

# Optimum Sizing and Performance Assessment of Modified Energy Efficient Jaggery Unit for Economic Self Sufficiency of Farmers in India

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## ABSTRACT

The complete lockdown experienced in India since March 2020 has brought the nation's economy to a halt, severely impacting the destitute and the most vulnerable, including farmers and migrant laborers. However, the country envisaged the vision of "Atmanirbhar Bharat Abhiyan" (Self-reliant India Movement) on May 12, 2020, that focuses on the importance of promoting local products and encourages manufacturing industries including the agricultural sector. The awareness campaign includes reforms to encourage businesses, attract investments, and strengthen production processes. Agriculture businesses are playing a major role in boosting the economy, such as Jaggery manufacturing, which is one of the most popular food processing enterprises that promotes job openings in rural India. Though, the country is the leading exporter of jaggery to the world, most of the production units, situated in remote places are designed without any scientific base and are seriously facing energy inefficiency problems. This research aims to design and develop a modified energy-efficient jaggery unit for the farmer producer groups, to achieve a "Self-reliant India". The proposed cost effective "Energy Efficient Jaggery Unit" is self reliant to meet all the requirements of the production process, such as combined heat and power (CHP) with the generation of biofuel, termed as Tri-Generation System.

**Keywords:** Bagasse; energy improvements; jaggery units; mass-energy balance; sugarcane

## INTRODUCTION

Jaggery is one of the most popular sweeteners, manufactured by boiling sugarcane juice in a conventional open pan-furnace heating system. It is also known as "medicinal sugar", which is nutritionally equivalent to "honey" and is considered healthier than refined sugar as it primarily contains sucrose, glucose, minerals, and vitamins. The major minerals are Iron (11%), calcium (0.4%), phosphorus (0.045%), magnesium (0.08%), protein (0.25%), fat (0.05%), as well as a small amount of zinc, copper, vitamin A, and vitamin B. Jaggery is well known as a good source of energy that prevents constipation, strengthens the liver, treats flu-like

symptoms, purifies blood, and avoids disorders of the bile. It also helps in relieving fatigue, relaxes muscles, nerve tissues, and vascular bundles, and keeps blood pressure and hemoglobin at a normal level. It also helps prevent anemia and boosts intestinal health (Shetkari 2017). According to the Agricultural and Processed Food Products Export Development Authority (APEDA), India has recently supplied around 632,000.00 MT of jaggery at 359.USD Millions (Rs. 2659.57 Crores) and has been recognized as the leading exporter of the products to the world (APEDA 2021).

Previous research on energy optimization methods for the jaggery manufacturing process indicated that adopting uniform fuel usage over the random or

batch pattern reduces specific bagasse consumption from 2.39 to 1.73 kg (Sardeshpande et al., 2010). Air dampers are required at the entrance of furnace air openings and flue gas passages in chimneys to improve the system efficiency (Shiralkar et al., 2013). Reversible heat pumps are used to pre-concentrate and separate cane juice from water. This method conserves thermal energy, equivalent to 15% of heat addition during evaporation (Rane et al., 2015). A computational fluid dynamic (CFD)-based simulation model is used to design and develop a fire-tube pan to replace the conventional finned flat type. It is observed that the heat transfer rate and the thermal efficiency of the manufacturing process improve considerably by replacing finned flat pans by fire tube type (Madrid et al., 2017). Solar photovoltaic-thermal (SPVT) systems are suggested for performance improvement, mainly using solar collectors for preheating sugarcane juice, input air and bagasse (Jakkamputi et al., 2016; Kulkarni et al., 2015). Techno-Economically sized grid-connected solar PV system 140 Kwp is suggested for semi-automatic jaggery plant located at Chakan Pune, India and relieves the farmers from use of diesel generator (DG) sets and helps in a drastic reduction of carbon emission (Hasarmani et al., 2018). Furthermore, various configurations of optimally sized renewable energy sources like solar PV-DG hybrid systems are suggested to overcome the effect of bad weather conditions on the generation of electricity for agricultural enterprises (Philip et al., 2015; Kant et al., 2016; Hasarmani et al., 2019). Moreover, a Programmable logic controller is suggested for optimum generation scheduling of Solar PV-DG set that maximizes the use of solar PV system and minimizes the operational cost of jaggery units (Hasarmani et al., 2020). This research

presents the design and development of an energy-efficient jaggery unit, based on mass-energy balance theory, that meets not only the heat requirement of the jaggery production process but also improves bagasse utilization.

