Method for customizing an organic Rankine cycle to a complex heat source for efficient energy conversion, demonstrated on a Fischer Tropsch plant

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HIGHLIGHTS

▶ Methods for customizing organic Rankine cycles are proposed.
▶ A set of cycle modifications help to target available heat sources.
▶ Heat sources with complex temperature–enthalpy profiles can be matched.
▶ Significant efficiency improvements can be achieved over basic ORC's.

ARTICLE INFO

ABSTRACT

Organic Rankine cycles (ORCs) provide an alternative to traditional steam Rankine cycles for the conversion of low grade heat sources into power, where conventional steam power cycles are known to be inefficient. A large processing plant often has multiple low temperature waste heat streams available for conversion to electricity by a low temperature cycle, resulting in a composite heat source with a complex temperature–enthalpy profile. This work presents a set of ORC design concepts: reheat stages, multiple pressure levels, and balanced recuperators; and demonstrates the use of these design concepts as building blocks to create a customized cycle that matches an available heat source. Organic fluids are modeled using a pure substance database. The pinch analysis technique of forming composite curves is applied to analyze the effect of each building block on the temperature–enthalpy profile of the ORC heat requirement. The customized cycle is demonstrated on a heat source derived from a Fischer Tropsch reactor and its associated processes. Analysis shows a steam Rankine cycle can achieve a 20.6% conversion efficiency for this heat source, whereas a simple organic Rankine cycle using hexane as the working fluid can achieve a 20.9% conversion efficiency. If the ORC building blocks are combined into a cycle targeted to match the temperature–enthalpy profile of the heat source, this customized ORC can achieve 28.5% conversion efficiency.

1. Introduction

The concept of using organic working fluids in a Rankine cycle, known as an organic Rankine cycle (ORC), dates to at least 1962, when Tabor et al. patented vapor turbines capable of extracting power from organic working fluids [1]. Fig. 1a is a schematic diagram of a basic ORC, and Fig. 1b is a *T–s* plot of the fluid states for this basic cycle, with the loci of saturated states for the drying fluid represented by a dotted line. A saturated liquid at State 1 is pumped to high pressure at State 2 and then preheated to State 4 and boiled along a high pressure isobar. No condensation occurs when the fluid is expanded directly from a saturated vapor at State 5 to a superheated vapor at State 6. This occurs because the fluid shown is of a drying nature, meaning that the saturated vapor curve has a region of positive slope on a temperature vs. specific entropy (*T–s*) diagram, $(dT/ds)_{sat} > 0$. This drying characteristic makes many organics advantageous over water, which is not of a drying nature. In an expansion process for steam from a saturated vapor state, condensation occurs which degrades expander efficiency and causes equipment wear. Thus, the steam must be superheated before being expanded to low pressure to avoid condensation. An ORC operating with a drying fluid does not require superheat to avoid the condensation process.

In recent years, organic Rankine cycles have received much attention for their ability to efficiently convert low temperature heat sources into electrical power. Today, multiple companies offer ORC systems capable of generating power from heat sources which

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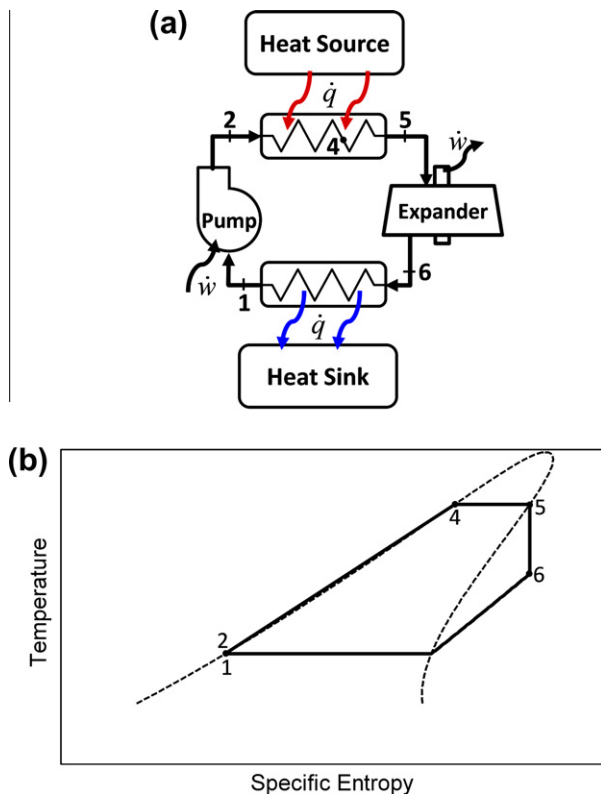   [1] Tel.: +1 617 253 2273; fax: +1 617 258 7754.

