Freeze Concentration of Sugarcane Juice in a Jaggery Making Process-Modeling

Abhishek B. Sahasrabudhe, Ranjit R. Desai, and Siddharth K. Jabade

***Abstract*—Freeze concentration is a process in which water is selectively separated out of a binary solution in the form of ice, resulting in concentration of the solution. Among several configurations of a freeze concentration system the one employing a layer freezing process is considered in this paper. The application of this system for the present paper is in the process of jaggery making used to concentrate sugarcane juice. A mathematical model is developed that helps in analyzing the system under the action of various operating parameters. The model is validated using previously published experimental results. Finally, based on simulation, effects of various system parameters on ice growth and subsequent juice concentration have been assessed and discussed.**

***Index Terms*—Freeze concentration, jaggery, layer freezing.**

I. Introduction

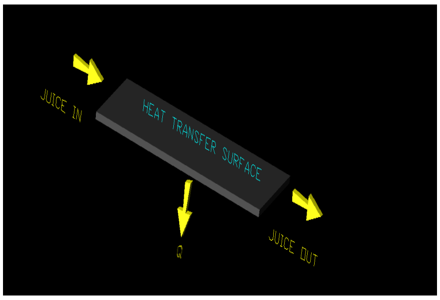

Fig.1.0 Schematic of a Layer Freeze Concentration Heat Transfer Surface

Freeze concentration technology is based on the principle of selective separation of water from a binary solution by cooling or freezing, crystallizing ice and leaving behind a concentrated fluid. The advantage of process is that nutritional quality, aroma retention of the freeze concentrated juices is better than those concentrated by conventional methods like evaporation, due to lower temperatures involved in this process [1, 2]. Suspension and film freeze concentration are two basic methods for concentrating solutions by freezing. Layer freeze concentration is a type of film freeze concentration which can be used for concentrating sugarcane juice in jaggery making process. With reference to Fig: 1.0, the juice flows over a refrigerated flat plate which acts as a heat transfer surface. The layer freezing of water from sugarcane juice

over this surface occurs thus gradually concentrating the juice. According to J. Sanchez *et. al.* [1] a layer freeze concentration system (LFCS) is expected to have future industrial prospects. In jaggery making process, juice is extracted from sugarcane and is further concentrated by separating water content from it. The application of freeze concentration system to separate the water in the form of ice is considered in the present paper.

Prediction of ice formation on the heat transfer surface is of importance in the design and development of freeze concentration system. To establish a frame of reference to develop a method to predict ice formation on the heat transfer surface for the freeze concentration system, relevant literature is reviewed. The problems with change of phase have in common characteristic non linearity resulting from the boundary (solid-liquid interface) movement, which complicates the analysis and renders each problem somewhat unique [3]. General solutions need a three-dimensional, transient analysis of the temperature distribution before, during and after the change of phase in a body, whose physical properties are often temperature dependent. Because of the unavailability of analytical solutions for these nonlinear and parabolic type phase change problems, various numerical methods are developed [4], namely: (a) fixed grid [5] (b) variable grid [6] (c) front-fixing [4] (d) adaptive grid generation [7] and (e) enthalpy or total heat [8]. Variation in the thermal properties with temperature, which is usually considerable over the ranges of temperature, involved in problems on solidification and melting can be taken into account in numerical methods.

Due to various physical and thermodynamic property changes, with space and time associated with the freeze concentration system, their modeling by analytical methods is complex. Further the challenge is in extending the freeze concentration analysis as facilitating means for system design. Thus, authors have proposed a unique and simple numerical model for such a system, applied for sugarcane juice concentration. The same is validated using experimental data taken from previously published work [9].

II. Rationale of the Model

Sugar cane juice is a binary mixture of sucrose and water. The binary eutectic equilibrium diagram of sugarcane juice up to eutectic point is published [10]. As juice is slowly cooled, below the liquidus line, water in the juice crystallizes out as ice, thereby increasing juice concentration (Brix) along liquidus line up to eutectic point. Thus the concentration increases, freezing point decreases according to phase diagram. With reference to Fig. 1, in layer freezing, as juice flows down the refrigerated heat transfer surface that is in the form of a plate, due to temperature driving force between juice and refrigerant, heat is extracted from juice and it is cooled gradually below liquidus temperature at initial concentration, leading to ice crystallization. Thus along the plate, water content of juice decreases and

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concentration increases and subsequently freezing point decreases. This results in gradual variation in physical and thermodynamic properties like viscosity, density, specific heat, thermal conductivity etc. of juice. These property changes result in varying heat transfer rates with time and space. Moreover, ice layer formed adds to thermal resistance for next coming juice batches. Hence, defrosting the system after specific time becomes necessary.

