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Improving the Performance of Jaggery Making Unit using Solar Energy

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Abstract

The thermal performance of open earth pan furnace used conventionally for preparing jaggery (gur) is very low. Dry bagasse is used as a fuel to produce heat in a combustion process in the open earth furnace. The energy loss due to inefficient combustion process, the energy loss through exhaust gases and other losses due to furnace wall, convection and radiation bring the thermal efficiency of open earth pan furnace to a low value. Certain quantity of energy produced in combustion process is used to sensibly heat the sugarcane juice to its evaporation temperature. Solar collectors can supply the sensible heat required to raise the sugarcane juice temperature up to its boiling point, thereby reducing the total quantity of heat required in preparing the Jaggery. Solar drier can be used to supply hot air required for the combustion process to burn the bagasse in more efficient manner. This paper presents analytical calculations done to study the performance improvement of the jaggery making unit using solar collector and solar drier.

Keywords: Bugasse, Heat transfer, Jaggery, Solar energy, Sugarcane.

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1. Introduction

Jaggery prepared conventionally in open earth pan furnaces has been used as a sweetener in many places of India from ancient times. Sugarcane juice and bagasse extracted after crushing sugarcane are used as the raw materials to prepare jaggery. Out of total sugarcane annually produced in India, around 2/3rd is used to produce sugar, 1/5th used to produce jaggery and remaining is used for other commercial purposes [1]. The preparation of jaggery is considered as a small scale industry, giving employment to many formers in rural India. Jaggery contains 65-85% of sucrose, 10-15% of reducing sugars, 3-10% of moisture, and the remaining is insoluble matter [2].

Mechanical and thermal energies are required to prepare jaggery using open earth pan furnace. Mechanical energy is required to crush the sugarcane to produce sugarcane juice, and thermal energy is required to heat the sugarcane juice to prepare jaggery in the furnace. Crushing the sugarcane will produce sugarcane juice and bagasse as a by-product. At the initial moment the moisture content in the bagasse is around 40-50% [3]. The moisture content can be reduced to 8-10% by drying the bagasse in open area, and then dry bagasse is used as a raw material to produce heat by combustion in the open earth furnace. It was observed that out of the total energy produced in the combustion process, around 45% is used for jaggery preparation and remaining is lost through flue gases, ash and furnace walls. Sugarcane juice used in preparation of jaggery in the open earth pan consists of three different stages. The first stage of process begins with supplying sensible heat (around 6% of total energy produced in the combustion process) required to raise the temperature of sugarcane juice from ambient to its boiling point. Measured quantity of additives like bendi, calcium carbonate and phosphoric acid (each at around 30-50 gm/100 kg of sugarcane) will be added to the sugarcane juice to maintain the required pH in this stage [4]. The second stage consists of removal of water from the sugarcane juice at its saturation/boiling temperature. The amount of heat supplied during this stage (around 39% of the total energy produced in the combustion process) is considered to be latent of vaporization required to convert water to steam. Floating residue known as molasses (around 3 to 5 kg/390 kg of sugarcane juice) is formed at this point and needs to be removed from the free surface. At the end of the second stage, the sugarcane juice will become rich in concentrated solids as the water is completely removed. In the last stage of jaggery preparation, the heat supplied (around 0.1% of the total energy produced) is utilized to increase the temperature of the sugarcane juice from its boiling point to striking point. The striking point is the temperature at which the sugarcane juice converts to a semisolid paste which slides on the pan surface instead of sticking to the pan. At this stage the sugarcane juice in semi-solid state is removed from the pan and cooled to room temperature to prepare the jaggery. The conventional process of jaggery preparation is represented in Fig. 1.

