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Low heat power generation system

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HIGHLIGHTS

- The low-heat power generation (LHPG) system in a refinery was developed in Japan.
- The low-grade heat was less than 120 °C from the overhead vapor.
- Average 8.0% of gross thermal efficiency in full-year was attained.
- 50.4% in the exergy recovery ratio was attained.
- Sturdy and reliable performance even with a heavily fluctuating heat source.

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ABSTRACT

Large quantities of low-grade heat, especially below about 150 °C, are generated within many process industries and so far it is either exhausted to the atmosphere, discarded to cooling water or otherwise lost. The recovery of low-grade heat is important for improving process efficiency, but it is often difficult to find an appropriate internal heat load. There is an alternative solution using thermal engines to convert the low-grade heat into electricity for use on site.

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 than the Rankine cycle in producing acceptable power at the given process conditions because it uses 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, by utilizing the low-grade heat of the overhead vapor from the fractionator, at about 120 °C, which could achieve 3300 kW of power generation and average 8.0% of gross thermal efficiency in full-year. In other words 50.4% in the exergy recovery was achieved.

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1. Introduction

Nowadays, energy efficiency improvement has become one of most important key factors in the heavy chemical industry, with further energy saving efforts being perceived as the way forward to reach the goal and conserve the environment at a global level. Carbon dioxide makes up more than 90% of GHG and approximately 90% of this is emitted by combustion of fossil fuels, which means that more than 80% of GHG emissions are caused by using fossil fuel as a source of energy. Today, the mainstream opinion accepts that energy efficiency will help to reduce GHG emissions (Thernesz et al. [1]). Additionally, an increase in energy efficiency will contribute to decreasing fuel costs and increasing profitability (Varga et al. [2], Kapil et al. [3]). A huge amount of heat is wasted through air coolers and water coolers to cool streams in heavy chemical processes with temperatures lower than 150 °C.

The conversion of 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 units' operation and results in emission of low-grade heat. Many types of low-grade heat remain unused and discarded in industry (chemical plants, steel plants, cement plants, etc) where a large amount of heat exists in the range of 100–150 °C as well as in other heat ranges. Such low-grade heat, not only found in industry but also in geothermal, solar thermal power, engine exhaust gases, and domestic boilers, is usually exhausted to atmosphere or discarded through coolers. However it could be transformed into electricity by using a thermal engine such as the Rankine and the Kalina cycles which are binary

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Nomenclature

LHPG	low heat power generation

systems, so called because they use a second fluid that is heated by the hot heat source. Papadopoulos et al. [4] developed a systematic approach to the design and selection of working fluids for the organic Rankine cycle (ORC) processes. Quoilin et al. [5] developed the thermodynamic model of the ORC to select the optimal working fluid. Handayani et al. [6] reported that in the ORC, ammonia and isobutane had the highest thermal efficiency at 90 °C evaporation temperature among other working fluids (R152a, R245fa, R236ea, and R134). Varga et al. [7] 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. Rodríguez et al. [8] offered the appropriate working fluids which were R290 for the ORC and 84 wt% of ammonia–water mixture for Kalina cycle. Fu et al. [9] offered the appropriate working fluids which were R236fa for the ORC and 80 wt% of ammonia–water mixture for Kalina cycle. 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 of the overhead vapor from the fractionator in a refinery (120 °C). As the heat source of the overhead vapor fluctuates heavily, it was necessary to develop a countermeasure.

2. 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.

2.1. Organic Rankine cycle

The Rankine cycle is a mathematic model that is used to predict the performance of steam engines. The Rankine cycle, which was invented by W. Rankine in the 1850's and is widely used for boiler steam power generation systems, is an idealized thermodynamic cycle of a heat engine that converts heat into mechanical work. The heat within a Rankine cycle is supplied externally to a closed loop, which usually uses water as the working fluid. The process system flow of the Rankine cycle is shown in Fig. 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.

A Rankine cycle that employs water as a working fluid is not economical when recovering heat below 370 °C (Walsh and Thornley [10]). For that reason organic chemicals or refrigerants are often substituted for water, resulting in what has been termed the Organic Rankine Cycle (ORC). The ORC (Dai et al. [11]) uses the same configuration as Fig. 1. The choice of working fluid (ammonia, isobutane, isopentane and etc) will depend on a number of operational parameters such as thermodynamic performance, stability, flammability etc. (Hung et al. [12]). The ORC has been used to produce the power with the low-grade heat from geothermal heat in USA, New Zealand, Germany, and Philippines [13].

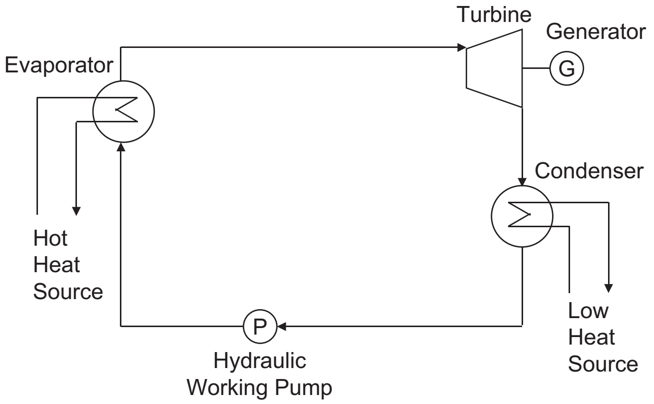

Fig. 1. Rankine cycle.

2.2. Kalina cycle

The Kalina cycle, invented by Kalina [14], 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 Fig. 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 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

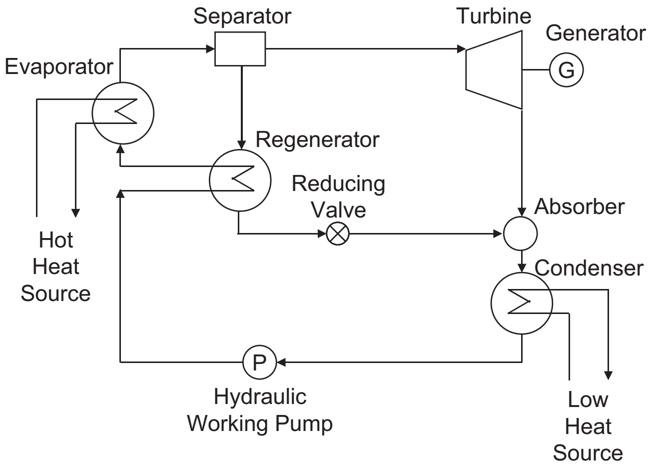

Fig. 2. Kalina cycle.

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