



Chemeca2026
Innovate. Integrate. Impact.

28 – 30 September 2026
Melbourne, Australia



*Chemeca 2026 and Hazards Australasia
28 – 30 September, Melbourne, Australia*

Mechanistic Development of CFD-Derived Zonal Rate Models for Membrane Chromatography

N. Yousuf ^a, B. Hunt ^b, I. Beckard ^b, S. Kentish ^a

^a Department of Chemical Engineering, The University of Melbourne, Parkville, Victoria, Australia

^b CSL Innovation, Melbourne, Victoria, Australia

n.yousuf@unimelb.edu.au

ABSTRACT

Membrane chromatography has largely replaced resin beads in high-throughput bioprocessing, due to larger pore sizes and shorter bed heights that enhance convection mass transfer. In these devices, performance can be governed not by intrinsic adsorption kinetics but by non-ideal flow distributions arising from upstream and downstream hold-up volumes. In axial-flow capsules, high length-to-diameter ratios induce radial flow inhomogeneities, leading to early breakthrough and pronounced tailing, even under non-binding conditions. Similarly in radial pleated geometries, the hydrodynamic dispersion shapes the residence time distribution (RTD), thereby controlling breakthrough curve shape and dynamic binding behaviour. Failure to decouple these geometry-dependent hydrodynamic effects from intrinsic adsorption kinetics can result in inaccurate mechanistic models that often break down during model-based scale-up.

To independently quantify flow and binding-related non-idealities, a Zonal Rate Model (ZRM) has been developed that partitions these devices virtually into interconnected dispersive plug-flow and continuously stirred tank regions, with sector-wise volumetric flow fractions capturing inhomogeneous flow distributions. With suitable parameterisation, the model reproduces asymmetric breakthrough curves under both binding and non-binding conditions. However, calibration remains semi-empirical, as flow fractions and residence times are typically obtained by regression to breakthrough data rather than derived from resolved hydrodynamics. At manufacturing scale, this reliance on *in vitro* experimentation extends development timelines and drives up overall costs. On this account, numerical approaches, such as Computational Fluid Dynamics (CFD), offer considerable promise, as these approaches explicitly resolve the hydrodynamics of hold-up volumes and membrane domains and have demonstrated predictive capability even at large scale. However, their substantial computational cost and the level of technical expertise required limit their routine use in system optimisation

and process development.

In this study, CFD is leveraged as a mechanistic tool to systematically develop reduced-order zonal rate representations that capture flow non-idealities. Fully resolved simulations of fluid flow and tracer transport across industrially relevant conditions are used to compute velocity fields in hold-up and membrane domains. From these computations, flow statistics such as RTDs and sector-wise velocity distributions are extracted and mapped onto a reduced-order zonal rate structure without the use of regression. The resulting models retain dominant convection–dispersion characteristics while remaining computationally efficient, enabling robust modelling of intrinsic binding kinetics. Applied to axial stacked and radial pleated devices, the framework shows promise in adequately reproducing tracer RTDs and breakthrough curves. By explicitly linking resolved hydrodynamics to simplified process-scale models, the approach enables rigorous decoupling of flow-induced and binding effects, supporting predictive, geometry-independent model-based scale-up.

KEY WORDS

Membrane chromatography, Zonal Rate Models, Computational Fluid Dynamics, Mechanistic modeling

BIOGRAPHY

Dr. Yousuf is a Postdoctoral Research Fellow at the University of Melbourne within the Australian Research Council (ARC) Digital Bioprocess Development Hub. He holds a PhD in Chemical Engineering from RMIT University, where he contributed to an ARC Linkage Project on efficient wastewater sludge pipeline transport. His expertise includes Computational Fluid Dynamics (CFD), predictive modelling and model-based scale-up of complex transport and separation systems across wastewater and bioprocess engineering applications.

CONFERENCE PROGRAM

Please indicate which conference program your abstract relates to:

Hazards Australasia

Chemeca