

Case Study on Heat and Mass Balance of Traditional Two Pan Jaggery Plant

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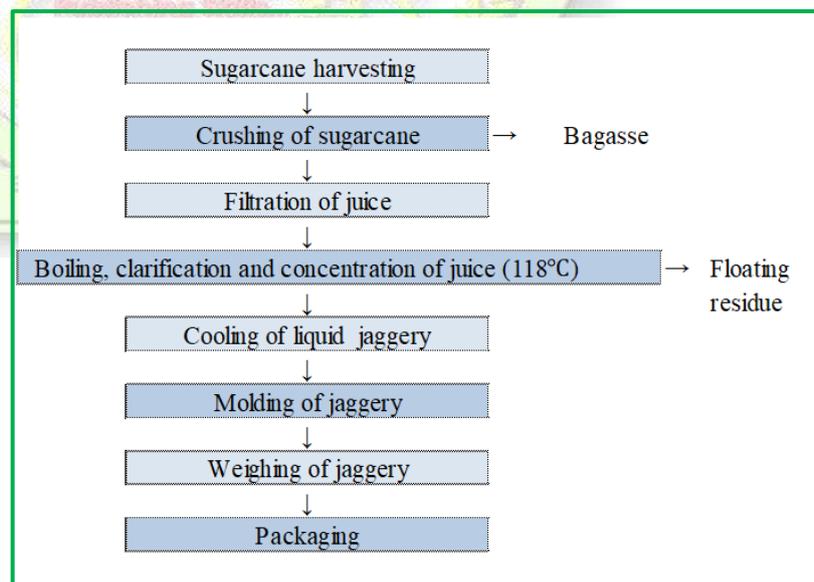
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The production of jaggery is a traditional process typically carried out in small to medium-scale industries, which expanded alongside the growth of sugarcane cultivation in Sri Lanka. Efficient utilization of thermal energy plays a fundamental role in enhancing process performance and maintaining effective operation of production equipment. In a two-pan jaggery furnace system, each pan functions as an open heat exchange surface containing sugarcane juice and positioned directly above the flue gas passage. The hot combustion gases flowing beneath the pan transfer thermal energy to the juice, supplying the latent heat required for moisture evaporation. As evaporation progresses, the concentration of dissolved solids increases, resulting in progressive thickening of the juice. Upon sufficient removal of water, the concentrated mass transforms into a viscous syrup that eventually develops a semi-crystalline structure. When cooled, this mass solidifies into jaggery. Therefore, the rate and effectiveness of heat transfer between the flue gases and the juice significantly influence overall fuel utilization and system performance. The thermal efficiency of the plant is found to be 10.39 %.

Keywords: Jaggery, Firewood, Furnace, Mass balance, Energy balance

Introduction

Sugarcane (*Saccharum officinarum*) is the only crop cultivated in Sri Lanka for manufacture of sugar & it is usually used to produce sweeteners like sugar, jaggery. Solid sugarcane jaggery is prepared by the concentrating the sugarcane juice using thermal energy. Jaggery plants can be single pan, two pan & multi-pan (Three & four boiling pan) with the requirement Kulkarni et al. (2018). In all these plants, sugarcane juice is boiled and concentrated. Afterword, it cools down and mold in solid shape called jaggery. Key components of a jaggery furnace include the combustion chamber, fuel feeding hole, flue gas duct, chimney, and ash pit.



Method of jaggery preparation
(Figure 01: Process Flow diagram)

Structural configuration of the two pan furnace

The two-pan furnace consists of a primary boiling pan and a secondary heating pan fabricated from stainless steel (gauge 17). The primary pan, positioned directly above the combustion chamber, has an upper diameter of 880 mm, bottom diameter of 618 mm, and a depth of 200 mm, and is used to heat sugarcane juice to the striking point. The secondary pan, located above the flue gas passage, has an upper diameter of 882 mm, bottom diameter of 620 mm, and a depth of 200 mm, and utilizes residual heat from exhaust gases for preliminary heating. Hot gases flow through a brick-lined flue gas passage constructed below ground level and exit through a chimney fitted with a metal cap to maintain draft. Fuel (Bagasse & firewood) is supplied through inlet into the combustion chamber, with an ash pit provided below for residue collection.

