Modelling and Optimal Operation of a Forward Osmosis Process

M. Ružička[1], I. Helgeland[2], R. Paulen[1]

[1]Faculty of Chemical and Food Technology, Slovak University of Technology in Bratislava, Slovakia

[2]Aquaporin A/S, Denmark

Goals

The forward osmosis process represents a promising but still less established membrane technology. Our aim is to study its optimal operation, minimising energy consumption and batch duration. We use a model-based approach and compare white-box, black-box, and grey-box modelling perspectives.

Forward Osmosis Plant Description

Process components

FO module

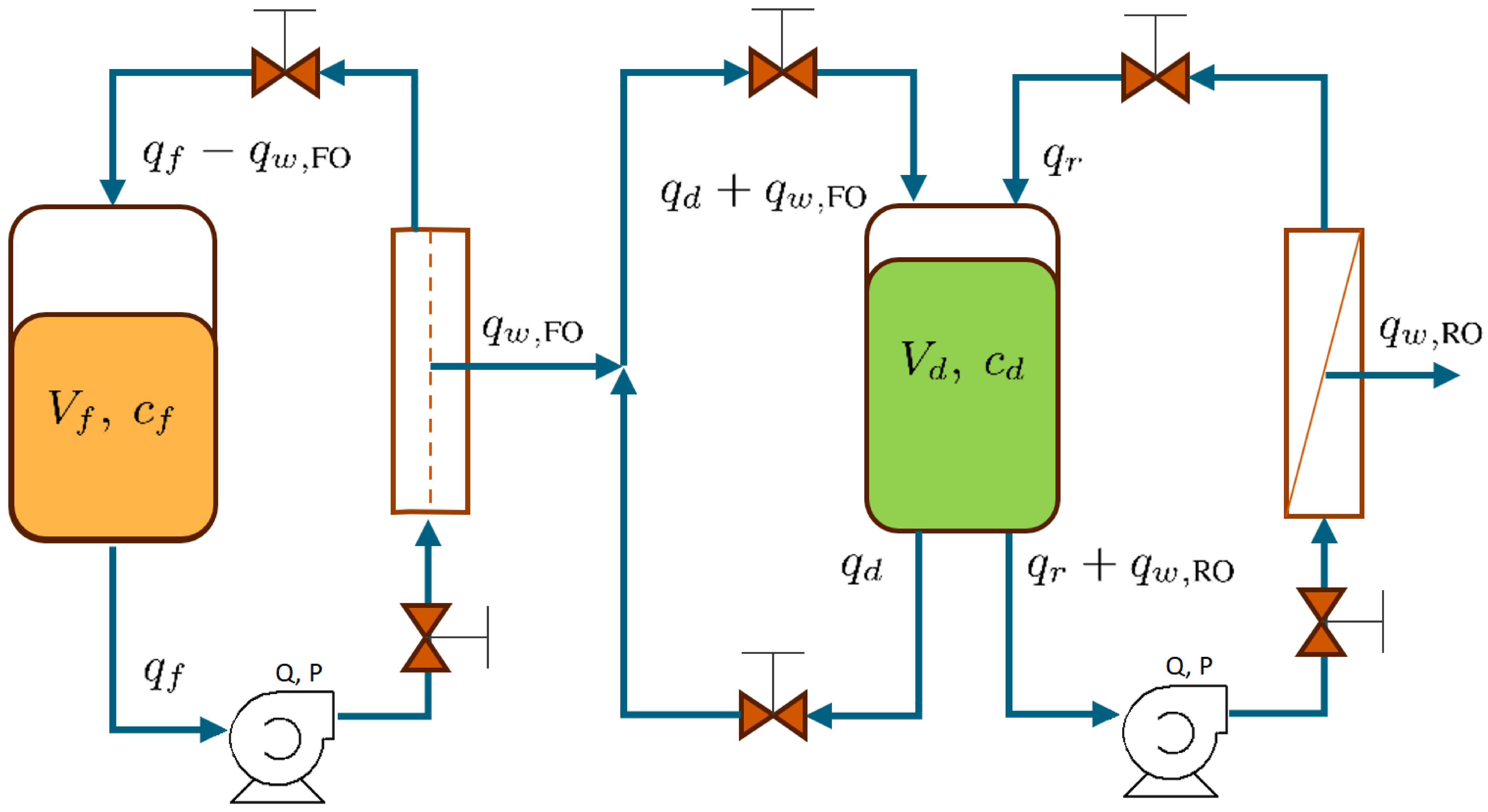
- feed tank (solution to be concentrated)
- aquaporin membrane