## MATERIALS AND METHODS

### Jaggery Production Process

Jaggery production involves multiple activities, such as transportation, cutting and crushing sugarcane, open sun drying of bagasse, juice filtering, preheating, removal of scum (molasses), and packaging of the finished product. This entire process requires mechanical, electrical, and thermal energy. The conventional jaggery production process is completed at three different stages as shown in Figure 1a. In the first stage, sugarcane is crushed using a diesel engine or electric motor-driven crusher, and juice is collected in a tank. Air and sundried bagasse is supplied to the furnace for combustion through the inlet holes, and finally, flue gases are released into the environment via the chimney. In the second phase, fixed amounts of chemicals like calcium carbonate, hydrous powder, and ladyfinger mucilage are added to remove the floating scum from sugarcane juice, after which the product becomes rich in concentrated solids. In the third stage, juice is further heated from boiling to a striking point, which converts to a semisolid paste that slides on the pan. Finally, jaggery in a semisolid state is cooled, poured into molds, and packed as a final product. The mass balances of the jaggery making process are shown in Figure 1b.

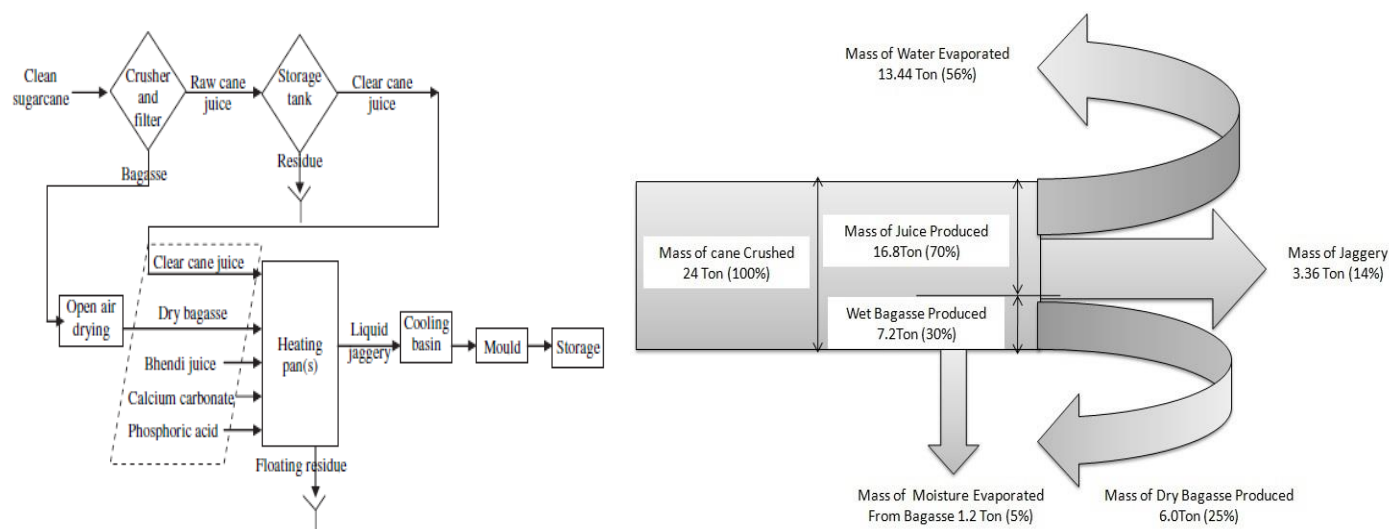


Figure 1. Conventional jaggery making process (a), mass balance sankey diagram of jaggery unit (b)

### Mathematical Modelling of Energy Efficient Jaggery Unit

Energy optimization and scientific design of jaggery unit start with a mass-energy balance of the pan-furnace system as described in Equation 1.

Mass balance: In steady state conditions,

$$\dot{m}_{in} - \dot{m}_{out} = 0 \quad (1)$$

In this phase, the input masses of jaggery units are cane juice, chemicals like calcium carbonate, phosphoric acid, open sun-dried bagasse, and air. Similarly, output masses include final jaggery, floating scum, steam, ash, and flue gasses.

