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Review of the Modified Kalina Cycle for Cogeneration Systems (MKCS)

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Abstract

The increasing demand for electricity and cooling, resulting from accelerating urban growth, growing economies and the integration of technology into daily life, leads to continued research and study of theories related to the optimal exploitation of energy sources, including those with low temperatures, for a sustainable environment free of CO₂. The authors regard the Kalina cycle, which uses ammonia and water as its working fluid, as the most efficient system in this field. This manuscript presents a comprehensive review of the published literature on the modified Kalina cycle, a cogeneration system that simultaneously produces electricity and cooling. It also provides an overview of the original Kalina cycle, other types of Kalina cycles, and their various applications. We also discuss the properties of the binary solution, which the cycle uses as a working fluid. Discuss the boiling and freezing points to maintain the fluidity of the working fluid through the cooling process. Additionally, we discuss the corrosion-related aspects of applying the Kalina cycle, specifically the reaction between ammonia and metal components, as well as strategies for mitigating this corrosion, as previously mentioned in the literature.

Keywords: Modified Kalina cycle; Generation power and cooling; Boiling and freezing points; Low-temperature source; Ammonia-water fluids.

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1. Introduction

Providing electricity and cooling is critical, particularly during summer, due to high energy consumption. Studies emphasise the considerable impact of cooling requirements on electricity consumption, with operating cooling representing a substantial portion of electricity use during hot seasons. Therefore, planning for cogeneration power and cooling is a better way to solve the energy deficiency, especially when providing cooling without affecting or reducing electricity production. The original and modified Kalina cycle system (MKCS) has emerged as a promising cogeneration system, enhancing energy efficiency, envi-

ronmental sustainability, and economic viability in various applications. The system utilises various energy sources, including low-grade heat sources (373 K – 473 K), such as wind, geothermal, solar and waste heat, to generate power, cooling and heating. Research has demonstrated that the Kalina cycle (KC) excels in operating with low-heat sources, making it a perfect choice for obtaining energy from these sources [1]. In Kumar et al. [2], the working solution of the Kalina cycle is a non-zeotropic mixture of NH₃-H₂O. These binary mixture properties improve the thermal match between the heating source, which has a low temperature, and the working fluid, leading to more efficient low-heat source utilisation. Optimising the operational

Nomenclature

- \dot{E} – exergy rate, kW
- h – specific enthalpy, kJ kg⁻¹
- \dot{m} – mass flow rate, kg·s⁻¹
- P – pressure, kPa
- Q – heat rejected, kW
- Q_r – cooling capacity, kW
- s – specific entropy, kJ kg⁻¹ K
- \dot{W} – rate of work, kW
- W – output power, kW
- x – dryness fraction

Greek symbols

- η_{th} – thermal efficiency, %
- η_{exe} – exergy efficiency, %
- $(\eta_{pump})_{isent}$ – isentropic efficiency of the pump
- $(\eta)_{isent}$ – isentropic efficiency of the turbine

Subscripts and Superscripts

- con* – condenser
- d* – destruction
- exe* – exergy
- exh* – exhaust
- gen* – generator
- isent* – isentropic
- max* – maximum
- min* – minimum
- sep* – separator
- tot* – total
- t* – turbine
- th* – thermal
- thr* – throttle valve

Abbreviations and Acronyms

- ACH – absorption chiller
- AHP – absorption heat pump
- ARC – absorption refrigeration cycle
- AWKRC – ammonia-water Kalina Rankine cycle
- BTC – bottom cycle
- CCP – collected cooling and power
- DF – dryness fraction
- DNI – direct normal irradiance
- DC – direct current
- ERC – ejector refrigeration cycle
- GEN – generator
- HGH – high-grade heat cycle
- HRVG – heat recovery vapour generator
- HE – heat exchanger
- KC – Kalina cycle
- KCS – Kalina cycle system
- KFC – Kalina flash cycle
- KLPPCS – Kalina lithium power-cooling cycle system
- LGH – low-grade heat cycle
- LiBr – lithium bromide
- LNG – liquefied natural gas
- MKCS – modified Kalina cycle system
- NH₃-H₂O – ammonia-water
- ORC – organic Rankine cycle
- PPR-KC – parallel cogeneration of power and refrigeration–Kalina cycle
- PTSC – parabolic through solar collector
- SGS – separate generation system
- TIT – turbine inlet temperature
- TEG – thermoelectric generator
- VAS – vapour absorption system

conditions and the composition of the working fluid can enhance the performance of the Kalina cycle. Esmailzadeh et al. [3] added a Kalina cycle with a polymer membrane fuel cell and a vacuum heat tube collector, improving the energy efficiency and exergy efficiency by 13.12% point and 10.35% point, respectively.

2. Glance of Kalina cycle

The rapid expansion of cities and the rapid rise in global population have posed significant challenges to the global energy system. To address these challenges, it is crucial to prioritise waste heat recovery technology and reduce greenhouse gas emissions and fossil fuel consumption for a sustainable future [4]. The Rankine cycle received the first nomination for the use of this low-temperature heat energy, but its efficiency in this area is very low. The second nominee was the organic Rankine cycle (ORC), in which the selection of working fluid and the turbine design (or expander in ORC) are important problems. Dr. Alexander Kalina (1983) first presented the Kalina cycle as in Fig. 1, using a non-azeotropic pair mixture (NH₃-H₂O) working fluid, and compared the three cycles in power generation and for cogeneration application. The Kalina cycle exhibits greater efficiency when operating at maximum fluid pressure due to the

fluid mixture's variable boiling temperature [5,6]. The available literature has broadly discussed different Kalina cycles and their applications, as shown in Table 1 [7,8].

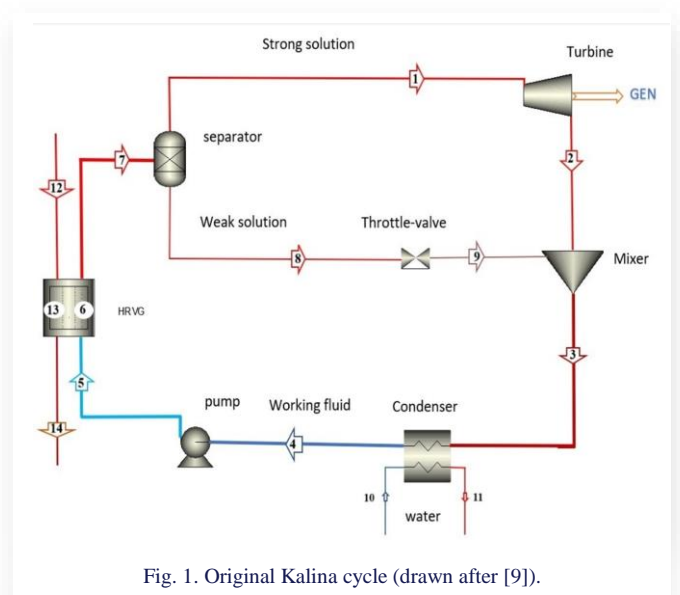


Fig. 1. Original Kalina cycle (drawn after [9]).

Table 1. Different types of Kalina cycle [7,8].

System	Application	Net output power ratio (KC/RC)	Cycle efficiency ratio (KC/RC)	State of development
KCS0	Used for a one heat exchanger plant below 1 MW	-	-	Design completed
KCS1	Bottoming cycle small plant about 8 MW	$(49.5/46.0) = 1.07^a$	$(32.0/26.6) = 1.2$	Design completed
KCS2	Low-temperature geothermal plant for heat source under 623 K	$(17.6/10.3) = 1.71^{b,c}$	$(20.5/13.1) = 1.56^a$	Design completed
KCS3	High-temperature geothermal and industrial waste			Under development
KCS4	Cogeneration			Planned
KCS5	Direct-fired for coal and other solid fuels	$(40.9/34.6) = 1.18^d$	$(48.6/42.2) = 1.15$	Design completed
KCS5n	High-temperature gas-cooled nuclear reactor	$(46.0/36.0) = 1.28$	$(46.0/36.0) = 1.28$	Design completed
KCS6	Bottoming for a utility combined cycle above 20 MW	$(56.4/51.0) = 1.11^a$	$(37.8/28.7) = 1.32$	Design completed
KCS7	Direct-fired, split cycle	$(42.4/34.6) = 1.22^d$	$(50.0/42.2) = 1.19$	Under development
KCS8	Bottoming cycle, split cycle	$(56.67/51.0) = 1.11^a$	$(39.0/28.7) = 1.36$	Under development
KCS9	Retrofit subsystem for the existing plant	$(40.4/34.6) = 1.17^d$	N/A	Under development
KCS11	Bagasse-fired cogeneration plant of the sugar industry, for heat source temperature range 394 – 477 K			Under development
KCS12	Low-temperature geothermal	$(16.5/10.3) = 1.6^{b,c}$	$(19.2/13.1) = 1.47$	Design completed
KCS34	Cascade utilisation of low-grade waste heat, combined power system	N/A	N/A	Design completed
KCS34g	Low temperature small size plant	N/A	N/A	Design completed
KCSCS	Biomass chip plants	N/A	N/A	Design completed
KCS17	Double-flash geothermal system (hybrid cycle)	N/A	N/A	Design completed

^aFor the entire combined cycle.

^bCompared to the Heber plant binary cycle

^cIncludes losses due to injection pumps and other auxiliaries.

^dIncludes losses from fuel handling and plant auxiliaries.

