International Engineering Journal For Research & Development

Vol.4
Issue -7

E-ISSN NO:-2349-0721

Impact factor : 6.03

ORGANIC RANKINE CYCLE (ORC): A VIABLE TECHNOLOGICAL OPTION FOR LOW-GRADE WASTE HEAT RECOVERY

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Abstract—

Energy is a crucial input in any industrial process, and thus directly determines to a great extent, the ecological impact of the manufacturing process and the products of any industry. Waste heat emission occurs in more or less all processes. The extent of energy in these low-grade waste heat emissions can be huge and losses, both economic and in terms of energy, can amount to considerable values. A waste heat recovery technology generates power by using the heat energy lost to the surroundings from thermal processes, at no extra fuel input. The quality of the total amount of wasted energy is relatively low due to its low temperature and has limited potential for power production. Novel and effective energy conversion technologies are essential in order to assure the production of electricity without generating environmental pollution. Among them, low-grade heat sources are considered as suitable candidates for the new energy sources. For low temperature waste heat recovery applications, a superior technology that may be used is the Organic Rankine Cycle. The purpose of this paper is to study and explore the potential of waste heat recovery, especially the application of Organic Rankine Cycle (ORC) technology in the industrial sector. The study focuses on overview of energy scenario, basic thermodynamic processes of ORC, and working fluids with key aspects of their selection in the cycle and applications of ORCs with a concluding remark that Organic Rankine Cycle (ORC) is a viable technological option for low-grade waste heat recovery.

Keywords: Organic Rankine Cycle (ORC), low-grade waste heat recovery, organic working fluid, ORC applications.

INTRODUCTION

Energy Scenario

The world economical development has accelerated significantly over the last century. Industrialization and the world population are the leading factors that drive global energy demand. The industrial growth, the ever-increasing number of vehicles on the road and the burgeoning of energy consuming domestic equipments have caused an important growth of the energy demand. Amongst the different sources of energy (fossil fuels, wind, solar, hydro, geothermal etc.), unfortunately, this demand has been mostly covered by a huge consumption of fossil fuels, which causes many serious environmental problems, such as global warming or atmospheric pollution. In 2010, the energy information administration (EIA) estimated that the total global energy consumption was about 553 x 10^{18} J [1]. Out of this quantity, about 80% was produced through the burning of fossil fuels [1]. The projection for 2040 was estimated to be about 865 x 10^{18} J [1], with fossil fuels still playing a leading role, although there is likely to be an incredible improvement in the use of renewable energy. This shows that fossil fuels will still play a dominant role in energy production and it will likely continue to dominate for many years to come.

A substantial quantity of total energy consumption is used by industry. Studies carried out by the International energy agency showed that energy-intensive industries (i.e. chemical, iron and steel, electronics,

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electrical, cement, sugar industries, textiles and pulp and paper) accounted for about one half of total commercial industrial energy consumption [1].However, the percentage of energy use by industry differs from one country to another. Industry accounted for 44% of the total national final energy consumption in India in 2010 (TERI Energy Data 2012). In India, the trend in industrial energy use has changed significantly between 1980 and 2011. The percentage of energy usage by industry is decreasing over time (TERI Energy Data 2012). This shows the impact of the use of energy conservation measures and energy-saving technologies following the oil crises of the 1970s and the shift from energy-intensive heavy industries to high technology and sophisticated service industries. However, the majority of energy consumption comes from fossil fuels, while energy production from other sources, such as the use of renewable and heat energy are still under-utilized.

Therefore to develop alternative energy sources for cleaner energy generation, it is important in the interim to practice efficient use of energy so as to reduce the quantity of fossil fuels consumed. This can be achieved by avoiding energy wastage, as well as by practicing efficient recovery (recycling) of wasted energy. Several industrial processes have low-temperature waste heat sources that cannot be efficiently recovered. Because of lack of efficient and economic recovery methods, in some industries low waste heat has generally been ignored and these have damages for environment as heat pollution.

Technological Options for Waste Heat to Power Generation

The described scenario has led the scientific community to explore new technologies capable of efficient recovery of industrial waste heat for generating efficient localized power.

Waste heat to power (WHP) is the process of capturing heat discarded by an existing process and utilizing that heat to produce electricity. Waste heat to power technologies falls under the WHR category. In general, the least expensive option for utilizing waste heat is to re-use this energy in an on-site thermal process. If it is not feasible to recover energy from a waste heat stream for another thermal process, then a WHP system may be an economically attractive option.

