Open Access Journal

Journal of Power Technologies 97 (4) (2017) 302–307

journal homepage:papers.itc.pw.edu.pl

Comparison of ORC and Kalina cycles for waste heat recovery in the steel industry

Jarosław Milewski[a,*], Janusz Krasucki[b]

[a] Warsaw University of Technology, Institute of Heat Engineering) 21/25 Nowowiejska Street, 00-665 Warsaw, Poland
[b] CIM-mes Projekt Sp.z o.o. 125/127 Aleje Jerozolimskie, 02-017 Warsaw, Poland

Abstract

This paper presents the results of a comparative study of waste heat recovery systems based on the Organic Rankine Cycle (ORC) and Kalina Cycle (KC) that could be applied to the steel industry. The simulations were performed for an electric arc furnace (EAF) steel mill and waste heat recovery system with saturated steam as a heat carrier. Commercial software ASPEN-HYSYS™ was used to calculate system performances under different loads for ORC with different working fluids (butylobenzene, n-hexane, n-pentane) and for KC. Each case was optimized for maximum system efficiency. In terms of net system electric efficiency and electric power output, under nominal operating conditions similar performances were obtained for ORC with n-pentane working fluid and KC based systems. The highest system efficiency was observed for ORC with butylobenzene as working fluid, whereas the KC becomes competitive versus ORC for heat carrier temperatures of 200 °C and above.

Keywords: Waste heat recovery, EAF process, ORC system, Kalina Cycle system

1. Introduction

The Organic Rankine Cycle (ORC) is a known technology with important opportunities in waste heat recovery from energy intensive industrial processes. ORC which applies the principle of the steam Rankine cycle, but uses organic working fluids with low boiling points, can be used to recover heat from lower temperature (150–300 °C) heat sources. ORC has been developed for a long time, and the main challenge with ORC is the choice of appropriate working fluids [9]. For the lowest temperature range (100–200 °C), one object of oncreasing interest in recent years has been a new concept power cycle—the Kalina cycle (KC)—using an ammonia-water mixture as the working fluid [5, 13]. However, commercial marketing of the technique started only a few years ago and successful application of the Kalina cycle in industry has been scarce [1].

Recent studies on ORCs have been extended to address complex cycle design issues such as accommodating discontinuous waste heat recovery–for example in the steel industry–and the influence of outlet temperature of the heat source on cycle efficiency [12]. The utilization of low grade heat in ORCs for the steel industry has been investigated with a view to improving energy efficiency through the environmental and techno-economic evaluation of a case study using waste heat available in the steel-making process [11]. The process integration concept was adopted in [8]to carry out a systematic investigation of the possible use of low grade heat in process industries. The concept evaluates different technologies, including ORC, and identifies the most appropriate way to recover industrial waste heat. This paper presents the results of preliminary investigations that compare ORC and KC based power systems applied for the recovery of waste heat in steel mills.

2. System description

2.1. Waste heat recovery system in a steel mill

As part of the European funded PITAGORAS project (FP7, Smart Cities Programme) [2], a large scale pilot plant based on ORC technology was built and commissioned for electricity and heat production using waste heat from the fumes of an Electric Arc Furnace (EAF) in the ORI Martin steel mill in Brescia (Italy). The plant, commissioned in June 2016, has a recovery potential of 16 MWth and produces electricity in the summer (1.800 kWe) and district heat in the heating season (10 MWth). Fig. 1 shows the simplified process scheme of an ORC unit installed at the bottoming of an EAF in the steel works.

