non-toxic in working fluid selection should also be considered. The chemical stability of the working fluid is one of the limitations in the temperature of the heat source. The working fluid should not be decomposed and produce toxic or unstable substances.

i. Safety data: The safety data presented here includes the lower flammability level LFL and safety classification of working fluids and refrigerants. The safety data are mainly taken from the Physical, Safety and Environmental Data by James M. Calm.

ii. Lower flammability limit (LFL): The lower flammability limit LFL is usually measured in volume percent and refers to the lower end concentration of a flammable solvent in ambient air when the mixture can ignite in a given temperature and pressure. There is a variation in LFL values among separate laboratories and that is because they use different vessels or ignition sources or different evaluation standards.

iii. Safety classification: According to ASHRAE standard 34 (ASHRAE, 2010a and 2010b) the letters A refers to “lower” toxicity while the letter B means higher toxicity. The numbers 1, 2 and 3 refer to flame propagation, number 1 means no flame propagation, number 2 means lower flammability and number 3 means higher flammability. The shortening “wwf” indicates the worse case of fraction of flammability or worse case of formulation, and it means that the working fluid is flammable in either vapour or liquid phase. In some cases group 2 is signified with letter L (like A2L and B2L) and here the letter L means more difficult to ignite.

	Lower Toxicity	**Higher toxicity**
Higher flammability	A3	B3
Lower flammability	A2	B2
No flame propagation	A1	B1

Table 2. Safety classification

D.Chemical trends

According to the Application Guide AG 31-007 (2002) from McQuay International the following trends occur with use of various elements. They are

- ✓ The molecular weight and the boiling point generally increase with increasing carbon.
- ✓ The compound becomes more reactive generally with increasing nitrogen. This can lead to toxicity and instability issues.
- ✓ Increasing oxygen generally reduces atmospheric stability, which is good for GWP and ODP but may lead to toxicity, flammability and reactivity issues.
- ✓ Toxicity increases and decreases stability generally with increasing sulphur.
- ✓ Increasing hydrogen generally reduces atmospheric lifetime, which is good for GWP and ODP but increases flammability.
- ✓ Increasing fluorine attached to carbon increases GWP.
- ✓ Increasing chlorine improves lubricant miscibility but also increases ODP and toxicity.
- ✓ Increasing bromine increases ODP but lowers flammability.
- ✓ Using boron in lieu of carbon creates chemicals that are reactive and generally toxic.
- ✓ Using silicon in lieu of carbon creates substances that adversely react with water and have not performed well thermodynamically."

III. CONCLUSION

The selection of optimal working fluid for Organic Rankine Cycle is always a trade-off between thermodynamic, environmental and safety properties. A working fluid which has certain advantages has certain disadvantages too. Hence there here is no ideal working fluid that can satisfy all the desirable properties.

From thermodynamic viewpoint, the selection of the optimal working fluid depends basically on the heat source and the heat sink temperatures. For every heat source and heat sink temperature there are a number of working fluid candidates. The selected working fluids should have good thermodynamic properties like high thermal efficiency, second law efficiency and Net Work Out. The volumetric flow rate and the working fluid viscosity should be as low as possible to reduce the components size, pressure losses and the work needed for pumping. The thermal conductivity of working fluid is another important aspect that should be taken in consideration in working fluid selection process.

IV. REFERENCES

[1]. Maria E. Mondejar, Jesper G. Andreasen, Maria Regidor, Stefano Riva, Georgios Kontogeorgis, Giacomo Persico, Fredrik Haglind, Prospects of the use of nanofluids as working fluids for organic Rankine cycle power systems, Energy Procedia 129 (2017) 160-167.

[2]. S Douvartzides and I Karmalis, Working fluid selection for the Organic Rankine Cycle (ORC) exhaust heat recovery of an internal combustion engine power plant, 2016 IOP Conf. Ser.: Mater. Sci. Eng. 161 012087.

[3]. Roberto Cipollone, Giuseppe Bianchi, Angelo Gualtieri, Davide Di Battista, Marco Mauriello, Fabio Fatigati Development of an Organic Rankine Cycle system for exhaust energy recovery in internal combustion engines, Journal of Physics: Conference Series 655 (2015) 012015.

[4]. Suyog S. Bajaj, Harshal B. Patil , Gorakh B. Kudal and S. P. Shisode, Organic Rankine Cycle and Its Working Fluid Selection-A Review, International Journal of Current Engineering and Technology, Special Issue-4 (March 2016).

[5]. Bo-Tau Liu, Kuo-Hsiang Chien, Chi-Chuan Wang, Effect of working fluids on organic Rankine cycle for waste heat recovery, Energy 29 (2004) 1207-1217.

[6]. Yan-Na Liu, Song Xiao, Comparative investigation of working fluids for an organic Rankine cycle with geothermal water, archives of thermodynamics Vol. 36(2015), No. 2, 75-84.

[7]. Sylvain Quoilin and Vincent Lemort, The Organic Rankine Cycle: Thermodynamics, Applications And Optimization, Energy Systems Research Unit, University of Liege, Belgium.

[8]. Brasz, Lars J. and Bilbow, William M., "Ranking of Working Fluids for Organic Rankine Cycle Applications", International Refrigeration and Air Conditioning Conference. Paper 2004.

[9]. Jamal Nouman, Comparative studies and analyses of working fluids for Organic Rankine Cycles-ORC, Master of Science Thesis KTH School of Industrial Engineering and Management, 2012, Stockholm.

[10]. Gary J. Zyhowskia, Andrew P. Brownb, Abdennacer Achaichia, HFC-245fa Working Fluid in Organic Rankine Cycle-A Safe and Economic Way to Generate Electricity from Waste Heat, 14-17th june 2010, Lausanne, Switzerland.