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Transient simulation of a solar heating system for a small-scale ethanol-water distillation plant: Thermal, environmental and economic performance

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ABSTRACT

The thermal, environmental and economic performance of a small-scale ethanol distillation system, where solar energy is used as primary energy source, was studied. Two different concentrations of ethanol at the feed stream (5 wt.% and 10 wt.%) were analysed to obtain a distillate product of 95 wt.% ethanol (hydrous ethanol). Evacuated tube solar collectors (ETC) and parabolic trough collectors (PTC) were considered for the solar heating system. A case of study for a specific geographical place (Monterrey, México) was developed herein to evaluate the solar ethanol distillation system; the results can be extended to other locations, weather conditions and operational parameters. The thermal results from the simulation showed that through an adequate selection of the solar collector area and an appropriate sizing of the different equipment of the solar distillation system, PTC represents a better option where energy savings of 80% and 71% can be achieved for 5 wt.% and 10 wt.% ethanol at the feed stream, respectively. However, the economic feasibility of the solar distillation system is achieved using ETC for a price of hydrous ethanol of 1.75 USD/L and a feed stream of 10 wt.% ethanol, reaching an internal rate of return (IRR) of 18.8% and payback period of 5.2 years. As an important technical result, selected ETC presented advantages over PTC where an average distillate product of 3.6 and 3.4 ml at 95 wt.% ethanol can be obtained per unit of solar energy (kW h) captured per area (m^2) of solar collector using 5 wt.% and 10 wt.% ethanol at the feed stream, respectively (36% more than PTC). The reduction of greenhouse gases (GHG) was of 72.4 kg CO_2/yr per area (m^2) for evacuated tube solar collector (at least 8% more than PTC). These results are considered useful as they would provide valuable information to members of the ethanol distillation industry, the fuel industry, policy makers in renewable energy, and installers.

1. Introduction

It is well known and accepted worldwide that efficient energy usage is one of the most important problems that humanity faces given that consumption is increasing every year to satisfy growing needs and sectors, e.g. transportation, industry, electricity among others. The estimated energy consumption in 2014 was of 13,389 millions of tonnes of oil equivalent (Mtoe) [1]. Fossil fuels (oil, gas and coal) have an intensive participation in energy production due to their availability. However, alternative fuels such as ethanol have been developed and produced in many countries such as Brazil and USA [2] because of sustainability and environmental concerns. Ethanol as a fuel has taken an important place in the energy market especially in the transportation sector since it contributes to reduce the use of fossil fuels and helps mitigate air pollution [3–5]. In order to use ethanol as a fuel it is necessary to have hydrous ethanol at a concentration of at least 95 wt.% [6–8]. This process is typically achieved by simple distillation using different products such as sugar cane, corn, and sorghum. Concentrations greater than 95 wt.% of ethanol need additional process (e.g. membrane distillation) since the solution presents azeotropic behaviour.

Recently, many investigations have been carried out to find out an efficient way to produce ethanol, and most of them have focused their research on the distillation process. Distillation takes up about 70–85% of total energy consumed in ethanol production

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Nomenclature

a_0	intercept of the collector efficiency [–]
a_1, a_2	linear and quadratic coefficients respectively [W/m^2 °C, W/m^2 °C^2]
A_{coll}	solar collector area [m^2]
Cp_w	specific heat capacity at constant pressure of hot water [kJ/kg °C]
E_t	total 95 wt.% ethanol distillate product [L/yr]
ETC	evacuated tube collectors
G	global solar radiation [W/m^2]
Inv	initial investment [USD]
IRR	internal rate of return [–]
LCOE	levelized cost of ethanol at 95 wt.% [USD/L]
n	estimated cycle life [years]
m_D	mass flow rate of distillate product [kg/h]
m_{reb}	mass flow rate in the reboiler [kg/h]
m_w	mass flow rate of hot water [kg/s]
NPV	net present value [USD]
O&M	operation and maintenance
PTC	parabolic trough collector
$\dot{Q}_{aux}$	heat duty in the auxiliary heater [kW]
$\dot{Q}_{coll}$	heat obtained in the solar thermal collectors [kW]
$\dot{Q}_{effec}$	effective solar energy [kW]
$\dot{Q}_{reb}$	input heat duty in the reboiler [kW]
$\dot{Q}_{tk}$	extra heat in the storage tank [kW]
$\dot{Q}_{lost}$	heat lost in the solar heating system [kW]
r	discount rate [%]
REL_D	energy consumption per unit mass of distillate product [MJ/kg]
SF	solar fraction [–]
SPB	simple pay back [years]
t	time of analysis [years]
T_{amb}	average temperature of the environment [°C]
T_{av}	average temperature of the fluid in the solar collector [°C]
T_{aux}	outlet temperature of the fluid in the auxiliary heater [°C]
T_{coll}	outlet temperature of solar thermal collectors [°C]
T_{pump}	outlet temperature in the pump of the solar heating system [°C]
T_{reb}	operational temperature of ethanol – water solution in the reboiler [°C]
T_{tk}	operational temperature in the heat storage tank [°C]
V	volumetric flow rate of the feed stream in the distillation system [L/h]