The Waste Heat Recovery Unit (WHRU) consisting of a waste heat boiler, steam drum and steam accumulator, is placed outside the EAF before the quenching tower. The

---

[*] Corresponding author
Email address: `jaroslaw.milewski@itc.pw.edu.pl` (Janusz Krasucki)

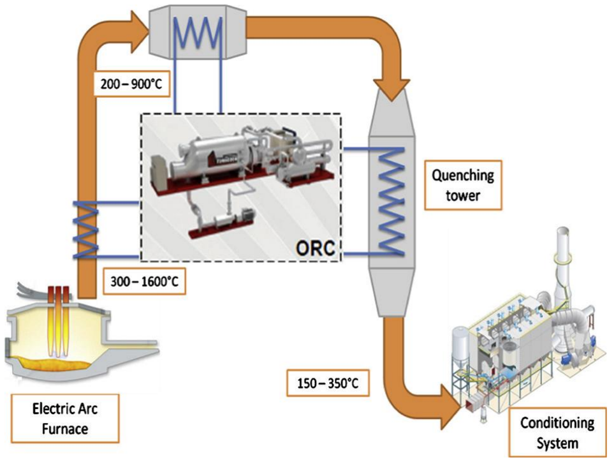

Figure 1: ORC at the bottoming of an EAF process Campana et al. [4].

boiler generates saturated steam due to thermal exchange with the EAF's exhaust gases. This means the saturated steam is a carrier of recovered heat and provides a heat source for the ORC unit. The EAF works in a cycle of almost one hour each (tap-to-tap time). Due to the cyclical work of the EAF, the steam parameters are subject to large fluctuation. Thus a steam accumulator is used to reduce the pressure steam fluctuations and to stabilize the ORC operating conditions. The various subsystems–as well as the whole system itself–were optimized to maximize plant performance. In particular, the investigations focused on selecting the best cycle configuration and working fluid. KC was taken into account as a possible alternative to an ORC based power system.

2.2. ORC based power system

The conceptual scheme of the considered system and the corresponding T-S diagram of the Organic Rankine Cycle are shown in Fig. 2.

The source heat carrier in the analyzed case is saturated steam. The steam transfers heat to the evaporator to preheat and vaporize a suitable organic working fluid in the evaporator (8,3,4). The working fluid vapor is sent into the turbine where through expansion (4,5) it rotates the turbine which is directly coupled to an electric generator. The exhaust vapor flows through the regenerator (5-9), where it heats the working fluid (2,8) and is then condensed in the condenser and cooled by the cooling circuit (9,6,1). The organic working fluid is then pumped (1,2) into the regenerator and evaporator, thus completing the closed-cycle operation.

The analysis was performed for selected load conditions (LC1, LC2, LC3, LC4, LC5) of ORC which are representative of real use of WHRU in the ORI Martin plant. The LC4 case refers to the design (nominal) load conditions.

Table 1: Load Cases for ORI Martin plant

	LC1 (min)	LC2	LC3	LC4 (nom)	LC5 (max)
Steam mass flow kg/s	1.33	2.13	3.29	4.44	4.91
Steam temp. ℃	168	177	188	200	205
Condensate out temp. ℃	105	109	107	107	107
Cooling water inlet temp. ℃	32	32	32	32	32
Cooling water outlet temp. ℃	35.2	37	39.6	42.2	43.2

Based on the literature review done Victor et al. [10], the most suitable working fluids for the temperature ranges LC1-LC5 and without pressure constraints were selected for the analysis, namely:

- Butylobenzene
- n-Hexane
- n-Pentane

For every LC, the system parameters were varied in order to achieve the maximum thermal efficiency.

The thermal efficiency of the ORC is defined on the basis of the first law of thermodynamics as the ratio of the net power output to the heat addition (the heat transferred from the waste heat to the working fluid) and is expressed as:

$$\eta_{ORC} = \frac{P_{TURBINE} - P_{PUMP}}{\dot{m}_{VAPOR}\left(h_{VAPOR} - h_{CONDENSATE}\right)} \quad (1)$$

where: P—power, $\dot{m}$—mass flow rate, h—specific enthalpy.

