CHEMICAL ENGINEERING TRANSACTIONS
VOL. 35, 2013
Guest Editors: Petar Varbanov, Jiří Klemeš, Panos Seferlis, Athanasios I. Papadopoulos, Spyros Voutetakis
Copyright © 2013, AIDIC Servizi S.r.l.,
ISBN 978-88-95608-26-6; **ISSN** 1974-9791

A publication of
AIDIC
The Italian Association
of Chemical Engineering
www.aidic.it/cet

DOI: 10.3303/CET1335037

Low Heat Power Generation System

Kazuo Matsuda

Chiyoda Corporation, Sustainable Business Development Section, 4-6-2, Minatomirai, Nishi-ku, Yokohama, 220-8765, Japan
kmatsuda@ykh.chiyoda.co.jp

Statistically low-grade heat below about 150 °C, which is the temperature range of waste heat emitted by industry, has so far not usually been recovered and utilized. A large amount of such unused heat is either exhausted to the atmosphere, discarded to cooling water or otherwise lost. When thermal engines such as the Rankine and Kalina cycles are used to generate power from low-grade heat, the second law of thermodynamics binds the conversion efficiency of low temperature heat into work or electricity. The Kalina cycle could achieve higher efficiency in producing acceptable power at the given process conditions than the Rankine cycle because it used a high concentration ammonia-water mixture as a secondary fluid and could be fitted to the falling temperature of a heat source with a finite heat capacity. A low heat power generation (LHPG) system based on the concept of the Kalina cycle has been successfully developed and implemented in Japan.

The overhead vapor from the fractionator was originally cooled down from about 120 °C by many air-fin coolers and further cooled by cooling water coolers but now, instead of the low-grade heat generated by the existing system being discarded to atmosphere or water as waste heat, the LHPG system can utilize such heat as the hot heat source to generate power. The LHPG system has sturdy and reliable performance and, even with a heavily fluctuating heat source, is under stable and safe operation.

Introduction

The conversion of the fossil fuel into useful work by combustion and thermal engine is subject to the fundamental laws of thermodynamics, which severely limits the efficiency of such unit's operation and results in emission of low-grade heat. Many types of low-grade heat remain unused and discarded in industry where a large amount of heat exists in the range of 100 to 150 °C among other heat range. Such low-grade heat is usually exhausted to atmosphere or discarded through coolers by paying cost. However it has a possibility to be transformed to electricity by using a thermal engine such as the Rankine and the Kalina cycles which are binary systems, so called because they use a second fluid that is heated by the hot heat source. Handayani et al. (2012) reported that in organic Rankine cycle (ORC), ammonia and isobutane had the highest thermal efficiency at 90 °C evaporation temperature among other working fluids

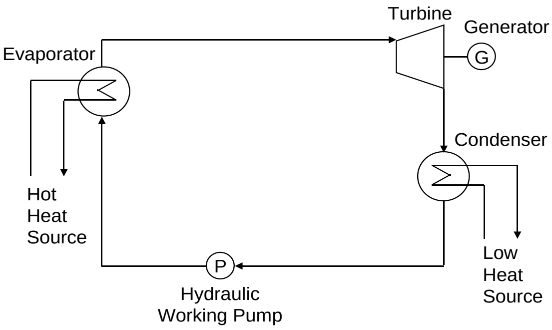

Figure 1: Rankine cycle

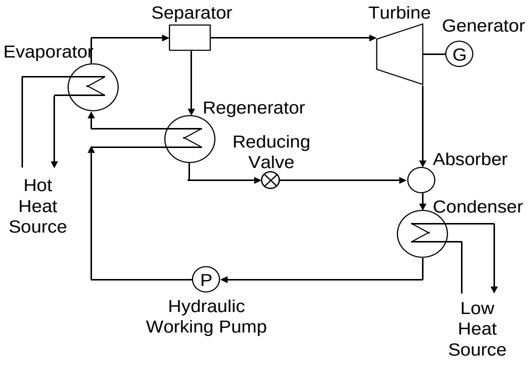

Figure 2: Kalina cycle

Please cite this article as: Matsuda K., 2013, Low heat power generation system, Chemical Engineering Transactions, 35, 223-228
DOI:10.3303/CET1335037

