A Multiphysics Framework For Investigating Coffee Extraction In Porous Media

Jie Chen[1], Bo Su[1]

[1] Innovation Department, WIK Group, Shenzhen, China

Abstract

Coffee extraction involves coupled fluid flow and mass transfer within a porous coffee bed. In this work, a multiphysics simulation framework was developed in COMSOL Multiphysics® by combining porous media flow, species transport, and extraction equations. A literature-based method was implemented and validated in COMSOL to predict the evolution of pressure, flow distribution, and soluble coffee concentration in a specified brewing process. The model provides 3D distributions of extraction-related transport phenomena, serving as a guide for experimental investigation while establishing an efficient workflow for brewing research. Future work will extend the framework to incorporate heat transfer and additional body forces, such as centrifugal loads and high-frequency oscillations, enabling quantitative evaluation of extraction performance and supporting the development of next-generation brewing technologies.



Fig.1 Brewing process

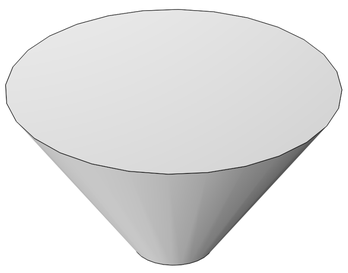


Fig.2 3D of coffee bed

Methodology

The cone filter (with radius r = 49 mm and height of coffee bed h = 54 mm) has been modeled. The numerical calculation is ruled by Porous Media Flow (Darcy's law) with Species Transport and Extraction Kinetics to simulate the brewing process. A time-dependent (transient) study was performed to capture the evolution of flow and concentration over 60 seconds.

Porous media flow model:

- Solid phase: $\vec{v_s} = 0$
- Liquid phase:

  Mass conservation equation: $\nabla \cdot \vec{v}_l = 0$

  Momentum equation: $\rho(\vec{v} \cdot \nabla)\vec{v} = -\nabla p + \mu\nabla^2\vec{v} - \frac{\mu}{K}\vec{v} + \rho\vec{g}$

$$K = \frac{\varepsilon^3 d_p^2}{180(1-\varepsilon)^2}$$

Coffee extraction model:

- Solid phase: $\frac{\partial c_s}{\partial t} = -\frac{6h_{sl}}{\phi_v d_s}(c_s - c_l)$
- Liquid phase: $\frac{\partial c_l}{\partial t} + \nabla \cdot (\vec{v}c_l) = \frac{6h_{sl}\alpha_s}{\alpha_l d_s}(c_s - c_l)$

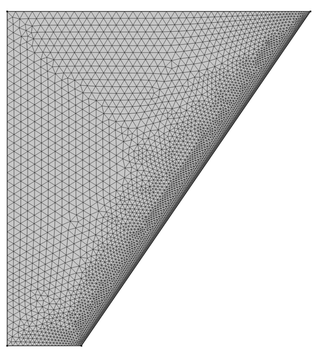


Fig.3 2D simulation model

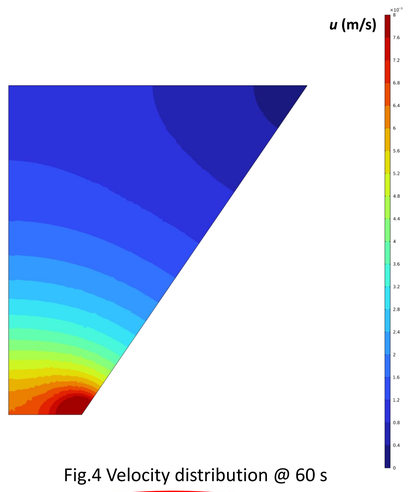


Fig.4 Velocity distribution @ 60 s

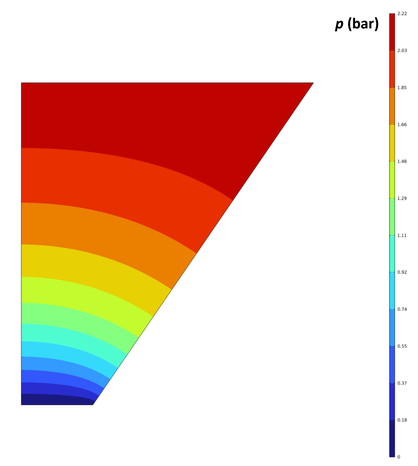


Fig.5 Pressure distribution @ 60 s

Summary

The result shows strong spatial-inhomogeneity in velocity and pressure within the porous coffee bed. A peak velocity region is observed at the outlet-cone wall junction, while the largest pressure drop occurs at the bottom of the coffee bed, confirming uneven flow distribution and preferential flow paths within the packed coffee grounds.

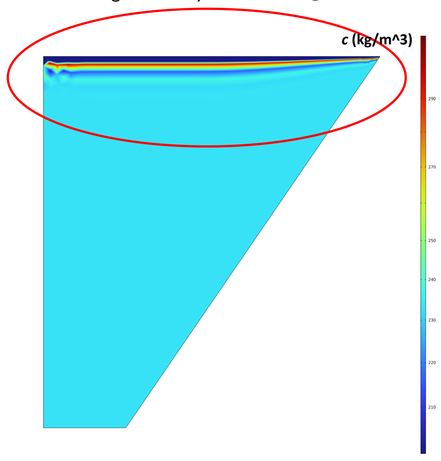


Fig.6 Concentration distribution

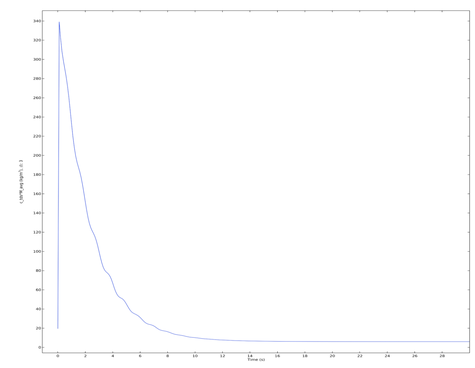


Fig.7 Outlet coffee concentration in 10 s

Reference

[1] Moroney K.M., O'Connell K., Meikle-Janney P., O'Brien S.B.G., Walker G.M., Lee W.T., "Analysing extraction uniformity from porous coffee beds using mathematical modelling and computational fluid dynamics approaches," PLoS ONE, 14(7), e0219906, 2019.