$$q_{w,\mathrm{FO}}^{\square} = k_w(\pi_d(c_d) - \pi_f(c_f))$$

Draw solution and its recovery system

- draw tank
- RO pump (energy intensive)
- RO membrane

$$q_{w,\mathrm{RO}}^{\square} = k_w(\Delta p - \pi_d(c_d))$$



Model Training

White-box approach $\square$

$q_{w,\mathrm{FO}}^{\square}, q_{w,\mathrm{FO}}^{\square}$ inadequate

Black-box approach $\blacksquare$

$$\min_{\theta} \sum_{k=1}^{N} \sum_{m\in\{\mathrm{FO,RO}\}} (q_{w,m}^{\mathrm{exp}}(t_k) - q_{w,m}(t_k))^2$$

$$\text{s.t. } q_{w,\mathrm{FO}}^{\blacksquare}(c_f^{\mathrm{exp}}, c_d^{\mathrm{exp}}) = \begin{cases} \theta_0 + \theta_1 c_f + \theta_2 c_d & \text{linear} \\ \text{linear} + \theta_3 c_f^2 & \text{quadratic} \\ \theta_0 c_d \log \dfrac{\theta_1}{c_f} & \text{logaritmic} \end{cases}$$

$$q_{w,\mathrm{RO}}^{\blacksquare}(c_d^{\mathrm{exp}}, \Delta p) = \theta_0(\Delta p - \theta_1 c_f)$$

Experimental data

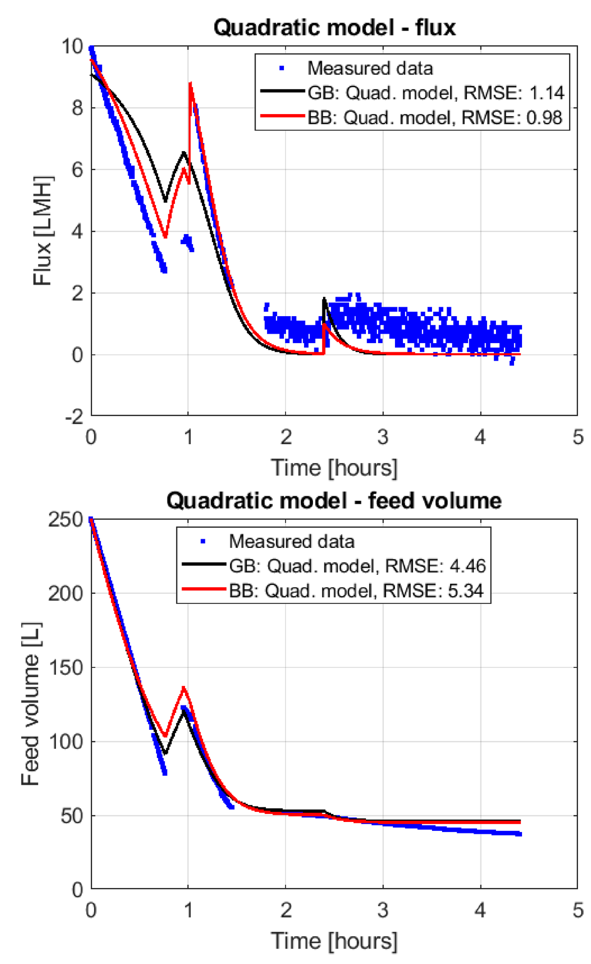
4 h batch run with different draw solutions