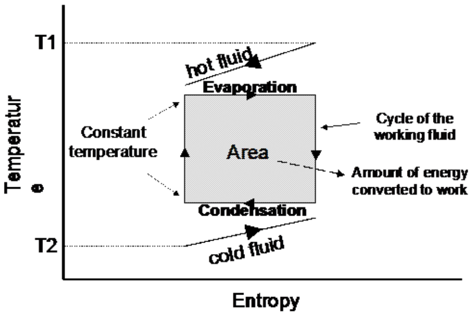

Figure 3: Single substance T-S diagram

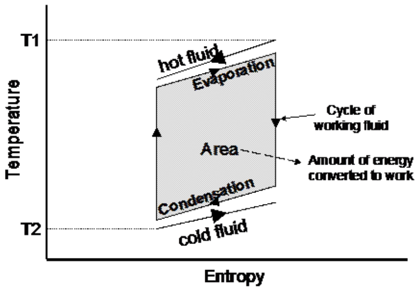

Figure 4: Mixed substance T-S diagram

(R152a, R245fa, R236ea, and R134). And Varga et al. (2012) reported that the most appropriate working fluid from n-pentane, isopentane, n-butane, and isobutene could not be selected at the heat source from 140 °C to 45 °C, based on the techno-economic evaluation of ORC. This paper studied that the principle of thermal engine, which was able to generate power by using low-grade heat, and the efficiency of both Kalina and Rankine cycles at around the temperature (120 °C) of the overhead vapor from the fractionator in a refinery. As the heat source of the overhead vapor was heavily fluctuated, it was necessary to develop the countermeasure.

1. Thermal engine

A thermal engine operated by low-grade heat often uses the binary cycle to generate power. The binary system utilizes a secondary working fluid, such as ammonia, isobutane, isopentane or HFC (hydrofluorocarbon), which has a low boiling point and high vapor pressure at low temperature as compared to steam.

1.1 Organic Rankine cycle

The Rankine cycle is a mathematic model that is used to predict the performance of steam engines. The Rankine cycle is an idealized thermodynamic cycle of a heat engine that converts heat into mechanical work. The Rankine cycle was invented by W. Rankine in the 1850's and is widely used for boiler steam power generation systems. The process system flow of the Rankine cycle is shown in Figure 1. This cycle consists of an evaporator, turbine, condenser, and hydraulic working pump. The working fluid (e.g. water) is sent from the hydraulic working pump to the evaporator, where it evaporates by exchanging with the hot heat source and becomes steam. The steam is sent to the turbine and produces work (electricity). The exhaust steam from the turbine goes to the condenser where it is condensed to water (condensate) by heat exchanging with the low heat source (cooling water). The condensate is then sent back to the evaporator by the hydraulic working pump. In the case of the low-grade heat source, the Rankine cycle uses ammonia and hydrocarbons (e.g. isobutane, isopentane etc) as a working fluid instead of steam and is called the organic Rankine cycle (ORC). The ORC (Dai et al., 2009) uses the same configuration as Figure 1.

