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Design of a Hydrogen and Water Production System Based on Coffee Husk Biomass Fuel

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1. ABSTRACT

In this work, an integrated system utilizing coffee husk biomass combustion and liquefied natural gas cooling for the simultaneous production of freshwater, hydrogen, electrical power, hot water, and cold water has been investigated and analyzed. This novel process encompasses biomass combustion, liquefied gas cooling, organic Rankine cycle, ammonia Rankine cycle, multi-effect desalination, and a water electrolysis. Thermodynamic analysis using energy and exergy methods, as well as parametric analysis, has been performed on the proposed system. The results show that the system has a thermal efficiency of 29.9%, an exergy efficiency of 14.38% and an electrical efficiency of 16.91%. Also, the effect of changing the operating conditions of the system on the performance of the components and the entire system has been evaluated. In the basic design, this new system is capable of producing 5053 kW of cooling power, 850 kW of heating power, 8391 kW of electrical power, 12.1 kg/h of hydrogen, and 1569 kg/h of fresh water. The total energy recovered by the evaporator heat exchangers is 568482 kW, and the irreversibility of the entire process is 52115 kW, with the largest share of exergy destruction being from the combustion chamber (37103 kW) and the E-100 heat exchanger (11293 kW). In order to reduce the irreversibility of the evaporator in the organic Rankine cycle, two solutions are proposed, and the effects of these solutions on the thermal efficiency and exergy of the system are studied in the sensitivity assessment section.

Keywords: Biomass, Integrated system, Desalination, Hydrogen Production, Exergy Analysis

2. INTRODUCTION

Fossil fuels have been widely used as the main energy sources, but their long-term consumption has caused severe environmental pollution and depletion of non-renewable resources [1]. The implementation of renewable energy sources has the potential to reduce the dependence of energy systems on fossil fuels and plays an important role in facilitating a more sustainable production approach [2]. The use of biomass feedstock in the energy system is essential for sustainable production due to its renewable nature and high energy density [3].

In this work, biomass from coffee husks has been used as a renewable energy source to enable the simultaneous production of various products such as electricity, hydrogen, hot water, cold water and fresh water. This innovative system, by utilizing the process of evaporation and expansion of liquefied natural gas, in addition to providing electricity and cooling, also provides the natural gas needed by the consumer. The key components of this new process include the combustion of coffee husk biomass, the use of cooling created by liquefied natural gas, the ammonia Rankine cycle, the organic Rankine cycle, an ion exchange membrane electrolysis and a desalination process.

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3. SIMULATION

Figure 1 shows the process flow diagram for the proposed multi-purpose system based on direct combustion of coffee husk. As can be seen, biomass is first introduced into the combustion chamber along with air and the energy flow released from its combustion (according to equation 1) is used by heat exchangers E-100 and E-101. At this stage, flue gas (stream 6) enters the flue and is discharged. Also, seawater, after passing through E-101, enters the flow splitter as a saturated liquid at a pressure of 1 atmosphere. Streams 9, 10 and 11 pass through valves VLV-100, VLV-101 and VLV-102 in equal proportions. By passing through these valves, the pressure of the brine is reduced and the flash operation is performed. As a result, the output of the aforementioned valves is converted into a two-phase state and the liquid and vapor phases are separated in the order specified in Figure (1) through separators V-100 to V-102. Streams 16, 18 and 20, which are the lower liquids of the separators, are first combined with each other by a mixer to form stream 23. This stream then enters V-103 to carry out the liquid and vapor separation process again. In the seawater desalination section, the vapors exiting the separators after mixing (stream 21) are condensed through heat exchanger E-102 and finally fresh water is produced as a product. The brine from V-103, which has a sufficient temperature, exchanges heat with the liquefied natural gas fluid exiting P-100, and in this process, the high-pressure liquefied natural gas exits heat exchanger E-103 as vapor (stream 26) and then expands in turbine T-101. The low-temperature gas stream exiting this turbine is used in heat exchanger E-104 to produce cold water (stream 33). After passing through E-104, the exhaust gas reaches a suitable temperature and is sent to the end user. Looking at Figure (1), it can be seen that the E-100 exchanger plays the role of an evaporator in the ORC cycle. In this section, the orthoxylene working fluid exiting pump P-101 is evaporated during the heat exchange process with the high-pressure flue gas, and then stream 4 enters turbine T-100 to be expanded there. Since the outlet of the T-100 turbine has a high temperature, its excess heat is used in three heat exchangers E-105, E-106 and E-107. This heat is used to feed the ammonia Rankine cycle, the water boiler and the single-stage absorption chiller cycle, respectively. During this triple heat exchange, the orthoxylene working fluid is completely condensed (stream 44) and then enters the pump P-101.

