A Review of Organic Rankine, Kalina and Goswami Cycle

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Abstract
In this paper review of three cycles namely Organic Rankine cycle, Kalina cycle and Goswami cycle and various works on them has been presented. This paper deals with the work done by different authors on optimization of the cycles and introduction of new cycles which gives better efficiency. Selection of fluids, three cycles namely Kalina Cycle, Goswami Cycle and Organic Rankine cycle (ORC) have been optimized by different authors using different types of fluids and their reviews are concluded here. Low grade heat topic deals with the electricity generation from low grade heat sources such as solar thermal, geothermal and industrial waste heat using different cycles mainly ORC, Goswami Cycle and Kalina Cycle. In this paper, analysis of different thermodynamic cycle, for combined power plant using low grade heat sources are reviewed. Different thermodynamic cycle, using low grade heat sources for combined power plant are reviewed. Various cycles have been compared so as to find a best cycle to convert various low temperature heat sources into electrical power in various conditions using different methodologies used in research.

Keywords: Organic Rankine, Kalina, Goswami Cycle, Review

1. INTRODUCTION
In today’s world, with the increasing population, the energy demands are rising but the resources (fossil fuels) are limited and depleting drastically. It is only a matter of time we run out of the major fuels namely oil, gas, and coal. Therefore we need to switch to some other source of energy. The other forms of energy available to us are solar, geothermal, wind, etc. Out of these solar and geothermal forms a source of heat, but there is a problem with them that they are low grade source of heat and possess low quality.

Heat is itself a low grade form of energy. But low grade heat implies heat that is extracted from low- and mid- temperature sources that has less exergy density and cannot be converted efficiently to work. Although there is no unified specification on the temperature range of low-grade heat, it is understood that a heat source with temperature below 370°C is considered as a low-grade heat source, because heat is considered not converted efficiently below that temperature using steam Rankine cycle. The main low-grade heat sources are from: Solar thermal, Geothermal, and industrial waste thermal.

These days the focus is majorly on the benefits of capturing and utilising low grade thermal energy which are highly dependent on the qualities and properties of the heat in the waste streams. The temperature of the low grade heat stream is the most important parameter, as the effective use of the residual heat or efficiency of energy recovery from the low grade heat sources will mainly depend on the temperature difference between the source and a suitable sink. The process for converting the energy in a fuel into electric power involves the creation of mechanical work. For successful conversion of heat into mechanical work, thermodynamic cycles are used.
1.1. Rankine cycle
The Rankine cycle is the fundamental operating cycle of all power plants where an operating fluid is continuously evaporated and condensed. The selection of operating fluid depends mainly on the available temperature range. Majorly Water (steam) is used as the working fluid. Fig. 1.1(a) shows the idealized Rankine cycle. Pressure-enthalpy (p-h) and temperature-entropy (T-s) diagrams of this cycle are given in Fig.1.1(b).

Fig.1.1 (a) Rankine cycle configuration [Source: Thermopidia]

Fig.1.1 (b) T-s and p-h diagrams

1.2. Organic Rankine cycle
The organic Rankine cycle (ORC) applies the principle of the steam Rankine cycle, but uses organic working fluids with low boiling points, instead of steam, to recover heat from a lower temperature heat source. Fig.1.2(a) below shows a schematic of an ORC and its process plotted in a T-s diagram in Fig.1.2(b). The cycle consists of an expansion turbine, a condenser, a pump, a boiler, and a super heater (provided that superheat is needed).

Fig.1.2(a)Schematic Diagram of ORC Fig. 1.2 (b)T-s Diagram of ORC [Source: eng.usf.edu]
1.3. Kalina cycle
The Kalina cycle was first developed by Aleksandr Kalina in the late 1970s and early 1980s. Since then, several Kalina cycles have been proposed based on different applications. Kalina cycle uses a working fluid comprised of at least two different components, typically water and ammonia. The ratio between those components varies in different parts of the system to decrease thermodynamic irreversibility and therefore increase the overall thermodynamic efficiency. A basic configuration of the Kalina cycle is shown in Fig.1.3.