Greek symbols

η_o	optical efficiency of the solar collector [–]
η_{coll}	solar collector efficiency [–]

[9]. Therefore an improvement in the distillation process would have a significant impact on ethanol production. Solar distillation represents a technique to generate ethanol using the solar thermal radiation as primary source of energy with small fossil fuel consumption, reducing operation costs and production of contaminants, compared to the conventional process [10].

Literature covering solar distillation of ethanol includes the usage of solar stills [11–13], distillation columns [14,15] and membrane distillation [14–16]. Here, simple distillation to obtain ethanol at 95 wt.% is considered.

Distillation columns for separation of aqueous ethanol solutions using solar power have been previously studied by Jorapur and Rajvanshi [9], Vorayos et al. [10], Jareanjit et al. [17] and Vargas et al. [18]. These references show various ways to provide solar thermal energy to an ethanol distillation system and calculate an estimated rate of ethanol production, but there is no information about the operational behaviour along the year of the useful energy provided by the solar thermal system, the temperature levels reached by the different equipment, the consumption of an auxiliary heater and the production of ethanol. This information would help evaluate with better accuracy the feasibility of a solar distillation system for aqueous ethanol solutions.

The objective of this work is to perform a transient simulation of a solar ethanol distillation plant using solar radiation as a source of energy to analyse the production of ethanol at 95 wt.% and the energy produced and consumed by different components of the system (solar collectors, column reboiler, auxiliary heater and storage tank). A rigorous simulation model is used for the solar distillation system and the analysis is focused on the solar heating system required for the reboiler to separate ethanol using a distillation process. Two different solar thermal collectors (evacuated tube collectors and parabolic trough collectors) and two different ethanol feed concentrations (5 wt.% and 10 wt.%) were analysed to select the optimum collector area for each case. Finally, thermal, environmental and economic aspects will be presented to determine the feasibility of the solar distillation system. Monterrey, México was considered as a case of study to simulate the operation of the solar distillation system.

2. Description of the solar ethanol distillation system

The main components used in the solar distillation system are shown in Fig. 1. The basic distillation system is composed of a reboiler, distillation column, pump and condenser. A preheater is used to reduce the amount of heat required in the reboiler [18]. The energy for the reboiler is provided by the solar heating system with the following components: solar thermal collectors, auxiliary heater, heat storage tank and a pump. The solar thermal collectors heat the fluid, in this case pressurized water, to the required temperature by the reboiler to distill the ethanol solution. If there is not enough solar energy to heat the fluid in the solar thermal collectors, an auxiliary heater will provide the rest of the energy required by the reboiler. A pump is used to move the hot fluid through the reboiler. If the temperature increases more than the temperature required by the reboiler, then the exceeding heat is sent to the heat storage tank. A pressure relief valve and an expansion vessel must be considered to protect the system components and control devices of excessive pressure build up [18].

2.1. Ethanol distillation subsystem

Modern ethanol solution distillation systems are multi-stage, continuous, countercurrent, vapor-liquid contacting systems that operate taking advantage of the difference in relative volatilities of the two components of the solution [19]. Mukherjee [3] has studied ethanol distillation in a farm setting, calculating the design parameters of the distillation system. Vargas et al. [18] have calculated system performance for a distillation unit of dilute ethanol aqueous solutions of varying concentrations with solar energy input. Their comprehensive study determines reboiler heat duty, solar collector area, column size, among other parameters consid-