Assessment of optimum energy demand for non-centrifugal sugar production through an alternate process

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Abstract. Non-centrifugal sugar (NCS), known conventionally as Jaggery, obtained by concentrating cane juice in large boiling pans using traditional furnaces. In the traditional process, cane juice at 20 Brix is heated in pan(s) to 70 Brix to evaporate the water in it. Traditional furnaces used for concentration of sugarcane juice have low heat utilization efficiency about 15%. In the quest of improving energy efficiency, freeze pre-concentrating operation could be done at the start to remove water in the form of ice and the remaining proportion of water could be removed by heating for production of NCS. A thermal model has been developed for assessing optimum energy demand for a prior freezing technique up to a certain intermediate Brix and further by a heating technique. The obtained analytical data indicate that 1880.83 KJ/kg of cane juice is required when the juice concentration is increasing from 20 to 70 Brix while heating. The energy demand is significantly low (i.e. 536.10 KJ/kg of cane juice) when prior juice concentration is done through freezing technique from 20 to 63 Brix and later the juice is concentrated through heating technique from 63 to 70 Brix. Since, the energy required for latent heat of fusion is quite low when compared with the latent heat of vaporization so; combination of freezing and heating technique for juice concentration seems to be a viable option for improving energy efficiency in NCS production.

1. Introduction

Jaggery, the non-centrifugal sugar (NCS), is an unrefined traditional sweetener which contains 65-85% sucrose, 10-15% invert sugar; 3-10% moisture and remaining are the insoluble matter, for example, fat, proteins, minerals and phosphorus [1]. At the point when contrasted with sugar, NCS contains minerals and vitamins present in the sugar cane juice, which can be made accessible to the commonalities to relieve the issues of ailing health and under-nutrition. NCS cottage industry generates employment up to 2.5 million people in rural India with an annual production of 10 million tonnes of NCS [2].

It is the concentrated product of sugarcane juice, which is traditionally produced by evaporation of water present in the juice by burning bagasse. Prior to utilizing the bagasse as a fuel, it is dried due to
the presence of 50-60% moisture [3]. Traditional NCS plants are made by semi-skilled village persons, which are primitive in nature with very little controls to keep upright air-fuel proportions resulting in the poor thermal efficiency about 15% [4]. With an aim to enhance this thermal efficiency an improved furnace has been examined. The modified 2-pan furnace configuration was developed in which fins are attached to the bottom of the main pan and gutter pan which resulted in heat utilization efficiency of about 30% [5]. Utilization of exhaust heat via, economizer and pre-heater showed an improved thermal efficiency from 16.16% to 24.36% [6]. Solar energy resource was tapped for furnace inlet air pre-heating and sensible heating of the sugarcane juice, which resulted in the reduction of the bagasse consumption by 0.12 kg for production of 1 kg of NCS [7]. A further report of utilizing 4-pan along with controlling the inlet air to the furnace by using dampers has improved the thermal efficiency of furnace about 50-60% [8]. Steam was used as a heating source in closed heat exchanger systems, which resulted in an increase in overall thermal efficiency up to 63.63% [9]. These and other literature reviews indicate that such sort of examinations principally centered on enhancing the furnace configurations to improve the thermal efficiency in the NCS production process. As a slight variation from these, a freezing technique was developed by using the reversible heat pump for the concentration of sugarcane juice from 20 Brix to 40 Brix [10]. In this paper, an attempt has been made to assess the optimum energy requirement of NCS production using a combination of heating and freezing techniques for different masses of water removal, with a perspective of finding the energy efficient combination to concentrate sugarcane juice for production of NCS.