![Fig. 1.3. Basic configuration of Kalina cycle](eng.usf.edu)

One drawback of the Kalina cycle is the fact that high vapour fraction is needed in the boiler, however, the heat exchanger surface is easy to dry out at high vapour fractions, resulting in lower overall heat transfer coefficients and a larger heat exchange area. Another drawback relates to the corrosivity of ammonia. Impurities in liquid ammonia such as air or carbon dioxide can cause stress corrosion cracking of mild steel and also ammonia is highly corrosive towards copper and zinc.

1.4. Goswami cycle
Goswami cycle, proposed by Dr. Yogi Goswami (1998) is a novel thermodynamic cycle that uses binary mixture to produce power and refrigeration simultaneously in one loop.

![Fig.1.4. Basic configuration of the combined power and cooling cycle](eng.usf.edu)
This cycle is a combination of Rankine power cycle and an absorption cooling cycle. Its advantages include the production of power and cooling in the same cycle, the design flexibility to produce any combination of power and refrigeration, the efficient conversion of moderate temperature heat sources, and the possibility of improved resource utilization compared to separate power and cooling systems. The binary mixture first used was ammonia-water, and later on new binary fluids were proposed and studied. A configuration of the cycle is shown in Fig.1.4.

2.0. LITERATURE REVIEW
Considering only the low grade heat operating cycles namely Organic Rankine cycle, Kalina cycle and Goswami cycle has been carried out. The following are the areas of sub-division of the whole review.

- **Comparison of different cycles.**
  This topic majorly deals with comparison of different cycles. Comparison of different cycles helps to combat and find an appropriate cycle for conversion.

- **Optimization**
  This topic deals with the various methods that has been done to improve the efficiency of existing cycles either by making changes with previous cycles or by introduction of new cycles

- **Selection of Working fluids**
  The efficiency of non-conventional cycles depends upon selection of fluids to a huge extent. The work done by number of authors on selection of fluid for ORC, Kalina and Goswami cycle is presented.

- **Low-Grade Energy**
  In this topic, developing other thermodynamics cycles to convert the low-grade heat into electrical power is implemented. Organic Rankine cycle, Goswami cycle and Kalina cycle are the major cycles that have been developed for the conversion of low grade of heat into electricity.

2.1. COMPARISON OF DIFFERENT CYCLES
In thermodynamics, the Carnot cycle has been described as being the most efficient thermal cycle possible, wherein there are no heat losses and consisting of four reversible processes, two isothermal and two adiabatic. It has also been described as a cycle of expansion and compression of a reversible heat engine that does work with no loss of heat. Moreover, there are vast amounts of renewable energy sources such as solar, thermal, geothermal, biomass and industrial waste heat. The moderate temperature heat from these sources cannot be converted efficiently to electrical power by conventional power generation methods. Therefore, how to convert these low-grade temperature heat sources into electrical power is of great significance. Therefore, comparison of different cycles helps to combat and find an appropriate cycle for conversion.
Prof. Pall Valdimarsson et al [24] said the Kalina cycle is a power cycle and competes with Rankine, Brayton, Diesel and Otto cycles. He compared it theoretically with other processes for different boundary conditions (in real life energy situations). Also both Y. Chena [12] and Zhang Shengjun [15] presented a comparative study between ORC and transcritical power Cycle. Y. Chena [12] compared the performance of carbon dioxide transcritical power cycle, which operates between subcritical and supercritical state (i.e. under and above critical point respectively) with an ORC (with R123 as a working fluid) in waste heat (low grade heat) recovery. Whereas Zhang Shengjun [15] performed comparison and parametric optimization of subcritical ORC and transcritical power cycle system for low temperature (i.e. 80–100°C) geothermal power generation & concluded that R125 in transcritical power cycle shows excellent economic and environmental performance and can maximize utilization of the geothermal power.

