Computer-aided design of the heating section of a continuous *kheer* (rice pudding)-making machine

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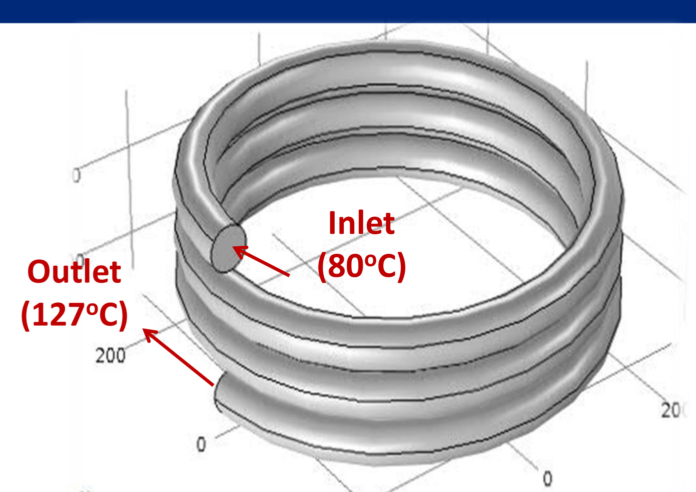
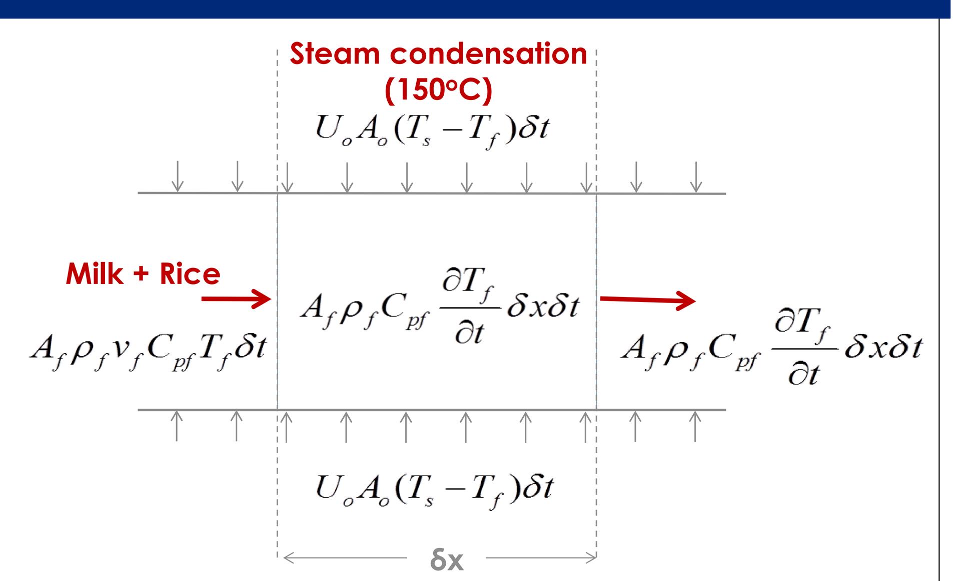
Introduction

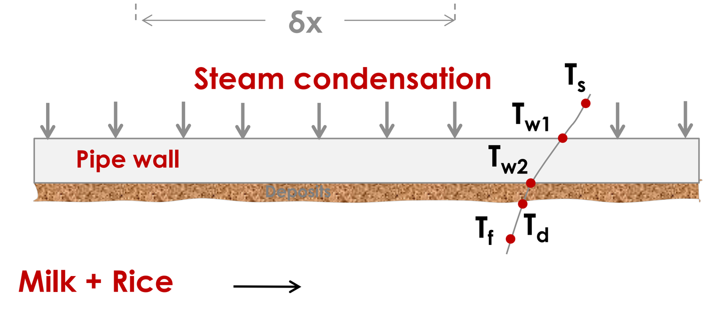
- *Kheer* is a popular Indian dairy dessert prepared from concentrating milk with simultaneous cooking of rice grains. Conventional methods of preparing *kheer* have limited its mechanized production. Therefore, a conceptual design of continuous *kheer*-making machine has been prepared which among other components consists of a heating section for cooking *kheer*
- The present study investigates the CFD analysis of fluid flow, heat transfer and fouling characteristics in the cooking section comprising of a helical coil heat exchanger heated with saturated steam on the outside.
- Development of such comprehensive models is appreciated to aid in efficient design of the continuous *kheer* making machine and to help overcome the adverse effects of milk fouling to obtain a product of desired quality