Fig. 1. (a) Schematic diagram of a basic ORC. (b) T–s plot of basic ORC cycle states for a drying working fluid.

range from less than 100 °C up to 400 °C [2]. These systems target low temperature heat sources including geothermal, waste heat, and solar thermal, biomass, and micro-combined heat and power applications [3]. Worldwide, ORC plants have a total installed capacity of over 1000 MW, with plants that range in size from hundreds of watts up to hundreds of megawatts [4]. Organic Rankine cycles are a maturing technology with great potential to generate electricity from low-grade heat sources.

Extensive effort has gone into identifying appropriate working fluids for ORC's. Thermodynamic properties, cost, chemical stability, safety, and environmental impact are all necessary considerations when choosing a working fluid. In 1964, Tabor and Bronicki originally proposed molecular weight, boiling point, chemical stability, and the shape of the T–s diagram as the most important fluid criteria for an organic Rankine cycle [5]. Many other selection criteria have been proposed since then, and Chen et al. provide a useful overview of the organic fluid research to date [6]. Much ORC research has focused on comparing the merits of different working fluids in a simple Rankine cycle configuration.

Quoilin et al. attest that simplicity is a primary advantage of ORC systems, as they propose control strategies for a simple ORC system targeting a time-invariant heat source [7]. At the same time, high fuel costs and, more recently, environmental concerns increasingly provide motivation for waste heat recovery applications [8]. As fuel costs and environmental concerns increase in the future, more complex waste heat recovery systems will become justifiable.

In this work, methods are proposed for configuring an ORC to fit whatever heat source is available. These design methods are most advantageous for low-grade heat sources with complex heating profiles. Many process plants have multiple streams of low-grade heat available for use in low temperature cycles. Combined, these streams form complex temperature–enthalpy curves which are difficult to thermally match with a standard cycle. In this work, the effects of ORC cycle modifications are demonstrated on a heat source derived from a Fischer Tropsch synthesis plant, and pinch analysis techniques are employed to calculate the best possible output for the customized organic Rankine cycles.

2. Methods

2.1. Pinch analysis methods

Pinch analysis was popularized in the 1970s as a method of setting design targets for heat exchanger networks in complex chemical process plants [9]. Since then it has been expanded to wider use as a design tool for integrated energy and process systems. A chemical processing plant contains many streams which flow between various processes within the plant as they are converted from feed stock into products and byproducts. Each process has temperature and heat requirements such that streams must be heated and cooled as they pass through the plant. Using pinch analysis techniques, waste heat streams in a process plant are combined into one composite heat source curve representing the entire plant.

For illustrative purposes, we have chosen the heat source for this work to be a Fischer Tropsch (FT) plant as modeled in an Aspen Plus® simulation of a coal to liquids plant that was developed as part of the BP-MIT conversion research program. This plant converts synthetic gas (syngas) into liquid fuels and waxes, with a total output of 1950 tons per day (TPD) of hydrocarbons. The general methods demonstrated using this heat source can be extended to other heat sources. Fig. 2 is a schematic diagram of the FT plant showing the reactor and its associated processes. A feed stream of syngas is preheated from 81 °C to 230 °C by heat transfer from the product stream that exits the FT reactor. The stream then undergoes Fischer Tropsch synthesis, an exothermic reaction that rejects 309.0 MW of heat rate at a constant temperature of 240 °C to the organic Rankine cycle. The product stream then leaves the reactor and enters a heat exchanger where it cools from 240 °C down to 182 °C to preheat the stream entering the reactor. A subsequent heat exchanger cools the stream from 182 °C down to 120 °C to separate the light gases from the heavy long chain hydrocarbons, providing an additional 51.8 MW of heat to the organic Rankine cycle. Heavy products are passed to the distiller, while the light gases are recycled to increase the percentage of syngas that is converted into liquid fuels in the plant. The recycle stream passes through an auto-thermal reformer, where some methane is oxidized to achieve a temperature of 950 °C and break down the recycle stream into carbon monoxide, carbon dioxide, hydrogen, and steam. This stream exiting the auto-thermal reformer must then be cooled from 950 °C down to 100 °C before it can pass through an amine separator that removes the carbon dioxide. The high temperature heat (>240 °C) is assumed here to be used for steam generation, and the low temperature heat (<240 °C) is assumed available for an organic Rankine cycle. This is a convenient cut-off temperature because it matches the temperature in the FT reactor, and because many organic working fluids become chemically unstable at higher temperatures. The recycle stream cooling from 240 °C down to 100 °C provides an additional 71.0 MW of heat. Finally, the recycle stream is passed through an amine separator where carbon dioxide is removed, and the recycle stream is recombined with the syngas feed stream.

Using pinch analysis techniques, the temperature vs. change in enthalpy per time ($T-\Delta\dot{H}$) profiles of individual process streams are combined into a composite heating curve. This is achieved by summing the enthalpy flow rates of all the streams at each temperature. Fig. 3a is a plot of $T-\Delta\dot{H}$ profiles for the three streams