Recently M. Yari et al [50] analysed the performance of trilateral power cycle (TLC) and compared it with ORC and the Kalina cycle, from the viewpoints of thermodynamics and thermo-economics. Whereas Zhi Zhang et al [51] introduced an integrated system of ammonia–water Kalina–Rankine cycle (AWKRC) for power generation and heating & studied the performances of the AWKRC system in different seasons with corresponding cycle loops.

### 2.2 Optimization

Optimization means the process of obtaining a favourable/ desirable condition. In case of thermodynamic cycles optimisation implies obtaining high performance by getting high work output with minimum heat input. This topic deals with optimization of the existing cycles as well as introduction of new cycles.
Donghong Wei et al [6] presented system performance analysis and optimisation using HFC-245fa as the refrigerant. They did optimisation by maximising the usage of exhaust heat and decreasing degree of sub-cooling at condenser. They also said that when the ambient temperature is too high, the system efficiency decreases. The analysis reports are given in Fig.2.1. Whereas Konstantinos Braimakis et al [47] investigates the waste recovery potential of the ORC and some innovations such as the supercritical cycle and the use of binary zeotropic mixtures. They performed simulations for different temperature heat sources and identified optimal operation mode and working fluids.

Unlike these two both Sylvain Quoilin et al [13] did experimentation and used working fluid HCFC-123. The ORC model is built by interconnecting different sub-models: the heat exchanger models, a volumetric pump model and a scroll expander model. This model is finally used to investigate potential improvements of the prototype. Like Sylvain Quoilin et al [13] Vincent Lemort et al [14] also used scroll expander. They used ORC to recover energy from low grade sources. They did experiment and compared result with analysed results and then worked on improving the design of expander.

Ricardo Vasquez Padilla et al [40] proposed a combined Rankine Goswami cycle (RGC) and conducted a thermodynamic analysis. The Goswami cycle, used as a bottoming cycle, uses ammonia–water mixture as the working fluid and produces power and refrigeration while power is the primary goal. Similarly Gokmen Demirkaya et al [36] presented optimization of a combined power/cooling cycle as shown in Fig.2.2, also known as the Goswami cycle. In this multi-objective genetic algorithms (GAs) are used for Pareto approach optimization of the thermodynamic cycle. The important thermodynamic objectives that have been considered in this work are namely work output, cooling capacity, effective first law, and exergy efficiencies. Also Feng Xua et al [33] proposed a cycle which combines a Rankine cycle and an absorption refrigeration cycle. They have used ammonia–vapour mixture for the cycle. They did parametric analysis.
Sanjay Vijayaraghavan [37] did investigation on rankine cycle. They develop several expressions for the first law, second law and exergy efficiency definitions for the combined cycle based on existing definitions in the literature. They have used the generalised reduced gradient (GRG) method to perform the optimization whereas Huijuan Chen [35] presents a review of the organic Rankine cycle and supercritical Rankine cycle (shown in Fig. 2.4) for the conversion of low-grade heat into electrical power and selecting 35 working fluids. The paper discusses the types of working fluids, influence of latent heat, density and specific heat, and the effectiveness of superheating. They used analysis method. SirkoOgriseck [18] presents the integration of the Kalina cycle process in a combined heat and power plant for improvement of efficiency for using low grade energy and waste energy recovery. Umberto Desideri et al [25] did investigation on exploiting geothermal energy by using closed Rankine and Kalina cycles. In this paper three configurations of the Rankine cycle are examined and compared to conventional single and dual flash steam power plants. Yiji Lu et al [52] paper proposed an optimised resorption cogeneration with a stabilisation unit and effective mass and heat recovery to further improve the performance of the original resorption cogeneration first proposed by Liwei Wang et al.
Fig. 2.4. Process of a CO2 supercritical Rankine cycle on T-s diagram (a-b-c-d-e-f-g) [Source: Huijuan Chen [35]]

The following authors optimized the Kalina cycle using exergy analysis. G. Wall et al [26] applied energy utilisation method (A graphic method to describe the exergy losses in industrial processes, i.e. for improving the exergy use) and optimized the cycle accordingly (Fig. 2.5 shows the energy utilisation diagram obtained.), while P.K. Nag et al [19] investigated to reduce the thermal irreversibility of Kalina cycle (One parameter i.e. mixture concentration at turbine inlet appears to have an optimum value with respect to second law efficiency). Effects of other parameters on the exergy loss of each component have been studied.