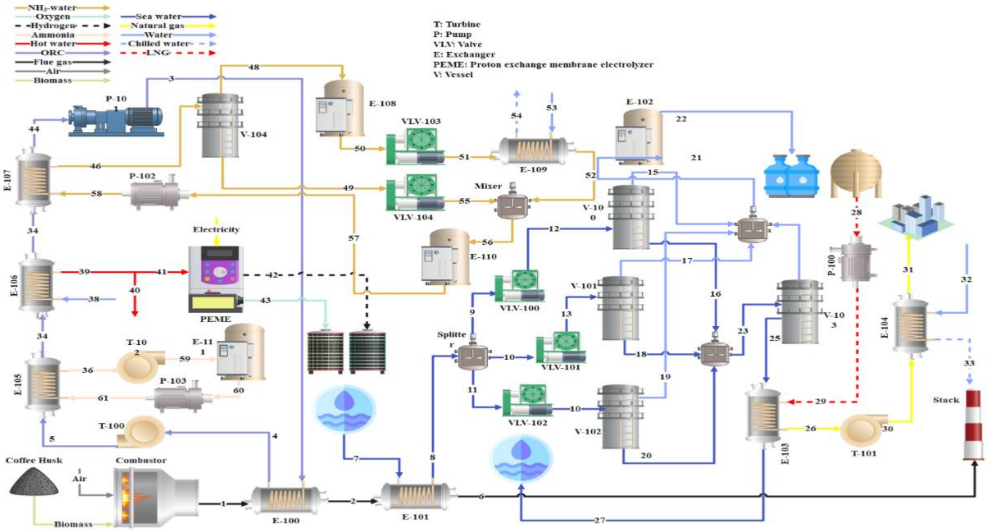

Figure 1. Process flow diagram for the proposed multifunctional system based on direct combustion of coffee husks

The ammonia fluid (stream 36) is evaporated by passing through the evaporator at high pressure and its pressure is reduced by T-102, which leads to the generation of electrical power. In the ammonia Rankine cycle, the heat exchanger E-111 and the pump P-103 are used to condense the working fluid and increase its pressure, respectively. According to Figure (1), the water flow reaches a temperature of 80°C after passing through the E-106 exchanger (stream 39) and part of this hot water is sent to the ion exchange membrane electrolysis. The electrical power required by the electrolysis is provided by part of the power of the T-100 turbine. In the process of electrolysis of water, hydrogen and oxygen products are produced and then directed to the relevant tanks. In the absorption chiller cycle, the E-107 heat exchanger acts as an evaporator. In this section, the mixed flow of water and ammonia exiting the P-102 pump is evaporated under high pressure and the liquid and vapor phases are separated from each other by V-104. The vapor phase is transferred to the E-108 condenser where it completely liquefies. Due to the high concentration of ammonia in this flow, its expansion in the VLV-103 valve causes a sharp temperature drop (stream 51). The low temperature of this stream is used in evaporator E-109 to produce chilled water (stream 54). In addition, the liquid leaving V-104 passes through a reducing valve and enters the mixer, where it is mixed with the refrigerant leaving E-109. The product leaving the mixer (stream 56) is sent to heat exchanger E-110, which acts as the absorber of the cycle. In this section, the working fluid is completely liquefied and then pumped by pump P-102 to heat exchanger E-107.

4. RESULTS AND DISCUSSION

For energy and exergy analysis and thermodynamic analysis of the proposed structure (Figure 1), the basic mass, energy and exergy balance relations in the control volume state have been used [4,5]. Thermodynamic evaluation showed that the proposed process has a thermal efficiency of 29.9%, an exergy efficiency of 14.28%, and an electrical efficiency of 16.91%. In addition, the coefficient of performance for the absorption chiller system was calculated to be 0.27. The total irreversibility in this process was 52,115 kW, the major contribution of which was related to the combustion chamber (37,103 kW) and the E-100 heat exchanger (11,293 kW). These two equipments together accounted for 92.7% of the irreversibility of the process.

5. CONCLUSION

In this study, a multifunctional and integrated system using coffee husk biomass and liquefied natural gas cooling was designed, developed and evaluated. This system is capable of simultaneously producing fresh water, hydrogen, hot water, cold water and electricity. The process modeling was performed in the Aspen HYSYS software environment and its thermodynamic performance was analyzed based on the first and second laws of thermodynamics. In the desalination section, multi-effect technology was used and for hydrogen production, an ion exchange membrane electrolysis was used. The overall thermal and exergy efficiencies of the system were 29.9% and 14.38%, respectively. Also, the coefficient of performance of the absorption chiller under baseline conditions was calculated to be 0.2704 and the results showed that by increasing the outlet refrigerant temperature from the evaporator to 0.5, a significant improvement in the system efficiency is achieved. The results of parametric studies indicate that the system performance is most affected by the temperature of the working fluid entering the organic Rankine cycle turbine, the temperature of the working fluid leaving the evaporator section, the temperature of the refrigerant leaving the evaporator in the refrigeration cycle, and the temperature of the orthoxylene leaving the water heater. To reduce the irreversibility in the organic Rankine cycle evaporator, two corrective solutions were proposed, and sensitivity analysis showed that implementing these solutions significantly improves the thermal efficiency and exergy efficiency of the system. Finally, it is suggested that future studies should consider multi-objective optimization and techno-economic evaluation of this system in order to determine the optimal operating conditions and investigate its industrial feasibility.

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