Kalina Cycle (waste heat recovery applications) – A Review

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Abstract

In this era of heavy energy demands, a moderate amount of energy from iron-steel industries, cement industries etc. remains untouched and is splurged in atmosphere. Thus it is necessary to exploit these low temperature heat sources. Kalina cycle was introduced to overcome the inefficiencies of the conventional rankine cycle by effectively utilizing the splurged energy from these industries; on the other hand this energy might be frittered away. This paper covers the review of kalina cycle. The kalina cycle normally utilizes an ammonia-water binary mixture as a working fluid and operates at a temperature lower than 200°C. 20-40% of thermal efficiency enhancement occurs over the rankine cycle based waste heat power plants. The reader needs a basic knowledge of rankine cycle for better understanding.

Keywords: *Heat Recovery, Kalina Cycle, Rankine Cycle*

1. Introduction

With the continuous increase in population of the world, the energy demands are also on a peak rise with continuous depletion of the non renewable energy sources. Thus it has become a necessity to utilize these sources with the most efficient way possible without affecting the environment (global warming). Therefore it is a challenge for humanity to efficiently utilize the energy we have at our disposal. The iron, steel, cement and some other industries have a lot of frittered heat energy at low temperatures which can be used to supplement the energy shortage in the current scenario. The extraction of useful work from low-grade heat requires innovative technology.

The first candidate for utilization of this low temperature heat energy is Rankine Cycle, since Rankine Cycle has highest efficiency among the conventional power conversion cycle [3]. But for low temperature application Rankine cycle has very low efficiency. In order to extract power from this low temperature waste heat other cycles were proposed namely Organic Rankine Cycle (ORC) and the Kalina Cycle. For Organic Rankine Cycle, selection of fluid and the design of turbine is an important task for the ORC [4].

In the Kalina Cycle, a binary fluid is used to extract useful work from the heat source. Typical low-grade heat sources are those associated with waste heat from industrial processes such as steelmaking and cement manufacturing that are energy intensive and where waste heat recovery can make a significant impact on energy-efficiency.

Kalina Cycles have been designed to extract thermal energy efficiently from sources such as splurged heat and geothermal wells. One consequence is that National Energy Development Organization (NEDO) in Japan has identified the Kalina Cycle as one of the most suitable technologies for further improving the energy efficiency of the Japanese steel industry [1].

Kalina Cycle systems are now in operation in waste heat recovery and geothermal power applications worldwide. As demand for higher efficiency in energy use intensifies to combat the deleterious effects of greenhouse gases it is anticipated that demand for this type of technology will increase drastically.

The maximum temperature for the cycle is varied between range 100-200°C and the sink temperature for the cycle is assumed as 27°C at the exit of the condenser. The model selected for this analysis is KCS-11 owing to its suitably for low temperature application.

2. The Kalina Cycle: Technical overview

The Kalina Cycle was developed by Dr. Alexander Kalina and is recognized as one of the most thermodynamically efficient power cycle technologies in the world [5]. This system uses a mixture of 70% ammonia-30% water as the working fluid, rather than a pure substance such as water, which is commonly used in the Rankine Cycle.

The five processes in the thermodynamic cycle include:

1. Compression in the pump
2. Heat addition in the boiler
3. Expansion in the turbine
4. Recuperation in the recuperators
5. Heat rejection in a condenser
6.