Commonly used Waste Heat to Power technologies are:

- Rankine Cycle (RC) :- The most general example of the Rankine cycle is the steam turbine, or steam Rankine cycle (SRC). In a SRC system, the working fluid is water, and steam is produced to drive a turbine.
- Kalina Cycle (KC) :- The Kalina cycle is a variation of the Rankine cycle, using a pair of binary fluid as the working fluid (usually water and ammonia), and has the potential to have higher efficiency than the SRC.
- Supercritical CO2 Cycle :- Another variation of the Rankine Cycle is the supercritical CO2 (sCO2) cycle, which uses carbon dioxide in place of water/steam for a heat-driven power cycle.
- Organic Rankine Cycle (ORC) :- Organic Rankine cycle (ORC) systems are similar to SRC systems, but are usually used at lower temperatures, and instead of water the working fluid is a hydrocarbon, hydrofluorocarbon, or ammonia.

The conventional Steam Rankine Cycle (SRC) has been one the most efficient options for waste heat recovery from exhaust streams with temperatures above (340-370°C). At lower waste heat temperatures, this cycle becomes less cost effective because the Low pressure steam generated from low temperature waste heat requires larger, bulkier and costlier equipment and Low temperature waste heat does not provide sufficient energy to superheat the steam, which causes steam to condense resulting in the erosion of the turbine blades and other metallic units.

Thermodynamic power cycle based on ammonia–water mixture i.e Kalina Cycle is a modified form of Rankine Cycle and has a better operating efficiency for number of applications. The most promising utilization and significant efficiency gains are realized in the low temperature heat sources, making it a suitable option for waste heat recovery [2]. However there are some potential drawbacks to a Kalina cycle operation. Regardless of many years of the development of safe handling regimes and operational requirements for ammonia, it is still a hazardous chemical to deal with. It is highly complex and will likely be more expensive to develop. A disadvantage of the Kalina cycle is that the absorption and distillation equipment added to the cycle creates further complexity to the system, and significantly increases the cost of plant installation compared with other types of power plants.

Moreover, the Kalina cycle has a high sensitivity towards the pressure and composition of the ammonia - water mixture, which limits the operation of the cycle over the whole range of possible geothermal reservoir temperatures.

For low temperature waste heat recovery applications, the Organic Rankine Cycle seems to be a better technology that may be used since this cycle uses organic fluids which not only have lower boiling point temperatures than steam has, but also do not corrode the metallic parts of the equipment

The Organic Rankine Cycle (ORC) accepted more attention since it is capable of producing electrical energy when it is coupled with a renewable energy source and hence converts wasted thermal energy into electricity. These capabilities make this technology suitable for different applications, such as biomass, geothermal, solar and waste heat recovery. The purpose of this paper is to study and explore the potential of waste heat recovery, especially the application of Organic Rankine Cycle (ORC) technology in the industrial sector.

The waste heat temperature is a most important factor determining waste heat recovery feasibility. Waste heat temperatures can vary significantly. In order to enable heat transfer and recovery, it is necessary that the waste heat source temperature is higher than the heat sink temperature. Moreover, the magnitude of the temperature difference between the heat source and sink is an essential determinant of waste heat's utility or quality. The source and sink temperature difference influences the rate at which heat is transferred per unit surface area of heat exchanger, and the maximum theoretical efficiency of converting thermal from the heat source to another form of energy i.e., mechanical or electrical. Finally, the temperature range has important inference for the selection of materials in heat exchanger designs.

The key parameter that determines the choice of technology is the temperature of the heat source, whether it is waste heat or renewable energy. Figure 1 shows the applicability of different type of ORC technologies at different waste heat source temperatures. Usually, the Steam Rankine Cycles are used if the temperature of waste heat source is higher than 350°C.