As per mass conservation theory, equations with heating pan-furnace system are,

$$m_{bg} + m_{ar} = m_{fg} + m_{as} \quad (2)$$

$$m_{cj} + m_{cm} = m_{jg} + m_{sm} + m_{st} \quad (3)$$

Where,  $m_{bg}$ ,  $m_{ar}$ ;  $m_{fg}$ ,  $m_{as}$  are masses of bagasse, air, flue gasses, and ash, respectively.

Similarly,  $m_{cj}$ ,  $m_{cm}$ ,  $m_{jg}$ ,  $m_{sm}$ ,  $m_{st}$  are masses of cane juice, chemicals, jaggery, floating scum, and steam.

Similarly, applying conservation of energy for inputs and outputs of pan furnace system,

$$h_{in} - h_{out} = 0 \quad (4)$$

Where,  $h_{in}$  is the input heat supplied to jaggery unit by combustion of bagasse,

$$h_{in} = m_{bg} * CV_{bg} \quad (5)$$

Where,  $CV_{bg}$  is calorific value of the bagasse

Output heat,

$$h_{out} = h_{cj} + h_{sm} + h_{st} + h_{fg} + h_{as} + h_{fw} + h_{uf} \quad (6)$$

Where,

$h_{cj}$  = heat required to raise sugarcane juice temperature from initial to boiling point.

$h_{sm}$  = heat required for conversion of water to steam.

$h_{st}$  = heat required to raise temperature of sugarcane juice from boiling to striking stage.

$h_{fg}$ ,  $h_{as}$ ,  $h_{fw}$ , and  $h_{uf}$  are heat losses in flue gas, ash, furnace wall, and unburnt fuel respectively.

Variables of Equation 6 are calculated using following equations,

$$\begin{aligned} h_{cj} &= m_{cj} * c_{cj}(t_{jb} - t_{ji}) \\ h_{sm} &= m_{sm} * \lambda \\ h_{st} &= m_{jg} * c_{jg}(t_{st} - t_{jb}) \end{aligned} \quad (7)$$

Similarly,

$$h_{fg} = m_{fg} * c_{fg}(t_{fg} - t_{ab}) \quad (8)$$

$$h_{as} = m_{as} * c_{as}(t_{as} - t_{ab}) \quad (9)$$

Heat loss in furnace wall takes place because of conduction, convection, and radiation as mentioned,

$$h_{fw} = (h_{fw})_{cd} + (h_{fw})_{cv} + (h_{fw})_{rd} \quad (10)$$

Where  $t_{jb}$ ,  $t_{ji}$  and  $t_{st}$  are boiling, initial, and striking temperatures of sugarcane juice ( $^{\circ}C$ ), respectively.  $c_{jg}$ ,  $c_{cj}$  are specific heat of jaggery and sugarcane juice in (kJ/kg K) respectively.

Similarly,  $c_{fg}$ ,  $c_{as}$  are specific heat of flue gas and ash in (kJ/kg K) respectively

The ideal amount of bagasse required for jaggery production process:

*Amount of Jaggery in cane juice* = 20% (As per actual measurement)

*Therefore, Water to jaggery ratio in cane juice,*

$$m = \frac{\text{mass of water}}{\text{mass of jaggery}} = \frac{m_{wt}}{m_{ja}} = \frac{80\%}{20\%} = 4 \quad (11)$$

Where the total mass of cane juice= mass of water+ mass of jaggery (kg)

The heat required per kg of jaggery production by evaporating water from the juice is calculated with the following Equation 12 (Shiralkar et al., 2013).

$$\frac{Q_{ut}}{m_{jg}} = \{[m * c_p(t_{jb} - t_{ji}) + m * \lambda]wt + [m * c_{jg}(t_{st} - t_{ji})]jg\} / m_{jg} \quad (12)$$

Where,

$c_p$  = specific heat capacity of water=4.186 (kJ/kg K)

$\lambda$  = latent heat of evaporation of water=2270 kJ/kg

$t_{st}$  = Juice striking temperature=118 ( $^{\circ}C$ )

$t_{ji}$  = Juice initial temperature=30 ( $^{\circ}C$ ).