3. Modified Kalina cycle for cogeneration

The Kalina cycle is a thermodynamic cycle that is useful for the generation of electricity and cooling at the same time. As a cogenerator, the primary aim is to produce additional energy. You can achieve this by either obtaining additional electricity from the same waste heat input source, which you can then use to operate a separate cooling cycle (traditional compression cooling), or using waste heat from the power generation of the Kalina cycle to provide heating or cooling. The type of collected cooling and power (CCP) is effective for large cooling needs in hot places, industrial facilities that generate a significant amount of waste heat, or for a plant that produces both power and cooling [10]. By integrating the Kalina cycle system (KCS) and the system of vapour absorption (VAS), you can seamlessly combine power with other applications, such as water and hydrogen production. This approach enables you to select double, triple or even more services in a single step [11]. Seçkin [12] studied a combined power and cooling system, as shown in Fig. 2. The system comprises the Kalina cycle (KC), which uses aqua-ammonia working fluid for power generation, and the ejector refrigeration cycle (ERC), which uses R-134a working fluid for cooling. The results indicate an enhancement in both thermal and exergy efficiencies with an increase in maximum pressure. However, an increase in the turbine entrance temperature adversely affects only the exergy efficiencies. Shankar et al. [13] looked into a cogeneration cycle that uses the Kalina cycle to make electricity and cool the air, as seen in Fig. 3. The condenser, situated after the turbine, transforms the ammonia vapour into a liquid state, which then expands through the sub-cooler with a constant heat content to generate refrigeration. The results show that when the source temperature was 383 K for a 0.25 of the ammonia mass fraction, the coefficient of performance (COP) was 0.16.

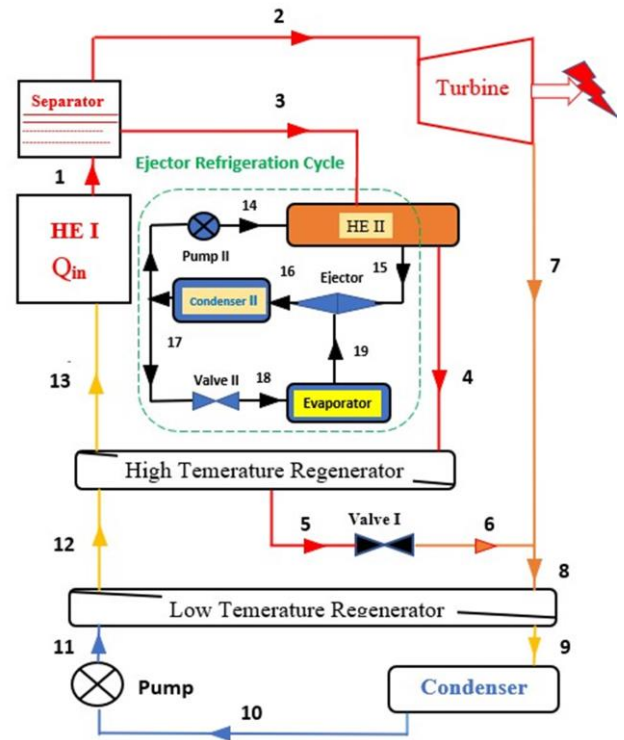


Fig. 2. Combined cycle with a Kalina sub-cycle with ejector refrigeration cycle ERC (drawn after [12]).

Karaali [14] studied a cogeneration aqua-ammonia cycle (Kalina cycle) to generate power and refrigeration. A turbine expands a strong solution and generates power. The ammonia vapour that leaves the turbine is used to produce cooling. The results show that raising the turbine entrance pressure reduced energy, exergy efficiencies and output power. Abam et al. [15]

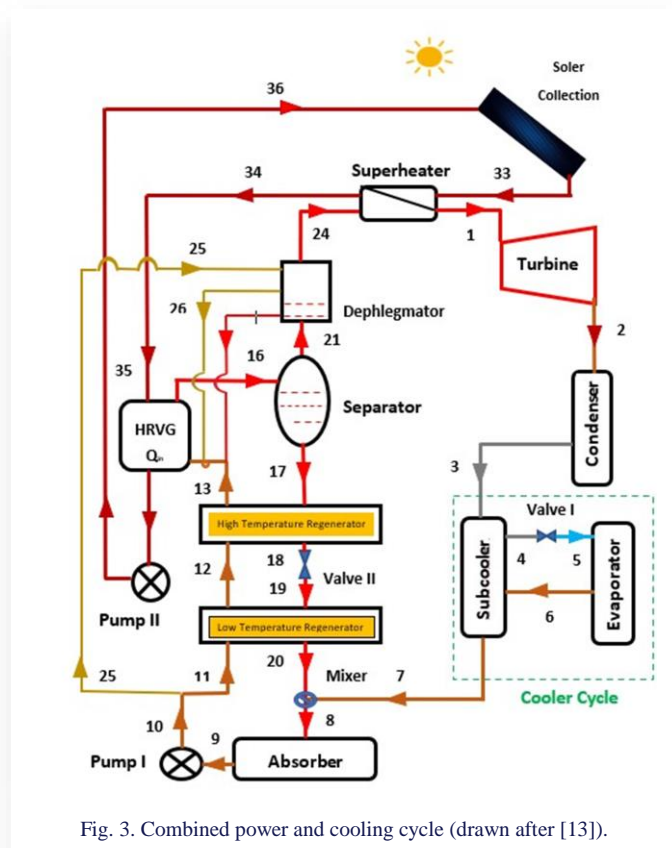


Fig. 3. Combined power and cooling cycle (drawn after [13]).

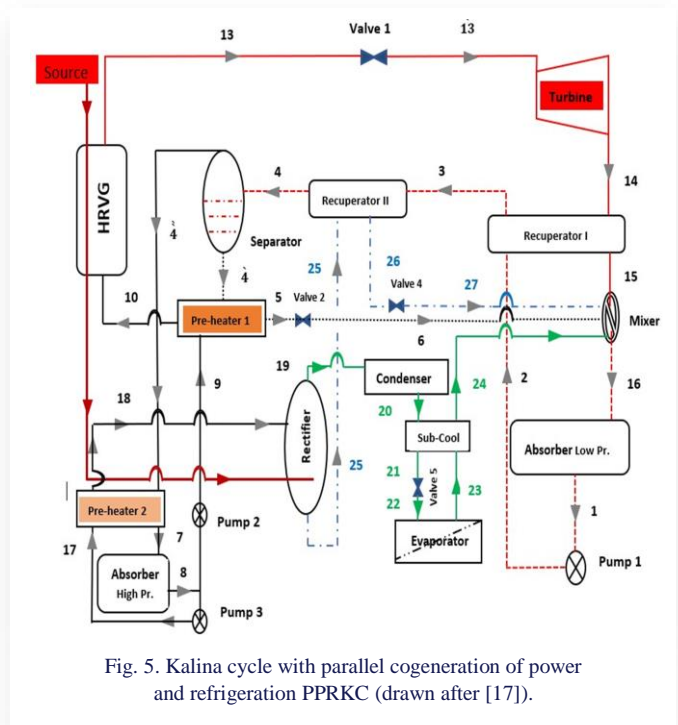


Fig. 5. Kalina cycle with parallel cogeneration of power and refrigeration PPRKC (drawn after [17]).

The cooling circuit is integrated with the power circuit, ensuring simultaneous efficiency. The proposed cycle significantly improves heat-waste recovery efficiency to 27.2%, compared to the reference cycle KCS1-2 of approximately 22.62% efficiency. Hua et al. [18] provided a new cogeneration cycle, including a modified Kalina cycle (ammonia-water) to generate power and an absorption chiller for air conditioning with low-grade temperature sources. The results indicate that energy and exergy efficiencies increase by 3.19%-points and 3.64%-points, respectively, as compared to the reference Kalina power cycle. Cao et al. [19] worked on a proposed combined system including the absorption refrigeration cycle and a Kalina cycle, as illustrated in Fig. 6. Next, they compared it to a system that generates electricity under identical conditions, and powers a DC

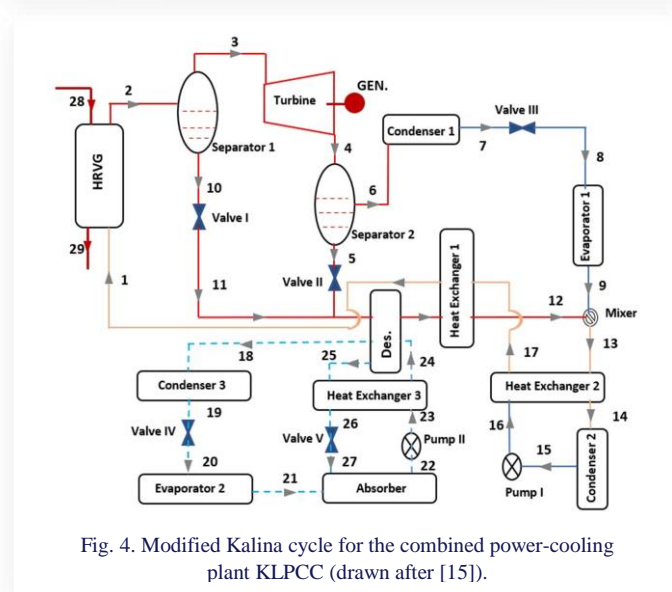


Fig. 4. Modified Kalina cycle for the combined power-cooling plant KLPC (drawn after [15]).

looked into a cogeneration system called the Kalina lithium power-cooling cycles system (KLPCCS), as seen in Fig. 4.