Problem Formulation



. The Heating Section





Assumptions:

- rice and milk form an **overlying continua**
- for 3D modeling, **flow** is **fully developed** – the **transient period** is assumed **small and ignored**
- **thermal equilibrium** between rice and milk

Governing Equations

Fluid flow: k-ε turbulence model

Momentum balance

$$\rho(\vec{u}\cdot\nabla)\vec{u} = \nabla\cdot\left[-p\vec{I} + (\mu+\mu_T)(\nabla\vec{u}+(\nabla\vec{u})^T) - \frac{2}{3}(\mu+\mu_T)(\nabla\cdot\vec{u}) - \frac{2}{3}\rho k\vec{I}\right] \quad \text{----(1)}$$

$$\mu_T = \rho C_\mu \frac{k^2}{\varepsilon}$$

Turbulent kinetic energy equation:

$$\rho(\vec{u}\cdot\nabla)k = \nabla\cdot\left[\left(\mu+\frac{\mu_T}{\sigma_k}\right)\nabla k\right] + P_k - \rho\varepsilon \quad \text{----(2)}$$

Turbulent dissipation energy equation:

$$\rho(\vec{u}\cdot\nabla)\varepsilon = \nabla\cdot\left[\left(\mu+\frac{\mu_T}{\sigma_\varepsilon}\right)\nabla\varepsilon\right] + C_{\varepsilon1}\frac{\varepsilon}{k}P_k - C_{\varepsilon2}\frac{\varepsilon^2}{k}\rho_k \quad \text{----(3)}$$

$$P_k = \mu_T\left[\nabla\vec{u}:(\nabla\vec{u}+(\nabla\vec{u})^T) - \frac{2}{3}(\nabla\cdot\vec{u})^2\right] - \frac{2}{3}\rho k\nabla\cdot\vec{u}$$

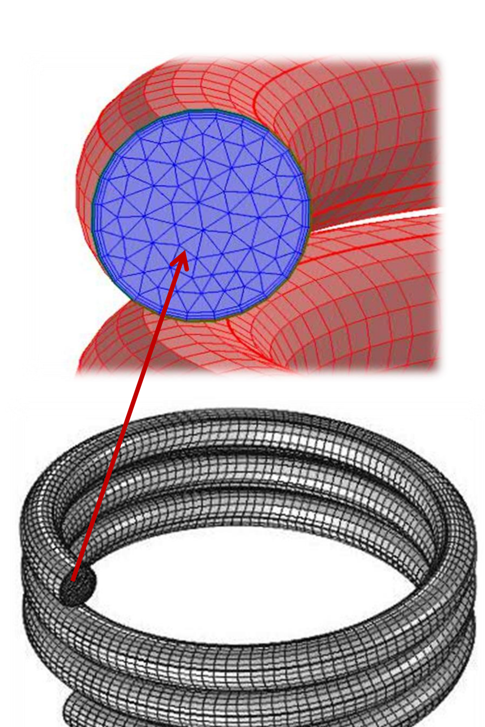
Heat transfer in fluids

$$\rho C_p\vec{u}\cdot\nabla T = \nabla\left(\left[k+\frac{\mu_T C_p}{Pr}\right]\Delta T\right) + Q_{vh} \quad \text{----(4)}$$