Optimized system parameters:

- turbine inlet pressure in the range (0.01 . . . 150) bar
- turbine outlet pressure in the range (0.01 . . . 150) bar

2.3. KC based power system

Despite having a similar thermodynamic cycle as the Rankine cycle, the layout of the Kalina cycle differs significantly from ORC due to the complexity of the design. The Kalina cycle requires additional equipment including a liquid/steam separator and intermediate heat exchangers as a low temperature (LT) recuperator and high temperature (HT) recuperator—see Fig. 3

This configuration is used to manipulate the ammonia-water ratio in the mixture, with water being added to the ammonia-rich stream before the condenser. The mixing of these streams delivers a liquid mixture at the outlet of the condenser, and results in a condensing operating pressure above atmospheric pressure.

In contrast to a pure working fluid in which phase transition occurs at a constant saturation temperature for a specified pressure, the phase transition of a zeotropic mixture as a working fluid occurs over a wide range of temperature for a specified pressure. The phase transition starts at the bubble point and ends at the dew point of the mixture. When the ammonia concentration is 99%, the phase transition is naturally similar to that of pure ammonia by showing that most of the phase change occurs at constant temperature. As the ammonia concentration decreases for a fixed pressure or as the pressure increases for a fixed ammonia concentration, both the bubble and dew temperatures as well as the

Table 2: Assumed parameters for Kalina Cycle simulations Parameter

Parameter	Value
Minimum vapor fraction at turbine outlet	0.85
Recuperator effectiveness, %	50
Evaporator temp. minimum approach, °C	10
Condenser temp. minimum approach, °C	4
Turbine adiabatic efficiency, %	75
Pump adiabatic efficiency, %	75
Minimum condenser pressure value, bar	0.05
Maximum NH3 Fraction, %	85

Table 3: ORC optimal parameters for design load condition and different working fluids

Parameter	Butylo-benzene	n-Hexane	n-Pentane
1*Efficiency, %	17.3	13.1	12.1
Turbine power, MW	1.84	1.39	1.29
Turbine inlet pressure, bar	0.64	5.06	9.95
Turbine outlet pressure, bar	0.01	0.45	1.36
Turbine inlet temp., °C	188.6	130.9	124.5

Table 4: KC system optimal parameters for different load conditions

Parameter	LC1	LC2	LC3	LC4
Efficiency	9.4	11.1	12.6	13.9
Turbine power, MW	0.3	0.56	0.99	1.48
Turbine inlet pressure, bar	54.9	69.3	83.1	99.5
Turbine outlet pressure, bar	12.8	12.8	12.8	12.8
Turbine inlet temp., °C	132.1	153.2	172.7	188.7

temperature range of phase transition rise and the portion of subcooled liquid increases, while the portion of superheated vapor decreases. This phenomena is illustrated in Fig. 4.

By appropriate choice of the ratio between the components of the mixture, the boiling point of the working fluid can be adjusted to suit the heat input temperature and allows to achieve the optimal system performances.

Based on the literature review, the Kalina Cycle with an NH_3 fraction of about 85% was judged the most suitable for waste heat utilization in the temperature ranges 180—220°C. To make the KC based system comparable to the other ORC based system, the number of recuperators should be reduced to just one—LT.

System performance also depends on the turbine inlet and outlet pressure values and the ammonia fraction in the working fluid. These parameters are usually monitored and controlled to adjust to current load conditions, so as to obtain the desired performance characteristics of the system. This means that for a specific operation point the optimum system characteristics can be achieved by varying selected system parameters.

- For simulation purposes the following parameters were varied during optimization:
- Turbine Inlet Pressure in the range 0.01...150 bar
- Turbine Outlet Pressure in the range 0.01...150 bar
- NH_3 fraction in the range 0.1...0.85

The investigations were carried out for the same load cases as for ORC–see Table.1

The objective function for the optimization process is system thermal efficiency and that is expressed in the same manner as for ORC according to equation 1.

3. Simulation results

In order to compare the ORC and KC cycle performances the input data describing the system main parameters were assumed to be at the same level and they are summarized in Table 2.