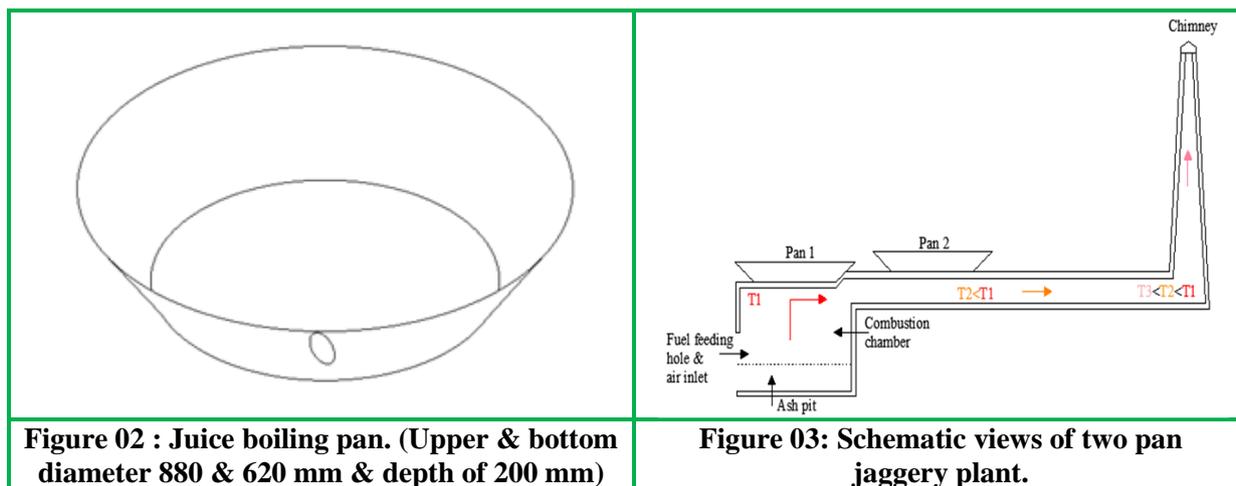


Figure 02 : Juice boiling pan. (Upper & bottom diameter 880 & 620 mm & depth of 200 mm)

Figure 03: Schematic views of two pan jaggery plant.

Material and Method

The temperature variation of the two pans were recorded periodically until the cane juice reached the striking point (118°C). Before the boiling, initial climatic parameters, juice temperature, and Total Soluble Solids (TSS) (Brix) were recorded. During the boiling process, temperature readings were taken every 30 minutes from pan1 & pan 2. Additionally, the weight of firewood and bagasse used was recorded. The moisture percentage of the firewood was also measured according to the ISO 18134-1 standard using oven dry method. The temperature of the cane juice continuously increased until it reached the striking point of 118±1°C. It took average 185 minutes for the first pan to reach this temperature. During this time, the juice temperatures in the secondary pan was around 100°C respectively. The temperature rise in the secondary pans was likely due to the flue gas flowing through the inner passage toward the furnace chimney, utilizing waste heat for heating. This is the advantage of the two-pan furnace. The second boiling operation started by transferring the juice from the second pan to the boiling pan, and it took average 65 minutes to reach the striking temperature.

Apply mass balance

$$M_{juice} = M_{jag} + M_{evp} + M_{fr}$$

$$82.6kg = 14kg + 63.5kg + 5.1kg$$

$$82.3kg = 13.2kg + 63.9kg + 5.2kg$$

$$M_{juice} = \text{Mass of juice per a pan (kg)}$$

$$M_{jag} = \text{Mass of jaggery produced per pan (kg)}$$

$$M_{evap} = \text{Mass of moisture evaporated per pan (kg)}$$

$$M_{fr} = \text{Mass of floating residue per pan (kg)}$$

The mass balance of the combustion of bagasse & firewood is presented in equation.

$$M_{bagasse} + M_{firewood} + M_{air} = M_{flue} + M_{ash}$$

$$M_{bagasse} = \text{Mass of bagasse per batch (kg)}$$

$$M_{firewood} = \text{Mass of firewood per batch (kg)}$$

M_{air} = Mass of air for combustion per batch (kg)

M_{flue} = Mass of flue gas produced per batch (kg)

M_{ash} = Mass of ash produced per batch (kg)

Energy balances are used to quantify the energy used or produced by a system. The energy balance for the control volume is presented in equation.

$$\begin{aligned} & \text{Rate of energy from firewood and bagasse} \\ &= \text{Rate of energy for juice heating} \\ &+ \text{Rate of energy for juice evaporation} \\ &+ \text{Rate of energy carried in liquid jaggery} \\ &+ \text{Rate of energy carried in flue gas} \\ &+ \text{Rate of energy in loss through walls} + \text{Rate of heat loss in ash} \\ &+ \text{Rate of heat loss in un - burnt fuel} \\ &+ \text{Rate of heat loss in moisture content of firewood} \end{aligned}$$