The proposed numerical model is based on following fundamental assumptions**:** Thermal energy abstraction in sub-cooling the ice may be considered as negligible relative to the latent heat of freezing requirement. Heat transfer process is quasi steady; all the heat transferred to or from ice is utilized towards melting or freezing the ice. Ice already present on heat transfer surface offers resistance, but no thermal capacity. This, idealization of negligible heat capacity is valid (Finer, 1993)[11].Thickness of ice layer is uniform along a single incremental segment and axial conduction is neglected. Physical properties of the juice, such as the specific heat capacity, the volume and the density do not change in each segment during the ice formation. Temperature gradient across the heat transfer surface wall is assumed to be linear.Supercooling of the juice is neglected. Thermal properties variation of the heat transfer surface material due to temperature change is negligible. Thermal properties of ice ρ, k and c are considered as constant. Thermal properties of sugarcane juice are constant in each segment. Density, specific heat and viscosity of secondary refrigerant are calculated at the average temperature. The effect of diffusion of solute at solid interface has been neglected as based on previous work its magnitude may be considered negligible [9].

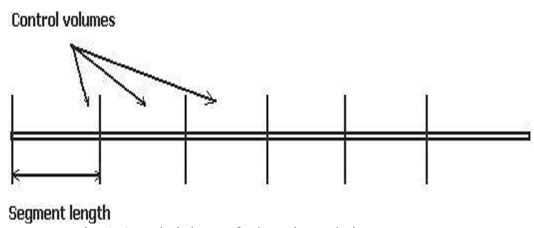

Fig 2.0: Division of plate length into segments

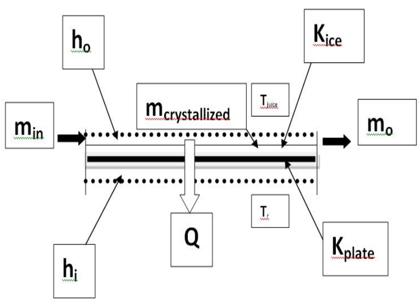

Fig.3.0 Segment heat and mass transfer.

The model is based on the following method. The length of plate is divided into small imaginary segments, as shown in Fig 2.0, each segment acting as a control volume. Attention is focused on heat and mass transfer from juice in each segment after infinitesimal time step and thus time discretization is used over each control volume. The time step and segment length being infinitesimal, properties of juice are assumed constant in each time step and hence over each segment. With time, in each control volume i.e. segment due to build up of the ice layer the parameters and properties vary except for first segment. Every segment is analyzed for stipulated time. Energy and mass balance (Fig 3.0) equations are applied at every time step to calculate thickness of ice crystallized.

III. Flowchart:

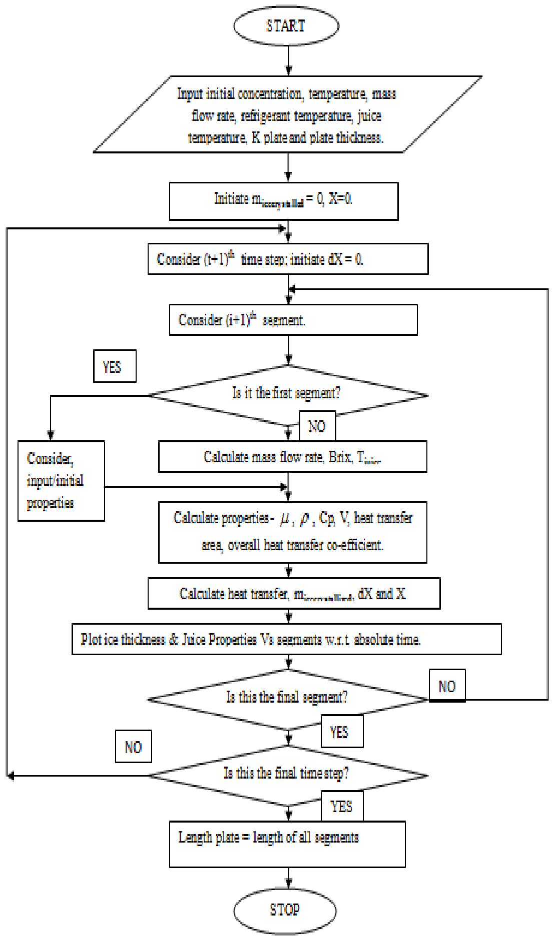

Fig 4.0: Flowchart for model

Flow chart for model is given in Fig. 4.0. For the first segment, input properties of juice are considered for all time steps up to observation time. In every time step properties of subsequent segments are calculated based on values of those properties in previous segment in that time step. Also, for each segment ice thickness is zero when time is zero and gradually increases with time.