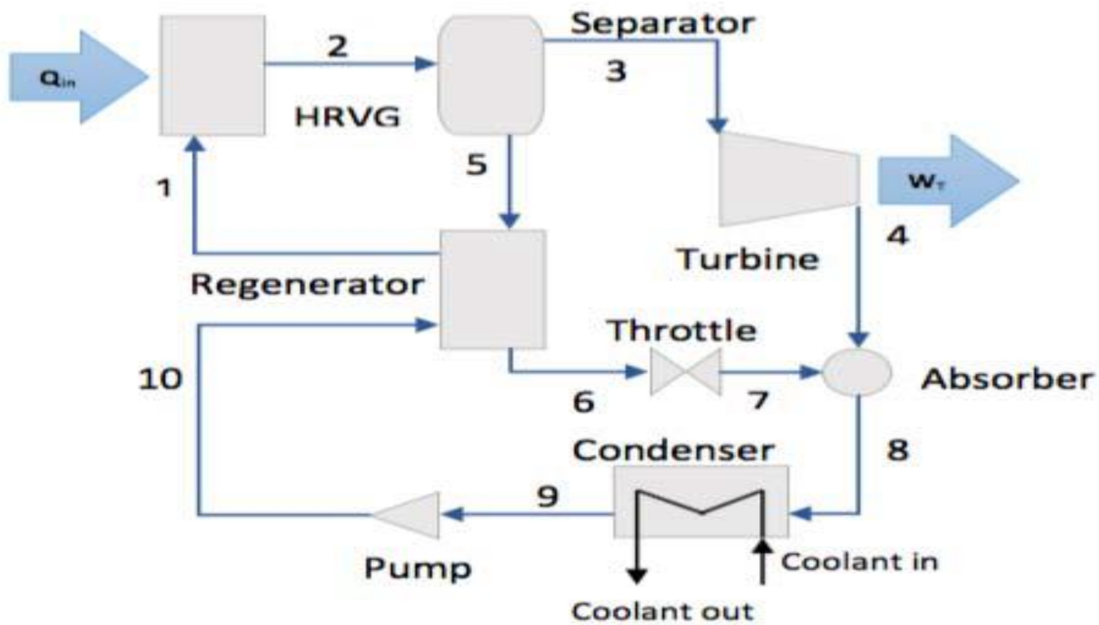

Fig.1 Kalina cycle system 11(KCS 11) [7]

The added degree of freedom of a variable mixture working fluid, which can be heated at one composition and condensed at a different composition, leads to the DCSS which serves the functions of distillation, recuperation and heat rejection in the condenser[1].

A binary fluid allows the composition of the working fluid to be varied through the use of distillation, providing a richer concentration through the Heat Recovery Vapor Generator (HRVG) and leaner composition in the low-pressure condenser. As the molecular weight of ammonia is close to that of water, a standard back-pressure turbine can be used [1].

The distinguishing feature of the Kalina Cycle is that the working fluid is composed of at least two different components with different boiling points. Since a two-component mixture will boil over a range of temperatures and the ratio of the two components can be varied in different parts of the system, the overall effect is to increase the thermodynamic efficiency of the process [1].

The performance data from the early demonstrator units provided the information necessary to validate the thermodynamic modelling of Dr. Alexander Kalina.

According to Henry A. MLcak, PE, [6] The modifications that complete the transformation of the cycle from Rankine to Kalina consist of proprietary system designs that specifically exploit the virtues of the ammonia-water working fluid. These special designs, either applied individually or integrated together in a number of different combinations, comprise a family of unique Kalina cycle systems. This is somewhat analogous to the Rankine cycle which, in fact, has many design options such as reheat, regenerative heating, supercritical pressure, dual pressure, etc. all of which can be applied in a number of different combinations in a particular plant. “Kalina Cycle System 6” (KCS6) is applicable to gas turbine based combined cycles and “Kalina Cycle System 11” (KCSI 1) is applicable to low temperature geothermal plants. There are a host of other systems which are applicable for other fuels or heat sources such as municipal waste, waste gas stream in processing plants, solar and even nuclear.

Generally, there are different types of Kalina cycle families, which are known by their unique names. For example, KCS5 is particularly applicable to direct fired plants. KCS6 is applicable to gas turbine based on combined cycles and Kalina cycle system 11 (KCS11) and KCS34 are designed for exploiting low temperature heat sources. For this work, KCS11 was selected as it is the most applicable for low-grade waste heat sources at temperatures below 200^0C [9]. The choice of the mixtures is based on their environmental favorable characteristics such as zero ozone depletion, low GWP and non-toxicity. According to Ahmed Elsayed, Mebrahtu Embaye, Raya AL-Dadah, Saad Mahmoud and Ahmed Rezk, 19 working pairs were investigated for replacing the water–ammonia working pair in the KCS11 as shown in Table 1. These mixtures are classified in four groups based on the component with low boiling point, namely, CO2, R32, propane and propylene [8].

