Energy 109 (2016) 751–764

Contents lists available at ScienceDirect

Energy

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

Thermodynamic modeling and evaluation of high efficiency heat pipe integrated biomass Gasifier–Solid Oxide Fuel Cells–Gas Turbine systems

S. Santhanam [1], C. Schilt, B. Turker, T. Woudstra, P.V. Aravind*

Delft University of Technology, Energy Technology Section, Leeghwaterstraat, 2628 CB, Delft, The Netherlands

ARTICLE INFO

Article history:
Received 25 November 2015
Received in revised form
25 April 2016
Accepted 28 April 2016

Keywords:
Solid Oxide Fuel Cell
Gas Turbine
Biomass gasification
Heat pipes
Exergy

ABSTRACT

This study deals with the thermodynamic modeling of biomass Gasifier–SOFC (Solid Oxide Fuel Cell) –GT (Gas Turbine) systems on a small scale (100 kW_e). Evaluation of an existing biomass Gasifier–SOFC –GT system shows highest exergy losses in the gasifier, gas turbine and as waste heat. In order to reduce the exergy losses and increase the system's efficiency, improvements are suggested and the effects are analyzed. Changing the gasifying agent for air to anode gas gave the largest increase in the electrical efficiency. However, heat is required for an allothermal gasification to take place. A new and simple strategy for heat pipe integration is proposed, with heat pipes placed in between stacks in series, rather than the widely considered approach of integrating the heat pipes within the SOFC stacks. The developed system based on a Gasifier–SOFC–GT combination improved with heat pipes and anode gas recirculation, increases the electrical efficiency from approximately 55%–72%, mainly due to reduced exergy losses in the gasifier. Analysis of the improved system shows that operating the system at possibly higher operating pressures, yield higher efficiencies within the range of the operating pressures studied. Further the system was scaled up with an additional bottoming cycle achieved electrical efficiency of 73.61%.

1. Introduction

Solid Oxide Fuel Cells are highly efficient devices. Their second law efficiencies are usually above 90%, as they produce electricity and heat at very high temperatures. By utilizing this heat to produce mechanical work, subsequently, electricity is expected to result in very high efficiencies in electricity production [1–8]. Efficient heat management, helps to achieve high efficiencies in such systems especially with a direct or indirect internal reforming in the fuel cell when carbonaceous fuels are used. SOFC–GT (Solid Oxide Fuel Cell–Gas Turbine) systems using natural gas as fuel are expected to attain thermal efficiencies of 60%–80% [9]. Operating such systems loaded with biosyngas and produced in a biomass gasifier, are expected to result in highly efficient and sustainable electricity production. Biosyngas can be produced by endothermic reactions, when gasification agents, such as steam and CO_2 are used. The heat produced in SOFCs being partly used for gasification, is expected to help minimize exergy losses in such integrated systems. The use of heat pipes for exchanging heat between solid oxide fuel cells and gasifiers, has been studied in the past [10–12]. The EU (European Union)-funded project 'BioHPR' was successfully completed, using heat pipes in gasifiers while producing biosyngas with a high LHV (Lower Heating Value). Mol fractions of 40% H_2, 20% CO and 5% CH_4 in the biosyngas are reported [13]. Another EU funded project, Biocellus, has gained significant progress in integrating heat pipes with the gasifiers. System studies at Delft, Imperial College and other places have shown that electrical efficiencies above 60% from solid fuels are achievable for SOFC based systems [14,15]. Recently it has been shown a better thermal

* Corresponding author.
E-mail addresses: Santhanam.Srikanth@dlr.de (S. Santhanam), A.PurushothamanVellayani@tudelft.nl (P.V. Aravind).

[1] Permanent address: German Aerospace Center (DLR), Institute of Engineering Thermodynamics, 38-40 Pfaffenwaldring, 70569, Stuttgart, Germany. Tel.: +49 7116862755.

http://dx.doi.org/10.1016/j.energy.2016.04.117
0360-5442/

integration between the SOFC and biomass gasifier can further assist in reducing the exergy losses in the gasifier and thereby increase the efficiency [16]. In this work a new and simple strategy for heat pipe integration is proposed, with heat pipes placed in between stacks in series, rather than the widely considered approach of integrating the heat pipes within the SOFC stacks. Further the use of SOFC anode off gas as gasification agent is an additional new concept proposed in this work. To the best of authors knowledge, solutions presented in this work are new. This paper presents a detailed description of the second law of evaluation and optimization of very high efficiency, small power level, gasifier–SOFC–GT systems, having novel integration concepts. A scaled up version of the proposed system model with a steam rankine bottoming cycle is later presented in this paper to evaluate the efficiency at higher capacities.