This system has a top cycle (TPC) that uses aqua-ammonia as a working fluid to make electricity and a bottom cycle (BTC) that uses the vapour absorption cooling system (VAB) with LiBr as the working fluid. Kim [16] studied a combined system of Kalina cycles (KCS11) to produce power, using NH₃/H₂O as the working fluid and an absorption chiller for cooling. The results indicated that as the source temperature rises, the power increases, but the cooling capacity reduces. Zhang et al. [17] studied a Kalina cycle (KCS1-2) in parallel cogeneration of power and refrigeration (PPR-KC), which generates both electricity and cooling, as illustrated in Fig. 5.

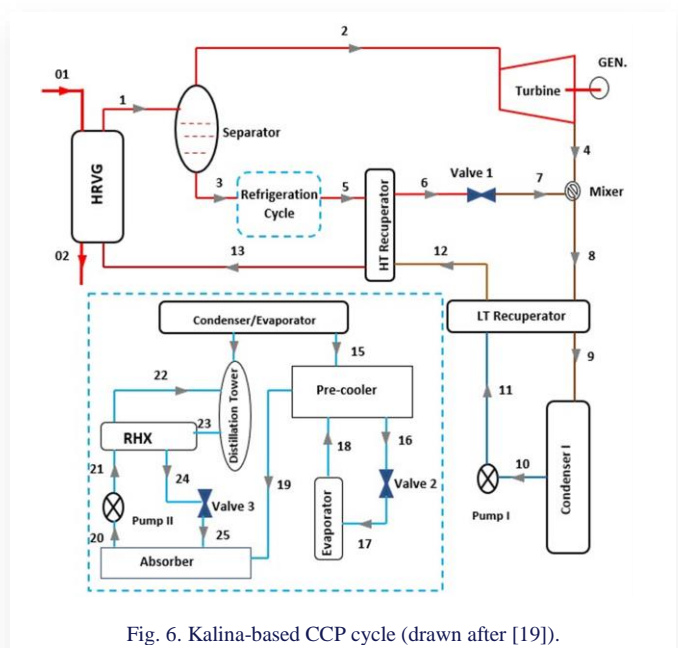


Fig. 6. Kalina-based CCP cycle (drawn after [19]).

cooling unit. The results indicated that the proposed cycle outperformed the separate generation system (SGS). Furthermore, the separate generation system consumed an additional 12.54 kW of energy compared to the suggested cycle, specifically for operating the cooling unit's compressor. Wang et al. [20] suggested a system that integrates a Kalina cycle for electricity generation with an ammonia-water absorption refrigeration cycle (AWARC). This system extracts purer ammonia vapour from the exhaust of the ammonia-water turbine using a second separator. The purer vapour is then condensed and throttled before entering the evaporator to produce cooling output. The outcomes reveal that an increased first separator pressure increases the system thermal and exergy efficiencies. The system provides electricity and cooling output simultaneously, minimising redundancy in certain components across both cycles, which leads to reduced costs and a smaller size. Seçkin [21] looked into a system that integrates both the Kalina cycle (KC) for power generation, which utilises ammonia and water as working fluids, and the ejector refrigeration cycle (ERC), which employs refrigerants such as R290, R134a, and R152a. ERC is installed at the weak solution stream of KC. The results indicated that R290 achieved the highest thermal efficiency, while R134a attained the highest exergy efficiency, respectively. Seçkin [22] proposed combining the Kalina cycle (using ammonia solution) with the ejector refrigeration cycle (ERC) using R134a as a coolant to produce electricity and cooling. The process of burning biomass (organic waste) drives this combined cycle. The results indicate that an increase in the evaporator temperature of ERC leads to an increase in overall thermal efficiency, gross power output, and cooling capacity. Additionally,

the energy efficiency of the proposed cycle is dependent on the Kalina cycle efficiency. Zhang et al. [23] utilised a system that operates with ammonia-water, known as the Kalina-Rankine cycle (AWKRC); this system employs a valve to switch between the Rankine and Kalina cycles. In the winter, the Rankine cycle functions as a cogeneration plant that provides power and heating water, while during the rest of the year, the Kalina cycle operates solely to produce electricity. As illustrated in Fig. 7, with the Kalina cycle, an increase in ammonia concentration slightly enhances the heating recovery efficiency.

A summary of the conducted study on the application of the modified Kalina cycle for combined power, cooling and heating is presented in Table 2.

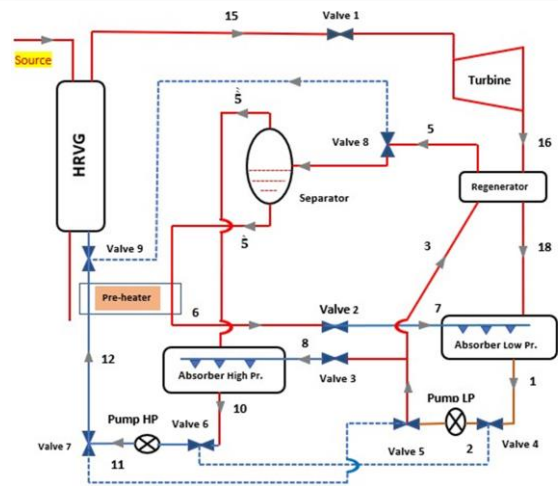


Fig. 7. Kalina cycle in non-heating application (drawn after [23]).

Table 2. Modified Kalina cycles for cogeneration.

Articles	Type of cycle	Cycle specifications	η_{th} , %	η_{exe} , %	Remarks
Wang et al. [10]	KC + ARC	TIT:473 K, P_{max} = 5 MPa	24.62	11.52	Both cycles working with the ammonia-water mixture.
Abam et al. [11]	KC+ VAS	TIT= 1350 K	53.48	50.05	The power output and flow rate of hydrogen are 86.320 MW and 0.1524 kg/h, respectively.
Seçkin [12]	KC+ ERC	P_{max} = 2.5 MPa	10.8	45	The refrigeration capacity of ERC remained constant at about 44.65 kW with ammonia-water as the working fluid.
		P_{max} = 4 MPa	11.88	76.5	
		TIT= 388 K	11.5	75	
		TIT= 413 K	19.55	44.25	
Shankar et al. [13]	MKCS	TIT= 383 K, x =0.25	3.6	-	At TIT=398 K, the highest power output of 1.8 kW and 2.2 TR of cooling.
Karaali [14]	MKCS	P_{max} = 4 MPa, x =0.54	23	68	The mechanical power and cooler heat energy were 197 kW and 26 kW, respectively.
Abam et al. [15]	KC+ VAS	TIT= 453 K P_{max} = 2 MPa	8.15	16.97	A reach of about 1077 kW of refrigeration was produced, and power output was 291 kW.
Kim [16]	KC+ARC	TIT= 393 K P_{max} = 3.6 MPa Output power 16.9 kW	60	-	The maximum cooling capacity is 64.7 kW at TIT= 393 K and pressure of 1600 kPa.
Zhang et al. [17]	PPR-KC KCS1-2	TIT= 673 K x =0.5	27.96 27.19	-	The system recorded approximately 699.2 kW in net output power, whereas the cooling output system recorded 299.9 kW.
Hua et al. [18]	Chilling cogeneration	P_{max} = 2.74 MPa TIT= 468 K	16.4	48.3	At a chilling fraction of about 5%, specific cooling capacity is 119.53 kJ/kg, and specific output power is 139.1 kJ/kg
Cao et al. [19]	KC+ ARC SGS	TIT= 413 K P_{max} = 4 MPa	-	25.76 23.44	The combined system recorded approximately 89.59 kW, whereas SGS recorded 77.81 kW in net output power.
Wang et al. [20]	KC+ AWARC	TIT= 453 K P_{max} = 2 MPa	13.72	5.40	A reach of about 75.12 kW of refrigeration was produced, and power output was 37.63 kW.
Seçkin [21]	KC+ ERC	R290 as a working fluid	16.7	26	At 415 kPa, the maximum cooling capacity is approximately 120 kW when using R290, while the net output power is around 95 kW with R134
		R134a as a working fluid	15.5	30	
		R152a as a working fluid	15	28	
Seçkin [22]	KC+ ERC	P_{max} = 3.25 MPa x =0.7	1.2	-	With an evaporator temperature of 283 K in ERC, the cooling capacity and net output power are 53 kW and 95 kW, respectively.
Zhang et al. [23]	KC-system RC-system	TIT=553 K P_{max} = 6 MPa	20.85 17.09	-	With a heating recovery efficiency of 55.3% to generate heating water in the winter season by RC.

4. Adjusted Kalina cycles for Integration with other systems and applications

One of the greatest operant exploits of energy is cogeneration. But that's not all that's needed. Other aspects need work. The available literature has broadly discussed the modified Kalina cycles and their applications in this scope; we mention them as examples, not as exclusives.