Fig. 2.5. Energy Utilization Diagram for the Kalina cycle [Source: G.Wall et al [26]]

Nasruddin et al [31] did simulation to obtain the data of efficiency, energy and exergy that could be generated from the heat source. Both G. Tamma et al [42] and AfifAkelHasan et al
[43] worked on similar type of project. They investigated a combined thermal power and cooling cycle (i.e. Goswami Cycle) but G. Tamma et al [42] investigated a combined thermal power and cooling cycle both theoretically and experimentally whereas AfifAkelHasan et al [43] did research and performed second law efficiency and irreversibility experiment and optimised the cycles accordingly.

A.L. Kalina et al [30] selected a cycle among several Kalina cycle variations that is particularly well suited as a bottoming cycle for utility combined cycle applications. Using an ammonia/water mixture as the working fluid and a condensing system based on absorption refrigeration principles the Kalina bottoming cycle outperforms a triple pressure steam cycle by 16 percent.

H.D. MadhawaHettiarachchi et al [2] presented a cost-effective optimum design criterion for Organic Rankine power cycles utilizing low-temperature geothermal heat sources. The optimization method converges to a unique solution for specific values of evaporation and condensation temperatures and geothermal and cooling water velocities. The choice of working fluid also affects the objective function (Ratio of total area of heat exchanger to net power output) Huijuan Chen et al [41] proposed a supercritical Rankine cycle using zeotropic mixture working fluids for the conversion of low-grade heat into power and proposed that it creates a potential for reducing the irreversibilities and improving the system efficiency than conventional Rankine cycle.

2.3 SELECTION OF FLUIDS

Power generation has recently become popular. However, conventional electricity is not always economically feasible due to its capital cost and source of high priced fuels. Under this circumstance, use of non-conventional cycles becomes an important aspect to work upon to meet energy requirements. The efficiency of non-conventional cycles depends upon selection of fluids to a huge extent. The work done by number of authors on selection of fluid for ORC, Kalina and Goswami cycle is concluded.

Feng Xua et al [38] did research on the thermodynamic properties of ammonia-water mixture for Goswami cycle by using Gibbs free energies and empirical equations and dew point temperature to calculate phase equilibrium. The methodology adopted by them is experimental and analytical. V. Maizza [11] investigated analytically the thermodynamic and physical properties of some unconventional fluids for use in ORC supplied by waste energy sources. Bo-Tau Liu et al [1] investigated analytically the performance of ORC subjected to the influence of various working fluids on the thermal efficiency and on the total heat-recovery efficiency. Tzu-Chen Hung [4] researched theoretically waste heat recovery of ORC using different dry fluids such as benzene (C6H6), toluene (C7H8), p-Xylene (C8H10), R-113 and R-123. From the conclusions, p-Xylene shows the highest efficiency while benzene shows the lowest and also shows that the irreversibility depends on the type of heat source. Fig .2.6. shows a typical T-s process diagram for the investigated ORC.
Two of the equation used by them is given below.

\[
\begin{align*}
\dot{i} &= T_0 \frac{d s_{\text{tot}}}{dt} = \dot{m}T_0 \left[ \sum_{\text{exit}} s - \sum_{\text{inlet}} s + \frac{d s_{\text{sys}}}{dt} + \sum_k q_k \right] \\
\dot{Q}_b &= \dot{m}(h_3 - h_2) \\
\dot{W}_i &= \dot{m}(h_3 - h_{4a})
\end{align*}
\]

The total efficiency is

\[
\eta_{\text{th}} = \frac{|\dot{W}_i| - |\dot{W}_p|}{\dot{Q}_b} = 1 - \frac{h_{4a} - h_1}{h_3 - h_2}.
\]

In 2004, Huijuan Chen et al [42] analysed the supercritical Rankine cycle which uses a zeotropic mixture as working fluid for the conversion of low-grade heat, whereas UlliDrescher et al [3] paper presents an theoretical analysis of fluid selection for the ORC in biomass power and heat plants with the help of a software and it was found that the highest efficiencies are found within the family of alkyl benzenes.