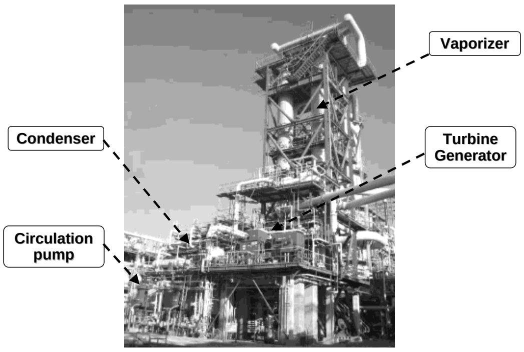

Figure 6: Low heat power generation system

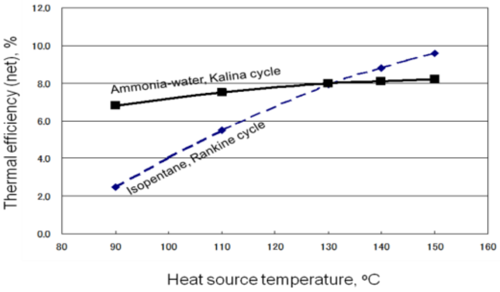

Figure 5: Thermal efficiency

Table 1: Performance

	Design	Summer	Winter	Annual Average	Remarks
Heat input, kW	42,000	39,800	42,300	41,100	
Electricity generated, kW	4,000	2,630	3,790	3,300	
Cycle efficiency					
1) Gross thermal efficiency, %	9.5	6.6	8.9	8.0	
2) Net thermal efficiency, %	8.2	5.2	6.9	6.6	Circulation pump, 560 kW
Annual operating rate, %	97				Periodical maintenance, once in every two years

1.2 Kalina cycle

The Kalina cycle, invented by Kalina (1983), uses a working fluid which is a mixture of two fluids with different boiling points. Since the mixture evaporates gradually over a range of temperatures, more of the heat can be extracted from the heat source than with a pure working fluid. The process system flow of the Kalina cycle is shown in Figure 2. This cycle consists of an evaporator, turbine, condenser, hydraulic working pump, separator, regenerator, reducing valve and absorber, and uses a high concentration ammonia-water mixture as the working fluid. The ammonia-water mixture is sent to the evaporator, heated by the hot heat source where it partially evaporates, and is sent to the separator, where the mixed phase stream is separated into vapor and liquid. The ammonia-rich vapor is sent to the turbine and produces work (electricity). The liquid (water-rich liquid) is cooled at the regenerator, reduced in pressure by the reducing valve and is then sent to the absorber, where the exhaust gas from the turbine is mixed and absorbed into to the cooled liquid. After passing through the absorber, the stream is sent to the condenser, where it is cooled by the low heat source (cooling water) and condensed to a full liquid phase (the high concentrated ammonia-water mixture). When the exhaust gas is absorbed by the cooled liquid, the volume flow rate of the exhaust gas is reduced, which leads to an increase in the pressure drop between the inlet and outlet of the turbine and in power generation. The hydraulic working pump then sends the ammonia-water mixture back to the evaporator through the regenerator.

1.3 Thermodynamic evaluation

The Rankine cycle uses a single substance such as 100 % ammonia, isobutane or isopentane as the working fluid, whereas the Kalina cycle uses an ammonia-water mixed substance. The T-S diagram (Temperature - Entropy Diagram) for the single substance fluid is shown in Figure 3 and that for the mixed substance fluid in Figure 4.

For a single substance fluid, a phase change occurs at constant temperature such as evaporation and condensation, as shown in Figure 3. However, as the mixed substance fluid is heated by hot fluid evaporation takes place gradually and the temperature of the mixed substance fluid, likewise, gradually increases. As the mixed substance fluid is cooled by cold fluid, it gradually condenses and the temperature of the mixed substance fluid also gradually decreases. Thus the mixed substance fluid can be

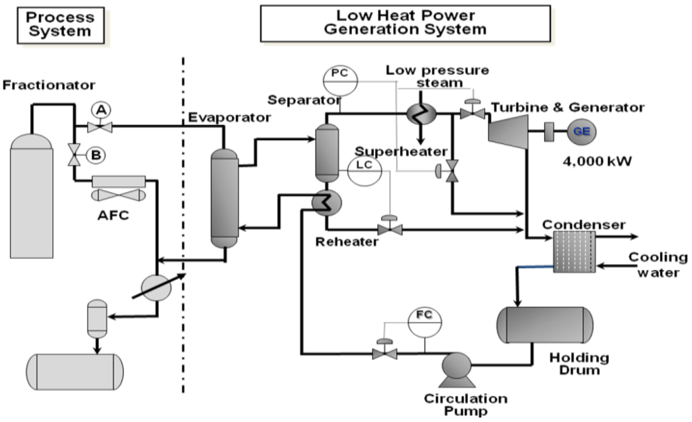

Figure 7: Process flow of low heat power generation system

fitted to the falling temperature of the hot fluid and to the climbing temperature of the cold fluid as shown in Figure 4.