4.1. Cycles integrated with solar heat and geothermal energy

The Kalina cycle effectively utilises low- and medium-temperature heat sources and can be integrated with solar heat and geothermal energy to enhance power generation efficiency and sustainability, resulting in higher efficiency and lower emissions

than traditional cycles. Khanmohammad et al. [24] utilised the waste heat from a solar collector (PTSC) to drive a Kalina cycle, generating the power needed to operate reverse osmosis desalination (RO) to produce drinking water, which is connected to a unit of a thermoelectric generator (TEG) to cogenerate electricity. The results show that increasing either the direct normal irradiance ($750\text{--}1000\text{ W/m}^2$) or the pressure of the turbine inlet, both the gross power output and desalinated water output will increase. Qu et al. [25] suggested a system that uses concentrating photovoltaics and the Kalina cycle, equipped with an absorption chiller cycle; this absorption chiller cycle can recover waste heat from photovoltaic cells to cool the working fluid of the Kalina cycle at the turbine's exit. As illustrated in Fig. 8, the findings suggest that the proposed cycle improves the efficiency of heat loss recovery from the photovoltaic cell compared to the Kalina cycle, which does not utilise a chiller.

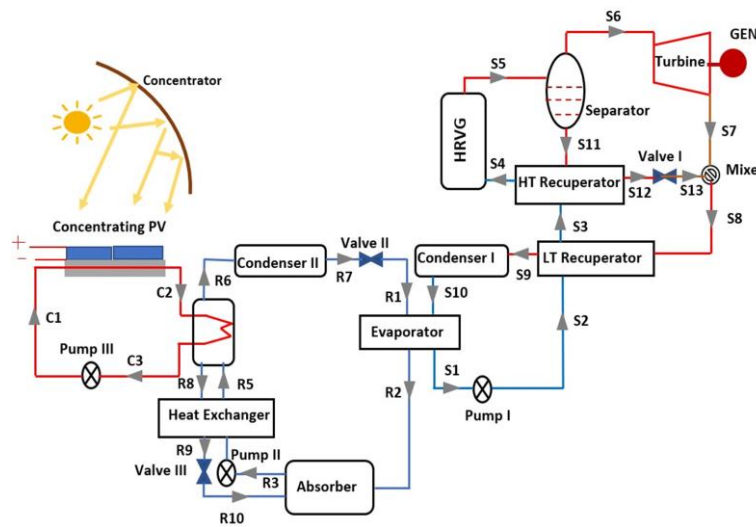


Fig. 8. Concentrating photovoltaic/thermal and Kalina cycle combined system (drawn after [25]).

Lei et al. [26] proposed to utilise the modified Kalina cycle (MKC) for recovering energy from geothermal well water and enhancing the net output power. Taking the geothermal parameters of the Husavik Power Plant in Iceland, where the geothermal well temperature is approximately 395 K and the well water

temperature is around 353 K, the results indicated that the gross power extracted by MKC was enhanced compared to that of the reference KC.

A summary of studies that focus on the integration of KCS with solar heat and geothermal energy is presented in Table 3.

Table 3. Cycle integrated with solar heat and geothermal energy.

Articles	Type of heat source and connected cycle	η_{th} , %	η_{exe} , %	Remarks
Khanmohammadi et al. [24]	PTSC with KCS	24.3	—	The system can generate a gross power output of 372.1 kW and a drinking water output of 48.09 m ³ /h as DNI increases to 1000 W/m ² .
Qu et al. [25]	Photovoltaic cells: - with absorption - without absorption	24 4.2	41	Able to exploit a waste heat temperature range (333 – 343 K) Increase the Kalina cycle energy efficiency by 2 – 3%.
Lei et al. [26]	Geothermal well water: - with MKCS, - with KCS	13.43 9.42	—	The gross power of MKC and KC is approximately 2329 kW, 2108 kW and 9.4 kW, respectively.

4.2. Contribution to internal combustion engines

Kalina cycle's integration with internal combustion engines (ICE) can enhance energy efficiency and reduce environmental impact by recovering waste heat from exhaust gases from ICEs.

Studies of Gao and Chen [27] focused on integrating a Kalina cycle as a subsystem with an internal combustion engine (ICE) to utilise exhaust gases for energy production. The outcomes indicate that the increase in energy efficiency exceeds 10% across all operating loads of ICE while also contributing to a reduction

in greenhouse gas emissions. Larsen et al. [28] suggested a unique type of Kalina split-cycle that utilises hot flue gases from large marine diesel engines as a low heat source. In this innovative cycle, the concentrations of the binary solution can be varied during the HRVG process to better match the temperatures

of the heat source and binary solution. Results show that the suggested cycle process can improve thermal efficiency when using rehear, as compared to a traditional cycle. Table 4 summarises the most important findings related to the contribution of KCS in internal combustion engines.

Table 4. Contribution of KCS to internal combustion engines.

Articles	Condition specifications	η_{th} , %	η_{exe} , %	Remarks
Gao & Chen [27]	ICE operates at full load	46.94	74	The energy and exergy efficiencies of KC exceed those reported in other articles for all ICE loads.
Larsen et al. [28]	Kalina split-cycle Traditional cycle	23.2 20.8	-	When reheating in both cycles.

4.3. Contribution to enhancing the power production

By utilising a binary mixture as a working fluid, the Kalina cycle enhances efficiency compared to conventional cycles and significantly boosts power production. Akimoto et al. [29] investigated a combination of Kalina cycles and absorption heat pumps to produce power in multiple stages, utilising the Kalina cycle to produce power. When the heat rejected from the first cycle is insufficient to drive another Kalina cycle (KC), use an absorption heat pump (AHP) to increase the heat rejected. This enables the system to reproduce the power from a second Kalina cycle, and so on, for the entire chain of Kalina cycles, while also utilising an absorption heat pump to handle multiple electric heat energies. The result is an 81% increase in net power compared to the traditional Kalina cycle.

Zhang and Li [30] suggested a dual modification for the three Kalina cycles KCS 11, 34 and 34g by substituting the throttle valve with a single-screw expander (SSE). SSE is located between the absorber and the regenerator in the I-recom-

position cycle. The II-recomposition cycle places SSE between the regenerator and the separator. The results show enhancements in the energy efficiency, net power and exergy efficiency of two recomposition cycles compared to their reference KCS. The II-recomposition cycle performs better than the I-recomposition cycle. Nassir and Shahad [31] suggested two modifications to the original Kalina cycle (KC). As shown in Fig. 9, the first adjustment (MKCS1) consists of adding a heat exchanger (HE1) before the throttle valve, while the second adjustment (MKCS2) consists of adding a heat exchanger (HE2) after the turbine. The Kalina cycle uses aqua-ammonia as a working fluid. The results demonstrate an enhancement in the maximum efficiencies for both adjustments, MKCS1 and MKCS2, when compared to the original reference cycle.

Kim et al. [32] looked into a Kalina flash cycle (KFC) that incorporates an additional flash vessel in the stream of weak ammonia solution from the original cycle. This vessel generates both a strong and weak solution; the strong solution powers a second turbine, increasing the cycle's power output (Fig. 10).

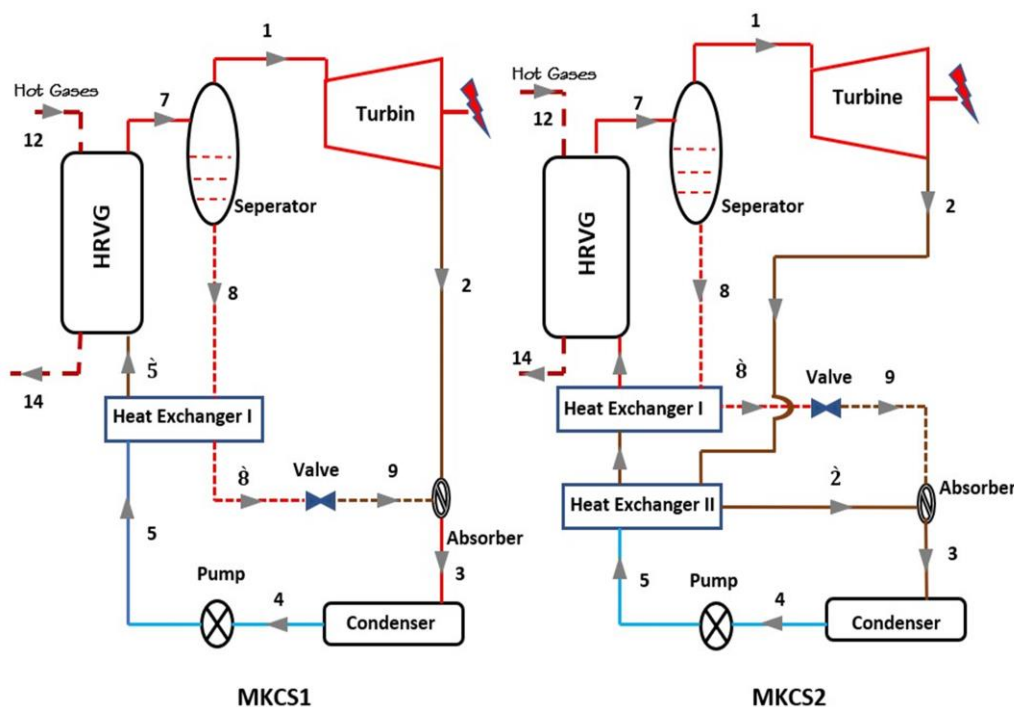
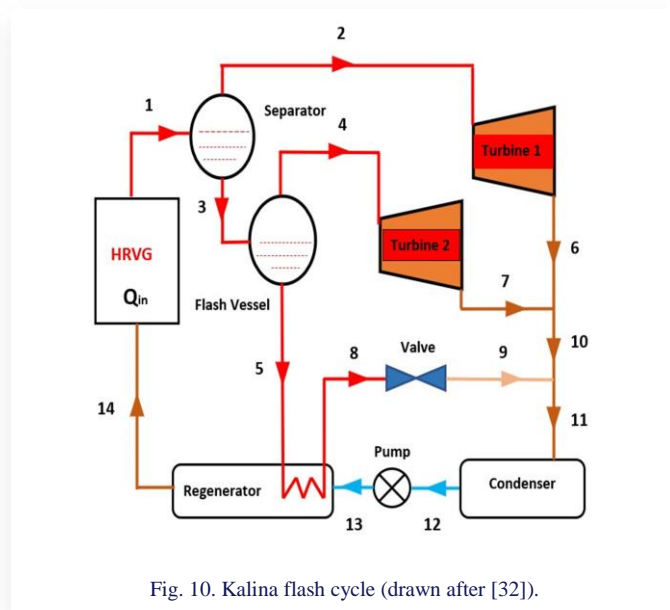


Fig. 9. Two modifications of Kalina cycle system (drawn after [31]).