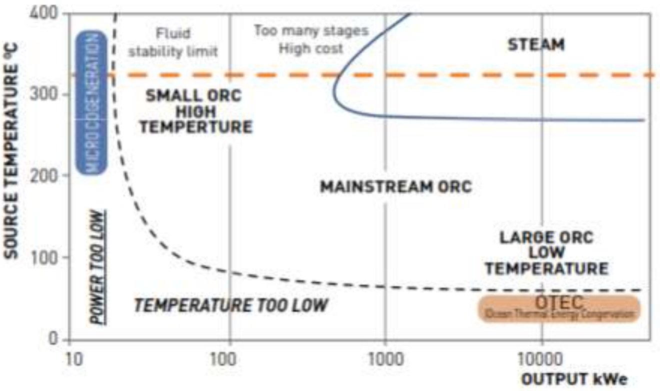

Figure 1: Option of Technology for Different Waste Heat Source Temperature

In addition to the temperature of the waste heat a number of factors must be considered to determine the economic feasibility of power generation from waste heat sources:

- Weather the waste heat source is gas or a liquid stream?
- The availability of the waste heat:- weather it is continuous, cyclic, or intermittent?
- The load factor of the waste heat source:- weather the annual operating hours sufficient to repay the capital costs of the WHP system?

- Does the temperature of the waste stream vary over time?
- The flow rate of the waste stream, and does it vary?
- Pressure of the waste stream weather it is positive or negative, and does this vary?
- What is the composition of the waste stream?
- Are there contaminants that may corrode or erode the heat recovery equipment?

The response to these factors will determine system design and, ultimately, the economic viability of a WHP technology. Many high-temperature waste heat sources are straightforward to capture and use with existing technologies. Other sources must be cleaned prior to use.

Organic Rankine Cycle

Many researchers have presented the study on performance of ORC for the conversion of low-grade heat into electrical power. The supercritical ORC when compared with subcritical one, it was found that the efficiency of the ORC system could be improved by operating in the supercritical region [3]. The research carried out on the thermodynamic performance analysis and optimization of ORC for waste heat recovery from exhaust heat concluded that the quality of waste heat affects system efficiency and net power of the system output performance of the plant deteriorates under high ambient temperature [4]. A low-temperature solar thermal electric generator using a regenerative ORC was analyzed and found that the overall system efficiency was higher for the regenerative cycle than for the non-regenerative cycle [5]. Gequn Shu et.al. [6] proposed a novel dual-loop organic Rankine cycle (DORC), which consists a high-temperature (HT) loop and a low-temperature (LT) loop to recover the waste heat of the exhaust, engine coolant and residual heat of the HT loop. Yiping Dai et al. [7] carried out their work on parametric optimization and comparative study of ORC for low-grade waste heat recovery. S. Lecompte et. al. [8] has developed a thermo-economic design methodology for an Organic Rankine Cycle (ORC) based on the specific investment cost (SIC), taking into account changing operating conditions and part load behavior. Yari, M. et al. & Naser Shokati et al. [9,10] carried out work on the utilization of exhaust waste heat from Gas Turbine – Modular Helium Reactor for electrical power generation using different arrangements of ORCs. G. Pikra et. al. [11] presents development of a concentrated solar power plant which includes the conceptual design of the small-scale system using Organic Rankine Cycle (ORC) that can be operated in remote, isolated areas.

Thermodynamic Processes of ORC

ORC is a technology that operates similarly as the Steam Rankine cycle, except that the former uses an organic working fluid instead of steam. This organic working fluid has a lower boiling point and a higher vapour pressure than water, and is, thus able to use low temperature heat sources to run a turbine for power generation.

For low-grade heat recovery an ORC consists of a pump, evaporator, expander, and a condenser, as shown in Figure 2. The cycle is divided into four different process; pumping (1–2), isobaric heat addition (2–3), expansion (3–4), and isobaric heat rejection (4–1) processes. The saturated liquid organic working fluid from the condenser is pumped into the evaporator where it gains heat from the hot fluid and finally converted into saturated or superheated vapor. The vapor expands in the expander and thus power is generated. The working fluid leaving the expander flows back into the condenser and is cooled to saturated liquid again. The working fluid is circulated in an ORC through these processes.

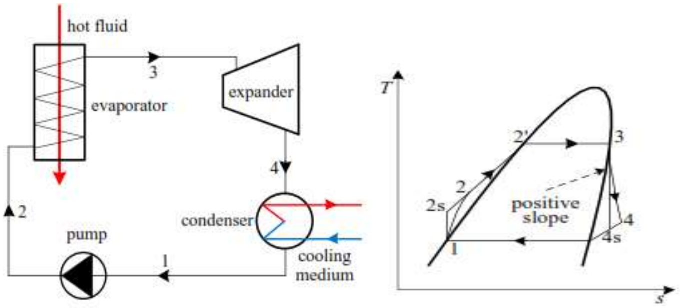

Figure 2: Configuration of an Organic Rankine Cycle and representation on T-s Diagram

The ideal Rankine Cycle (Reversible) is described as 1-2s-3-4s-1 in which pumping (1-2s) and expansion (3-4s) processes are assumed to be isentropic and there are no pressure drops in the evaporator, the condenser, and the pipes, and no heat loss in all components.