Therefore

$$\frac{Q_{ut}}{m_{jg}} = \{[4 * 4.186(100 - 30) + 4 * 2270] + [1 * 2(118 - 30)]\} = 10428 \text{ kJ/kg} \quad (13)$$

However,  $CV_{bg}$  =16, 000 kJ/kg (Shiralkar, et al., 2013)

Therefore, ideal amount of bagasse per kg of jaggery

$$\begin{aligned} &= \frac{\text{Heat required per Kg jaggery production}}{\text{Calorific value of bagasse}} \\ &= 10428/16000=0.65\text{kg}. \end{aligned} \quad (14)$$

Energy lost in flue gas as per Equation 8 calculated.

Similarly, natural draft,  $\Delta P = h * g * (\rho_a - \rho_{fg}) - \Sigma \Delta P_f$  (15)

Where  $h$ = Chimney height,  $\Sigma\Delta P_f$ =frictional pressure loss, and  $\rho_a$  and  $\rho_{fg}$  are air and flue gas densities.

Velocity of flue gas in chimney,  

$$v_{fg} = \sqrt{2 * [h * g * (\rho_a - \rho_{fg}) - \Sigma\Delta P_f] / \rho_{fg}} \quad (16)$$

And frictional pressure loss,  

$$= 2 * f * L * \rho * v^2 / D \quad (17)$$

Where,

$L$  = length of air duct

$D$  = diameter of duct

$v$  = velocity of flue gas

$\rho$  = density of flue gas

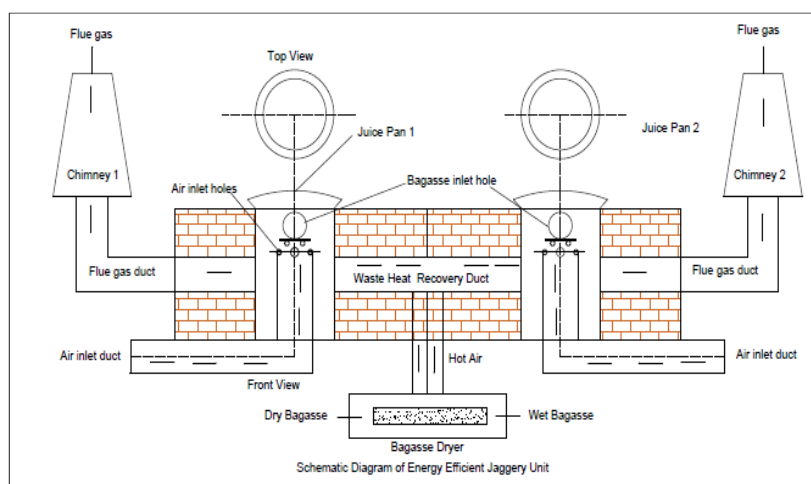
### Design of Energy Efficient Jaggery Unit

Mathematical modeling of conventional jaggery unit of various losses was estimated in the production process. During the detailed site survey, two conventional jaggery units of both 24 TCD crushing capacity were studied, first in Maharashtra (MH) and second in Karnataka (KA) states in India. The Chimney of the first unit was taller than the second, causing more input airflow due to increased draft and consequently decreased the inner temperature of the furnace, leading to lesser heat transfer to the juice pan and lower thermal efficiency in the range of 50 to 60%. However, the lesser height of the chimney in the second unit caused a lower draft, which resulted in inefficient combustion of fuel (bagasse), and ultimately larger amount is left unburnt, causing lower thermal efficiency in the range of 45 to 55%. Based on these critical findings during the site survey, the scientifically

based study was conducted, aiming toward optimum sizing and energy improvement of jaggery units. As per outcomes of mathematical modeling, modified energy efficient jaggery unit of 24 TCD is designed and developed for the farmer producer group located at Post-Maindargi, District-Solapur, Maharashtra (MH), India, as shown in Figure 2a. In this method, the main stress is given towards optimum sizing of pan-furnace and chimney system that minimizes the losses and improves fuel combustion during jaggery production process. The heat recovered from various losses is used for hot air supply to the furnace and bagasse drying, as shown in Figure 2b. Therefore, cautious efforts are made to improve the thermal performance of conventional units, which led to bagasse saving. A furnace with thick firebricks rather than a simple masonry brick significantly reduces heat loss. Similarly, cast iron fire grates were provided at the bottom of the furnace for proper mixing of fuel (bagasse) and combustion air. During combustion, bagasse fired into the furnace, falls on these grates and burns by combining with hot air from the front wall openings and that entering from the bottom openings of the fire grates. Fire grates also facilitate the automatic drop of ash in to the bottom trays that are collected periodically. Similarly, a modified chimney has a circular cross-section and is designed per outcomes of mathematical modeling results and practical experiences. Sliding dampers made of mild steel [M.S] plates inserted into the chimney help in the smooth flow of exhaust gases with the sufficient draft. Using a heavy-duty sugarcane crusher with a planetary gearbox (Kiran, crushing capacity-1200 kg/hr, Rajkot, India) has caused juice extraction to improve efficiently