The T-S diagrams can show the essential difference between the Rankine cycle and the Kalina cycle in consideration of the performance of the heat-to-power conversion efficiency based on the thermal engine. The gray square in Figure 3, shows the area where the amount of energy is converted to work (power) for the single substance fluid. On the other hand, the gray area for the mixed substance fluid is larger than that for the single substance fluid because the cycle lines at evaporation and condensation are fitted to the hot and cold fluids. Therefore the mixed substance fluid leads to higher efficiency power generation from heat than does the single substance fluid.

In this way, the Kalina cycle utilizes the non-isothermal evaporation and condensation characteristics of the mixed ammonia-water substance fluid. Furthermore it is possible to optimize the concentration of ammonia in the water as appropriate according to the temperature condition of the hot fluid.

Kalina and Rankin cycles were studied in Figure 5 by a process-simulation (VMGsim ver.7.0, VMG) to compare the net thermal efficiency in various temperature conditions of the heat source. The net thermal efficiency was to subtract the power for hydraulic working pump from the generated power at the turbine. The study constraints were the following: constant quantity of the heat input, minimum temperature approach was 10 °C for both the evaporator and condenser, inlet temperature of cooling water for the condenser was 25 °C. As can be seen in Figure 5, Kalina cycle which used the working fluid of ammonia-water, showed higher efficiency at less than 130 °C, but lower efficiency at more than 130 °C, comparing to ORC which used isopentane. It was found that the Kalina cycle had a favorable operating temperature condition of the heat source to produce higher performance than the Rankine cycle.

2. Implementation of low heat power generation system

Fuji Oil Co. Ltd. (FOC), a company located in the Tokyo bay industrial area in Japan, has many fractionators in its refineries, one of which has a large heat duty in its overhead cooling system. The overhead vapor at 116 °C was cooled down by numerous air-fin coolers and further cooled by cooling water coolers. The low-grade heat in this system was discarded as waste heat to atmosphere and water. FOC decided to utilize such heat and generate electric power by using a thermal engine, which would allow the company to reduce the amount of purchased power. FOC undertook a study and confirmed that it was possible to provide higher power generation efficiency with the Kalina cycle at the temperature conditions of the overhead vapor than with the Rankin cycle, judging from the result of Figure 5. Eventually FOC developed an LHPG system to utilize the heat (116 °C) that had previously been discarded by the air-fin coolers. The LHPG system has a multi-stage structure as shown in Figure 6, which was required because the plot area for the LHPG system was limited (20 m x 24 m) and the LHPG system utilized a high elevation vapor line for the evaporator.