Local Fouling Rate

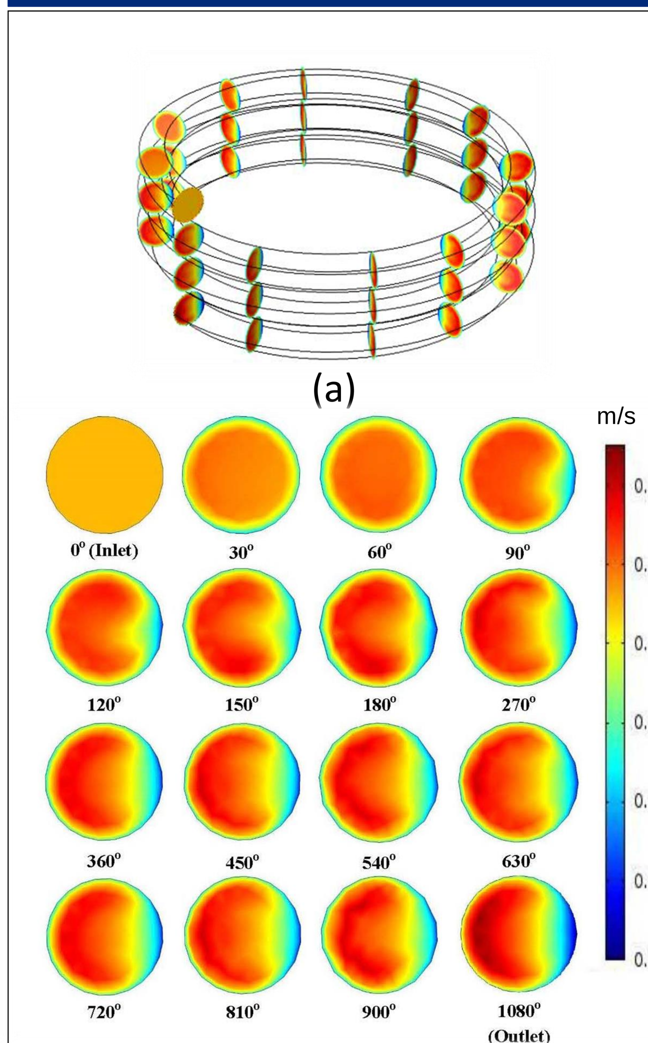
$$\frac{dBi_m}{dt} = k_d exp\left[-\frac{E_a}{R}\frac{\phi_m + f(Bi_m) + \frac{r_o}{r_i}}{(T_s+273)\left(\frac{h_f^o r_o}{h_f r_d}\right) + (T_f+273)\left[\phi_m + \frac{r_o}{r_i}Bi_m\right]}\right] - k_r Bi_m \quad \text{----(5)}$$

Initial and Boundary Conditions

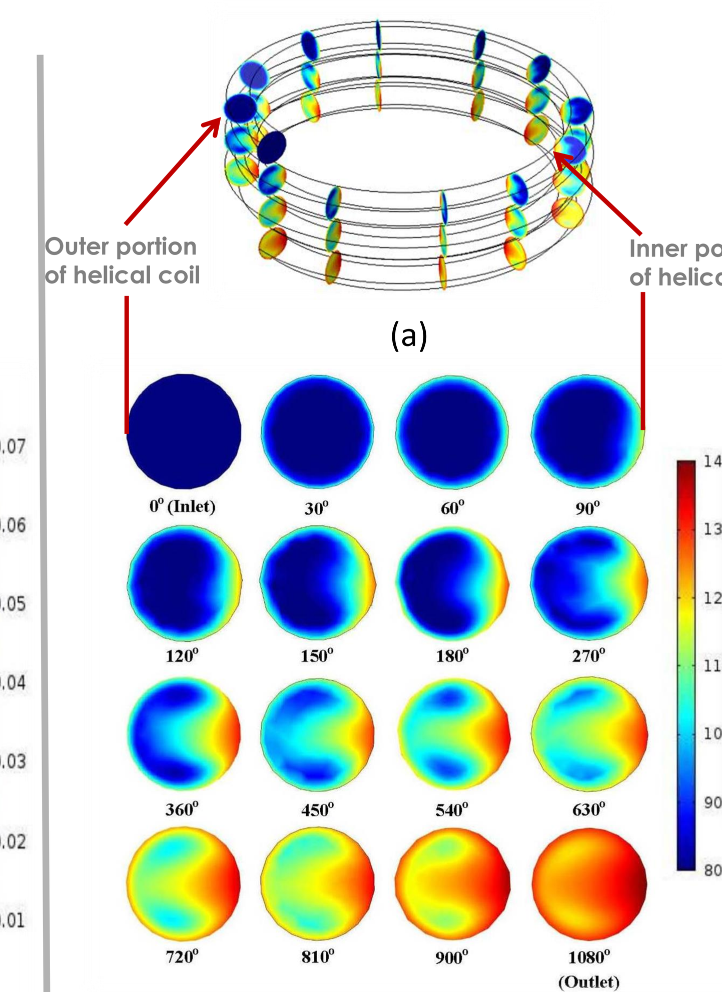


	Rice-milk	Unit
Fluid flow		
Inlet velocity	0.055	m s^{-1}
Wall	No slip	-
Heat transfer		
Inlet temperature	80	ºC
Steam	150	ºC
Heat flux	$U_oA_o(T_s-T)$	W
Fouling		
Inlet Biot number	0	-