The outcomes indicate that the net power in both cycles (KFC and KC) increases as the ammonia concentration (x) decreases from 0.8 to 0.4; however, the higher power output from KC remains lower than that of KFC under the same conditions. He et al. [33] studied two modified versions of Kalina cycle 11

(KCS11) with a replacement for the throttling valve by an expander in the ammonia-weak stream loop of the Kalina cycle: (I-modified cycle) the expander is located between the regenerator and the absorber; (II-modified cycle) the expander is located between the separator and the regenerator. The outcomes indicated the II-modified cycle has a better thermodynamic impact than the I-modified cycle and the KCS 11, and the best performance at an ammonia concentration of approximately 0.875. Li et al. [34] studied an ejector Kalina cycle (EKalina) that uses an ejector instead of a throttle valve and absorber in the Kalina cycle (KCS 11). This adjustment decreases the expander output pressure, leading to an increase in the working pressure difference and, consequently, the cycle's power output. The outcomes indicate that the E Kalina cycle exhibits a higher net power output and thermal efficiency compared to the original Kalina cycle when the ammonia concentration is 0.55 and the source heat temperature is 383 K. Dubey and Sharma [35] worked on a review of several Kalina cycle adjustments, such as using an ejector, a distillation column, a split unit, sliding condensation pressure, double pressure, and composition-adjustable. These modifications have several advantages for Kalina power systems, such as improved power, enhanced performance and lower losses. Table 5 summarises the key findings regarding the contribution of KCS to enhancing the power production application.

Table 5. Contribution of KCS to enhance the power production.

Articles	Type of cycle	η_{th} , %	η_{exe} , %	Remarks
Akimoto et al. [29]	KC	2.2	8.9	KC+AHP+KC achieved greater economic efficiency above a source temperature of 353 K.
	KC+AHP	3	11.5	
	KC+AHP+KC	3	11.5	
Zhang & Li [30]	II-KCS 34	11.44	56.59	Also, at an ammonia concentration exceeding 0.75 and a maximum pressure of 3 MPa, the highest recorded net power was 5.42 kW with KCS34.
	II- KCS 11	11.14	55.4	
	II-KCS 34g	10.85	53.7	
Nassir & Shahad [31]	KC	8.64	34.21	Operating at $P_{max} = 3500$ kPa, $P_{min} = 300$ kPa and $x = 0.85$.
	MKCS1	12.7	51.92	
	MKCS2	18.85	75.34	
Kim et al. [32]	KC	11.4	41	The highest net power of KFC for $P_{max} = 2.4$ MPa and $x = 0.40$ is approx. 5.05 kW, which is greater than that of KC at $P_{max} = 4$ MPa and $x = 0.8$.
	KFC	11.6	41.5	
He et al. [33]	KCS11	10.23	50.61	The highest net power of cycles is approximately 4.83 kW, 4.83 kW and 4.96 kW, respectively, at 3 MPa.
	I-modified cycle	10.24	50.65	
	II-modified cycle	10.51	52	
Li et al. [34]	KCS11	8.16	-	The highest net power of ejector Kalina cycle is approximately 13.11 kW greater than 12.48 kW of KCS11 at the same operating conditions.
	Ejector Kalina cycle	8.36	-	

4.4. Kalina cycle integrated with traditional cycles

The incorporation of the Kalina cycle with conventional power cycles, such as the Rankine cycle, the Organic Rankine cycle, and other combined cycles, provides significant advantages across a variety of applications. Liu et al. [36] use a combined system that incorporates an absorption chiller with a lithium bromide-water mixture ACH(LiBr-H₂O), utilising the heat rejected by the Kalina cycle (KCS-34) from the ammonia solution before the pump's entrance, which also aids in cooling the ammonia solution. As shown in Fig. 11, the outcomes indicate that the net power output is rising with the suggested cycle and higher ammonia concentrations. Ayou and Evely [37] studied a system that combines cold (heat), electricity and liquefied natural gas using a Kalina cycle (KC-CP-LNG), which generates electricity

with aqua-ammonia, and an open Rankine cycle that uses LNG heated by waste heat from the KC condenser to turn it into gas. The gas then goes into a turbine that powers a DC chiller cycle to cool the air. The bottom cycle feeds this vapour into the turbine, which operates a DC chiller cycle to cool the air. As shown in Fig. 12, it was found that natural gas provided about 561 kJ of cooling and 151 kJ of output power at a 403 K heat source. Khankari and Karmakar [38] suggested a combined system that includes the main-cycle coal-fired steam power plant according to the Rankine cycle, and the sub-system is the Kalina power cycle (KCS11), which uses an NH₃/H₂O working fluid mixture. The study found that replacing the main cycle condenser with the KC evaporator enhanced the energy and exergy efficiency of the 500 MW independent power plant. Mirjavadi et al. [39] suggested two systems with various bottom cycles. The first cy-

cle utilised the organic Rankine cycle (ORC), while the second cycle employed the Kalina cycle (KC), with a fixed top cycle that used a steam Rankine cycle (SRC) powered by solar energy. The outcomes indicated that KC outperformed ORC as a bottom cycle, and therefore, the overall efficiency of the second system was better than that of the first system. Okten et al. [40] proposed a system to exploit renewable sources stored by connecting a Kalina cycle (KC) to a thermal integral pump for a thermal energy storage (TI-PTES) system; it includes a heat pump circuit, which links both a low-grade heat cycle (LGH) and a high-grade heat cycle (HG). Each circuit relies on water circulating between the hot tank and cold tank to maintain and regulate a consistent heat level in the heat pump circuit. As shown in Fig. 13, the outcomes indicate that increasing the evaporator entrance temperature of the heat pump cycle enhances the exergy efficiency of the system.

A summary of all important results of integrating the Kalina cycle with traditional cycles in this section is given in Table 6.

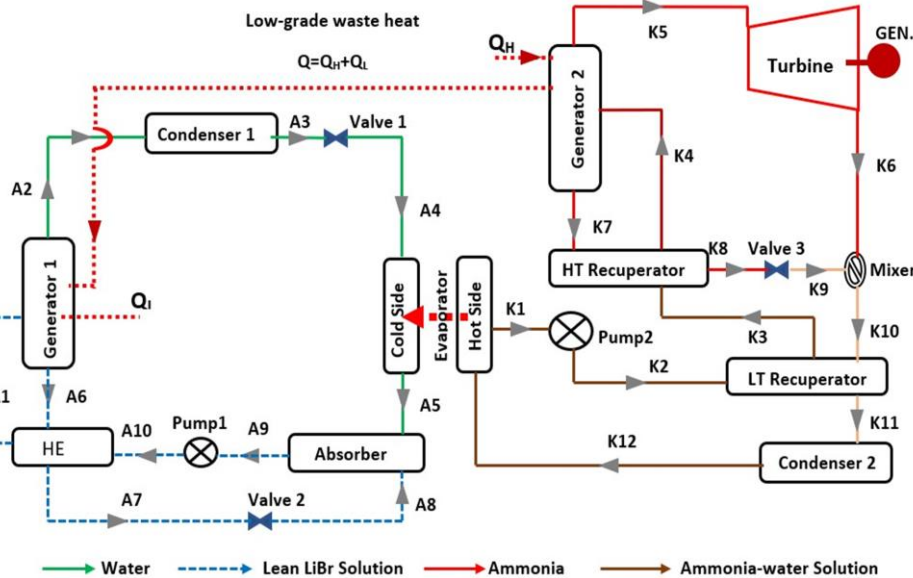


Fig. 11. Coupled LiBr-H₂O absorption chiller/Kalina cycle (drawn after [36]).