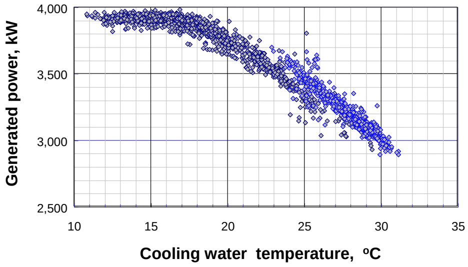

Figure 8: Generated power with cooling water temperature

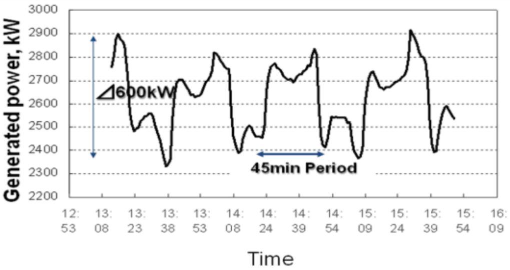

Figure 9: Power generation along with fluctuating heat source

2.1 The process flow of low heat power generation system

Instead of the overhead vapor being cooled conventionally by air fin coolers (from 116 °C to 73 °C), an LHPG system was introduced to utilize such heat as the hot heat source, as shown in Figure 7. The overhead vapor was introduced in two parallel sets of evaporators, the high concentration ammonia-water mixture of working fluid heated and vaporized at a high pressure of approximately 3 MPaG. After the separator, a high-pressure ammonia-rich vapor was introduced into the turbine to generate 4 MW of electricity. It should be noted that before entering the turbine generator, the high-pressure ammonia-rich vapor was heated at the superheater by low-pressure steam. The vapor needs to be superheated to increase its temperature which, consequently, reduces the amount of the liquid drop entrainment which otherwise would cause erosion in the turbine. In summer, low-pressure steam often becomes surplus in a site and purchased power becomes expensive. This superheater in the LHPG system is able to increase the power generation and reduce the need for purchased power. The function of the absorber in Figure 2 was built in the condenser of the LHPG system in Figure 7 to reduce the cost.

2.2 Operation result

The performance of the LHPG system is summarized in Table 1, which shows not only the design performance but also the operating performance. The LHPG system was designed to attain 4,000 kW of power generation and 9.5 % of gross thermal efficiency. In actual operation it attained 3,300 kW of power generation and 8.0 % of gross thermal efficiency in full-year average. Table 1 shows that the generated power was lower in summer than in winter. Figure 8 shows that the generated power changes with the cooling water temperature. The cooling water is supplied to the condenser that cools the exhaust gas from the turbine. As the cooling water temperature becomes lower, the saturated condition (bubble point) of the exhausted gas becomes lower which results in increase in a thermal pressure drop around the turbine and in power generation. Table 1 and Figure 8 lead to the understanding that the power generation performance of the LHPG system is subject to the air temperature because the cooling water temperature relies on the air temperature.

3. Discussions

3.1 Exergy recovery

The LHPG system extracted heat from the low-grade heat and transformed it into work. As can be seen in Table 1, the gross thermal efficiency was 9.5 % in the design condition. The LHPG system was studied if there was any potential for further improvement. In general, energy conversion efficiency is the ratio between the useful output of a device and the input, in energy terms. Heat engines transform thermal energy or heat, Qin, into mechanical energy or work, Wout. The thermal efficiency of a heat engine is the percentage of heat energy that is transformed into work. Thermal efficiency is defined as below.

$$\text{Thermal efficiency} = W_{out} / Q_{in} \quad (1)$$

Table 1 shows the gross thermal efficiency of LHPG system based on Eq(1). Meanwhile it was considered that the amount of the work extracted from the low-grade heat inherently was small and it was difficult to improve the thermal efficiency any further (Galanis et al. 2009). Thus the second law of thermodynamics was studied to evaluate the performance of the LHPG system by using the Carnot efficiency based on Carnot's theorem. The Carnot efficiency (Esposite et al. 2010 and Van den Broeck 2005) is:

$$\text{Carnot efficiency} = 1 – TC / TH \quad (2)$$

where T_H: the heat enters the engine

T_C: the temperature of the environment into which the engine discharges its waste heat