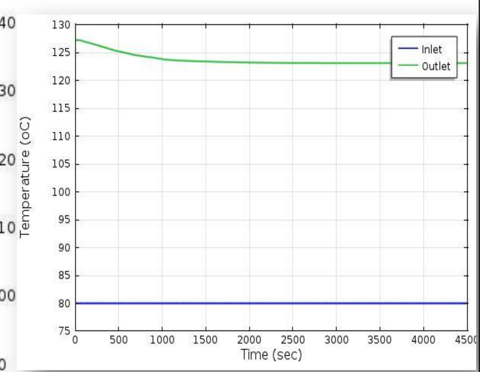
Simulation Results



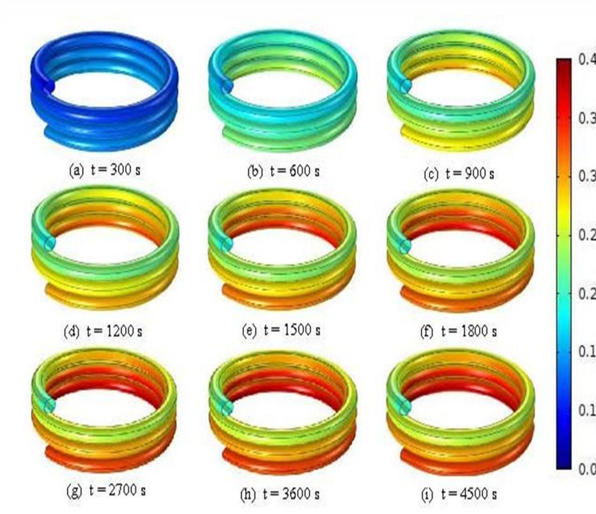
Velocity profile at different cross-sections



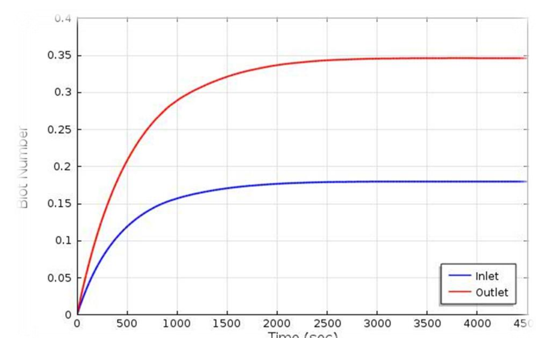
Temperature profile at different cross-sections



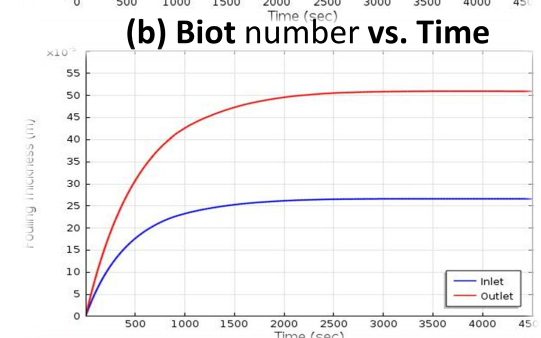
(c) Temperature vs Time



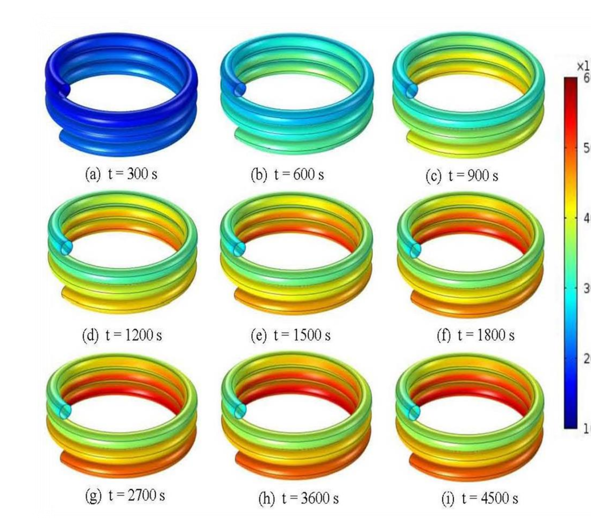
(a) Biot number along the length at different Time