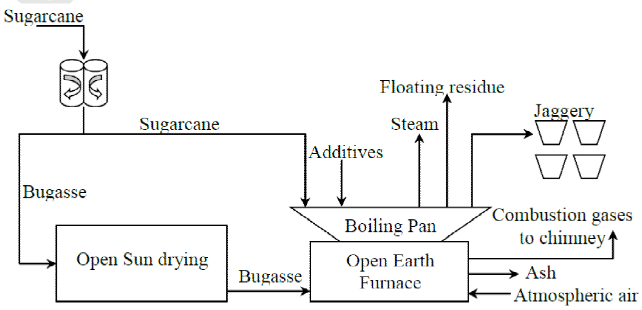

Fig. 1 Conventional process of jaggery preparation

This paper discusses the use of solar energy in the supply of partial or full amount of the heat required in the first and second stages of jaggery preparation. Combustion efficiency of the open earth furnace can be increased by using preheated air in place of atmospheric air and bagasse with low moisture content at the inlet to the furnace. Solar collectors and solar driers can be used as a source of heat in the jaggery preparation. Sugarcane juice can be heated to its boiling temperature using solar collectors and then send to the boiling pan for jaggery preparation. Solar drier can be used to preheat the air supplied to the furnace and remove the moisture content from the bagasse which enhances the combustion efficiency. The suggested modified process of jaggery preparation with solar energy as a heat source is shown in Fig. 2.

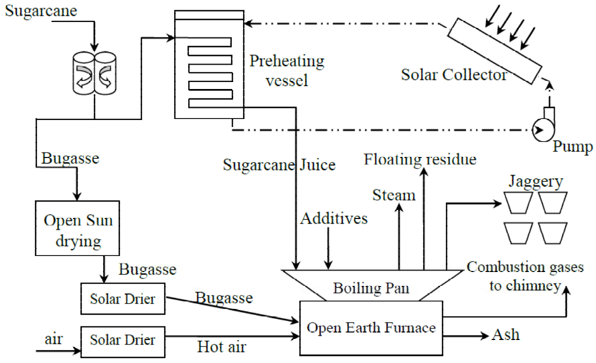

Fig. 2 Modified process of jaggery preparation with solar energy

2. Mathematical Modelling

Applying conservation of mass, Eq. (1) is used to write mass balance between various inputs and outputs to the Jaggery preparation unit.

$$\left(\dot{m}_{in} - \dot{m}_{out}\right) + \dot{m}_{gen} = \partial m / \partial t \qquad (1)$$

For a steady state operation and assuming there is no mass generation Eq. (1) can be modified as,

$$\left(\dot{m}_{in} - \dot{m}_{out}\right) = 0 \qquad (2)$$

In Eq. (2), $\dot{m}_{in}$ and $\dot{m}_{out}$ are the total mass flow rate in and out to the production unit. The various mass quantities supplied to the production unit are mass of sugarcane juice, additives, dry bagasse and combustion air. The various mass quantities produced from the production unit are mass of jaggery, floating residue, steam, flue gas and ash. Along the combustion line and sugar cane to jaggery preparation line the mass conservation results in,

$$\dot{m}_{db} + \dot{m}_{da} = \dot{m}_{fg} + \dot{m}_{ash} \qquad (3)$$

$$\dot{m}_{sj} + \dot{m}_{add} = \dot{m}_{jag} + \dot{m}_{fr} + \dot{m}_{st} \qquad (4)$$

In Eq. (3), $\dot{m}_{db}$, $\dot{m}_{da}$ are the mass flow rates of dry bagasse and dry air supplied for combustion. $\dot{m}_{fg}$ and $\dot{m}_{ash}$ are the mass flow rates of flue gases and ash produced in the combustion. In Eq. (4), $\dot{m}_{sj}$, $\dot{m}_{add}$ are the mass flow rates of sugarcane juice and additives, $\dot{m}_{sj}$ mass flow rate of jaggery produced, $\dot{m}_{fr}$ mass flow rate of floating residue and $\dot{m}_{st}$ is the mass flow rate of steam produced due to evaporation of water in the sugarcane juice.

