Research paper

Application of an exergy-based thermo characterization approach to diagnose the operation of a biomass-fueled gasifier

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ABSTRACT

In this paper the exergy-based thermocharacterization method is used to optimize a small scale downdraft gasifier. The optimization model is based on a Beta-parameter that is used to estimate the variation of exergy change in a component due to either intrinsic or induced malfunctions. As a novelty, the proposed method performs two analyses independently: one to find the variation of efficiency with respect to the change of the system enthalpy and another with respect to the change of the system entropy. This permits to characterize the thermodynamic performance of any gasifier by means of parametric maps. Hence thermo-characterization premises are deeply revised and adapted to the gasifier. To assess the system performance and determine the irreversibilities of the components, a plant simulator is constructed and a parametric study is performed. According to results, the exergy efficiency of the gasifier can be improved from 49.64% to 57.52%.

1. Introduction

In the light of rising energy costs, limited deposits of raw materials and global warming due to CO_2 emissions, the efficient use of energy is becoming a major issue of concern. In this context, biomass is foreseen as a promising alternative for future power generation [1–3]. The use of biomass is a potentially sustainable and environmentally friendly renewable energy source [4,5]. In fact, the main technologies for conversion of biomass are: 1) direct combustion processes, 2) biochemical processes, 3) thermochemical processes and 4) agrochemical processes.

However, conversion of biomass into gas (syngas) through gasication technologies is among the most intense areas of scientific interest [6–9]. It presents several advantages over waste combustion: 1) its effective response to increasingly environmental restrictive regulations; 2) its syngas can be used to produce valuable products as chemicals and fuels; and 3) its flexible use on different operating conditions [8–11].

As reported in literature [8,12–14], it can be found that there are parameters that modify the performance of the gasifier, such as the type of gasifier and the operating conditions (e.g. temperature, gasification agent, pressure, biomass particle size and type of bed materials). Hence there are several works focused on optimizing the gasification process, predominantly, its operating conditions by means of mathematical software. However, these methods of energy optimization do not consider the effect that a change in an operating condition have on the global performance of the gasifier.

There are few reports on literature combining parametrical analysis and thermodynamics in order to optimize the efficiency of the gasifier [15]. Even fewer reports on methods to detect and quantify malfunctions. In this regard, Zaleta et al. [16] proposes the thermo-characterization theory, which is an exergy-based method to optimize energy systems by isolating each component with respect to its impact on anomalies and so determining the overall effect on the process. Later, they proceed to determine the irreversibilities in a combined cycle power plant, thus increasing the efficiency of system [17]. Other works focuses mainly on optimization of biomass integrated gasification combined cycle through energy and exergy analysis [18,19]. More recently, an exergy optimization is applied to a biomass-cogeneration power plant [20]. The results are in agreement with those worked out by Yahya et al. [21], who developed a chemical and physical exergy analysis on an assisted fluidized solar gasifier. Damiani et al. [22], on the other hand, investigated the effect of fuel composition on the exergy efficiency of the gasifier by using equilibrium and non-equilibrium models.

Considering that the approach of the thermo-characterization theory still needs to be applied to energy systems, this paper presents the optimization of a biomass-fired small scale gasifier. However, in contrast to the thermo-characterization proposed previously [16], in this work the method does not consider the changes in enthalpy and entropy at the same time, but it performs two individual analyses instead. One is to find the variation of efficiency with respect to the

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variation of the total change of enthalpy, ω, and the other is to find the efficiency impact with respect to the total change of the system entropy, σ. So in this new approach, it is intended to consider the variations of the two parameters: ω and σ, in a single new parameter β, which represents the change of the system exergy. The mathematical model of the thermocharacterization is developed in the Engineering Equation Solver (EES) software [23].

In this paper a novel exergy-based method to characterize the thermodynamic performance of any gasifier (parametric maps) as well as its energy consumption at different operation modes and likely malfunctions is presented. The thermodynamic characterization method with malfunction reconciliation can be used in any system as long as a mathematical model is developed with dependent and independent variables. So it is possible to have an on-line energy diagnosis system that can be able to detect malfunctions and determine their energy impact on the overall system. Application of this methodology to gasification systems has not been reported thus far. Finally, it is important to mention that, in this paper, the concept of malfunction is used to refer to off-design operation as well as adjustments to set-point variables describing operation far from the reference point.