Grey-box approach ${\color{gray}\blacksquare}$

$$\min_{p} \sum_{k=1}^{N} \sum_{m\in\{\mathrm{FO,RO}\}} \frac{(q_{w,m}^{\mathrm{exp}}(t_k) - J_{w,m}(t_k))^2}{2\sigma_{q_{w,m}}^2} + \sum_{s\in\{f,d\}} \frac{(V_s^{\mathrm{exp}}(t_k) - V_s(t_k))^2}{2\sigma_{V_s}^2} + \frac{(c_s^{\mathrm{exp}}(t_k) - c_s(t_k))^2}{2\sigma_{c_s}^2}$$

s.t. dynamic mass balance

$$q_{w,\mathrm{FO}}^{{\color{gray}\blacksquare}}(c_f, c_d) = q_{w,\mathrm{FO}}^{\blacksquare}(\cdot),\quad q_{w,\mathrm{RO}}^{{\color{gray}\blacksquare}}(c_f, c_d) = q_{w,\mathrm{FO}}^{\blacksquare}(\cdot)$$



Process Optimisation

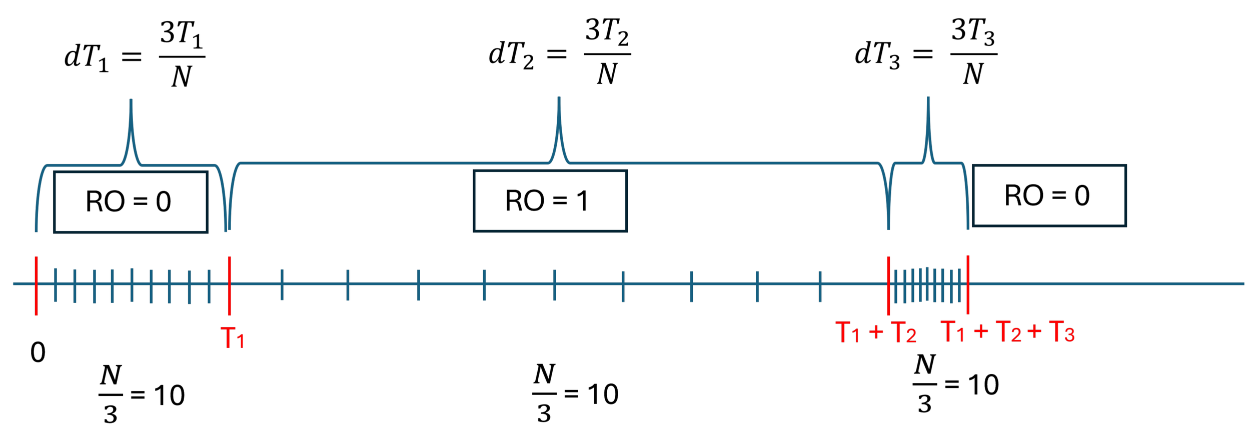
Dynamic optimisation problem (time vs. energy)

