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Research paper

# Exergy analysis of a four pan jaggery making process

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ABSTRACT

Jaggery is a non-traditional sweetener that is produced from boiling sugarcane juice. Due to the energy intensive nature of the combustion process in jaggery making, previous studies in literature have presented various process and equipment modifications to affect its energy efficiency. This study adds to the understanding of the resource transformations and consumptions in the jaggery process by presenting its exergy analysis. The baseline process was operationally modified for which the exergy efficiency and exergy destruction are calculated. Through the modifications, the exergy efficiency and exergy destruction increased by 11.2% and 0.8% respectively. A significant amount of exergy was wasted as surplus heat in the form of flue gas, which reduced by 11.5% due to process modifications. The results show that while the most evident form of resource waste was due to flue gas released into the environment, the largest form of resource consumption was actually due to exergy destruction arising from irreversibilities in combustion, a result not clearly evident through energy analysis alone. Through modelling process flows in terms of exergy, the analysis presented in this paper increases the visibility of the resource consumptions and losses in the jaggery making process. This study should aid the efforts of researchers and practitioners aiming to reduce resource consumption in the jaggery making process.



## 1. Introduction

Jaggery is natural unrefined sugar which is consumed in Asia, Africa, Latin America and the Caribbean (Singh, 2013). Its production is a significant part of the agricultural industry in the Indian subcontinent, mostly prevalent in its rural population which is 65% of the total (The world bank, 2015). In India, about 30% of the sugarcane produced goes into making jaggery and unrefined sugar (Gonsalves, 2006). Rao et al. (2007) reported similar statistics that the jaggery industry used 24.5% of the cane produced in India for the year 2007. A typical jaggery making processes uses open pan furnaces to concentrate the cane juice to required specifications. This is an energy intensive process which has attracted researchers to understand the energy and mass transformations in the process, and to investigate strategies to minimize its energy use. For example, Anwar (2010) made equipment modifications to improve the energy efficiency of the process, by applying the concept of fins to the open pan jaggery making furnace, which resulted in significant energy savings (31.34%). In another example of equipment modification, Manjare and Hole (2016) employed preheating using the flue gas to improve the thermal performance of the process. Jakkamputi and Mandapati (2016) showed that a specific bagasse consumption per kilogramme of jiggery could be reduced by 0.23 kg if solar collectors were employed to preheat the cane juice. Shiralkar et al. (2014) demonstrated efficiency improvements by improving combustion; and analysed both single, and multi pan furnaces. Dampers at air inlets were used to reduce excess air for combustion, thus increasing energy efficiency. In another study along similar lines of investigation, Sardeshpande et al. (2010) modified the fuel feeding rate to achieve a higher energy efficiency. Tiwari et al. (2004) conducted an experimental study to determine the convection rate of heat transfer for boiling cane juice. La Madrid et al. (2016) performed a study which demonstrated the use of computational fluid dynamics (CFD) towards designing highly energy efficient jiggery making equipment. A follow up study by La Madrid et al. (2017) found through the use of CFD analysis that a fire-tube pan heat exchanger would result in better thermal performance as compared to the conventional flat-pan design.

It is important to note that all the studies that have been mentioned are based on energy analysis. The limitation of such an approach is that it does not allow the analyst to consider the quality of energy along with an inability to identify the locations of irreversiblities along the process. This paper, by presenting an exergy analysis, aims to provide a greater visibility of the losses

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associated with resource transformations that occur during the jaggery making process, which is its main contribution. Additionally, the study will add to the scarce body of literature aimed at improving the resource efficiency of the jaggery process.

This paper is based on the experimental study previously conducted by Sardeshpande et al. (2010) in which the energy efficiency in a four-pan furnace arrangement was analysed and improved through process operational modifications. Essentially, the fuel feed rate was modified to improve the energy performance of the four-pan furnace system. This paper presents an exergy analysis of the same process with the aim of providing a deeper understanding of resource transformations and consumptions that occurs during the process. All flows for the baseline and modified scenario are modelled in terms of exergy followed by the calculation of exergy efficiency and exergy destruction in the process. Exergy is a property of not only the system, but also the surroundings, and therefore the selection of reference environment (R.E.), directly impacts the results generated by exergy analysis. Each reference environment model is fixed by its chemical composition, and the exergy values derived from them are necessarily linked it. For this study, the widely accepted and used reference environment, proposed by Szargut et al. (2005) is used. Unless otherwise stated, the chemical exergy values of the elements and compounds in the analysis, derived from the selected R.E., are taken from CIRCE (2008).