2. Theoretical development

2.1. Fundamentals of the thermocharacterization method

In this section, a deep revision of the main premises on which thermocharacterization are based is presented:

Premise 1: Components of the energy system and local processes. All advanced energy systems can be disaggregated into isolated sub-systems, delimited by a control volume which is strategically defined by borders according to instrumentation, process sections, and other factors. The downdraft gasifier shown in Fig. 1 consists of three such autonomous sub-systems. Sub-system I: a heat exchanger between the inlet air and the hot gas produced. Physically, it consists of an 1-inch diameter stainless steel highly finned flexible hose. The air passes through the hose and preheated up to 100 °C before entering the reaction zone. The syngas yielded in the reactor circulates on the outer surface of the pipe from the bottom to the upper part where connects to a cyclone. The cyclone is used to recover solid particles from unburned carbon and ashes.

Sub-system II: a gasifier including a feeder, the place where the gasification reactions take place. The main reactor is an 8-inch inner diameter and 15-inch height cylinder. At the zone where the air enters, the so-called "heart", it is located a 4-inch diameter reduction where combustion reactions take place; hence the highest temperatures are
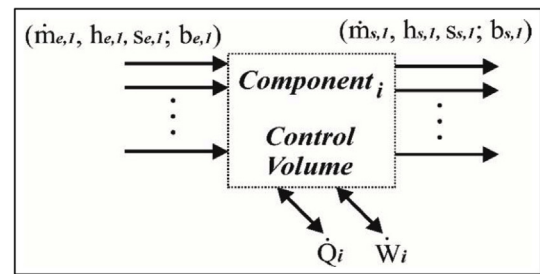

Fig. 2. Definition of the control volume for the *i*-th component.

found here (850 °C). The reactor is made of 316 stainless steel coated with 1-inch thickness refractory cement. The inlet consists of five ¼-inch diameter nozzles.

And subsystem III: the syngas cleaning system. It consists of a cyclone to capture solid particles. Then the syngas passes through an activated carbon filter to eliminate tar dragged down by the gas stream. The idea of using this system instead of having an electrostatic precipitator (ESP) with wet scrubber or a Fischer-Tropsch system is to reduce costs.

Each control volume satisfies mass and energy balances. Changes in the thermodynamic states of the input or output mass flows in each *i*-th component, during a process (heating, cooling, work, reaction, etc.), can be characterized by parameters such as ω_i, σ_i, β_i and P. The parameter P stands for the total system power (thermal power). Each variable is applied according to the control volume and the properties of the defined mass flows, refer to Fig. 2.

Premise 2. Definition of the reference state at different loads and modes of operation. An energy system is designed to operate at different loads depending on its energy demand. To regulate the load, control systems are used to regulate the input of both the working fluid and the gasifying agent. The load changes (FR) are investigated to know the causes and their impact on thermal efficiency since there is a dependence on power generated by an energy system with the global efficiency [24]. Although flow properties change, β-variable can be calculated for every parameter. If malfunctions are not considered in the components of the energy system the set of calculated parameters allows us to establish the reference state of the *i*-th component (path in two-dimensional space (β, P) of the component). The reference state is calculated from thermal balances provided by the designer, together with a thermodynamic simulator. A path, from a two-dimensional space (β, P) for each β-parameter, is obtained as a function of power load. The reference state is calculated from the thermal balances provided by the
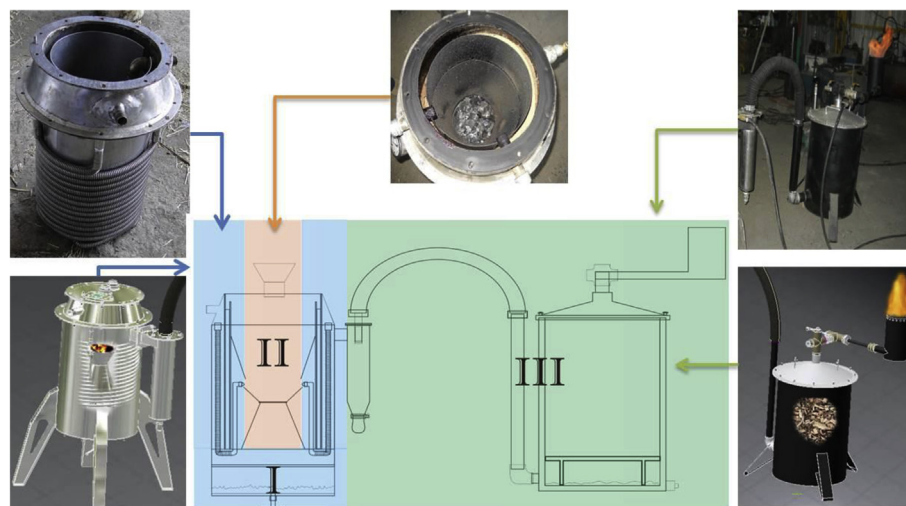

Fig. 1. Gasifier subsytems: I air-to-gas heat exchanger, II gasifier, III cleaning system.