The term “temperature minimum approach” in Table 2 means the minimum temperature difference between tube and shell sides in the heat exchanger.

The simulations of the ORC system and the Kalina system were performed using the commercial software ASPEN-HYSYS™. The BOX method was used for optimizing all load cases, the procedure being loosely based on the "Complex" method of Box [3] and the BOX algorithm of Kuester and Mize [7]. This method is a sequential search technique which solves problems with non-linear objective functions, subject to non-linear inequality constraints.

3.1. ORC based power system

The ORC efficiency characteristics for analyzed working fluids depending on heat source temperature are shown in Fig. 5. The highest efficiency is obtained for butylobenzene for LC5 system operation, the lowest one also for butylobenzene but for LC1.

The highest pressure ratio (>100) is obtained for butylobenzene for LC5 (max temp.) load condition, the lowest one for n-pentane (≈ 8). However, it should be noted that both n-pentane and n-hexane are operated at condenser pressure above ambient level, whereas butylobenzene requires practically vacuum conditions in the condenser.

The characteristics of turbine outlet power for the analyzed working fluids are shown in Fig. 6. For heat source temperatures above 1800C, the the highest power is obtained for butylobenzene. The values for n-pentane and n-hexane are comparable for the analyzed load cases.

Table 3 shows a comparison of the main paramers of optimized ORC for the analyzed working fluids calculated for design load condition (LC4).

3.2. KC based power system

Maximum system efficiency reaches 14.5% and is observed for the highest heat source temperature (LC5), but simultaneously with high operational pressure (>100 bar), giving 1.7 MW of total power–see Fig. 7

The main system parameters for the analyzed load cases are presented in Table 4.

For all the analyzed load cases, the ammonia fraction meets its limit of 85%, which gives additional flexibility with increasing temperature but not so much with decreasing temperature, due to the possibility of decreasing the ammonia fraction during system operation (by extracting the fluid

Table 5: The comparison of ORC & KC based systems for design conditions (LC4)

Parameter	ORC-B	ORC-P	Kalina
Thermal power input, kWth	10420	10420	10420
Working fluid pump power, kWel	2.54	55.5	206.5
Cooling water pump power, kWel	28.4	31.3	30.9
Mass flow cooling water, kg/s	189	208	206
Turbine outlet pressure, bar	0.002	1.36	12.8
Turbine inlet pressure, bar	0.760	11.1	120
Turbine inlet temperature, ℃	195	130	189
Net electric power output, kWel	2161	1358	1455
Net efficiency, %	20.7	13.0	14.0

fraction from the separator and replacing it with water). Decreasing the ammonia fraction moves the optimal operational point of the system to higher heat source temperatures. The Kalina Cycle operates under pressure above the ambient conditions for both evaporator and condenser, which is an advantage over the near-vacuum conditions with ORC systems.

4. Discussion

The ORC based system was analyzed and for five different load cases with three different working fluids and optimized to obtain the highest electric efficiency by varying the turbine inlet pressure. The highest efficiency value was obtained for butylobenzene as working fluid but with very low condensation pressure, close to vacuum condition (0.01 bar), which may cause some technical problems with the operation of the system. ORC based on n-hexane or n-pentane has very similar performances with lower efficiency, but with moderate values of other parameters. The differences in efficiency and output power between n-pentane and n-hexane do not exceed 8%. Regarding the KC based system, the highest system output in terms of both efficiency (14%) and power (1.6 MW) is obtained for the highest temperature heat source (LC5). For LC4 and LC5 (temperatures of about 200℃) the Kalina cycle permits a gain in performance with respect to ORC. For temperatures below 200℃ the Kalina cycle efficiency declines and for LC1 and LC2 KC performances are distinctly worse. In order to compare more specific ORC and KC performances, additional calculations were performed for LC4 (design) conditions and for slightly different system parameters that are common to both ORC and Kalina cycles:

- isentropic efficiency of turbine: 83%
- mechanical efficiency of turbine: 95%
- isentropic efficiency of working fluid/cooling water pump: 70%
- mechanical and electric efficiency of working fluid/cooling water pump: 95%
- heat losses relative to the thermal input power: 0.3%
- pressure loss cooling water pump: 1 bar

Two ORC systems were analyzed, with butylobenzene (ORC-B) and n-pentane (ORC-P) as working fluids, and KC based system with a constant ammonia fraction of 85%. The results of the comparison are summarized in Table 5.