(b) Biot number vs. Time



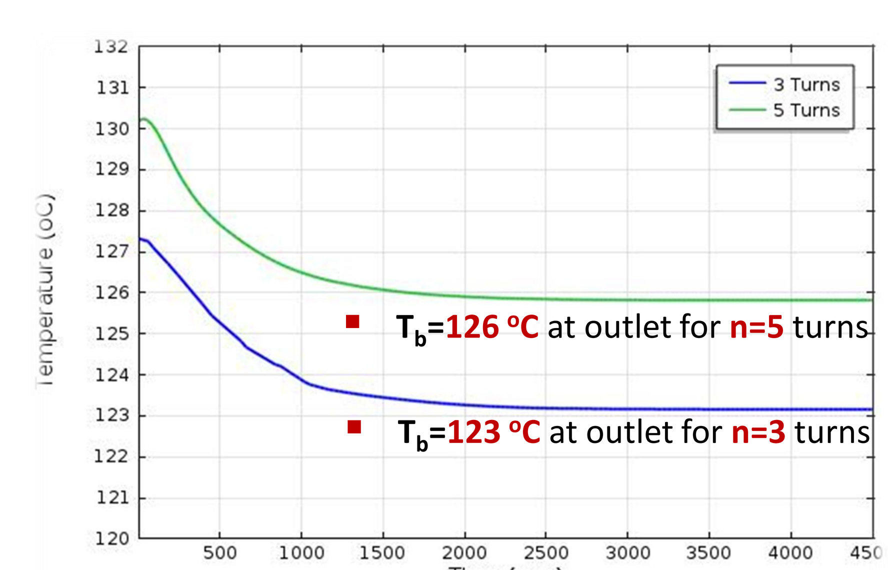
(c) Fouling thickness vs. Time



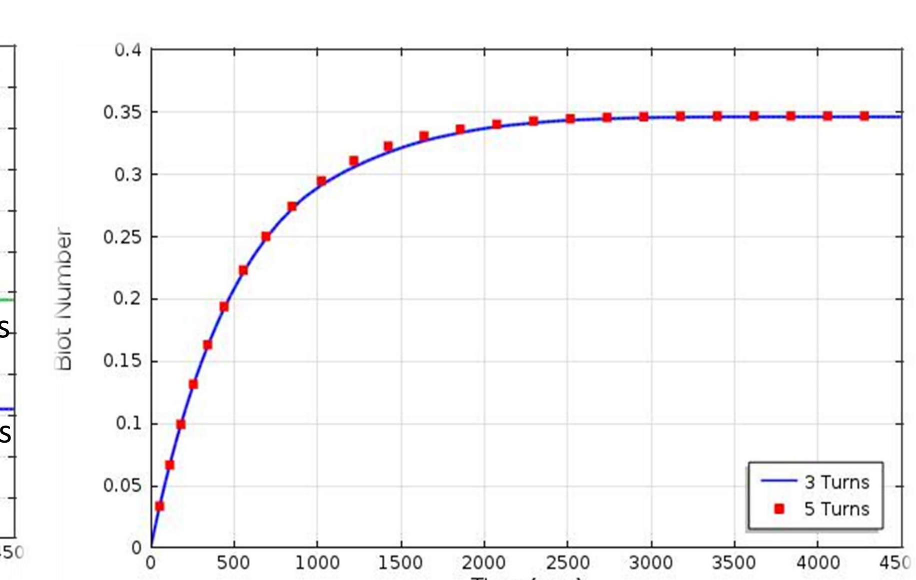
(d) Fouling thickness along the length at different Time