It is not possible for any device to exceed this efficiency when converting heat into mechanical energy. The performance of the LHPG system was evaluated by using Eq(2) and the following conditions. The heat source of the overhead vapor from the fractionator was cooled down from 116 °C to 73 °C by the evaporator in LHPG system. This means that overhead vapor in the range from 116 °C to 73 °C heats the engine gradually. The arithmetic mean temperature of 94.5 °C, in between 116 °C and 73 °C, was used for $T_{H.}$ and the standard condition, 25 ^{o}C, was used for T_C. The Carnot efficiency was then calculated to 0.1891 as exergy ratio. The heat duty of the evaporator heated by the overhead vapor was 42,000 kW and consequently its exergy was calculated to 7,972 kW. This was the ideal power existing in the overhead vapor from 116 °C to 73 °C, which heated the LHPG system. Eventually the LHPG system was able to extract the exergy from the low-grade heat, convert it and produce 4,000 kW of the power. It was therefore confirmed that the exergy recovery ratio of the LHPG system was able to attain 50.4 %. It was considered that the LHPG system had an excellent high performance in exergy recovery compared with the average automobile engine (less than 35 %).

3.2 Operation reliability

The heat source for the LHPG system was the overhead vapor but it fluctuated heavily, swinging from 80 % to 100 % every 45 min, and caused the heat duty of the overhead vapor to fluctuate accordingly. However the LHPG system was able to follow the severe fluctuations and generate power continuously and safely. Figure 9 shows that the generated power from the LHPG system was able to produce power along with a heavy fluctuating heat input. This demonstrated that the LHPG system was sturdy and little affected even with the heavy disturbance despite the working fluid circulating in a closed loop system. With such high reliability, the LHPG system was able to attain unmanned operation.

The annual operating rate of the LHPG system in Table 1 was established in 97 %, which was very high compared to the other renewable energy systems such as a wind and solar power that showed 20 % at most. This demonstrated that the LHPG system was highly reliable in operation as well.

4. Conclusions

The world's first low-heat power generation (LHPG) system to be used in a refinery was developed and implemented in Japan. It was possible for the LHPG system in actual operation to attain 3,300 kW of power generation and 8.0 % of gross thermal efficiency in full-year average, notwithstanding that the low-grade heat less than 120 °C contained a small amount of work originally. From the thermodynamic point of view, the LHPG system was found to attain 50.4 % in the exergy recovery ratio, which is considered to be supremely high performance in exergy recovery when compared with the efficiency of the average automobile engine of less than 35 %. The LHPG system also has sturdy, reliable performance even with a heavily fluctuating heat source and has been under stable and safe operation. The high reliability of the LHPG system was able to attain unmanned operation as well. Low-grade heat of around 100 °C exists not only in industrial waste heat from refineries, steel plants, and cement factories but also in geothermal heat. There are many areas where the LHPG system can be applied to. Further considerations in industrial application would see the LHPG able to attain higher power outputs by applying cold heat from LNG plants as a coolant for the condenser.

Acknowledgements

The author thanks Fuji Oil Co. Ltd. for supporting this study.

References

Dai Y., Wang J., Gao L., 2009, Parametric optimisation and comparative study of organic Rankine, Energy Conv. and Mgmnt, 50 (3) 576-582.

Esposito M., Kawai R., Lindenberg K., Van den Broeck C., 2010, Efficiency at maximum power of low-dissipation Carnot engines, Phy. Rev. Lett. 105, 150603.

Galanis N., Cayer E., Roy P., Denis E.S., Desilets M., 2009, Electricity generation from low temperature sources, J. App. Fluid Mech. 2 (2) 55-67.

Handayani T., Harvey A. P., Dalton J. and Reay D., 2012, Selection of the optimum working fluids in organic Rankine cycles using topsis, Chem Eng Trans, 29, 139-144.

Kalina A.I., 1983, Combined cycle and waste heat recovery power systems based on a novel thermodynamic energy cycle utilizing low-temperature heat for power generation, American Soc. of Mech. Eng, Joint power generation conference, Indianapolis, USA, 25 Sep, 83-JPGC-GT-3.

Van den Broeck C., 2005, Thermodynamic efficiency at maximum power, Phy. Rev. Lett. 95,190602.

Varga Z., Rabi I. and Farkas C., 2012, Waste heat recovery with Organic Rankine Cycle in the petroleum industry, Chem Eng Trans, 29, 301-306.