Regarding net system electric efficiency and electric power output, similar performances are observed for ORC with n-pentane as working fluid and KC based systems. Both systems behave similarly taking into account the pressure in the condenser, in both cases we are dealing with positive gauge pressure, with a greater value (12.8 bar) for the KC system. The highest efficiency value (21.7%) was obtained for ORC with butylobenzene as working fluid but with very low condensation pressure, near-vacuum condition (0.002 bar) which can provoke serious technical problems during operation.

5. Conclusions

The analysis presented in this paper sets out the multiple factors involved when selecting the optimal waste heat recovery system for application in the steel industry. It depends in essence on the characteristics of the heat source and the type of working fluid. The highest KC output in terms of both efficiency and power is obtained for the highest temperature heat source. When saturated steam is used as a heat carrier, the KC can be competitive versus ORC for steam temperatures of 200℃ upwards. The main advantage of using the Kalina cycle is the possibility of reacting to the heat source temperature by adjusting the amount of ammonia in the water. By utilizing an additional loop of the heat carrier together with a heat accumulator (steam), the temperature is quite constant and this advantage cannot be utilized. Use of the Kalina cycle instead of a heat (steam) accumulator, in light of the flexibility, could be considered but detailed dynamic simulations would need to be performed to guage the possible advantages. Any final decision as to cycle selection should also acknowledge the commercial and environmental issues inherent in both cycles.

Acknowledgement

The research leading to these results received funding from the European Union Seventh Framework Programme FP7/2007-2013 under grant agreement n° ENER / FP7EN / 314596 / PITAGORAS. This publication reflects only the author's views and the European Union is not liable for any use that may be made of the information contained herein.

References

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

[2] Pitagoras project webpage, . URL `http://pitagorasproject.eu`.

[3] M.J. Box. A new method of constrained optimization and a comparison with other methods. *The Computer Journal*, pages 42–45, 1965.

[4] F. Campana, M. Bianchi, L. Branchini, A. De Pascale, and others. Orc waste heat recovery in european energy intensive industries, Energy and GHG savings. *Energy Conversion and Management*, 76:244–252, 2013.

[5] A. I. Kalina. Combined-cycle system with novel bottoming cycle. *ASME Journal of Engineering for Gas Turbines and Power*, 106:737–42, 1984.

[6] Kyoung Hoon Kim, Hyung Jong Ko, and Kyoungjin Kim. Assessment of pinch point characteristics in heat exchangers and condensers of ammonia-water based power cycles. *Applied Energy*, pages 970–981, 2014.

[7] J.L. Kuester and J.H. Mize. *Optimization Techniques with FORTRAN. McGraw-Hill Book Company*. 1973.

[8] D. H. Kwak, , S. Y. Oh, and J. K. Kim. Process integration study for the use of industrial low grade heat. *Chemical Engineering Transactions*, 29:1591–6, 2012.

[9] B. K. Saleh, M. Wendland, and J. Fischer. Working fluids for low-temperature organic rankine cycles. *Energy*, 32:1210–21, 2007.

[10] R. A. Victor, J. K. Kim, and R. Smith. Composition optimisation of working fluids for organic rankine cycles and kalina cycles. *Energy*, pages 114–126, 2013.

[11] C. Walsh and P. Thornely. Cost effective greenhouse gas reductions in the steel industry from an organic rankine cycle. *Chemical Engineering Transactions*, 25:905–10, 2011.