Proposed binary mixtures						
CO_2 mixtures	R32 mixtures		Propane mixtures		Propylene mixtures	
CO_2−DME	R32−DME		R290−R601		R1270−R601	
CO_2−R1270	R32−R600		R290−R600		R1270−R600	
CO_2−R290	R32−R600a		R290−R600a		R1270−R600a	
CO_2−R601a	R32−R601a		R290−R601a		R1270−R601a	
CO_2−R601						
CO_2−R600a						
CO_2−R600						
Refrigerant	NPB (°C)	GWP	Hfg (kJ/kg)	Flammability	Toxicity	ASHRAE safety [14]
Ammonia (R717)	−33.34	<1	1370	Yes	Yes	B2
Water (R718)	100	0	2256	No	No	A1
Carbon Dioxide (R744)	−78.46	1	232	No	No	A1
Difluoromethane (R32)	−51.65	650	382	Yes	No	A2
Propylene (R1270)	−47.62	3	438	Yes	No	A3
Propane (R290)	−42.11	3	425	Yes	No	A3
Butane (R600)	−0.49	3	386	Yes	No	A3
Iso-butane (R600a)	−11.749	3	365	Yes	No	A3
Pentane (R601)	36.06	3	357	Yes	No	A3
Iso-pentane (R601a)	27.5	3	343	Yes	No	A3
Dimethylether (DME)	−24.782	2	465	Yes	No	A3

Table 1: Investigated Working Pairs for the KCS 11 [8]

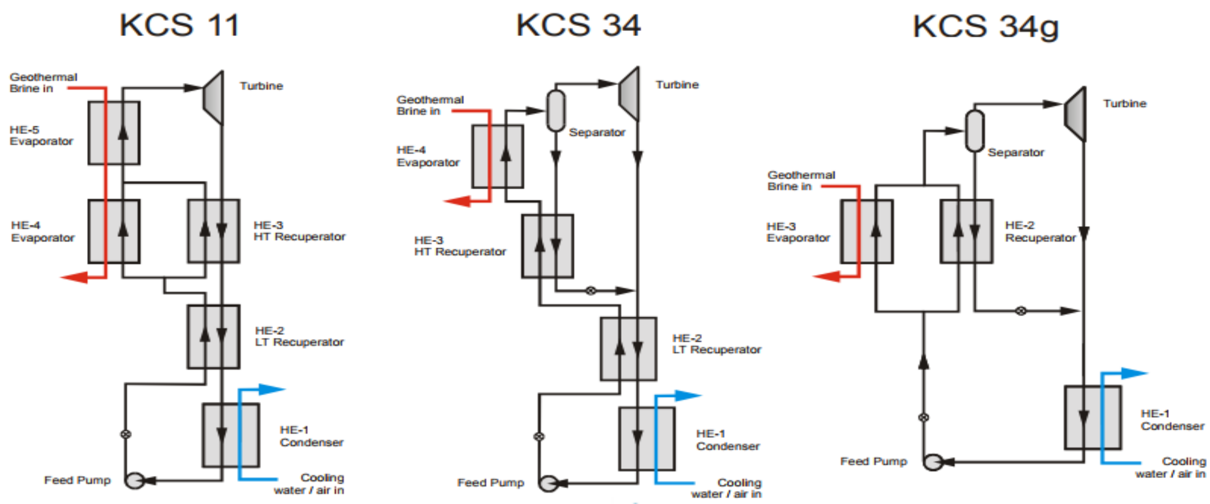

Fig.2 Kalina Cycle Systems for Low Temperature Applications [2]

2.1 Benefits of using Ammonia-Water Working Fluid

- Less hazardous and flammable than organic cycle working fluids
- Environmentally benign, one of the most common compounds found in nature
- Ammonia vents easily, and is self-alarming
- Ammonia is the 6th largest chemical produced in the U.S.
- Proven safety record in ammonia synthesis, power plants and refrigeration plants
- Higher efficiencies conserve fuel and water [1]

2.2 Benefits of ammonia-water mixture:

- NH_3 & H_2O have similar molecular weights.
- Mixture is a new fluid with different properties.
- Excellent heat transfer coefficients [2].
- Fluid circulated is equivalent to 1/3 – 1/2 of ORC plant.
- Ammonia-Water fluid will not freeze.
- Pressure stays above atmospheric
- Ammonia is environment friendly.