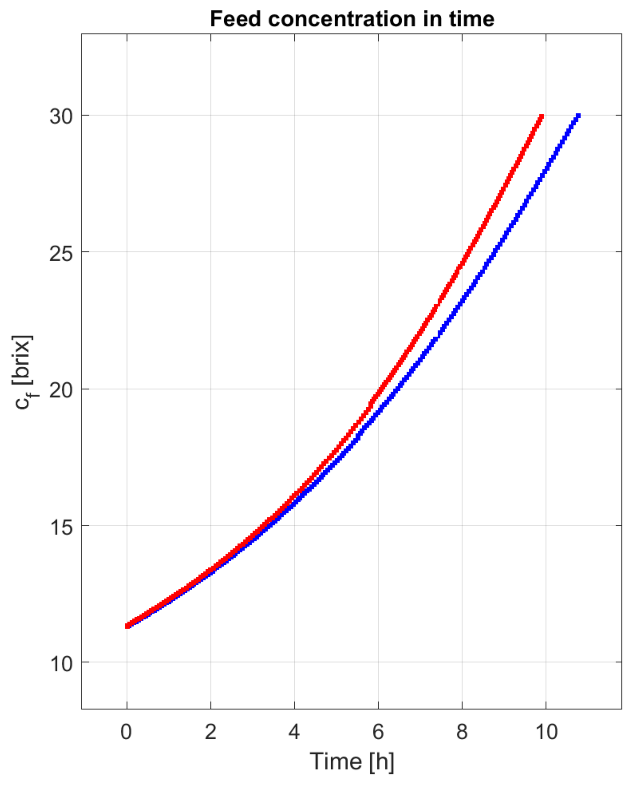
$$\min_{\substack{\Delta p(t), Q(t) \\ T_1, T_2, T_3}} \lambda_t T_{\mathrm{batch}} + \lambda_E \int_0^{T_{\mathrm{batch}}} \Delta p(t) Q(t) \mathrm{d}t$$

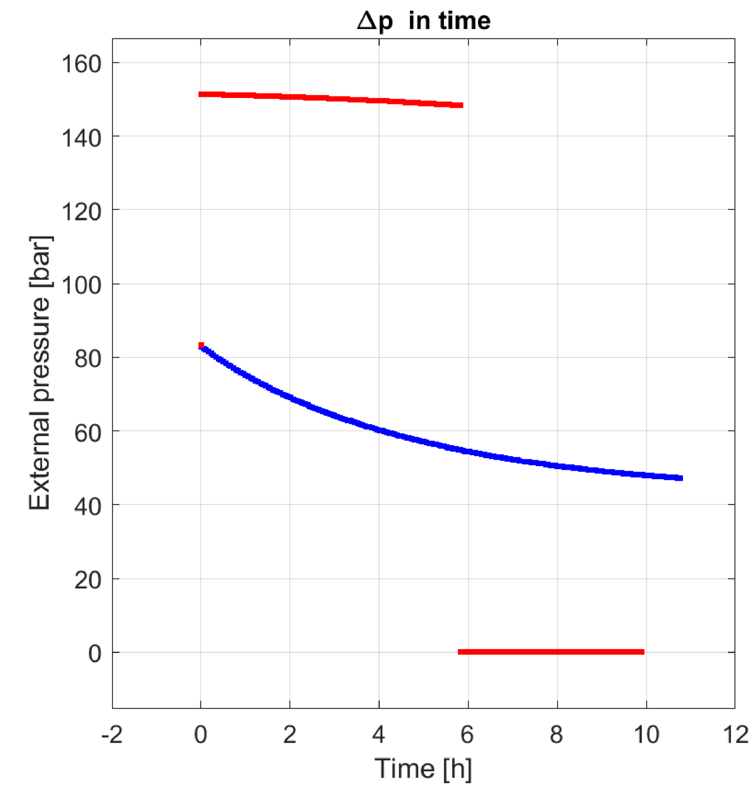
s.t. dynamic mass balance

$$T_{\mathrm{batch}} = T_1 + T_2 + T_3$$

$$c_f(T_{\mathrm{batch}}) = c_{f,\mathrm{desired}}$$







	T_1	T_2	T_3	time [h]	energy [bar m^3]
best time	0	5.82	4.07	9.89	15.7
best energy	5.5	0	5.3	10.8	0

Conclusions

White-box modelling approach was found inadequate. Black- and grey-box models are competitive, both linear, quadratic, and logarithmic forms. Grey-box models adhere to mass balance principles giving a more reliable model. An optimal trade-off between energy consumption and batch length can be achieved.

Acknowledgements: This research is funded by the Slovak Research and Development Agency under the project APVV-21-0019, by the Scientific Grant Agency of the Slovak Republic under the grant 1/0691/21, and by the European Commission under the grant no. 101079342 (Fostering Opportunities Towards Slovak Excellence in Advanced Control for Smart Industries).