Applying conservation of energy, Eq. (5) is used to write energy balance between various inputs and outputs to the jaggery preparation unit.

$$\left(\dot{E}_{in} - \dot{E}_{out}\right) + \dot{E}_{gen} = \partial E / \partial t \qquad (5)$$

Assuming that there is no addition to energy generation and that the process of energy transfer is a steady state process, Eq. (5) can be written as,

$$\dot{E}_{in} - \dot{E}_{out} = 0 \qquad (6)$$

In Eq. (6), $\dot{E}_{in}$ rate of energy input to the production unit and equal to the heat produced by burning dry bagasse in the furnace is given by,

$$\dot{E}_{in} = \dot{m}_{db}\left(CV\right)_{db} \qquad (7)$$

In Eq. (7), CV_{db} is the calorific value of dry bagasse can be calculated with the Eq. (8) available in [5].

$$\left(CV\right)_{db} = 18260 - 207.1 \times \zeta_1 - 182.06 \times \zeta_2 - 37.1 \times \zeta_3 \qquad (8)$$

In Eq. (8), ζ_1 is the moisture content in kg/kg of dry bagasse, ζ_2 the ash content in kg/kg of dry bagasse and ζ_3 is the sugar content of the bagasse.

In Eq. (6), $\dot{E}_{out}$ is the rate of energy coming out from the production unit and is equal to the sum of heat used by the sugarcane juice to raise its temperature from initial temperature to its boiling temperature, $\dot{E}_{sj}$, heat used to convert water in sugarcane juice to steam, $\dot{E}_{st}$, heat used to raise the temperature of the sugarcane juice from its boiling point to striking point, $\dot{E}_{str}$ and heat lost through flue gases, wall, ash and un burnt fuel.

$$\dot{E}_{out} = \dot{E}_{sj} + \dot{E}_{st} + \dot{E}_{str} + \dot{E}_{fg} + \dot{E}_{ash} + \dot{E}_{uf} + \dot{E}_{w} \quad (9)$$

In Eq. (9), $\dot{E}_{fg}$ is the energy lost through flue gases, $\dot{E}_{w}$ the energy lost to the walls, $\dot{E}_{ash}$ the energy lost through the ash and $\dot{E}_{uf}$ is the energy lost through the un burnt fuel. The various quantities in Eq. (9) are calculated using the following equations given in Eq. (10) to Eq. (12).

$$\dot{E}_{sj} = \dot{m}_{sj} C_{sj} \left(T_{bsj} - T_{isj}\right),\ \dot{E}_{st} = \dot{m}_{st} h_{fgst},\ \dot{E}_{str} = \dot{m}_{j} C_{j} \left(T_{str} - T_{b}\right) \quad (10)$$

$$\dot{E}_{fg} = \dot{m}_{fg} C_{fg} \left(T_{fg} - T_{amb}\right),\ \dot{E}_{ash} = \dot{m}_{ash} C_{ash} \left(T_{ash} - T_{amb}\right) \quad (11)$$

$$\dot{E}_{w} = \left(\dot{E}_{w}\right)_{cond} + \left(\dot{E}_{w}\right)_{conv} + \left(\dot{E}_{w}\right)_{rad} \quad (12)$$

It is proposed to reduce the sensible heat required for sugarcane to raise its temperature up to its boiling point and the heat lost through flue gases by using solar energy. Then $\dot{E}_{sj}$ and $\dot{E}_{fg}$ are modified as,

$$\dot{E}_{sj} = \dot{m}_{sj} C_{sj} \left(T_{bsj} - T_{isj}\right),\ \dot{E}_{fg} = \dot{m}_{fg} C_{fg} \left(T_{fg} - T_{ia}\right) \quad (13)$$

The inlet temperature of the sugarcane juice, T_{isj}, to the pan and inlet temperature of the air to the combustion chamber of the furnace, T_{ia}, can be increased by using solar energy. Then the amount of bagasse used for jaggery preparation plant will be reduced as the magnitudes of $\dot{E}_{sj}$ and $\dot{E}_{fg}$ are reduced.

3. Results and Discussion

Analytical calculations were done to show the effect of inlet temperature of sugarcane juice and inlet temperature air on the performance of the jaggery preparation plant. Calculations were made to find the performance of the plant on the basis of unit jaggery produced by using (7) to (13). The following assumptions were made for the analytical calculations.