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2. Juice concentration techniques

Sugarcane juice colour varies from green to yellow, which depends on the variety of the sugarcane stalk. The sugarcane juice contains around 80% of water and 20% of sucrose content which is responsible for the NCS production [3]. Table 1 indicates the nomenclature for parameters and table 2 represents the assumed values used in the thermal modelling assessments.

| Parameter  | Description of Parameter                                      |
|------------|----------------------------------------------------------------|
| $C_j$      | Specific heat of sugarcane juice (J/kg-K)                     |
| $E$        | Total energy demand for combined technique (MJ/kg)            |
| $E_{\text{freeze}}$ | Energy demand for freezing technique per kg of cane juice (MJ/kg) |
| $E_{\text{vap}}$ | Energy demand for traditional technique per kg of cane juice (MJ/kg of juice) |
| $L_{\text{LHF}}$ | Latent heat of fusion for water (kJ/kg-K)                     |
| $X$        | Intermediate Brix                                            |
| $L_{\text{LHV}}$ | Latent heat of vaporization for water (KJ/kg)                 |
| $M_{\text{w2}}$ | Mass of water removed during heating technique in combined process (kg) |
| $M_j$      | Mass of cane juice (kg)                                      |
| $M_w$      | Mass of water removed (kg)                                   |
| $T_{\text{amb}}$ | Ambient temperature (°C)                                    |
| $T_{\text{boil}}$ | Boiling Temperature for cane juice (°C)                       |
| $T_{\text{freeze}}$ | Freezing temperature of water present in juice (°C)          |
| $\Delta\text{Brix}$ | Successive increase in change of Brix                         |
Table 2. Assumed values of parameters.

| Parameter | Value          |
|-----------|----------------|
| $T_{amb}$ | 30 °C          |
| $L_{LHV}$ | 2260 KJ/kg-K  |
| $L_{LHF}$ | 223 KJ/kg-K   |
| Initial Brix | 20            |
| Mass of juice | 1 kg         |

The concentration of sugarcane juice is done by removal of water from the juice. Brix is the amount of solute i.e. NCS present in the solution i.e. sugarcane juice. During concentration process there is a decrease in quantity of water but, the amount of NCS present in it remains constant. According to equation 1, if NCS amount present in the solution is constant then with the successive increase in change of Brix value there will be decrease trend in the mass of water removal value. Table 3 represents the decrease in water removal data with successive increase in change of Brix value.

$$Brix' = \frac{Brix1}{1 - (1 - \frac{Brix1}{100} \times M_w)}$$  \hspace{1cm} (1)

Table 3. Mass of water removed with respect to successive increase in $\Delta$Brix.

| Successive increase in change of Brix ($\Delta$Brix) | Mass of water removed (kg) |
|---------------------------------------------------|-----------------------------|
| 20-25                                             | 0.2                         |
| 25-30                                             | 0.133                       |
| 30-35                                             | 0.095                       |
| 35-40                                             | 0.071                       |
| 40-45                                             | 0.055                       |
| 45-50                                             | 0.044                       |
| 50-55                                             | 0.036                       |
| 55-60                                             | 0.030                       |
| 60-65                                             | 0.025                       |
| 65-70                                             | 0.021                       |

2.1. Traditional technique for water removal

NCS is a concentrated product of sugarcane juice which is traditionally produced by evaporation of water in the juice. The traditional NCS making process involves number of phases which are shown in figure 1. Sugarcane juice is obtained as an outlet from the crushing phase when sugarcane stalks are inserted as an inlet. Sugarcane juice contains around 80% of water, which is evaporated in the boiling pan(s) by burning bagasse as fuel in the furnace. Heating of juice starts in the boiling pan for the evaporation of water present in the juice. During this process, certain additives like calcium oxide (0.2 kg/m³ of sugarcane juice) and phosphoric acid (0.00015 m³/m³ of sugarcane juice) are added in measured quantities to maintain the pH and also for clarification of the solution at respective temperatures, which results in the formation of scum that is removed from time to time. Boiling is continued till 2 hours till the concentrated juice attains a striking temperature i.e. 118 C where it converts itself into a semi-solid...
paste which doesn’t stick to the boiling pan, further small amount of cooking oil (0.0002 m$^3$/m$^3$ of juice) is added for easily transferring to the cooling tray. The concentrated syrup is stirred in the cooling tray and moulded [11]. In the traditional process, the concentration of sugarcane juice is done up to 70 Brix [12]. The traditional technique computation of heating sugarcane juice in order to produce NCS is represented in figure 2.