Yiping Dai et al [5] did a comparative study analytically of the effects of the thermodynamic parameters on the ORC for each working fluid. They optimized exergy efficiency as an objective function by means of the genetic algorithm whereas George Papadakis et al [8] proposed an innovative theoretical approach for fluid selection of Solar ORC. Thermodynamic and environmental properties of few fluids have been comparatively assessed. A. Schustera et al [10] presented an energetic and economic investigation of ORC applications by method of simulation. The favourable characteristics of ORC make them suitable for being integrated in applications like solar desalination with reverse osmosis system, waste heat recovery from biogas digestion plants. E.H. Wanga [16] presented the performance of different working fluids.
operating in specific regions using a thermodynamic model. Nine different pure Organic working fluids were selected according to their physical and chemical properties. He used method of simulation. Nishith B. Desai et al [17] presented that an ORC offers advantages over conventional Rankine cycle with water as the working medium, as ORC generates shaft work from low to medium temperature heat sources with higher thermodynamic efficiency. The dry and the isentropic fluids are most preferred working fluid for the ORC. A. Benato et al [45] investigated the critical dynamic events causing thermo-chemical decomposition of the working fluid in ORC power systems. Charles H. Marston [20] did parametric analysis of Kalina Cycle. Investigation on water ammonia mixture was done using the enthalpy-temperature curve of a hot gas heat source. Computer models have been used to optimize a simplified form of the cycle. He used simulation method whereas Xinxin Zhang [23] proposed and analysed research on the Kalina cycle by analytical means. The three systems used by them is shown in Fig. 2.7.

E.D. Rogdakis [34] proposed a high efficiency NH3–H2O absorption power cycle. The new cycle employed a mixture of H2O and NH3 as the working fluid and used an absorption process similar to that of absorption refrigerators. The new cycle was 20% more efficient than that of the Rankine cycle if the boiling temperature is high, while for low boiling temperatures, the superiority of the proposed cycle was much more pronounced. Their methodology was analytical. Mounir B. Ibrahim [28] proposed Kalina cycle application for power generation, investigated a multi-component (NH3/H2O) Kalina cycle that utilized the exhaust from a gas turbine. The figure below shows diagram of components used in this work. The multi-component working fluid cycle proved 10–20% more efficient than a Rankine cycle with the same boundary conditions.
Table 2.1. Fluids and cycles used by different authors to do their research.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Fluid used</th>
<th>Cycle</th>
</tr>
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<tbody>
<tr>
<td>Feng Xua et al [38]</td>
<td>Ammonia-water mixture</td>
<td>Goswami cycle</td>
</tr>
<tr>
<td>Bo-Tau Liu et al [1]</td>
<td>water, ammonia, and ethanol</td>
<td>ORC</td>
</tr>
<tr>
<td>Tzu-Chen Hung [4]</td>
<td>Benzene (C6H6), Toluene (C7H8), p-Xylene (C8H10), R-113 and R-123</td>
<td>ORC</td>
</tr>
<tr>
<td>Huijuan Chen et al [42]</td>
<td>Zeotropic Mixture</td>
<td>Supercritical Rankine cycle</td>
</tr>
<tr>
<td>George Papadakis et al [8]</td>
<td>R134a, R152a, R600a, R600 and R290</td>
<td>ORC</td>
</tr>
<tr>
<td>A. Schustera et al [10]</td>
<td>R11,R113,R114,Toulene and fluorinol</td>
<td>ORC</td>
</tr>
<tr>
<td>E.H. Wanga [16]</td>
<td>R11, R141b, R113 and R123</td>
<td>ORC</td>
</tr>
<tr>
<td>Nishith B. Desai et al [17]</td>
<td>16 different fluids</td>
<td>ORC</td>
</tr>
<tr>
<td>Benato et al [45]</td>
<td>Ammonia-water mixture</td>
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<td>Mounir B. Ibrahim [28]</td>
<td>Ammonia-water mixture</td>
<td>Kalina cycle</td>
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2.4 LOW GRADE HEAT