Apply energy balance (The theoretical minimum energy required for the jaggery processing is presented in equation.)

$$\begin{aligned} Q_{\text{liq.jag}} &= M_{\text{juice}} \times C_{\text{juice}} \times (T_{\text{evap}} - T_{\text{amb}}) + M_{\text{evap}} \times h_{\text{fg}} + M_{\text{liq.jag}} \times C_{\text{jag}} \\ &\quad \times (T_{\text{stri}} - T_{\text{evap}}) \\ &= 82.6\text{kg} \times 3.71 \left(\frac{\text{kJ}}{\text{kgK}} \right) \times (100 - 29)\text{K} + 63.5\text{kg} \times 2256.6 \left(\frac{\text{kJ}}{\text{kgK}} \right) + 14\text{kg} \\ &\quad \times 2.28 \left(\frac{\text{kJ}}{\text{kgK}} \right) (118 - 100)\text{K} + 82.3\text{kg} \times 3.71 \left(\frac{\text{kJ}}{\text{kgK}} \right) \times (100 - 29)\text{K} \\ &\quad + 63.9\text{kg} \times 2256.6 \left(\frac{\text{kJ}}{\text{kgK}} \right) + 13.2\text{kg} \times 2.28 \left(\frac{\text{kJ}}{\text{kgK}} \right) (118 - 100)\text{K} \\ &= 332.04 \text{ MJ} \end{aligned}$$

$Q_{\text{liq.jag}}$ = Minimum quantity of energy required for jaggery processed per batch (kJ)

M_{juice} = Mass of juice per batch (kg)

C_{juice} = Specific heat of juice per batch (kJ/kg K)

T_{evap} = Temperature of evaporation of moisture ($^{\circ}\text{C}$)

T_{amb} = Ambient temperature ($^{\circ}\text{C}$)

M_{evap} = Mass of moisture evaporated per batch (kg)

h_{fg} = Latent heat of evaporation (kJ/kg)

M_{jag} = Mass of jaggery produced per batch (kg)

C_{jag} = Specific heat of jaggery per batch (kJ/kg K)

T_{stri} = Striking temperature of jaggery ($^{\circ}\text{C}$)

Average moisture content of firewood (0.21) & bagasse (0.19)

Energy supplied for jaggery process is by combustion of bagasse and can be expressed as

$$\begin{aligned} Q_{\text{bagasse}} + Q_{\text{firewood}} &= M_{\text{bagasse}} \times CV_{\text{bagasse}} + M_{\text{firewood}} \times CV_{\text{firewood}} \\ &= 6.9\text{kg}(1 - 0.19) \times 14\text{MJ} + 207.7\text{kg}(1 - 0.21) \times 19\text{MJ} \\ &= 3194.76 \text{ MJ} \end{aligned}$$

Q_{bagasse} = Quantity of heat supplied per batch by bagasse (kJ)

Q_{firewood} = Quantity of heat supplied per batch by firewood (kJ)

M_{bagasse} = Mass of bagasse used as fuel in a batch (kg)

M_{firewood} = Mass of firewood used as fuel in a batch (kg)

CV_{bagasse} = Calorific value of bagasse (kJ/kg)

CV_{firewood} = Calorific value of firewood (kJ/kg)

The energy loss associated with jaggery processing.

$$Q_{\text{loss}} = Q_{\text{bagasse}} + Q_{\text{firewood}} - Q_{\text{liq.jag}}$$

Q_{wall} = Quantity of wall losses per batch (kJ)

Q_{ash} = Quantity of heat lost in ash per batch (kJ)

Q_{unburnt} = Quantity of heat lost in un-burnt fuel due to incomplete combustion per batch (kJ)

Q_{flue} = Quantity of heat lost through flue gases per batch (kJ)

Jaggery processing in the pan results in various losses, including convective and radiative heat loss from the pan's surface (when uncovered by juice) etc., these losses are difficult to quantify, so they are considered part of the wall losses. (Kulkarni et al. (2018))

The energy loss from flue gas and ash can be estimated using the following equations

$$Q_{flue} = M_{flue} \times C_{flue} \times (T_{flue} - T_{amb})$$

Q_{flue} = Quantity of heat lost through flue gases per batch (kJ);

M_{flue} = Mass of flue gases per batch (kg)

C_{flue} = Specific heat of flue gases (kJ/kg K)

T_{flue} = Temperature of flue gases ($^{\circ}$ C)