[12] D. Wang, X. Ling, and H. Peng. Performance analysis of double organic rankine cycle for discontinuous low temperature waste heat recovery. *Applied Thermal Engineering*, 48:63–71, 2012.

[13] X. Zhang, M. He, and Y. Zhang. A review of research on the kalina cycle. *Renewable and Sustainable Energy Reviews*, 16:5309–5318, 2012.

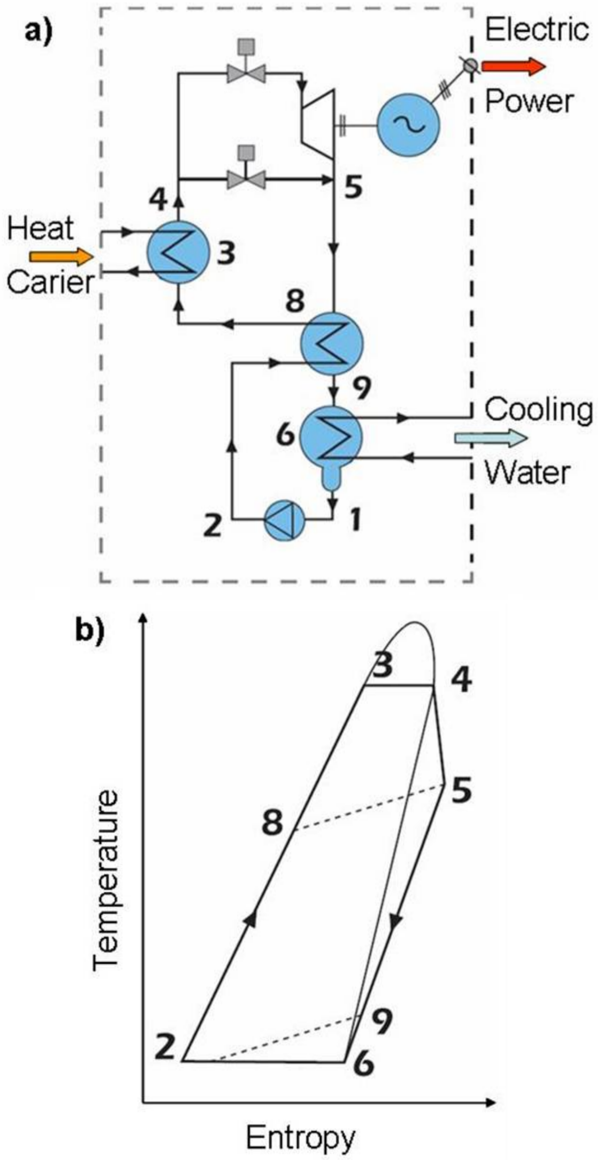

Figure 2: ORC based power system a)–schematic layout, b)–T-S diagram (by Turboden)