**Figure 1.** NCS making process.

**Figure 2.** Traditional technique computation for juice concentration.

### 2.2. Freezing technique for water removal

In contrast with the traditional technique, in this technique, the water is expelled in the form of ice, when the juice is subjected to refrigeration process. The juice temperature is decreased from the surrounding temperature to a freezing point temperature which results in the formation of ice. The ice lump formed in the juice is expelled to increase the sugarcane juice concentration. The total amount of water content in juice cannot be removed just by freezing because the sucrose-water phase equilibrium indicate that the freezing technique is limited by the eutectic point i.e. concentration of sugarcane juice can only be done up to 63 Brix [13]. Else if, freezing is continued even after the subsequent sucrose concentration has reached 63 Brix, then the sucrose content also freezes along with the water present in the juice and
forms a frozen blend. For obtaining concentrated sugarcane juice, if this frozen blend is removed then it leads to loss of sucrose from the juice. So concentration of sugarcane juice is done only up to 63 Brix by freezing technique. The computation of freezing sugarcane juice in order to produce NCS is represented in figure 3.

2.3. Combined technique for water removal
In this combined technique concentration of sugarcane juice is done by using both freezing and heating technique. At first, the sugarcane juice is concentrated to a certain extent by the freezing technique and further, the resultant juice concentration is increased by the heating technique. The Brix value will get increased when water removal takes place either by freezing or heating. Sugarcane juice needs to be concentrated from 20 Brix to 70 Brix in order to produce NCS. In this combined technique, prior the juice is concentrated by freezing from 20 Brix to an intermediate Brix of (X) and further from intermediate Brix of (X) to 70 Brix by heating. For an instance, if X is 45 Brix that implies the juice is concentrated from 20 Brix to 45 Brix by freezing and further from 45 Brix to 70 Brix by heating. The range of X Brix varies from 20 Brix to 63 Brix (20 Brix ≤ X ≤ 63 Brix), since freezing technique cannot be continued after 63 Brix due to the limitation of eutectic point. The process of cooling and heating of sugarcane juice in order to produce NCS is represented in figure 4.

3. Energy assessment
The energy assessment per kg of sugar cane juice can be computed as indicated in the above process figures. But, there is a variation in boiling point, freezing point temperature and specific heat of the juice when concentration of sugarcane juice is increasing.
According to Roult’s law, the boiling and freezing temperatures of a sugarcane juice are respectively elevated and depressed regarding the concentration of the juice. Sugarcane juice concentration increases by removal of water content in it, which results in increase in elevation of boiling temperature while heating and depression of freezing temperature while cooling as shown in table 4 [12].

Table 4. Elevation and depression in temp with respect to Brix.

| Brix | Elevated in Temp (°C) | Depression in Temp (°C) |
|------|------------------------|-------------------------|
| 20   | 0.40                   | 1.49                    |
| 25   | 0.50                   | 2.04                    |
| 30   | 0.70                   | 2.71                    |
| 35   | 0.90                   | 3.53                    |
| 40   | 1.20                   | 4.58                    |
| 45   | 1.60                   | 5.92                    |
| 50   | 2.00                   | 7.61                    |
| 55   | 2.40                   | 9.76                    |
| 60   | 3.00                   | 12.45                   |
| 65   | 4.00                   | -                       |
| 70   | 5.00                   | -                       |

Sugarcane juice consists of sucrose and water which have different specific heat values i.e. for water it is 4.18 kJ/kg-K and for sucrose, it is 1.24 kJ/kg-K. Specific heat of water is more than the sucrose, when water is removed from the sugarcane juice there is a trade-off between the resulting specific heat values which can be computed from equation 2. As a result, the effective specific value will come down as the Brix value increases as shown in table 5 [12].

\[ C_j = 4187 \times (1 - 0.006 \times \text{Brix}) \] \hspace{1cm} (2)

Table 5. Variation of specific heat with respect to Brix.

| Brix | \( C_j \) (kJ/kg-K) |
|------|---------------------|
| 20   | 3.717               |
| 30   | 3.482               |
| 40   | 3.248               |
| 50   | 3.013               |
| 60   | 2.779               |
| 70   | 2.545               |