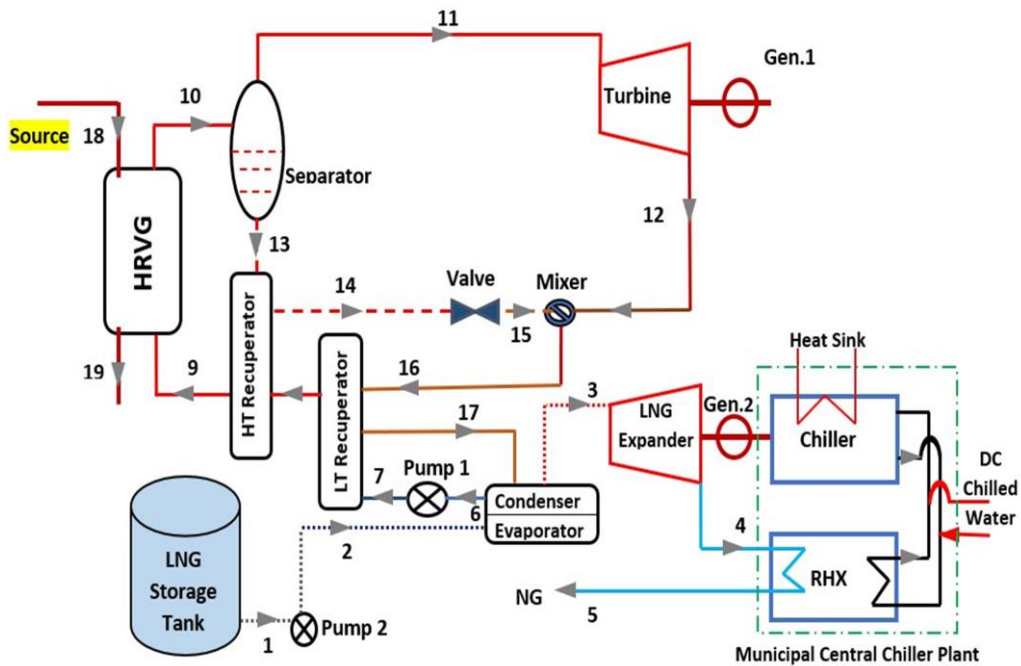


Fig. 12. Polygeneration system based on the Kalina cycle (KC) and aided by liquefied natural gas (LNG) for the production of electricity, vaporisation of LNG and municipal air conditioning (drawn after [37]).

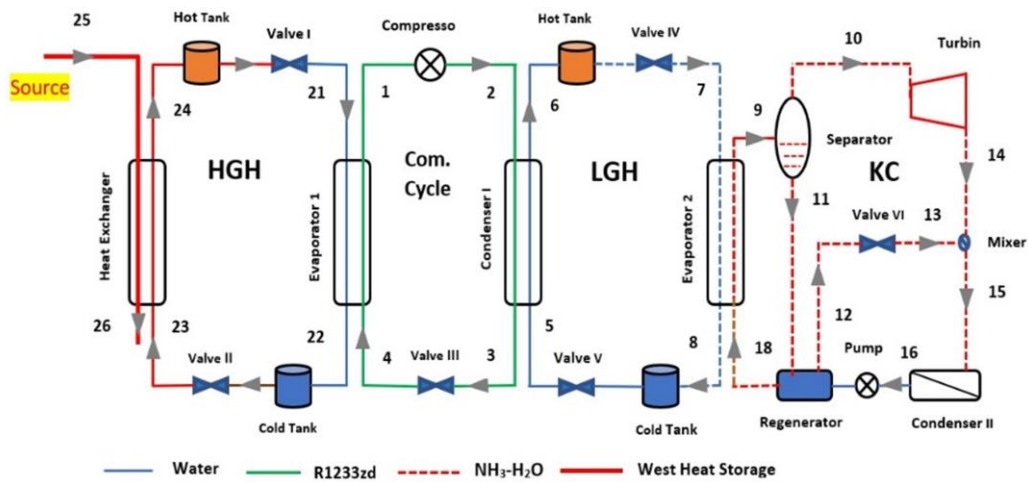


Fig. 13. Kalina cycle with TI-PTES system (drawn after [40]).

Table 6. Kalina cycle integrated with traditional cycles.

Articles	Type of Cycle	$\eta_{th}, \%$	$\eta_{exe}, \%$	Remarks
Liu et al. [36]	KC+ACH(LiBr/H ₂ O)	16.78	-	The gross power output of KC is increased by about 45% with respect to the reference cycle (KCS-34).
Ayou & Eveloy [37]	KC-CP-LNG	33	35	The net power gained yearly is approximately 74 GWh in comparison to the energy consumed by standard air conditioning, power and gas.
Khankari & Karmakar [38]	Coal-fired steam cycle (RC) Combine cycle	39.68 40.5	35.46 36.2	Able to reduce approximately 2.02 tons of CO ₂ emissions per hour by generating an additional 5.14 MWE of electricity.
Mirjavadi et al. [39]	RC+ ORC RC+ KC	29.85 31.24	- -	As the ORC energy efficiency was recorded at 9.51%, while KC was approximately 11.3% at a bottom cycle turbine input pressure of 3.5 MPa.
Okten et al. [40]	KC+ TI-PTES	-	48.5	As the hot tank entrance temperature in the LGH cycle increased from 373 K to 393 K, the gross power rose from 650 kW to 750 kW.

5. The working fluid

5.1. Binary fluid properties

Two solutions combine to form the binary fluid system, which possesses the desired properties for successful system operation. The binary mixture system holds the qualities of the two fluids. Below are the pros and cons of the binary solution system [41]:

- **Benefits**
 1. A binary fluid system is possible to run with a low-grade heat source.
 2. The phase change takes place at a wide range of different temperatures.
 3. Any system that uses a binary fluid that is highly adaptable to a heat source to generate the required energy.
- **Drawbacks (defects)**
 1. The system requires additional components, such as separators and mixers, thereby necessitating more space for installation.
 2. It may be challenging to create a homogenous mixture when the components are mostly immiscible.
 3. The variant molecular weight of the members may lead to coalescence and flocculation.
 4. The corrosion or reaction of some binary fluids with the vessel's materials may take place.

5.2. Type of a binary fluid (binary solution) as the working fluid

Several pairs of working fluids have been studied in research and industrial settings. These include NH₃-H₂O, LiBr-H₂O, CH₄O-H₂O, C₂H₆O-H₂O, C₃H₈O-H₂O, and other. Every pair consists of a refrigerant and an absorbent. This binary fluid comes back with more benefits than a single fluid in a cycle by allowing for a closer temperature match between the working fluid and the heat source, which improves energy efficiency and power output, making the Kalina cycle a future technology for several heat source applications [42]. It is important to choose a binary fluid having suitable properties, that is, one that is homogeneous in components and has a good temperature gradient (the difference in temperature between the boiling point and the dew point), which provides the possibility of changing the phase of the fluid with a change in temperature of the heat source, thus changing the ammonia concentration; in other words, for every ammonia concentration there is a certain temperature gradient of the phase change of the binary fluid. The key classified binary solutions below include [43], to name a few:

1. The alcohol group offers good dissolubility in water, and for this reason, the focus is on alcohol-water mixtures. The mix of alcohol with water declines with the increasing number of carbon atoms in it. Until three carbon atoms, it is a good mix in water; with four and five atoms, it is only

partially soluble in water, and greater than 5 atoms do not mix, see Table 7.

2. Binary alcohol-alcohol fluid refers to a mixture of a lower alcohol content (up to three carbon atoms) and a higher alcohol content (more than five carbon atoms).
3. Ammonia-water is a non-azeotropic working fluid.
4. Lithium bromide (LiBr) is a salt whose density is 3464 g/cm^3 that can be soluble in water to form a solution with new thermo-physical properties. Possesses varying makeup with the heating and cooling process, allowing for the best exploitation of lower-grade heat sources. Its good vapour-liquid balance makes the Kalina cycle more thermodynamically efficient, especially when it comes to recovering waste heat and cooling. However, the use of LiBr solutions presents issues with erosion and crystallisation; thus, only certain concentrations in water are used, which are considered non-flammable. Although it is considered non-toxic, it has a potential to cause health problems [44].

Table 7. The alcohol group [43].

Alcohol	Formula	Type	Water dissolubility
Methanol	CH ₄ O	Low alcohol	Complete
Ethanol	C ₂ H ₆ O	Low alcohol	Complete
Propanol	C ₃ H ₈ O	Low alcohol	Complete
Butanol	C ₄ H ₁₀ O	Medium alcohol	Partial
Pentanol	C ₅ H ₁₂ O	Medium alcohol	Partial
Hexanol	C ₆ H ₁₄ O	High alcohol	No
Heptanol	C ₇ H ₁₆ O	High alcohol	No

5.3. Why ammonia-water as the working fluid?

As previously mentioned, the Kalina cycle utilises ammonia-water as a working fluid, making it unique because it includes two distinct ingredients, each having a different boiling and freezing point. Given that a two-ingredient binary fluid allows for ratio changes in different applications and can boil and condense at various temperatures, it is considered unique and con-

sequently leads to improved thermodynamic efficiency. Additional features are listed below [8]:

1. The binary fluid is a new type of working fluid with unique properties.
2. Ammonia's molecular weight (17.03074 gram/mol) is quite similar to that of water (18.0157 gram/mol).
3. This binary fluid has high miscibility.
4. It is characterised by higher heat transfer coefficients.
5. Water containing ammonia does not freeze at 0°C; the freezing point varies with ammonia concentration in the solution.
6. Both are ecologically benign and available in nature.
7. No deposits occur in the binary fluid under the operating condition.
8. The solution has varying boiling point and dew point temperatures.
9. Because of the advantages of the binary fluid, KC recovers a greater amount of waste heat than ORC. However, the volume flow rate of the binary solution is lower in KC.
10. Ammonia is considered less amenable to flame and less hazardous compared to standard working fluids used in ORC, such as toluene, xylene, n-pentane, n-butane, R-11, R-22 and R-248fa, and it is self-alarming due to its odour, but there remains the issue of toxicity.
11. The temperature of a miscible substance can be low.
12. The ammonia has a high latent heat of evaporation.

6. Cycle thermodynamics analysis, assumptions, and T-s diagram

The mass, energy, and exergy conservation equations are needed to make the thermodynamic analysis of each part of the original Kalina cycle (KS) presented in Fig. 1. The balance equations for the components that make up the original Kalina cycle, including an HRVG, a separator, a turbine, a throttle valve, a mixer (also called an absorber), a condenser and a pump, can be found in Table 8.