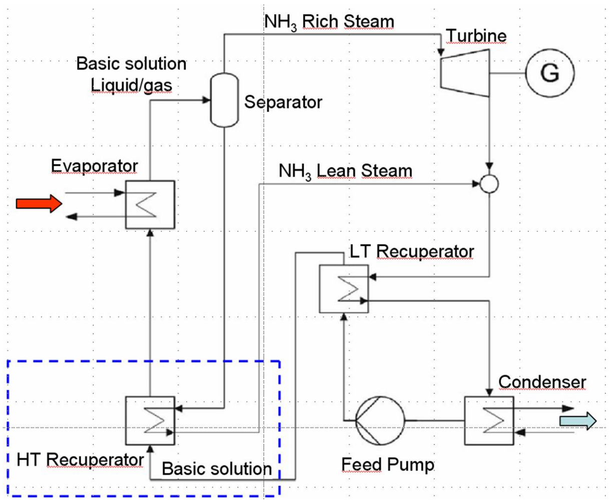

Figure 3: Schematic layout of KC based system

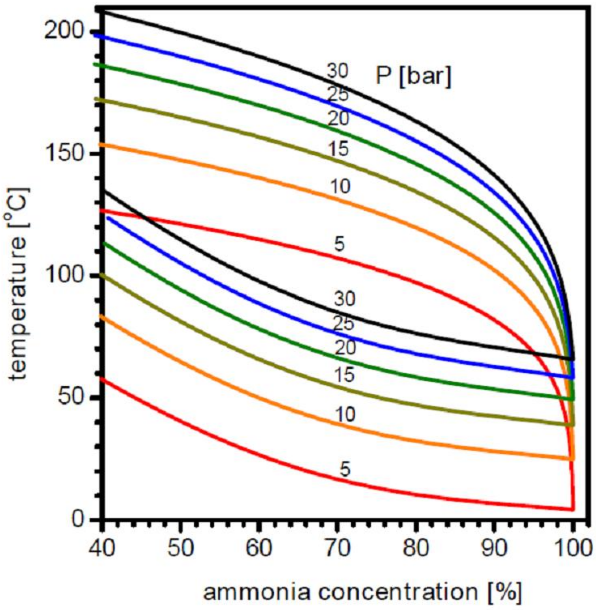

Figure 4: The effect of ammonia concentration and pressure on mixture saturation temperature Kim et al. [6]

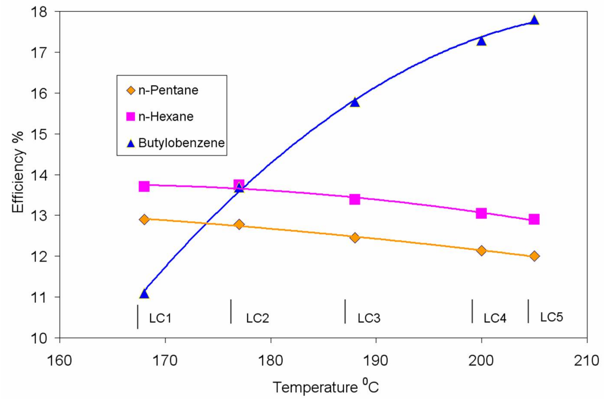

Figure 5: Optimized ORC system efficiency for analyzed working fluids

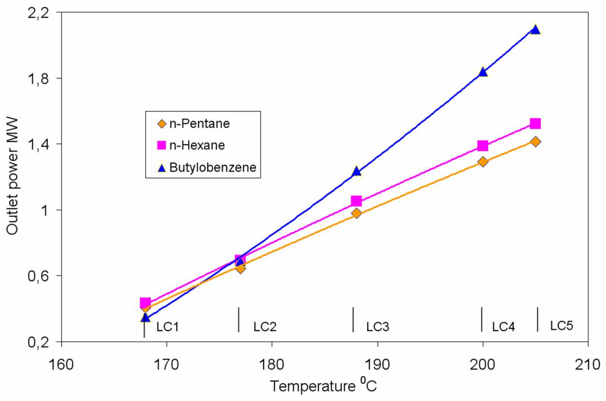

Figure 6: Optimized ORC turbine outlet power for analyzed working fluids

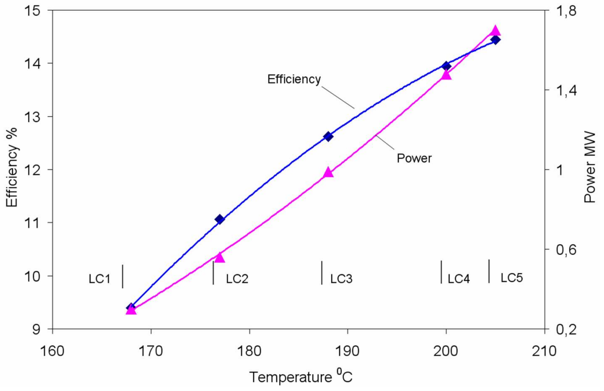

Figure 7: Efficiency and turbine outlet power of Kalina cycle