T_{amb} = Ambient temperature ($^{\circ}$ C)

$$Q_{ash} = M_{ash} \times C_{ash} (T_{ash} - T_{amb})$$

Q_{ash} = Quantity of heat lost through ash per batch (kJ)

M_{ash} = Mass of ash per batch (kg)

C_{ash} = Specific heat of ash (kJ/kg K)

T_{ash} = Temperature of ash ($^{\circ}$ C)

T_{amb} = Ambient temperature ($^{\circ}$ C)

$$\text{Thermal efficiency } (\eta) = \frac{\text{Useful heat output}}{\text{Heat Input}}$$

$$\text{Thermal efficiency } (\eta) = \frac{332.04 \text{ MJ}}{3194.76 \text{ MJ}} \times 100$$

$$= 10.39 \%$$

Average bagasse & firewood consumption for production of 1 kg of jaggery

$$= \frac{6.9 \text{ kg (Bagasse)} + 207.7 \text{ kg (Firewood)}}{14 \text{ kg} + 13.2 \text{ kg (Jaggery)}}$$

$$= 7.6 \text{ kg of Firewood per 1kg of jaggery}$$

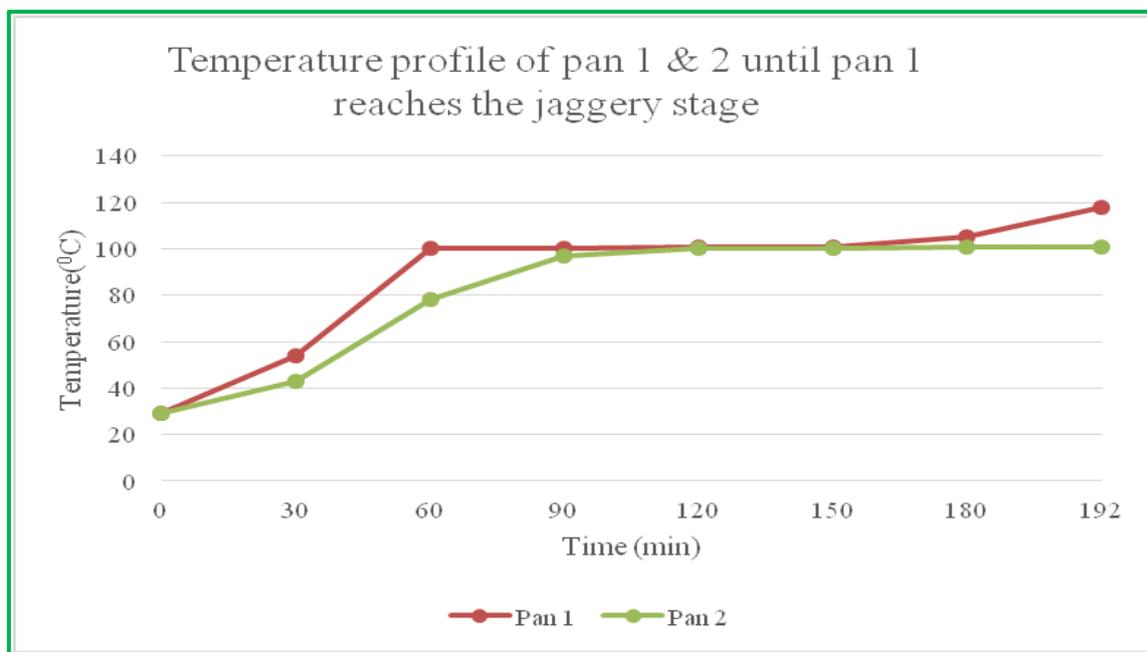


Figure 03: Temperature profiles of pan 1 and pan 2 until pan 1 reaches the jaggery stage

Conclusion

In the present experimental investigation, performance evaluation of the two-pan jaggery plant was conducted based on the three independent sets of observations in tradition two pan jaggery plant located in Rathnapura district, Sri Lanka. Using standard energy balance principles, the overall theoretical thermal efficiency of the system was calculated to be

10.39%, indicating that only a small fraction of the total heat energy released from fuel combustion is effectively utilized for juice concentration and jaggery production.

Potential modifications to enhance system performance include the incorporation of a third pan to facilitate better stage-wise heat utilization and improved thermal cascading. Additionally, optimizing the flue gas flow path particularly by reducing unnecessary flue length before the chimney, could minimize draft-related losses and improve effective heat transfer to the pans. Such modifications are expected to increase fuel utilization efficiency, reduce fuel consumption, and enhance overall process sustainability.

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