2.3 Safety aspects of Ammonia

- Common, widely used chemical

- Mature safety standards
- Little fire and explosion hazard
- Smell helps maintain tight plant
- Wide margin between level of smell & hazard
- Lighter than air (easy to vent off)
- Rendered harmless with water [2].

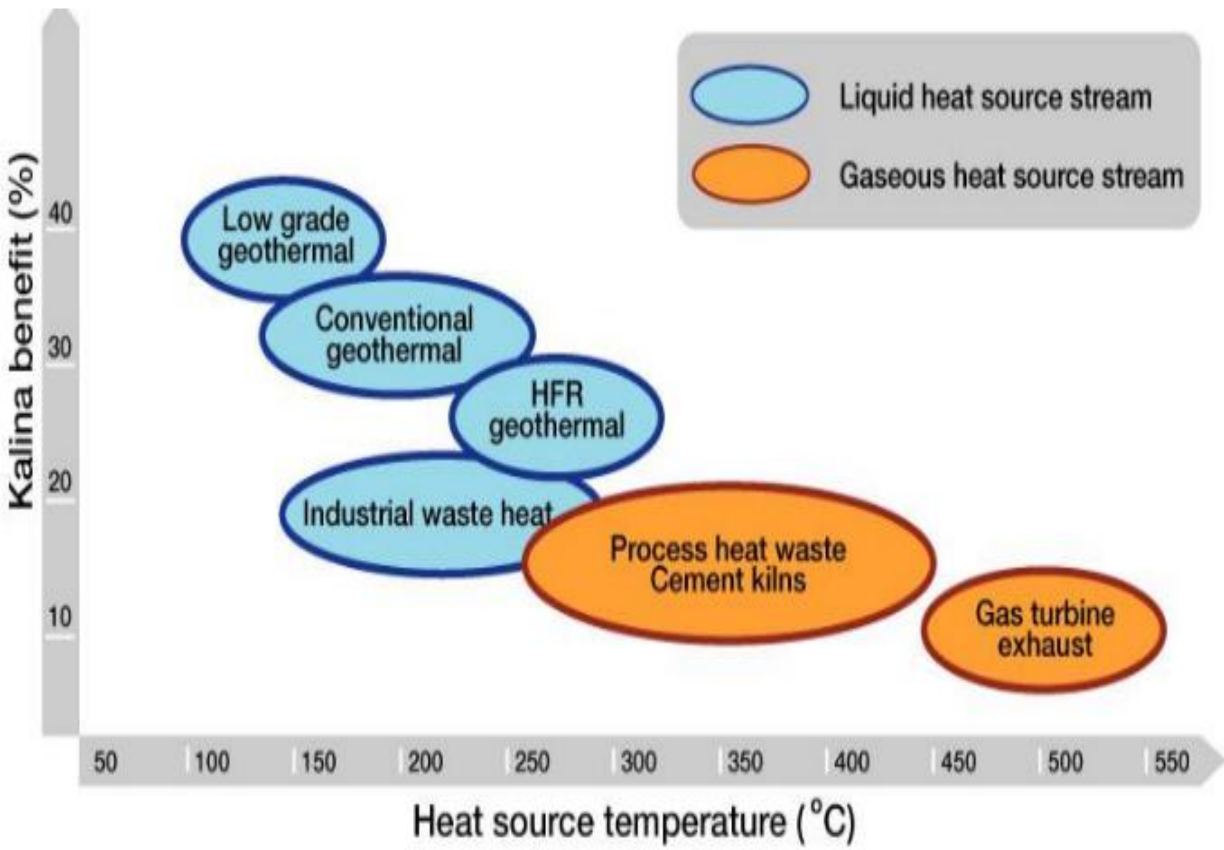

Fig.3 Kalina Cycle Technology Performance Advantage

3. Operational experience

3.1 Canoga Park:

- Configuration : Combined Cycle
- Construction site : California
- Electrical output : 6.5 MW [2]