Table 8. Governing equations for each component [45].

Component	Total mass	Ammonia mass	Energy balance	Exergy balance	Power and efficiency
HRVG	$\dot{m}_{exh} = \dot{m}_{fuel} + \dot{m}_{air}$ $\dot{m}_{12} = \dot{m}_{14}$ $\dot{m}_{tot} = \dot{m}_7 = \dot{m}_5$	$x_5 = x_7$	$\dot{Q}_{in} = \dot{m}_{exh} cp_{exh} (T_{12} - T_{14})$ $\dot{Q}_{in} = \dot{m}_{tot} (h_7 - h_5)$	$(\dot{E}_d)_{gen} = (\dot{E}_{12} - \dot{E}_{14})$ $-(\dot{E}_7 - \dot{E}_5)$	
Separator	$\dot{m}_7 = \dot{m}_1 + \dot{m}_8$	$\dot{m}_7 x_7 = \dot{m}_1 x_1 + \dot{m}_8 x_8$	$\dot{m}_7 h_7 = \dot{m}_1 h_1 + \dot{m}_8 h_8$	$(\dot{E}_d)_{sep} = \dot{E}_7 - (\dot{E}_1 + \dot{E}_8)$	
Turbine	$\dot{m}_1 = \dot{m}_2$	$x_1 = x_2$		$(\dot{E}_d)_t = (\dot{E}_1 - \dot{E}_2) - \dot{W}_t$	$\dot{W}_{tisent} = \dot{m}(h_1 - h_2)$ $(\eta_t)_{isent} = \frac{h_1 - h_2}{h_1 - h_2}$
Throttle-valve	$\dot{m}_8 = \dot{m}_9$	$x_8 = x_9$	$h_8 = h_9$	$(\dot{E}_d)_{thr} = \dot{E}_8 - \dot{E}_9$	
Mixer (absorber)	$\dot{m}_2 + \dot{m}_9 = \dot{m}_3$	$\dot{m}_2 x_2 + \dot{m}_9 x_9 = \dot{m}_3 x_3$	$\dot{m}_2 h_2 + \dot{m}_9 h_9 = \dot{m}_3 h_3$	$(\dot{E}_d)_{abs} = (\dot{E}_2 + \dot{E}_9) - \dot{E}_3$	$\eta_{exe} = \frac{W_{net}}{(E_{in} - E_{out})}$
Condenser	$\dot{m}_3 = \dot{m}_4$	$x_3 = x_4$	$\dot{Q}_{con} = \dot{m}_3 (h_4 - h_3)$	$(\dot{E}_d)_{con} = (\dot{E}_3 - \dot{E}_4)$ $-(\dot{E}_{11} - \dot{E}_{10})$	$\eta_{th} = \frac{W_{net}}{\dot{Q}_{in}}$
Pump	$\dot{m}_4 = \dot{m}_5$	$x_4 = x_5$	$h_5 = h_4 + v_f (P_5 - P_4)$	$(\dot{E}_d)_{pump} = (\dot{E}_5 - \dot{E}_4) - \dot{W}_p$	$W_p = v_f (P_5 - P_4)$ $W_p = \dot{m}_5 (h_6 - h_5)$ $(\eta_{pump})_{isent} = \frac{h_5 - h_4}{h_5 - h_4}$

Additionally, the mathematical analysis relies on certain assumptions, such as those outlined in [45]:

1. Each component of the system is steady.
2. The pressure and heat losses are ignored.
3. The cycle is an adiabatic process.
4. The strong solution at the turbine entrance represents a dry saturated vapour, $DF = 1$.
5. A saturated liquid with $DF = 0$ represents the weak solution at the separator outlet.
6. We ignore the changes in kinetic energy (KE) and potential energy (PE) in the components.
7. Working fluid exits the condenser in a saturated liquid state.
8. Working fluid exits the absorber in a wet vapour state.
9. The throttling process is isenthalpic.
10. The binary mixture is a wet vapour at the separator inlet.
11. The effectiveness of heat recovery vapour generation and the condenser is equal ($\epsilon = 1$).

The T - s diagram is an important relation for imaging the efficiency and energy distribution of the Kalina cycle. Each point on the figure represents a specific thermodynamic state (temperature, entropy and pressure) of the ammonia-water mixture at a given moment in the cycle. The heat is added and rejected at variable temperatures in the mixed-phase region cycle due to the use of a binary fluid (shown as lines 5–7 and 3–4). As temperature increases in the Kalina cycle, entropy also increases as the fluid absorbs heat and transitions from liquid to wet vapour (lines 5–7). Generally, increased temperatures at the turbine inlet increase the output work (line 1–2).

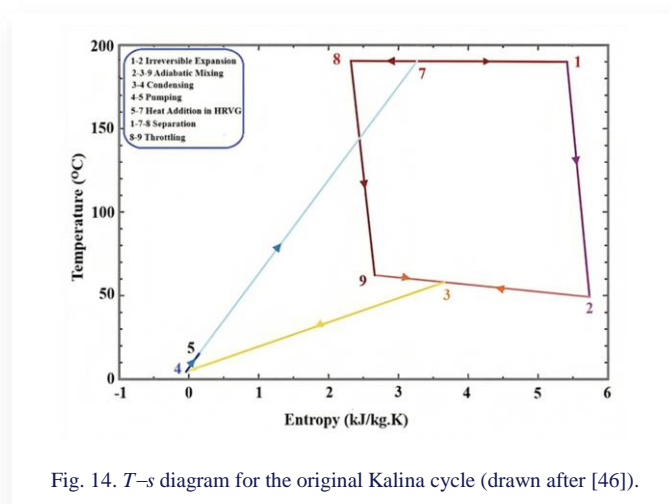


Fig. 14. T - s diagram for the original Kalina cycle (drawn after [46]).

7. The boiling and freezing points of ammonia-water mixtures

Ammonia solution (NH_3 - H_2O) has gained interest as a working fluid in alternative energy cycles and is also being used in the cooling industry. Varying this mixture's thermodynamic properties is crucial to improve the required processes. Their composition and thermodynamic properties affect ammonia solutions' boiling and freezing points. The ammonia and water mixtures show a non-azeotropic manner, meaning their boiling and freezing points vary with different ammonia concentrations. This

means that these properties are important for implementations in power and refrigeration production. The pure parts of this mixture are polar substances that are very similar to each other. For example, they have the same molecular structure and mass, even though hydrogen bonding makes them weaker in ammonia than in water [47]. Also, they have considerably different boiling points and critical points. So, at atmospheric pressure (99.75 kPa), the boiling point (T_b) of a mixture of ammonia and water with 0.04 NH_3 and 0.96 H_2O is 358.5 K [48]. Kherris et al. [49] examined the thermodynamic properties of ammonia-water mixtures used in absorption refrigeration systems. They did this by using theoretical modelling to look at high wet vapour equilibrium pressures of up to 11000 kPa and temperatures from 230 to 600 K. The results show that boiling points can vary greatly with pressure, with higher pressures leading to higher boiling temperatures. If the ammonia mass fraction is higher, the mixture's freezing point can reach about 197 K, which is closer to the freezing point of pure ammonia. If the ammonia mass fraction is very low, the mixture's freezing point can be closer to that of pure water. Ganesh and Srinivas [50] conducted a study on the ammonia-water binary solution to increase the overall efficiency of the Kalina cycle (KC) and vapour absorptive refrigeration (VAR) system. Evaluating the thermodynamic properties of the binary solution necessitates known mixture concentrations. As a result, the water exhibits favourable characteristics at high temperatures, while the ammonia demonstrates favourable characteristics at low temperatures. Ammonia freezes at a very low temperature, as it has a low freezing point (195.2 K). At a concentration of approximately 25% of ammonia in the binary solution, the freezing point can be as low as -40°C . Friend et al. [51] studied the properties of the ammonia solution, which are crucial as a working fluid in many energy cycles and for cooling applications. Research is limited to the thermodynamic properties of ammonia-rich fluids at pressures of 3500 kPa. It turns out that the boiling point varies with pressure as well. An increased pressure results in higher boiling points, and some studies have indicated that boiling points can reach up to 450 K, which is suitable for geothermal use. The main purpose of the study of Chettiyankandy et al. [52] was to investigate the impact of the ammonia mass fraction on the water's hydrogen bonding structure in the ammonia solution and, consequently, on the boiling and freezing behaviour of the mixture. Changing the ammonia mass fraction from $x_{\text{NH}_3} = 0.02$ to 0.30, and changing the pressure on the concentrated ammonia solution ($x_{\text{NH}_3} = 0.30$) from $P = 0.1$ MPa to 8 MPa is done at 293 K. The outcomes show that when the ammonia mass fraction increases, the hydrogen ties in the water increase more than the water-ammonia ties, and the last increase is greater than the ammonia-ammonia hydrogen ties in the solution. Therefore, the transition and diffusion of ammonia molecules is quicker than that of water molecules in the solution. Hence, the boiling and condensing points in ammonia-water are lower than those of water. Tables in the book of Srinivas et al. [53] show different properties of ammonia and water. These tables can be used to figure out a lot of facts, but the most important one is that the boiling and freezing points of the ammonia-water mixture drop as the ammonia concentration goes up. At 15 kPa with a 0.3 dryness fraction, the

boiling points for 0.3 and 0.7 ammonia concentrations are 278.47 K and 242.23 K, respectively. Additionally, at a constant mass and dryness fraction, increasing the pressure raises both the boiling and condensing points. This is evidenced at a 0.5 ammonia concentration and 0.3 dryness fraction, where increasing the pressure from 40 kPa to 100 kPa raises the boiling point from 274.47 K to 294.06 K. Kargel [54], as in much previous published research, used the diagram of the freezing point of aqueous ammonia to illustrate and discuss the solid-liquid phase

equilibria in the system $\text{H}_2\text{O}-\text{NH}_3$ at a pressure of 1 atm (~ 1 bar), as shown in Fig. 15. The freezing points of pure water and pure ammonia, along with the varying freezing temperatures of their mixture based on ammonia concentration in the binary fluid, thus form the freezing point curve. Within this curve, three distinct eutectic points (three hydrates I, II, and III) are prominent. Understanding these properties is essential for managing the state of the working solution and ensuring fluidity in refrigeration applications.