Working Fluid Selection

The working fluid plays a key role in the cycle. A working fluid must not only have the necessary thermo-physical properties that match the application but also possess adequate chemical stability in the desired temperature range. The fluid selection affects system efficiency, operating conditions, environmental impact and economic viability.

A working fluid can be classified as a dry, isentropic, or wet fluid depending on the slope of the saturation vapor curve on a T–s diagram (dT/ds) as shown in Figure 3. Since the value of dT/ds leads to infinity for isentropic fluids, the inverse of the slope, (i.e. ds/dT,) is used to express how ‘‘dry’’ or ‘‘wet’’ a fluid is [12]. When a wet fluid flows in expander as saturated vapor or becomes saturated vapor at the outlet of expander after actual expansion, the fluid inside the expander may form droplets, which results in erosion of the expander blades.

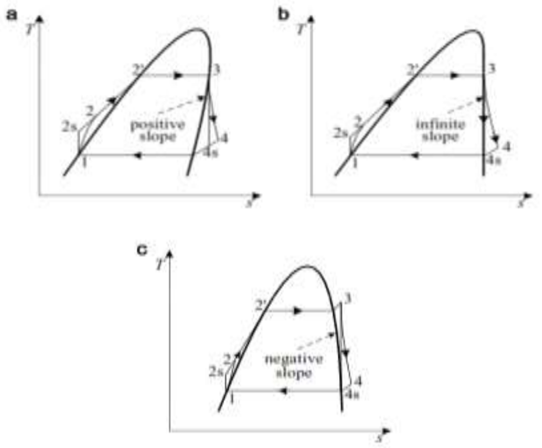

Figure 3: -ORC Working Fluids a) Dry Fluid; b) Isentropic Fluid; c) Wet Fluid

Therefore, the wet fluid at the inlet of an expander has to be superheated enough. Due to the lower heat transfer coefficient in the vapor phase, the heat transfer area required for superheating should be larger and the cost of ORC increases as compared with saturated expansions. For wet fluids, the degree of superheat should be set as small as possible, and it is applicable if the fluid becomes saturated vapor after isentropic expansion in the expander, as shown in Figure 2c. As for dry and isentropic fluids, there is no need for superheating and they normally expand under the saturated vapor state.

The choices of working fluids applicable for the low temperature Rankine cycle have been researched such as; Saleh et al. [13] carried out a thermodynamic screening of pure component working fluids for ORCs, using the BACKBONE equation of state. They found that the thermal efficiency of wet fluids increased significantly when combining superheating with the regeneration system while that of the dry fluids decreased by superheating. Liu et al. [14] investigated the effects of working fluids on ORC for waste heat recovery. They found that the presence of hydrogen bonds in certain molecules such as water, ammonia, and ethanol resulted in wet fluids due to larger vaporizing enthalpy, and are thus regarded as inappropriate for ORC systems. They also concluded that the thermal efficiency for working fluids is a weak function of the critical temperature. Hung et al. [15] investigated the suitability of 11 different organic working fluids for an ORC system used for the recovery of low-grade waste. They found that the slope of the saturation curve, the specific heat, and the latent heat had a major impact on the system performance of an ORC. Dai et al. [16] carried out their work on parametric optimization and comparative study of ORC for low-grade waste heat recovery and found that it does not always hold that an increase in the turbine inlet temperature will produce a corresponding increase in the turbine power output, especially with working fluids with a non-negative saturation vapour curve (i.e. isentropic and dry fluids). Quoilin [17] performed an experimental study and modelling of a low temperature organic Rankine Cycle for small scale cogeneration. Of all the organic fluids tested, he concluded that R123 was the best adapted for a hot source temperature between 100 and 200 ^{o}C. He also concluded that scroll expanders were better for small-scale units because of their robustness in two-phase flow conditions. Angelino et. al [18] studied the use of multi-component working fluids for ORC systems, and concluded that the ORC represented an effective heat-conversion device in many energy fields, and that its performance could be improved by using multi-component zeotropic mixtures as the working media.