Thus, concentration of juice entering current segment (segment under consideration) at a particular time step is given as

$$Bx_{i+1} = 1 - \left[\frac{\left(m_{juice,i} \times \frac{(100 - Bx_i)}{100} - m_{ice,i} \right)}{m_{juice,i} - m_{ice,i}} \right] \quad (1)$$

Since juice is a binary mixture of sucrose and water, as concentration of juice increases, freezing point decreases according to phase diagram. The relation between concentration and freezing temperature is obtained from the phase diagram using curve fitting as:

$$T_{juice,i+1} = -1 - (Bx_{i+1} - 15) \times 0.18 \quad (2)$$

Sugar cane juice viscosity varies with the temperature and concentration. The relation between viscosity and Brix in current segment at particular time step is obtained using a graph of temperature, concentration and viscosity [12] as:

$$\mu_{juice,i+1} = \frac{a}{\left(a + b \times Bx + c \times (Bx)^2\right)} \quad (3)$$

where, a = 1.8214, b = -0.0337, c = 0.0002

Specific heat of sugarcane juice varies with the concentration (Bx) it is calculated as [12].

$$c = \left\{1 - \left[a - b \times T_{juice} + c \times (100 - P)\right] \times \frac{Bx}{100}\right\} \times 4.18 \quad (4)$$

a= 0.6, b=0.0018, c=0.0008

where, P is juice purity.

Density of sugarcane juice in current segment is calculated as:

$$\rho_{juice,i+1} = \left[1.59 \times \frac{Bx_{i+1}}{100} + \frac{(100 - Bx_{i+1})}{100}\right] \times 100 \quad (5)$$

Velocity of the sugarcane juice in current segment at particular time step is calculated by substituting the values from equations 3 and 5 in the following equation [13]:

$$V = \frac{g \rho \delta^2}{3\mu} \quad (6)$$

For flat film surface, the film thickness is given by:

$$\delta = \left(\frac{3\Gamma\mu}{\rho^2 g}\right)^{1/3} \quad (7)$$

where, δ film thickness (m); ρ : density of the fluid (kg/m^3); μ :viscosity (kg/m.s); Γ : mass flow rate per unit width of the surface (kg/m.s). The inner side convective heat transfer co-efficient and refrigerant temperature (Phase change) are considered constant. From empirical co-relations outer side convective heat transfer co-efficient is found out [14]. At first time step, for all segments ice thermal resistance is zero. Hence, overall heat transfer co-efficient may be calculated as

$$/U = 1/h_i + 1/h_o + T_{plate}/K_{plate} \quad (8)$$

For subsequent time steps, for all segments, the overall heat transfer co-efficient for a particular time step, considering thermal resistance of ice may be calculated as:

$$1/U = 1/h_i + 1/h_o + T_{plate}/K_{plate} + X_{ice}/K_{ice} \quad (9)$$

The net heat transfer in a segment in the time step is calculated as

$$Q = UA\,(T_{juice\ i+1} - T_r) * \Delta t \quad (10)$$

where,
A: Effective heat transfer area for particular segment (m^2);
Δt: time interval (seconds);

Hence, mass of ice crystallized, neglecting sensible heat transfer

$$= (Q \div h_{fusion}) \quad (11)$$

Assuming uniform crystallization of ice over the length of segment in infinitesimal time step, ice thickness in the current segment within the time interval is given by

$$dX = (\text{mass of ice crystallized}) / (\rho_{ice} \times A) \quad (12)$$

These calculations are done for every segment after interval of an infinitesimal time step from t = 0 to time of observation.

IV. Results and Discussions:

Following plot is obtained when the numerical model was simulated using following set of parameters:

TABLE I. VALUES OF SET OF PARAMETERS

Sr. no.	Parameter	Value
1.	Refrigerant Temperature	-10^{0}C
2.	Initial Concentration	15 Brix
3.	Thickness, heat transfer surface	0.2 mm
4.	Thermal Conductivity of heat transfer surface (Stainless steel)	15 W/mK
5.	Mass flow rate	0.03 kg/s

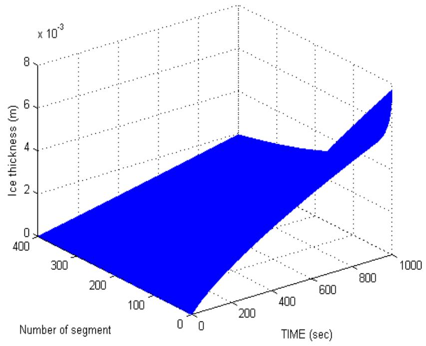

Fig: 5.0 Plot of Ice Thickness (m) Vs Time (sec) for different segments over the plate

