ABSTRACT

If rice is cooked in milk, starch-milk reaction results into a thick product, popularly known as *kheer* in India and rice pudding in the United States and Europe. Conventionally, *kheer* is prepared by cooking rice in milk in an open pan over low fire followed by addition of sugar towards the end. It is a batch process taking approximately 1 h. At present, attempts to make the process of *kheer* cooking continuous are non-existent. Therefore, this work aims to design and develop a continuous *kheer* making machine using optimized parameters of *kheer* cooking process and computational heat and mass transfer analysis of rice-milk flow through the designed heat exchanger of the machine. A design of a continuous *kheer*-making machine has been developed that consists of a rice conveyor, a pressurized cooking section (heating and holding section), a sugar conveyor, flash chamber and a condenser. For designing the cooking section, the relevant process parameters (operating pressures above atmospheric and reduced cooking time) were optimized. Sensory trials of *kheer* prepared conventionally and using pressurized methods were carried out and the data was analyzed using Fuzzy Logic (FL). Sensory results of open-pan samples indicated that there is a small range of Whiteness Index (WI) and Hardness (H) values that is desirable in *kheer*. An Artificial Neural Network-Genetic Algorithm (ANN-GA) model was developed to optimize the operating parameters to result in a product that would have the desired color and texture observed in *kheer* prepared conventionally. The developed ANN-GA model was successful in providing with input conditions leading to desired WI and H values. Finally, from the set of optimal input conditions, operating pressure of 0.27 MPa and cooking time of 7.5 min. was chosen for designing the pressurized cooking section of the continuous *kheer*-making machine.

Thermo-physical properties (density, thermal conductivity, viscosity and specific heat) of rice-milk mixture prepared using optimized process conditions were measured experimentally up to a temperature of 80^0C—obtaining properties at higher temperatures resulted in large variations. Therefore, predictive equations for estimating thermo-physical properties based on composition and as functions of temperature were developed using properties of individual components that are valid up to a temperature of 150^0C. Accurate thermo-physical properties of the rice-milk mixture would be necessary for heat transfer calculations and estimation of milk fouling when designing the heat exchanger of the heating section.

The heating section of the continuous *kheer* making machine comprises of a helical coil heat exchanger to cook rice in milk. A two dimensional (2D) fundamentals-based heat transfer model based on enthalpy balance was developed to include the effects of milk fouling in order to estimate the drop in temperature of the product at the outlet, degree of fouling and fouling thickness that would build up with time and length of the helical coil. Fouling thickness was found to increase towards the outlet and the rate of increase in fouling thickness decreased with time. At the outlet, a significant drop in temperature was observed (11 ^{o}C) as an adverse effect of milk fouling. For a more comprehensive understanding of the process of *kheer* cooking, the 2D model was extended to three dimensional (3D) to include the curvature effects of the helical coil and temperature dependent thermo-physical properties. Computational Fluid Dynamics (CFD) analysis of *kheer* cooking was carried out on the actual geometry using finite elements. The set of coupled partial differential equations for fluid flow, heat transfer and kinetics of milk fouling were solved using a commercial finite element software (COMSOL Multiphysics, V4.2a).

Velocity, temperature and fouling thickness profiles were obtained as outputs from the model to understand the dynamics of *kheer* making as a continuous process. Based on the results of 3D modeling, appropriate design changes were suggested in the heating section of the continuous *kheer* making machine. Development of such comprehensive models is appreciated to aid in efficient design of the machine and to help understand and overcome the adverse effects of milk fouling to obtain a product of desired quality.

Dynamics of moisture uptake in rice is a complex process and is certainly not a simple Fickian diffusion as has been shown through NMR studies. Therefore, a Relative Water Demand (RWD) model based on the extent of starch gelatinization and chemical potential of water in rice was developed to understand the moisture migration inside a single rice grain during cooking for raw and parboiled variety. Moreover, conjugate modeling approach was used to improve upon existing models of rice grain hydration that assume constant moisture content values at the grain boundary. The model successfully predicted the trends of moisture uptake in both varieties of rice. Parboiling results in morphological changes inside the rice grains providing an increased resistance to moisture transfer inside parboiled rice. A morphological parameter was defined to account for the differences in moisture uptake between raw and parboiled rice.

Keywords: kheer; optimization; hybrid ANN-GA; Fuzzy Logic; rice-milk properties; Fouling; CFD modeling;