Journal of Environmental Management xxx (2017) 1–11

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

A multi-objective optimization approach for the selection of working fluids of geothermal facilities: Economic, environmental and social aspects

Juan Martínez-Gomez [a], Javier Peña-Lamas [b], Mariano Martín [b, *], José María Ponce-Ortega [a]

[a] Chemical Engineering Department, Universidad Michoacana de San Nicolás de Hidalgo, Morelia, Michoacán, 58060, Mexico
[b] Department of Chemical Engineering, University of Salamanca, 37008, Salamanca, Spain

ARTICLE INFO

Article history:
Received 21 December 2016
Received in revised form
24 June 2017
Accepted 1 July 2017
Available online xxx

Keywords:
Geothermal facilities
Safety
Economic and environmental objectives
Optimal selection
Multi-objective optimization

ABSTRACT

The selection of the working fluid for Organic Rankine Cycles has traditionally been addressed from systematic heuristic methods, which perform a characterization and prior selection considering mainly one objective, thus avoiding a selection considering simultaneously the objectives related to sustainability and safety. The objective of this work is to propose a methodology for the optimal selection of the working fluid for Organic Rankine Cycles. The model is presented as a multi-objective approach, which simultaneously considers the economic, environmental and safety aspects. The economic objective function considers the profit obtained by selling the energy produced. Safety was evaluated in terms of individual risk for each of the components of the Organic Rankine Cycles and it was formulated as a function of the operating conditions and hazardous properties of each working fluid. The environmental function is based on carbon dioxide emissions, considering carbon dioxide mitigation, emission due to the use of cooling water as well emissions due material release. The methodology was applied to the case of geothermal facilities to select the optimal working fluid although it can be extended to waste heat recovery. The results show that the hydrocarbons represent better solutions, thus among a list of 24 working fluids, toluene is selected as the best fluid.

1. Introduction

The use of renewable resources for energy production has been presented as a clean alternative to the use of fossil-based resources. Intensifying the use of natural resources has as main advantage the reduction of the environmental impact (Gunther and Hellmann, 2017), by reducing or mitigating the emission of pollutants (Wolf et al., 2016). Nowadays, the most used renewable resources are: Hydroelectric, wind, solar, bioenergy and geothermal. Of these, geothermal energy produces less than 1% of the world's energy consumed, despite its wide availability, which is of 43×10^6 EJ (World Energy Council, 2016). In the American continent, countries like USA and Mexico have potential reserves that have not yet been widely exploited (Gutierrez-Negrín and Lippmann, 2016). In Asia, Indonesia has a high reserve potential representing 40% of world reserves (Nasruddin et al., 2016), meanwhile China has been a pioneer in the use of its resources and today presents an installed capacity of 27.78 MWe (Zhu et al., 2015). The technologies used for the conversion of geothermal to electrical energy depend on the type of source. For sources of high enthalpy (>180 °C), steam is used directly to produce power (direct-steam, Phair, 2016). If the temperature is between 101 and 180 °C, the reservoir is referred to as medium enthalpy and in this case a binary cycle is used (Spadacini et al., 2016). The Organic Rankine Cycle (ORC) technology is often used as an interface in energy conversion from medium enthalpy sources to allow for an economic exploitation of these resources. Note that this technology is also used for the production of power from waste heat in general. However, the efficiency of the ORCs is currently still low and improving it depends mainly on the proper selection of the working fluid (Hung et al., 1997). The selection of the working fluid is a complicated task, because the list of candidates is large. Each fluid has different thermodynamic properties, which have a direct impact on the overall efficiency of the cycle, such is the case of molecular structure, which has a direct effect on

* Corresponding author.
E-mail address: mariano.m3@usal.es (M. Martín).