(a)



(b)

Figure 2. Investigated energy efficient jaggery unit (a), schematic of jaggery production process (b)



from 65% of the conventional drive system to 70%, with additional advantages of zero transmission losses. This is due to direct shaft mounting, lesser operation and maintenance cost, noise-free, reduced space, and foundation expenses.

The main dimensions of various components of heating systems are detailed in Table 1.

### Measurements and Equipments

During detailed measurements, the fixed amount of sugarcane of 24 tons was crushed per day (TCD) at a per batch rate of 1.2 tons per hour. The masses of sugarcane, extracted juice, wet and dry bagasse were measured using digital industrial heavy-duty weighing machine (iScale, max load-200 kg, precision-20 gm, Kanpur, India). Similarly, the total batch time of jaggery process, Brix content in the juice, temperature at several points, moisture, and calorific value of bagasse were also measured. The soluble solid content in sugarcane juice that plays a vital role in calculating the amount of jaggery produced per ton was measured by a digital hand refractometer (Genex, Erma, 0-32 Brix, Japan). The moisture content in bagasse was calculated by actual measurement of weight loss, by putting fixed amount of bagasse in a thermostatic controlled hot air oven (Labline, HOS-6, 50-250 °C, accuracy  $\pm 0.5$  °C, Kochi, India) for 5 hours at 105 °C. The compositions in flue gasses (C, H, O Contents) were measured by using thermo-gravimetric analyzer (TGA) (Perkin Elmer, TGA8000, 20- 1200 °C, Thane, India). The calorific value of bagasse that remained almost constant at various locations of jaggery units was measured with bomb calorimeter (V-Tech, VT-05, 0-10 °C, Coimbatore, India).

## RESULT AND DISCUSSION

The energy-efficient unit, capable of crushing 24 tons (100%) sugarcane per day, was designed and

developed for farmer producer group. Per day mass balances of production process are shown in Figure 1b. The average working hours of the plant during the production process (September to February) were 20 hrs/day. Therefore sugarcane crushed per hour was 1.2 ton. The total mass of wet bagasse produced per day with 50% moisture content (as measured in lab) was 7.2 ton (30%). Where as the mass of dry bagasse with 6% moisture content (as measured in lab) produced after drying in bagasse drier was 6 ton (25%). Because of effective utilization, the heat lost in an enclosed bagasse drier as against open sun drying was reduced. The amount of dry bagasse produced in an energy efficient jaggery unit increased from 4.8 ton (20%) conventional to 6 ton (25%). The use of highly efficient sugarcane crusher with planetary gear box produced more amount of juice and final jaggery of 16.8 ton (70%) and 3.36 ton (14%), respectively. This was in contrast with the corresponding lower produced values of 15.6 ton (65%) and 2.88 (12%) respectively for similar capacity. In this way, the energy efficient unit produced additional 0.48 ton of jaggery and 1.2 ton of dry bagasse per day, that earned extra revenue for farmers with other benefits of lower operational and maintenance cost. With the proposed technology, the entire operation that involves, sugarcane crushing, bagasse handling, juice extraction (filtering, boiling, removal of molasses), and jaggery processing (cooling and packaging) requires only 10 skilled workers because of the eliminated manpower.

### Total Batch Time

The duration of each batch of the production process depends on several factors like efficiency of pan-furnace heating system, brix content in sugarcane juice, bagasse feeding rate, skill and experience of labours etc. The duration measured at site, varying between 150 min to 100 min is shown in Figure 3.