2. Description of the employed base-case model and subsystems

The model presented earlier by our team [17] is considered as the basis for the present study. In this model (Fig. 1), biosyngas is formed in the gasifier and it is cleaned using a set of high temperature gas cleaning devices. Clean biosyngas is fed to the SOFC which operates at an average temperature of 950 °C, and part of the anode and cathode gas is recycled to maintain the SOFC inlet temperature at 900 °C. Since not all the fuel is utilized in the fuel cell (85%), anode gas is combusted with cathode gas before the turbine. Turbine exhaust is used to preheat the cathode air flow, the gasification agent and for generating steam required to prevent carbon deposition. Detailed process system scheme is shown in the Fig. 9 in Appendix B. The model presented in this study which is a modified system involving heat pipes integration and anode off gas recirculation, is similar to the model presented in the earlier publication by the team of present authors [14].

2.1. Biomass gasification

Biomass gasification is a thermochemical process of converting solid biomass fuel to high calorific gas product when the biomass reacts with a suitable gasifying agent at high temperatures. The product of the gas composition is primarily a mixture of H_2 (hydrogen), CO (carbon monoxide), CO_2 (carbon dioxide), CH_4 (methane), as well as other hydrocarbons such as ethane and so on. Some amounts of H_2O (water) and N_2 (nitrogen), are also present depending on the gasification agent used. Air, oxygen, steam or carbon dioxide is majorly used as the gasification agents. Autothermal gasification take place when air or oxygen is used, and where the heat required for endothermic gasification reactions are supplied by the oxidation reaction occurring in the gasifier. The advantage of autothermal gasification is that no external heat is required, but it produces a significant amount of nitrogen in the gas product. Allothermal gasification occurs when steam or carbon dioxide is used as the gasifying agent. In such process, an external heat source is required to support the endothermic gasification reactions, more so, a higher energy content of gas product can be obtained. The main advantages and technical challenges of using different gasifying agents are summarized in Table 1 given below. Gasifier design, operating parameters and bed catalysts majorly determine the gas composition and the formed contaminants. The gasification process is modeled in the study, while assuming chemical equilibrium. However, simplified assumptions are taken, based on literature, from the percentage of char/carbon and methane produced in the high temperature gasification process and the carbon and hydrogen required for the production of char/carbon and methane are bypassed in the gasifier model.

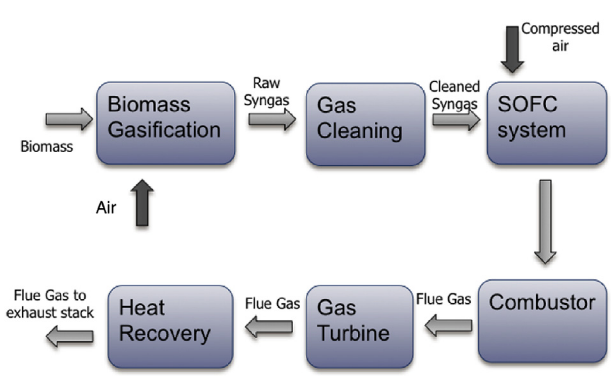

Fig. 1. Process flow diagram of the base case, biomass Gasifier–SOFC–GasTurbine, system.

2.2. Carbon deposition

As the syngas is heated or cooled down, solid carbon may get deposited. When carbon deposition occurs, it can lead to blockage in the pipes and apparatuses. This deposition is dependent on the thermodynamic C–H–O equilibrium composition of the biosyngas at different temperatures and pressures. In general, a higher carbon content in the gas tends to increase carbon deposition, while hydrogen and oxygen helps to reduce it. Addition of steam thus, helps to reduce carbon deposition. A discussion on carbon deposition in gasifier–SOFC systems is shown in Refs. [33,34].

2.3. Heat pipes

Steam or carbon dioxide gasification is an allothermal process, where high LHV biosyngas can be obtained, but additional heat is required for the process. Meanwhile, SOFCs produce heat as a result of exothermal electrochemical oxidation and internal losses. The heat produced by SOFC is usually removed by providing excess air on the cathode side, which affects the system's performance. By using heat pipes between the SOFC (acting as a heat source) and the allothermal gasifier (acting as a heat sink), the excess heat produced at SOFC can be transferred to the gasifier, where heat is required for gasification. Such an integration using heat pipes result in the cooling of SOFC stack, leading to a reduction in the required cathode air flow. Furthermore, integrating SOFC with gasifier using heat pipes, also reduces the exergy losses in the gasifier. Therefore, a higher system performance can be achieved, due to the two effects.

2.3.1. Principle

Heat pipes are simple and effective heat transfer equipment, without moving parts. A heat pipe is a hollow tube with layers of wire screen along the inner wall-the so-called wick. The wick is filled with the liquid, having properties similar to the evaporation and condensation temperature of the application. Heat pipes utilize the vaporizing liquid in order to create high heat fluxes from any heat source, in our case, it is utilized from the SOFC to the gasifier, where the endothermic gasification reactions take place. High temperature heat pipes are usually metallic pipes containing an alkali metal (Na, K, and so on). Heat is transferred into the heat pipe at the evaporation zone. This heat is released at the condensation zone, from the heat pipe to its environment. For application in