- About 2.39 kg of dry bagasse is required to produce 1 kg of jaggery.
- Mass of dry bagasse produced is about 20% of the sugarcane crushed.
- Mass of sugarcane juice produced is about 65% of the sugarcane crushed.
- Calorific value of dry bagasse is 16,230 kJ/kg.
- Mass of additives (calcium carbonate, phosphoric acid and okra) to the sugarcane juice is each 0.5 g per kg of sugarcane juice.
- Mass of floating residue (molasses) produced is 10.25 g per kg of sugarcane juice.
- Air fuel ratio in the combustion process is 5.4 [6].
- Specific heat of flue gases is approximately equal to the specific heat of air.

Inlet temperature of sugarcane juice and inlet temperature of air to the furnace were considered to be the variable parameters. Energy distribution for various quantities per kg of jaggery production is calculated. They are, $\dot{E}_{in}$ (given by Eq. (7)) = 38789.7 kJ; $\dot{E}_{sj}$ (given by Eq. (10)) = 2360.44 kJ; $\dot{E}_{st}$ (given by Eq. (10)) = 15212.33 kJ; $\dot{E}_{str}$ (given by Eq. (10)) = 30 kJ; $\dot{E}_{fg}$ (given by Eq. (11)) = 14990.08 kJ; $\dot{E}_{unaccounted}$ = 6638.87 kJ.

Variation of sensible heat required to heat the sugarcane juice from its inlet temperature to boiling temperature, E_{sj}, with different sugarcane juice inlet temperatures, T_{isj}, is presented in Fig. 3. The value of E_{sj} is changed from 2360.44 kJ/kg of jaggery to 295.05 kJ/kg of jaggery as T_{isj} changed from 20 ^{o}C to 90 ^{o}C. It is a clear indication that we can save the amount of heat required (about 2360 kJ/kg of jaggery) to prepare the jaggery by sending the sugarcane juice at higher inlet temperature to the open earth pan.

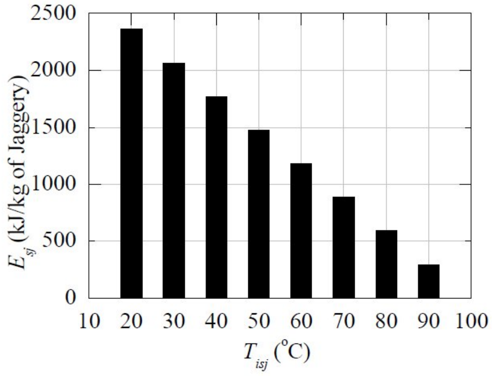

Fig. 3 Variation of sensible heat required to raise the sugarcane temperature from inlet value to its boiling point with inlet temperature of sugarcane juice

The variation of sensible heat energy, E_{sj}, saved when the inlet temperature of sugarcane juice is changed from 30 ^oC to 100 ^oC with that when the inlet temperature is 20 ^oC is shown in Fig. 4. The variation of dry bagasse saved as the temperature of inlet temperature of sugarcane is changed from 20 ^oC to 100 ^oC is also shown in Fig. 4. It can be found from Fig. 4 that the amount of dry bagasse which can be saved is increased from 0.02951 kg to 0.23604 kg per kg of jaggery preparation. The dry bagasse can be used as an alternative fuel and raw product for paper and pulp industry. Any savings in dry bagasse consumption in the jaggery preparation will add revenue to the farmers.

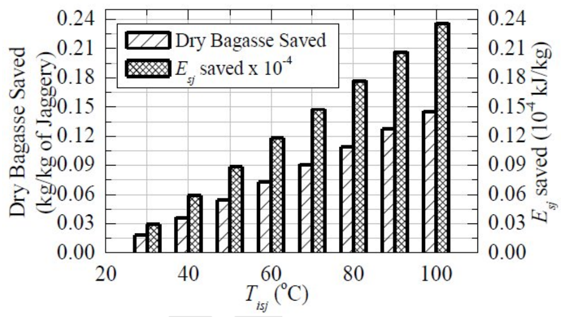

Fig. 4 Variation of Dry Bagasse saved and Sensible heat saved to raise the sugarcane temperature from inlet value to its boiling point with inlet temperature of sugarcane juice

Similarly variations in the heat lost through flue gases, E_{fg}, for different air inlet temperature, T_{ia}, are presented in Fig. 5. The amount of E_{fg} was observed to be changing from 14990.08 kJ/kg of jaggery to 13001.60 kJ/kg of jaggery as the air inlet temperature to the open earth furnace changed from 20^oC to 150^oC. The amount of heat lost can be minimized through flue gases which increase the performance of the jaggery preparation cycle.