Table 1. Dimensions of energy efficient jaggery unit

System parameters	Heating system parts of jaggery unit				
	Chimney (m)	Furnace (m)	Heating pan (m)	Air Inlet holes (m)	Bagasse Inlet hole(m)
Top internal diameter	0.480	3.125	3.950	0.150 (1 hole)	0.250
Bottom internal diameter	1.250	3.124	3.250	0.100 (5 holes)	
Wall and pan thickness	0.225	0.225	0.012		
Height	4.550	1.325	0.575		

Jaggery is manufactured in two shifts of 10 hours each (first shift working hours is 4:00 AM to 2:00 PM, the second is 2:00 PM to 12:00 PM). During each shift, 5 batches of jaggery productions are completed. Generally, the first batch takes more time compared to the second, because it is cold-started after a gap of 4 hours (from 12:00 AM to 4:00 AM). Due to uniform fuel feeding and efficient heating practices, the duration for subsequent batches also reduces (at lower rate as compared to the first batch) as efficient heating system retains more heat and avoids loss of temperature in furnace walls, ducts, and chimney.

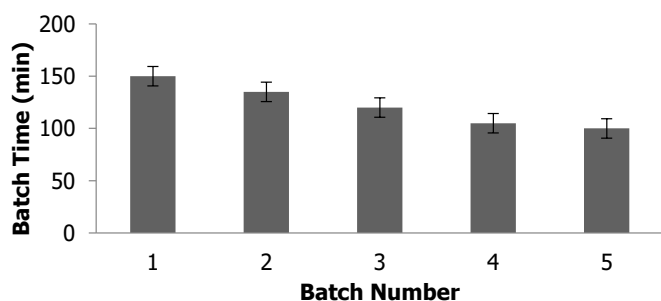


Figure 3. Variation in batch time with respect to the number

### Energy Requirements of Heating System

Thermal energy required for the production process depends on several factors like inlet temperature of sugarcane juice, air supplied to furnace, and design of heating system etc. Analytical calculations are done to determine thermal energy required at various stages of the production process as per Equation 1 to 9. The energy required or generated at different jaggery manufacturing stages are calculated. The variation in sensible heat required for water removal from juice with varying initial temperature is shown in Figure 4.

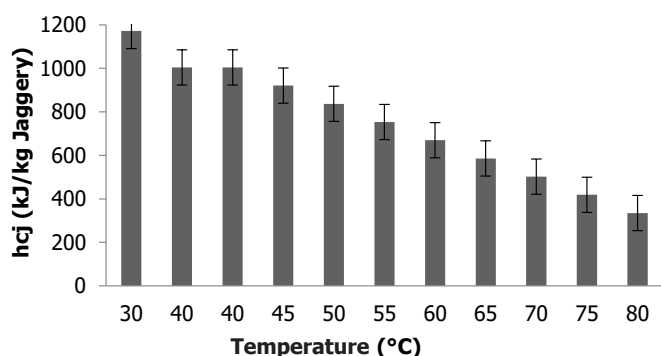


Figure 4. Sensible heat required for removal of water from sugarcane juice with initial temperature

The value of sensible heat ( $h_{c_j}$ ) decreases from 1180 kJ/kg to 380 kJ/kg jaggery with rising ( $t_{i_j}$ ) from 30 °C to 80 °C. This indicated that, by preheating sugarcane juice using waste heat recovery, substantial amount of temperature required is saved, consequently, fuel needed to prepare the jaggery. Variation in heat lost in flue gas ( $h_{fg}$ ) with varying ambient air temperature ( $t_{ab}$ ) is calculated using Equation 8 and shown in Figure 5. It is shown that, by supplying preheated air to furnace, huge amount of waste heat is saved, that helps in drastic reduction in green house gas (GHG) emission.