Canoga Park was the first large scale power plant to be commissioned using the Kalina Cycle and was built with US Department of Energy (DoE) support to demonstrate the technology. In the initial configuration the energy source was waste heat from a nuclear steam generator test plant. When this became unavailable, exhaust heat from a gas turbine was used as an alternative. The turbine throttle fluid conditions were 515°C and pressure of 110bara and the generating capacity of the bottoming cycle was about 3MW with surplus power being sold to the local utility. As a combined cycle power plant the Canoga Park demonstration was rated at about 6.5 MW [1].

3.2 Kashima Works (Sumitomo Metals):

- Configuration : Waste Heat
- Construction site : Tokyo
- Electrical output : 3.5 MW [2]

The Kalina Cycle Power Plant installed in the Kashima Works of Sumitomo steel was the first commercial application of the Kalina Cycle and has generated 3.5MW of electrical power. In this case waste heat from the steelmaking process was the energy source and the turbine throttle parameters were 236°C and 31bara [1].

3.3 Fuji Oil:

- Configuration : Waste Heat
- Construction site : Chiba, Japan
- Electrical output : 4.0 MW
- Heat Source : Condensing OH Vapors at 116 °C [2]

Commissioned in 2005, the Fuji Oil 4MW waste heat plant uses heat from two sources, a lightweight hydrocarbon vapour and low-pressure steam as part of a waste heat-to-electricity project within the Fuji Oil refinery in Chiba, Japan. The project was the first successful integration of a waste heat generation technology with the Eureka process for hydrocarbon processing. The temperature of the waste heat is 118°C and the plant has operated continuously since start-up with an availability of nearly 100% between scheduled outages. It was estimated that taken together the units at the Kashima Works and at Fuji Oil have contributed 60GWh annually which otherwise would have had to have been sourced from the grid [1].

3.4 Fukuoka:

Construction of this unit, which was also seen as a demonstrator, was subsidised by the Japanese Ministry for International Trade and Industry (MITI) and was the first waste incinerator to use the Kalina Cycle. As a result it achieved 20% greater efficiency than other similar plants of this type. The unit benefitted from the integrated incineration technology, which had been developed by Japan's Ebara Corporation. The 4.5MW plant burned 200t/day of municipal waste, producing a flue gas at approximately 900°C for waste heat recovery. The turbine throttle conditions were 293°C and 43bara [1].

3.5 Husavik:

The Husavik Geothermal Plant in Iceland began operation in 2000 using a brine flow at 121°C to provide 80% of the power requirement of this small town. The working fluid was 82% ammonia-water at a pressure of 34bara. In the evaporator the ammonia-water was partially vapourised to 75% vapour and 25% liquid and the vapour component was separated from the liquid component in the separator. Even with the brine temperature which was 3°C lower than the design temperature (which is highly significant given the thermodynamics of the system) the plant still developed ~1.7MW of power, successfully completing the plant performance testing requirement.While there were several reasons for the relatively poor reliability there were two main factors:

- Control of water quality was poor and did not comply with the operational guidelines provided by the OEM,
- The unit was not acid-cleaned prior to entering service as recommended by the supplier. This means that detritus from the manufacturing and fabrication processes was not removed [1].

4. Material selection

In addition to providing validation of the underlying thermodynamic principles, the successful implementation of the Kalina Cycle technology with a variety of heat sources also confirmed the long-term performance of the materials used for critical components in these applications.

Turbine materials used in Kalina Cycle systems are for the most part those that would be used in typical axial flow steam turbines or radial flow turboexpanders operating at the temperatures and pressures characteristic of the power plant application [1].

5. Control of water quality

In the power plant it is essential to ensure good water quality for reliable operation of a Kalina Cycle system. Water treatment is important in preventing corrosion, scaling and contamination of the working fluid and the water quality that is required depends largely on the temperature of operation. This in turn influences the reactivity of the chemical and degradation processes.