Table 6 represents the energy demand for heating technique and freezing technique with respect to increase in concentration of the sugarcane juice. As it seems that the energy requirement for consecutive change in Brix value is getting reduced because the amount of water removal also decreases, so the energy consumed will be less for the water removal. For an instance the heating energy demand for increase in juice concentration from 40 to 45 Brix is 45 to 50 Brix is 100.96 kJ.
Table 6. Energy requirements for individual technique: Heating and Cooling

| Successive increase in change of Brix (ΔBrix) | Heating Energy Required (KJ/kg of juice) | Cooling Energy Required (KJ/kg of juice) |
|---------------------------------------------|------------------------------------------|------------------------------------------|
| 20-25                                      | 713.36                                   | 185.31                                   |
| 25-30                                      | 301.72                                   | 46.29                                    |
| 30-35                                      | 215.77                                   | 33.58                                    |
| 35-40                                      | 161.87                                   | 25.73                                    |
| 40-45                                      | 126.16                                   | 20.59                                    |
| 45-50                                      | 100.96                                   | 17.06                                    |
| 50-55                                      | 82.75                                    | 14.60                                    |
| 55-60                                      | 68.98                                    | 12.81                                    |
| 60-63                                      | 36.41                                    | 6.62                                     |
| 63-70                                      | 72.86                                    | -                                        |

Similarly the cooling energy demand for increase in juice concentration from 30 to 35 Brix is 33.5 kJ and for increase in juice concentration from 35 to 40 Brix is 25.73 kJ. The energy demand for heating technique for increase in juice concentration from 20 to 70 Brix is 1880 kJ/kg of juice whereas, by freezing technique for increase in juice concentration from 20 to 63 Brix is 362.59 kJ/kg of juice. The energy demand for removal of water in heating technique is higher because of the greater value of latent heat of vaporization when compared to the latent heat of fusion in cooling technique. The concentration of juice needs to reach 70 Brix in order to produce NCS; this is possible only through heating technique because in cooling technique concentration of juice can occur up to only 63 Brix due to eutectic point.

Figure 5 represents the energy demand per kg of juice in combined technique for sugar cane juice concentration. In this technique, prior the juice is concentrated by freezing from 20 Brix to an
intermediate Brix of (X) and further from intermediate Brix of (X) to 70 Brix by heating. As X value is increasing from 20 to 63 Brix the energy demand for cooling technique is increasing while, for heating technique the energy demand is decreasing since, the X value is increasing, and the maximum concentration of juice is done by the freezing technique. From the optimum energy demand assessment with respect to variation in intermediate Brix (X), the maximum concentration of juice should be done by freezing technique. When intermediate Brix (X) value is 63 i.e. 20 to 63 Brix concentration of juice by freezing and 63 to 70 Brix concentration by heating technique indicates to be the optimum total energy demand of 536.10 kJ/kg of juice.

4. Conclusions
NCS is the healthiest sweetening agent in the world. When compared with sugar, during the production of NCS, the vital nutrients and minerals which are present in the molasses is retained. NCS produced using traditional technique consumes a lot of bagasse due to low furnace efficiency. In the quest of improving energy efficiency, a thermal model is developed which includes an alternative method of using freezing technique for the concentration of the sugarcane juice. To arrive at optimum energy demand three phases are followed (a) energy assessment for heating technique for increase in juice concentration from 20 Brix to 70 Brix (b) energy assessment for freezing technique for increase in juice concentration from 20 Brix to 63 Brix (c) energy assessment for combined technique is to increase juice concentration from 20 Brix to an intermediate Brix by freezing technique and further, increase in juice concentration from intermediate Brix to 70 Brix by heating. It has been computed that the production of NCS by heating technique requires energy demand of 1880 kJ/kg of juice. But, the optimum energy demand shows 536.10 kJ/kg of juice when initial juice is concentrated by freezing from 20 to 63 Brix and further, from 63 to 70 Brix by heating technique. The combined technique should be utilized for sustainability of NCS industry. For freezing technique the reversible heat pump can be used, and for heating technique multi-effect evaporators and vapor re-compression evaporators can be explored. Further, for increasing the efficiency of NCS industry the renewable energy resources can be captured.

Acknowledgments
The work and results presented in this paper are part of the project “Sustainable technological solutions for energy efficiency in jaggery industry (STEEJ)” funded by Royal Academy of Engineering (RAE) vide project reference #IAPP1R2\100083. The authors thankfully acknowledge the Royal Academy of Engineering for funding this project.

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