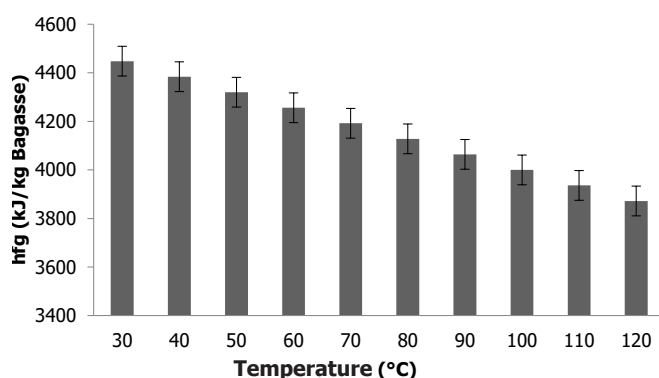


Figure 5. Heat loss in flue gas with input air temperature

The amount of change in bagasse and sensible heat saved during the initial stage of jaggery processing with raising sugarcane juice temperature is shown in Figure 6. As per Equation 14, the ideal value of bagasse required per kg of jaggery production is 0.65 Kg. However, in conventional units, because of illogical construction of pan-furnace heating system and non uniform fuel feeding practices, bagasse consumption per kg jaggery production is in the range of 1.5 to 1.75 kg. This consumes the entire dry bagasse produced during the production process. In the novel technology, dry bagasse produced per kg of jaggery production is 1.78 kg (as shown in mass balance Sankey diagram). After meeting the total heat requirement of the production process, the amount of bagasse saved, increases from 0.847 to 0.920 kg/kgjag preparation. The field survey and actual measurements performed after commissioning of the novel technology at farmer's site showed that, approximately 50% of dry bagasse was saved. Therefore, the proposed jaggery unit of 24 TCD is capable of saving around 540 ton of dry bagasse in 6 month, which gives extra revenue to farmers. The amount of heat saved from bagasse increases from 1.355 to 1.472 kJ/kgjag with the raising juice temperature from 30 °C to 75 °C.

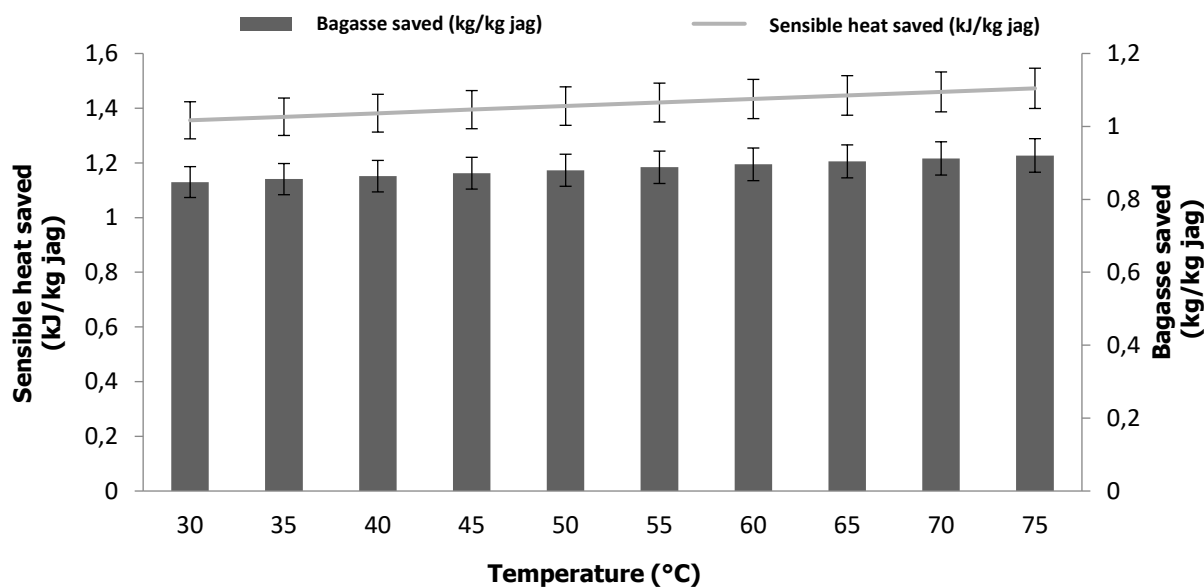


Figure 6. Bagasse and sensible heat saved with raising inlet juice temperature during jaggery processing

## CONCLUSION

Design based modifications in conventional jaggery unit plays major role in improving thermal efficiency of the manufacturing process. In this study, the heat wasted at various stages of the production process, like via flue gases, ash, and walls, are used for preheating of sugarcane cane juice, bagasse and air supplied to the furnace. The thermal efficiency of the investigated jaggery unit raised upto 75% compared to the conventional units ranging from 45 to 60%. By scientific design, approximately 50% of dry bagasse is saved, which is used as alternative fuel, raw product for paper and pulp as well as in biofuel industry. The saved dry bagasse during manufacturing, generates extra revenue to the farmers. Further research is recommended on design and development of affordable solar PV-DG-Battery hybrid system to meet the needs of energy efficient jaggery units, that make them self-reliant.

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## CONFLICT OF INTEREST

We declare that there is no conflict of interest regarding the publication of this article.

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