http://dx.doi.org/10.1016/j.jenvman.2017.07.001
0301-4797/

efficiency, because high efficiencies are favored by compounds with double bounds or cyclic (Zhai et al., 2014). In addition, the critical temperature is not significant in the thermal efficiency of each working fluid (Liu et al., 2004). The study of ORCs has focused on the selection of the working fluid and the design of the cycle, based on the use of methodologies that rely on the search of the fluid that provides the best energy efficiency. In this regard, Roy and Misra (2012) proposed a parametric optimization for the selection of the working fluid considering only energy efficiency. Borsukiewicz-Gozdur and Nowak (2007) presented a thermodynamic analysis, applied to natural and synthetic refrigerants and mixtures, to select the working fluid that shows the highest efficiency. Drescher and Brüggemann (2007) concluded that alkylbenzenes provide the highest efficiencies in biomass power and heat plants. Saleh et al. (2007) proposed an approach for the selection of the working fluid based solely on the thermodynamic aspect. However, the fluid selection should not only be based on the cycle economy, safety and environmental impact should also be taken into account simultaneously. The working fluids used for producing energy from geothermal sources belong to two chemical groups, hydrocarbons and refrigerants. Each group presents advantages and disadvantages. On the one hand, refrigerants show significant effects on the environment, presenting high values for ozone depletion potential (ODP) and global warming potential (GWP) (Saleh et al., 2007), the first related to the damage to the ozone layer and the second with global warming, since most of these belong to the family of freons. On the other hand, hydrocarbons have higher values of risk, due to their explosive and flammable nature. Therefore, the chemical nature of these working fluids requires that the selection and design of the cycle takes into consideration sustainability and safety issues. In this sense, several strategies have been proposed that consider the selection of working fluid considering thermodynamic efficiency, indicators related to environmental damage and safety. Some of those works consider formulations applied to the selection of the working fluid in an ORC for solar energy conversion. In these formulations, safety is shown as a relative (qualitative) measure between each compound (Tchanche et al., 2009). Other studies consider the calculation of the safety issues through the use of indexes referring to the toxicity and flammability of working fluids (Papadopoulos et al., 2010). In refrigeration, where ORCs are also frequently used, multi-objective optimization approaches have been presented to consider economic, environmental and safety issues for the optimization of the cycle. The developed model is used to decide between only two working fluids. In that work, the risk is based on the quantitative risk analysis (QRA), which is performed prior to optimization and it is obtained in economic terms (Eini et al., 2016). The importance of the study of ORC technology lies on its wide use. It can be used for the production of power from renewable sources (solar power plants) but it can also be used for recovering energy from waste heat sources (Quoilin et al., 2013). The growing use and widespread availability of renewable resources require improved energy conversion processes, thus generating methodologies to ensure the optimum selection for the working fluid and operation of the ORC is necessary. The novelty of the present work consists of presenting a multi-objective approach for selecting the working fluid in ORCs, applied to the particular case of geothermal power plants due to the need for actual operating values and the expectations on this energy source. The proposed approach considers simultaneously economic, environmental and safety objectives. It should be noticed that previously reported approaches have not simultaneously considered these three aspects. The three metrics are function of the operating conditions and the characteristics of the working fluids, in this work the social aspect was considered in terms of risk. This implies modelling a conventional Rankine cycle, where the addressed problem implies the optimal selection of the working fluid and the operating conditions for the cycle.

Fig. 1 shows a simplified scheme of a binary cycle used in the conversion of geothermal energy from medium enthalpy reservoirs into power. It corresponds to a basic flow diagram for ORC's that are reported elsewhere (see for example DiPippo, 2015). The cycle consists of a condenser, a pump, a turbine and a heat exchanger that operates between the working fluid and the water from the geothermal reservoir. The operating conditions of each of the components of the cycle are determined by the working fluid, in such a way that the efficiency of the cycle depends on an appropriate selection. Traditionally, hydrocarbons and refrigerants have been used, selecting the one that provides better energy efficiency. Under these selection criteria, it may be easy to select from an extensive list of hydrocarbons and refrigerants the most appropriate one. However, the concept of sustainability indicates that there are two other selection criteria that must also be considered. If the concept of sustainability is incorporated into the selection of the working fluid, it will be observed that the task is not simple, due to the properties and characteristics of each candidate fluid. On the environmental side, hydrocarbons are more environmentally friendly with respect to refrigerants, which are linked to the damage of the ozone layer. For the social part related to risk, hydrocarbons are more hazardous than refrigerants because they are explosive and flammable (Troynikov et al., 2016). Even choosing between one compound and another from the same group is complicated, due to the difference in the properties of one with respect to another. In this way, the problem to be solved is to find the optimum working fluid considering simultaneously economic, environmental and safety objectives. Next section describes the addressed problem. It is important to mention that, even though the presented methodology is general to any ORC, the correlations obtained are specific for the typical operating conditions of the various fluids, including the heat source. For different applications, the range of operating conditions may differ and the correlations may also be different. Section three shows the results and finally section four presents some conclusions. The work uses as example the geothermal resources in Spain. Among the various regions within the main land almost the most important is the one in Jaca-Sabiñánico, with temperature of about 170–180 °C and depths of about 3500 m–4000 m

2. Methods

In order to simultaneously consider the economic, environmental and safety aspects, a metric has been developed to quantitatively account for the three pillars. The flowchart shown in Fig. 1 is used as the basis for the development of an equation that describes each metric. For a better understanding, we define the sets as follows. J corresponds to the set of equipment that integrates the binary power cycle, I is the set of working fluids which is comprised of hydrocarbons and refrigerants. This section describes in detail the development of each term of the metric. We divide the section into four topics. The first three show the formulation of the terms corresponding to each of the three objectives, safety, economic and environmental ones, and the fourth one presents the solution strategy used to solve the multi-objective optimization problem.

2.1. Safety objective function

Traditionally the social aspect of a project or process is measured in terms of benefits to society, such is the case of jobs creation. Protection to workers as well as to populations that are settled in the surroundings of a chemical process can also be a criterion to account for the social issues of a particular process.