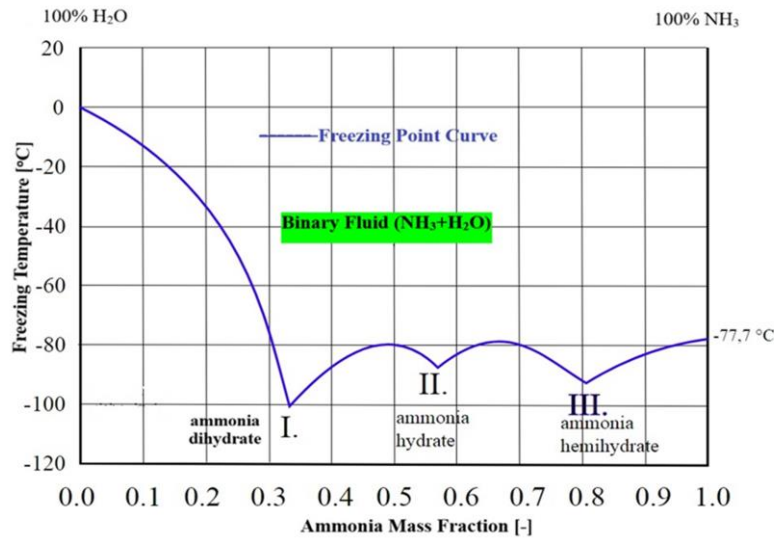


Fig. 15. Freezing points curve (solid-liquid separation curve) for the aqua-ammonia mixture (drawn after [54,55]).

Conde [55] explained the diagram of the freezing point and how the increasing ammonia concentration decreases the freezing point of the aqua-ammonia mixture. The curve shows the freezing points corresponding to the ammonia concentrations within the aqua-ammonia mixture. From zero ammonia concentration to 100%, pure water has a freezing point of 273 K (0°C). As the ammonia concentration increases, the freezing point of the mixture at first becomes lower, as shown in the freezing point curve. When the mixture contains 33.5% ammonia, its freezing point rapidly decreases, reaching 373 K (100°C), as indicated by point (I). When the ammonia concentration exceeds 33.5%, the aqua-ammonium mixture also reaches two low freezing points (II, III); generally, the freezing point remains in the range of 173 K to 199.7 K (-100°C to -73.3°C). When the ammonia concentration is 100%, the freezing point in anhydrous state is 195.4 K (-77.6°C).

8. Corrosion-related aspects in applying the Kalina cycle

This section aims to discuss material selection and protection for Kalina cycle plants. Therefore, the corrosion problem in the Kalina cycle, which utilises an aqueous ammonia ($\text{NH}_3-\text{H}_2\text{O}$) mixture as a working solution, poses significant challenges in planning, execution and maintenance due to the formation of corrosive species. Zhang et al. [56] explained that the working fluids can accelerate corrosion, leading to material spoilage and failure, especially at high temperatures. Materials like low nickel-

iron alloys, hastelloy and alloys with cobalt can motivate this reaction. Due to their characteristics, some of the most endangered parts of the Kalina cycle are the turbine, condenser, heat recovery vapour generation (HRVG) and heat exchanger. Whitaker [57] studied the effect of ammonia-water working fluid on parts of the Kalina cycle to produce geothermal energy in Húsavík, Iceland. The results show that aluminium and mild steel are not good materials for Kalina cycle systems. On the other hand, 316, 304, nitronic 60, duplex and many types of stainless steel, as well as 6Al-4V titanium, do not seem to corrode. Wear of the stainless-steel spacer ring was most likely caused by erosion due to the high speed of the working fluid. Kim et al. [58] looked at how ammonia changed the manner in which a titanium-aluminium-zirconium alloy was worn down, and tested it under pressurised water at 633 K for 20 months. The erosion examination outcomes indicated that adding ammonia accelerated the erosion and hydrogen freedom rates. Murugan and Subbarao [59] mentioned that utilising ammonia-water solution at a temperature higher than 673 K is not favourable since at higher temperatures ammonia becomes unstable and the conversion of ammonia into hydrogen and nitrogen is potential, which leads to nitride erosion. Hannon et al. [60] looked into a project to make a new method for stopping erosion on the carbon steel surfaces of aqua-ammonia absorption heat pumps and chillers that use rare metal salt compounds. These results show that cerium nitrate works better than chromate composites as an erosion inhibitor in high-temperature tests. Chromate composites are harmful to both people and the environment. Thorin

[61] studied a mixture with ammonia at a concentration of 0.8 for 24 hours, which was kept in a reactor at a temperature of about 823 K and a pressure of about 10 MPa. Three experiments exposed the mixture to incoloy 800 and 316 stainless steel materials. The examination revealed no traces of nitrogen or hydrogen. Shan and Nihaj [62] mentioned in a review that the Kalina cycle plant using aqua-ammonia as a working fluid presents different material issues compared to other energy plants. The oxidation of Kalina cycle parts through the power cycle is least likely due to deficient levels of oxygen inside the working fluid. Despite that, nitridation of high-temperature ingredients is a concern to keep in mind when additional heat exchangers, superheaters, reheaters and high-temperature turbine units are involved.

9. Summary of the benefits and drawbacks of the present versions of the Kalina cycle

Systems that utilise a binary solution possess all the advantages and disadvantages of the binary mixture that were mentioned and discussed in a previous section. The primary benefits and drawbacks of this cycle are outlined in Table 9.

Table 9. The main advantages and disadvantages of versions of the Kalina cycle.

Advantages
1. Cogeneration systems provide electricity and cooling at a single site.
2. Cogeneration reduces certain recurring components shared between the two cycles of the system.
3. It can exploit more of the recovery wasted heat to generate cooling without impacting electrical energy production.
4. It simultaneously produces electricity and refrigeration with greater efficiency (absorption cycle).
5. It works better with renewable energy sources, including geothermal, biomass and ray insolation heat.
6. It reduces greenhouse gas emissions compared to conventional cycles.
7. It makes it possible to work with low-temperature sources (373 – 473 K).
8. The Kalina cycle uses a binary working fluid with a regulable concentration ratio to control its freezing point and match it to a low heat source.
Disadvantages
1. More complex than standard cogeneration setups.
2. Power cycle design may be more complex than conventional cycles, leading to higher initial installation costs.
3. It requires skilled management for controls and operational expertise in power and cooling.
4. Requires materials that can withstand ammonia's corrosive effects, which may increase maintenance and replacement costs.
5. Dealing with ammonia presents potential safety hazards because of its toxicity and flammability.

10. Conclusions

1. The original Kalina cycle has a better efficiency than ORC. Also, the modified Kalina cycle has a better efficiency than the original Kalina cycle system under the same operating conditions [2].
2. The cycle to produce power and cooling together has been more efficient than the single power or cooling-only, and in

exploiting the waste heat sources or low-temperature sources.

3. When comparing the results, we found that the cogeneration in the Kalina cycle, which produces both power and cooling, has a higher energy efficiency than the Kalina cycle of the power generating system, which drives a separate cooling cycle to produce the same amount of refrigeration. The efficiency of these cycles was found 25.76% and 23.44%, respectively, under the same operating conditions [19].
4. We investigated and discussed several different applications of the Kalina cycle, including its use in solar collection, multi-absorption heat pumps, the Rankine cycle, the organic Rankine cycle, the Brayton cycle, exhaust gases, gasoline engines, geothermal well water, and other systems. The Kalina cycle improves all these applications by adding new power by recovering more waste heat from these systems.
5. As the ammonia mass fraction in a mixture increases, the boiling and freezing points decrease; the following trends have been observed:
 - for the mass fraction (0–10% NH₃), the freezing point is fairly high, about 268 K to 263 K; refrigeration is then considered not effective [51],
 - for the mass fraction (20–30% NH₃), the freezing point declines from 258 K to 253 K, promoting the effectiveness of refrigeration [52],
 - for the mass fraction (50–70% NH₃), the freezing point will decline to 243 K or less, benefiting low-temperature applications [49,50],
 - near pure ammonia (more than 90% NH₃), the freezing point reaches 196 K, indicating a sharp decline that makes it suitable for extreme cooling applications [51].
6. Some materials, like stainless steels (316, 304, nitronic 60, and duplex), carbon steel and 6Al-4V titanium, can be used with aqua-ammonia as the working mixture in the Kalina cycle. Others, such as mild steel, aluminium and copper alloys are unsuitable due to their rust [56–59,62].

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