In the majority of energy applications, energy is required in multiple forms. These energy forms typically include some combination of heating, ventilation, mechanical energy and electric power. Often these forms of energy are produced by a heat engine. A heat engine can never have perfect efficiency, according to the second law of thermodynamics; therefore a heat engine will always produce a surplus of low-temperature heat. This is commonly known as low grade heat. Renewable energy sources, such as solar thermal, geothermal and vast amounts of industrial waste heat or low grade heat are potentially promising energy sources capable, in part, to meet the world electricity demand. The temperature of the low grade heat stream is the most important parameter, as the effective use of the residual heat or the efficiency of energy recovery from the low grade heat sources will mainly depend on the temperature difference between the source and a suitable sink. In this topic, development of other thermodynamics cycles to convert the low-grade heat into electrical power is implemented. Organic Rankine
cycle, Goswami cycle and Kalina cycle are the major cycles that have been developed for the conversion of low grade of heat into electricity.

Table 2.2. Temperature range of different types of low grade sources

<table>
<thead>
<tr>
<th>Low Grade Heat Sources</th>
<th>Temperature Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar thermal</td>
<td>70°C-800°C</td>
</tr>
<tr>
<td>Geothermal</td>
<td>149°C-370°C</td>
</tr>
<tr>
<td>Industrial waste thermal</td>
<td>80°C-400°C</td>
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</table>

J. Larjola et al [9] deals with ORC-design experimentally and used a high-speed oil free turbo generator-feed pump. The use of high speed turbo generator made the ORC small, simple, hermetic and reduced significantly the maintenance expenses. D. Yogi Goswami et al [39] experimentally worked on a combined thermal power and cooling cycle (i.e. Goswami cycle) which was ideally suited for solar thermal power (low grade energy) using low cost concentrating collectors. H.D. MadhawaHettiarachchi et al [22] used the Kalina cycle system 11 (KCS-11) whereas OguzArslan [27] and [29] did research using the Kalina cycle system-34 (KCS-34). The former used experimentally the exergetic and life cycle cost concepts whereas the latter used an artificial neural network (ANN) (a new tool used to make a decision for the optimum working conditions of the processes within the expertise).

Ricardo Vasquez Padilla et al [40] said that improving the efficiency of a combined RGC plays a fundamental role in reducing the cost of solar power plants whereas P.A. Lolos et al [21] used a Kalina cycle with low-temperature heat sources to produce power. S. C. Kaushik et al [32] used a computer simulation of a Kalina cycle coupled with a coal fired steam power plant with the aim of examining the possibility of exploiting low-temperature heat of exhaust gases for conversion into electricity.

Recently Masatake Sato et al [52] used a binary power generation technology using low temperature heat source. The program included technical development associated with power grid coordination and technical development for determining the effects of the hot springs. Duen Sheng Lee et al [47] proposed an innovative approach for collecting the solar thermal energy from the concept of solar chimneys (Fig-2) for electricity generation via ORCs. Francesco Calise et al [49] did work on a dynamic simulation model of a novel prototype of a 6 KW solar power plant over a span of year and presented it for different seasons.

3.0 CONCLUSION:

In this review paper, various cycles have been compared so as to find a best cycle to convert various low temperature heat sources into electrical power in various conditions using different methodologies used in research. This paper also deals with the optimisation of various cycles by changing various parameters and finding the best possible set of parameters under which it must operate; also some new cycles have been introduced resulting in a more efficient power conversion. In the area selection of fluids, 16 papers have been reviewed and varieties of fluids...
are used to optimise the three cycles (Kalina cycle, Goswami cycle and ORC) by varying number of parameters. In the topic of low grade heat, analysis of different thermodynamic cycle has been done and thereby implemented to produce work (electricity) from low grade heat source.

4.0 REFERENCES