In Kalina Cycle systems the fluid temperature is considerably lower so that control of water quality is more straightforward. The key processes to maintain good water quality are; softening to reduce sulphate, chloride and nitride ions; deaeration to reduce the amount of gas; and good pH control. However the pH is controlled by the ammonia content of the fluid, which usually gives a pH of about 10. Demineralisation is carried out using synthetic anion and cation exchange resins [1].

6. Environmental Aspects of Ammonia & Kalina Cycle

- Bio-degradable – considered part of nature
- Does not contribute to global warming (GWP), smog , depletion of ozone layer (ODP)
- Higher efficiency conserves fossil fuels, water (for condenser) [1]

7. Conclusions

In the last decade or so several Kalina Cycle power plants have been commissioned to generate power from different types of low-grade heat source including industrial waste heat, waste incineration, and geothermal springs. Further opportunities to apply the Kalina Cycle in recovery of useful energy from industrial waste heat are being pursued in the iron-steel, cement industries. The overall performance has been highly satisfactory and units have performed reliably and met or exceeded performance targets. The level of efficiency achieved with the Kalina Cycle cannot be achieved with any other system for extracting useful energy from low-grade heat. Experience to date shows that, in common with any other power plant cycle, good control of water chemistry is an essential requirement if reliable operation and high availability is to be achieved. The high pH values consistent with Kalina Cycle environments should limit the risk of general corrosion.

References

[1]. http://www.globalcement.com/magazine/articles/721-kalina-cycle-power-systems-in-waste-heat-recovery-applications.

[2]. Recurrent Engineering LLC, www.globalgeothermal.com

[3]. Rachel Anne Victor, Jin-Kuk Kim, Robin Smith; Composition optimization of working fluids for Organic Rankine Cycles and Kalina cycles, Energy 55 (2013) 114-126.

[4]. Kalina AI. Combined-cycle system with novel bottoming cycle. ASME Journal of Engineering for Gas Turbine Power 1984; 106(4):737-42.

[5]. Kalina Cycle – Wikipedia, https://en.wikipedia.org/wiki/Kalina_cycle

[6]. Mlcak, H. A. "An Introduction to the Kalina Cycle," ASME Joint Power Generation Conference, Houston, Texas, 1996, Book No. H01077-1996.

[7]. International journal of Science and Research, ISSN(online): 2319-7064, Indea Copernicus Value (2013):6.14, impact factor (2014): 5.611 'Thermodynamic Analysis of Kalina Cycle' MogheesAhmad1, M. N. Karimi

[8]. Thermodynamic performance of Kalina cycle system 11 (KCS11): feasibility of using alternative zeotropic mixtures Ahmed Elsayed, Mebrahtu Embaye, Raya AL-Dadah*, Saad Mahmoud and Ahmed Rezk

[9]. Galanis N, Cayer E, Roy P, et al. Electricity generation from low temperature sources. J Appl Fluid Mech 2009;2:55–67.

[10]. Arash Nemati, Hossein Nami, Faramarz Ranjbar, Mortaza Yari, A comparative thermodynamic analysis of ORC and Kalina cycles for waste heat recovery: A case study for CGAM cogeneration system, Case Studies in Thermal Engineering 9 (2017) 1–13

[11]. Omendra Kumar Singh , S.C. Kaushik, Thermoeconomic evaluation and optimization of a Brayton–Rankine–Kalina combined triple power cycle, Energy Conversion and Management 71 (2013) 32–42.

[12]. Milad Ashouri, Amin Mohammadi Khoshkar Vandani, Mehdi Mehrpooya , Mohammad H. Ahmadi , Amir Abdollahpour, Techno-economic assessment of a Kalina cycle driven by a parabolic Trough solar collector, Energy Conversion and Management 105 (2015) 1328–1339.

[13]. Gaosheng Wei, Jie Meng, Xiaoze Du, Yongping Yang, Performance analysis on a hot dry rock geothermal resource power generation system based on Kalina cycle, Energy Procedia 75 (2015) 937 – 945.

[14]. Chen Yue , Dong Han, Wenhao Pu, Weifeng He, Comparative analysis of a bottoming transcritical ORC and a Kalina cycle for engine exhaust heat recovery, Energy Conversion and Management 89 (2015) 764–774