Before describing the exergy analysis, it is important to highlights some benefits of adopting the exergy approach which were the motivation for this study. Exergy has been defined by Szargut et al. (1988) as "the amount of work obtainable when some matter is brought to a state of thermodynamic equilibrium with the common components of the natural surroundings by means of reversible processes". A major benefit of using the exergy approach is the fact that is allows one to account for the qualitative nature of mass as well as energy flows. Therefore, a more accurate representation of surplus or waste resource flows can be obtained as compared to energy analysis alone. Additionally, the analysis of resource consumption is not segregated into mass and energy categories, rather both are represented in common physical units. This is helpful when an objective comparison between various improvement to a manufacturing is required that effect its energy, material and water efficiency. Also, when resource transformations occur, both their mass and energy are conserved even though their useful potential is lost, therefore making it difficult to account for resource consumption in an energy analysis. On the other hand, resource transformations are accompanied by the consumptions of exergy that are related to irreversibilities in real processes, termed as exergy destruction. This makes exergy particularly useful when the goal is to account for natural resource consumption in a system. For these reasons, exergy analysis has been considered a suitable technique for resource accounting in environmental science (Gong and Wall, 2001; Seager et al., 2002). Prominent researchers such Szargut et al. (2002) and Rosen et al. (2008) have linked the depletion of non-renewable natural resources to the consumption of non-renewable stocks of exergy, precisely due to the above mentioned reasons. In this paper also, the consumption of non-renewable resources is indicated by the consumption of non-renewable exergy. Section 2 provides a brief introduction to the jaggery making process while also detailing the analysis method, the exergy balance and the methodology for calculating the exergy content for all flows in the process. Section 3 presents the results of the exergy analysis along with a detailed discussion. The possibility of exergy reuse through integration with a fictitious secondary process is also provided that adds to the understanding of resource consumptions in the jaggery making process. Finally, the summary and concluding comments are provided in Section 4.

## 2. Jaggery production case study

The case study presented here is based on a processing plant in India. The jaggery production process involves extracting juice from the sugar-cane using a crushing machine. The juice is then transported via a conveyor to a set of pans. The juice in the pans is continuously stirred while being heated by a furnace up to a required temperature. The juice is thickened as water is driven off until it reaches the required specification when it is cooled and finally solidified in moulds. Fig. 1 depicts this process.

The instrumentation used for the experimentation in the previous study by Sardeshpande et al. (2010) is provided in Table 1. Based on experimental measurements of the base case, the energy efficiency of the process was improved by ensuring complete combustion. This was accomplished by shifting to a controlled and lowered bagasse feed rate that also increased the batch processing time. These changes resulted in a saving of 28% of the bagasse supplied to the baseline operation. This also had an associated effect of lowering the operating temperature of the furnace thus reducing the flue gas temperature from 900 °C to 700 °C. It should be noted that this was the minimum possible operating temperature at which the product quality was satisfactory. While the mass and energy balances were established in the previous study, this paper implements an exergy balance for the jaggery process which is presented in the following Section 2.1.

### 2.1. System analysis

In order to establish the mass, energy and exergy balances, a control volume approach has been taken. The evaporation of water from the juice is the core of the process, and this is accomplished in a bagasse fired furnace. The skin of the sugar-cane left after crushing is called bagasse and serves as renewable fuel. Before the bagasse can be used, it needs to be dried. Depending upon the recipe, small amounts of chemical additives (such as lime and okra juice) are also added to the cane juice. Fig. 2 depicts the control volume of the jaggery furnace which shows all the material and energy flows, where steady flow is assumed.

The mass balance is a pre-requisite to establishing the energy balance. The mass balance helps quantify flows which would have been difficult to measure. Based on Fig. 2 the mass balance in terms of the absolute amounts of masses used per day is as follows,

Mass of juice + Mass of bagasse + Mass of combustion air + Mass of chemicals and okra = Mass of flue gas + Mass of jaggery + Mass of water evaporated + Mass of ash + Mass of floating residue

$$m_{juice} + m_{bagasse} + m_{air} + m_{chemical\ \&\ okra} = m_{flue} + m_{jaggery} + m_{steam} + m_{ash} + m_{fr} \quad (1)$$

#### 2.1.1. Energy balance

From the flows in Fig. 2, the energy balance is established as follows,

Energy rate from bagasse = Energy rate for sensible heating of juice + Energy rate for juice evaporation + Energy rate in liquid jaggery + Energy rate carried in flue gas + Energy rate from wall losses + Energy rate lost from ash + Energy rate lost in unburnt fuel

$$\dot{E}_{bagasse} = \dot{E}_{pre-heat} + \dot{E}_{evap} + \dot{E}_{jaggery} + \dot{E}_{flue} + \dot{E}_{wall\ losses} + \dot{E}_{ash} + \dot{E}_{unburnt} \quad (2)$$

From the energy balance, the energy efficiency of the combustion process can be calculated. The efficiency of a process is useful in assessing its performance and is the ratio of the useful output to the supplied input. It is calculated as,

$$\eta_{energy} = \frac{\dot{E}_{jaggery} + \dot{E}_{evap} + \dot{E}_{pre-heat}}{\dot{E}_{bagasse}} \quad (3)$$