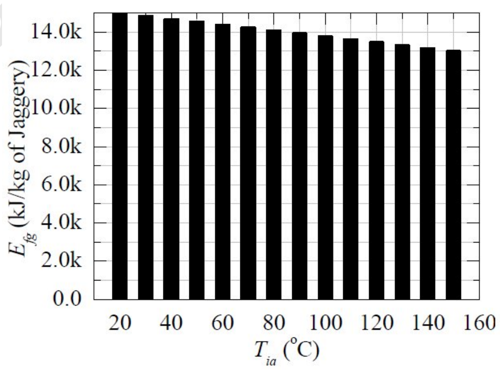

Fig. 5 Variation of heat lost through the flue gases with inlet temperature of air to the furnace

The amount of E_{fg}, saved when the inlet temperature of sugarcane juice is changed from 30 ^oC to 150 ^oC with that when the inlet temperature is 20 ^oC is shown in Fig. 6. The variation of dry bagasse saved as the air inlet temperature is changed from 20 °C to 100 °C is also shown in Fig. 6. It can be found from Fig. 6 that the amount of dry bagasse which can be saved is increased from 0.00942 kg to 0.12252 kg per kg of jaggery preparation.

The extent to which either the sugarcane juice or inlet air is preheated will be dependent on the performance of solar collector or solar drier. If the sugarcane juice is preheated close to its boiling temperature then there will be a maximum percentage gain in the dry bagasse saved. Similarly, if the air inlet temperature is more that 120°C then the gain in the dry bagasse saved is higher.

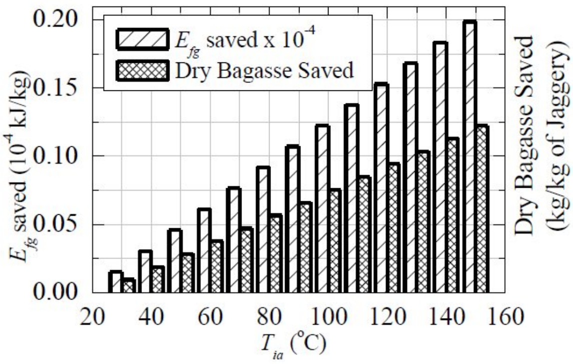

Fig. 6 Variation of Dry Bagasse saved and heat energy saved through the flue gases with inlet temperature of air to the furnace

4. Conclusion

In the conventional process of jaggery preparation, dry bagasse is used as raw material for the combustion process. Around 45% of total energy produced in the combustion process is effectively utilized for jaggery preparation and remaining 55% of total energy is lost through flue gases, ash and walls. Major amount of energy around 39.22 % is required to remove water from the sugarcane juice. Around 6.08 % is used as a sensible heat to raise the sugarcane juice temperature from its initial value to its boiling temperature, and 0.1% is used to raise the sugarcane juice temperature from its boiling temperature to its striking point. If the sugarcane juice was preheated close to its boiling temperature it was found that around 2360.44 kJ of heat energy and 0.23604 kg of dry bagasse could be saved per kg of jaggery preparation. If the air inlet temperature is increased up to 150 °C it was found that around 1988.48 kJ of heat energy and 0.12252 kg of dry bagasse can be saved per kg of jaggery preparation. To preheat the sugarcane juice or inlet air we can utilize the solar energy or any industrial waste heat available. The amount of heat energy and dry bagasse saved will increase if we supply the complete or partial amount of latent of heat to remove water from the sugarcane juice using solar energy or industrial waste heat.

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