There are a wide collection of organic fluids that can be used in ORC. Properties and characteristics of different working fluids for waste heat recovery system can be found in references reviewed. Generally, a good working fluid should exhibit low toxicity, good material compatibility, fluid stability limits, low flammability, corrosion and fouling characteristics. Another characteristic must be considered during the selection of an organic fluid is the saturation vapor curve. This characteristic affects the fluid applicability, cycle efficiency, and arrangement of associated equipment in a power generation system.

Organic Rankine Cycle applications

Organic Rankine Cycle finds application in many different industrial sectors that may be categorized in to three major heads, namely: Industrial waste heat recovery, Internal combustion engines (ICEs) and Gas turbines and Renewable energy power plants.

Industrial Waste Heat Recovery

In industries like cement, glass, iron and steel, sugar, food and paper industries, there are plenty of waste heat fluids of relatively low temperature that are dissipated to the environment, thereby wasting the thermal energy. Some of these heat sources are reused in other onsite applications (thermal applications) or are used for district heating. Thus, when there is no direct application for this thermal waste heat, it could be used to generate electricity by means of an ORC.

Internal Combustion Engines (ICEs) and Gas Turbines

In general, the thermal efficiencies of Internal combustion (IC) engines and gas turbines falls in the range of 20 to 50%. A major part of the energy produced by combustion of the fuel gets dissipated in the exhaust gases and jacket cooling. The exhaust gases often have a temperature level above 300°C, and thus, are suitable as heat input sources for ORC systems. Also the hot air used in the jacket for cooling having temperatures around 90°C, can also be used or integrated with an ORC system. In this manner, the total efficiency of the combined system (IC engine + ORC) can be substantially improved. Approximately 10% supplementary electric power can be generated from the same fuel input. Another application of the Organic Rankine Cycle is to use the waste heat from the gas turbines installed in compressor stations for running huge compressors that in turn maintain the pressure of these gases flowing in the pipelines.

Renewable Energy Power Plants

The ORC technology can be successfully integrated into renewable energy power plants, such as solar, geothermal and biomass fired units. In solar thermal plants, solar energy is being concentrated by parabolic troughs and used as an input heat source for a power cycle. The solar collectors can work at a temperature range of 300°C - 400°C. For a long time, this technology was linked to the traditional Steam Rankine Cycle for power generation. However, since the Steam Rankine Cycle needs higher temperature and a higher installed power in order to be profitable, the Organic Rankine Cycle that can work at much lower temperatures especially during periods of low solar radiation, offers a smaller equipment size and has good efficiency at such low temperatures. Utility scale solar thermal power plants are a well proven technology internationally. The parabolic dish, the solar tower and the parabolic trough are the three major technologies that are used to generate power in solar thermal technology. Geothermal energy is widely available and offers a broad range of temperatures, and the ORC technology is already applied for several decades to these heat sources. For low to medium temperature heat sources, the ORC is a favorable power generation cycle. This is a well-known application in Germany and in the rest of the developed world. For biomass fired boilers, often an ORC is preferred because of the lower operating pressure. The condenser heat can be used in (biomass) drier applications or for district heating

Conclusion

In this paper the Organic Rankine Cycle (ORC) technology for low grade waste heat recovery was described, with an emphasis on the basic thermodynamic processes involved, working fluids with key aspects of their selection and the prime applications of ORC.

The conventional waste heat to power technologies i.e. steam Rankine cycle and Kalina cycle were compared and discussed the limitations associated with their use for low temperature waste heat recovery. The study reveled that at low temperature waste heat the conventional steam rankine cycle becomes less cost effective. Kalina cycle have highest theoretical efficiencies but are highly complex and more expensive to develop.

The working fluid plays a vital role in the ORC cycle. Large number of working fluids were reviewed and studied from the literature. A working fluid must hold enough chemical stability in the desired temperature range apart from having the necessary thermo-physical properties. The fluid selection affects system efficiency, environmental impact, operating conditions, and economic viability. Also the slope of the saturation curve, the specific heat, and the latent heat had a major impact on the system performance of an ORC. The study also reveled that isentropic and dry fluids are preferred in organic Rankine cycles and superheating is necessary for wet fluids in organic Rankine cycle. Considering the potential application of ORC in industrial waste heat recovery, internal combustion engines, gas turbines and renewable energy power plant, it can be concluded that Organic Rankine Cycle seems to be a viable technological option for low grade waste heat recovery.

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