Biot number and fouling thickness profile at different cross-sections

Optimizing the design features of the heating section

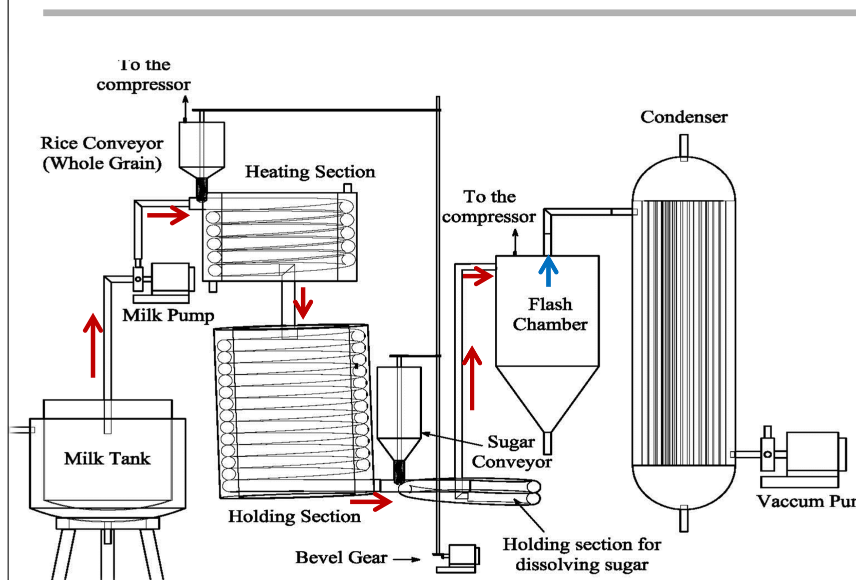


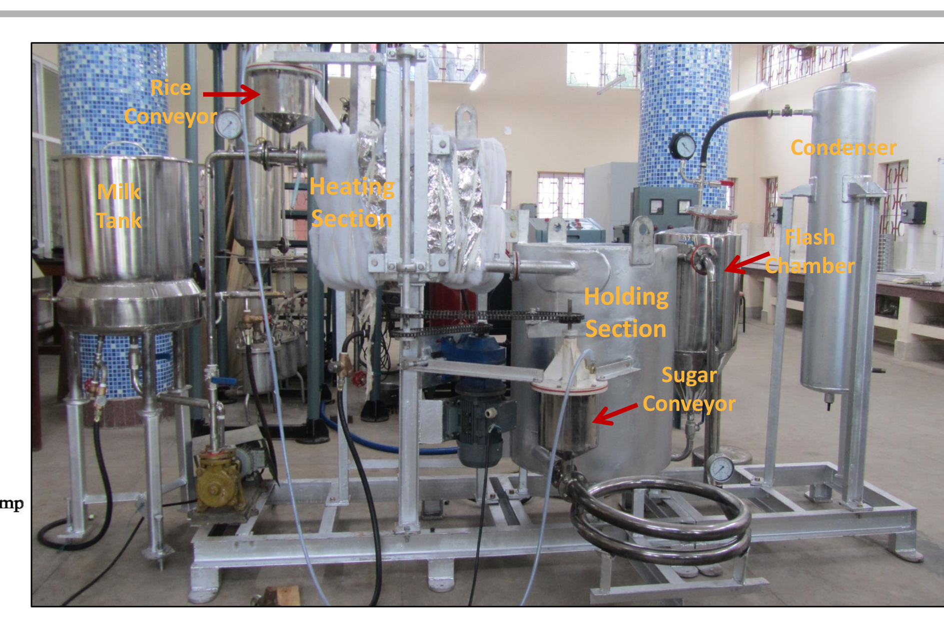
(a) Temperature vs. Time



(c) Biot number vs. Time

- Change in design suggested to **include 5 turns** in helical coil **opposed to 3**





Front view of continuous *kheer* making machine

Conclusions

- The 3D model is comprehensively built that includes the **coupling of fluid flow, heat transfer and fouling kinetics** with temperature dependent thermophysical properties
- **Inner portion** of the heating section is found **more prone to fouling** compared to the outer one **due to curvature effect** of the helical coil causing higher temperature and lower velocity
- Based on bulk mean temperature at the outlet of the helical pipe, **change in design** of the heating section is suggested **to include 5 turns instead of 3**

Excerpt from the Proceedings of the 2013 COMSOL Conference in Boston