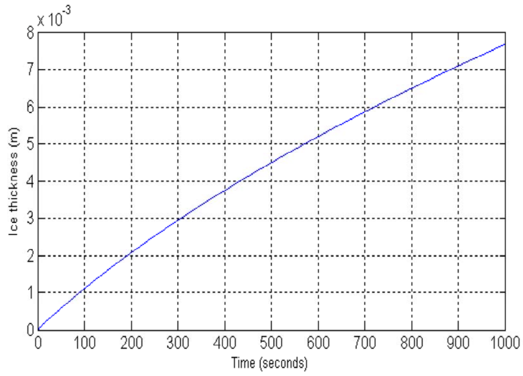

Fig 6.0 Ice thickness (mm) Vs Time (sec) for first segment

As depicted in Fig 5.0, for each segment (control volume) the ice thickness gradually increases with time due to heat extraction by refrigerant. From Fig 6.0 It can be observed that ice thickness increases at decreasing rate which was verified by a negative second derivative of the curve. For the first layer of juice, there is absence of ice layer over plate and hence no thermal resistance of ice. Thus, during the initial time step heat transfer is maximum for each segment. With time as ice crystallizes, its added thermal resistance lowers the heat transfer and hence for subsequent juice layers over each segment, heat extraction is of a lesser magnitude leading to lesser ice crystallization and lesser incremental ice thickness. So, increments in ice thickness (dX) go on decreasing with time. Fig. 5.0 shows that final ice thickness goes on decreasing along the length of plate. This can be attributed to the decreasing outer and overall heat transfer co-efficients at any time along plate as observed in fig 8.0. The outer heat transfer co-efficient decreases along plate length due to increasing thermal boundary layer thickness. Also increasing concentration along the plate length leads to increasing viscosity and increased viscosity leads to lower velocity (V α $1/\mu$). Concentration increase also leads to increasing density along the length. The specific heat of the juice however, decreases for successive segments. The property changes along plate length are clear from Fig. 8.0. Moreover, as seen from binary eutectic phase diagram the freezing temperature of juice lowers with increase in juice concentration. Thus, the temperature driving force between juice and refrigerant decreases along the length as observed in Fig.7.0. The combined effect of these phenomena is that for any time step heat transfer rate is maximum for the first segment and minimum for final. Therefore, increments in ice thickness in that time step are of lower magnitude along the plate length. Effectively the final ice thickness gradually decreases longitudinally.

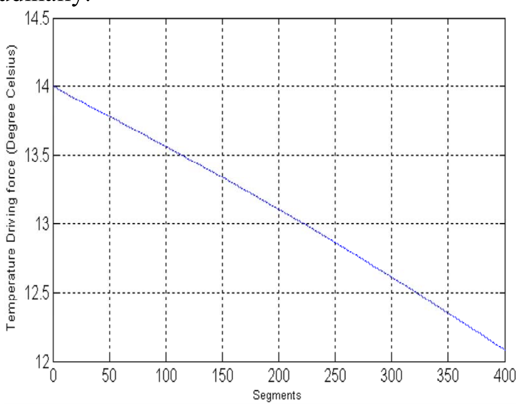

Fig.7.0 Temperature driving force (0C) Vs Number of Segments over heat transfer surface.

Thus, the model may be used to estimate dimensions of heat transfer surface for a desired output concentration. The effects of changes in input parameters viz. mass flow rate, refrigerant temperature, and thermal conductivity (plate material) on the final output concentration of juice may be ascertained. Suitable plate dimensions and values of input parameters could then be selected during prototype development. The ice built up after certain time may be obtained with sufficient approximation using this model. Hence, time after which accumulated ice should be melted for efficient system operation could be determined. Finally, thermo-physical properties of the output juice may be known which could aid deciding further juice treatment for jaggery making.

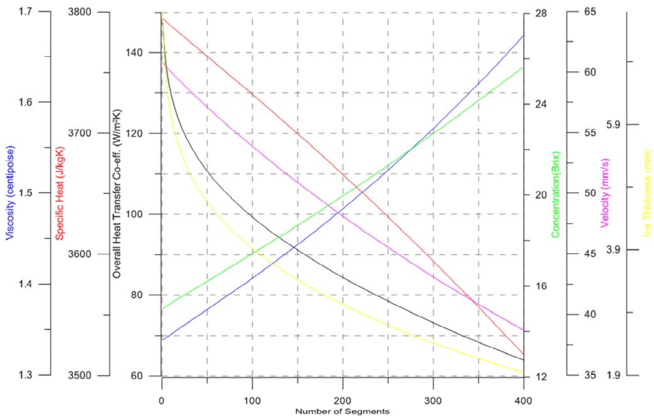

Fig 8.0 Plot depicting Property changes Vs Number of Segments along the heat transfer surface

V. CONCLUSIONS

The present model is an effective tool to estimate ice formation with respect to time for layer freeze concentration systems. The nature of system ice growth character with time, space and varying input parameters and dimensions can be estimated with this model, thereby, directing optimum system design and development. The model is easy to formulate and quick to simulate computationally as a handy tool to design freeze concentration system.

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