Chemical Switching Reforming (CSR)
The CSR concept combines two process advancements:
- Membrane assisted steam methane reforming:
  - Combines reforming and water-gas shift
  - Pure H₂ output stream from the membranes
  - Equilibrium shift towards greater H₂ production
- Chemical switching:
  - An oxygen carrier/catalyst remains in one reactor
  - Alternating fluidization with air and fuel/steam
  - Advantages:
    - Simplification of high pressure operation
    - Easier scale-up and design optimization

Reaction System
Three different reaction types with Ni/NiO as oxygen carrier/catalyst:
- Oxidation: \( O_2 + 2Ni \leftrightarrow 2NiO \)
- Reduction: \( CH_4 + 4NiO \leftrightarrow 4Ni + CO_2 + 2H_2O \)
  \( H_2 + NiO \leftrightarrow Ni + H_2O \)
  \( CO + NiO \leftrightarrow Ni + CO_2 \)
- Solid catalysed reforming reactions:
  - Steam methane reforming: \( CH_4 + H_2O \leftrightarrow CO + 3H_2 \)
  - Water-gas shift: \( CO + H_2O \leftrightarrow CO_2 + H_2 \)
- Overall steam methane reforming: \( CH_4 + 2H_2O \leftrightarrow CO_2 + 4H_2 \)

CFD Results for a Complete CSR Cycle
- Temperature rises during air stage:
  - Exothermic oxidation reaction
- Temperature drops during fuel stage:
  - Endothermic reforming and reduction reactions
  - Heating of cold feed gasses
- Complete O₂ conversion during air stage
- Decreasing H₂O and increasing H₂, CO & CH₄ during fuel stage
- Increasing oxygen carrier conversion slows reduction reactions
- Small amount of mixing between N₂ and CO₂ after switching between stages

Middle of air stage (32.5 s)
- Oxidation reaction rate is very high
- Potential to increase air flow rate to increase process throughput rate

Outlet stream switch from depleted air to fuel combustion products (62.5 s)
- Small amount of CO₂ and N₂ mixing limited by:
  - Small freeboard region
  - Limited backmixing in the bed due to the presence of membranes
- Freeboard size is important for optimization:
  - Larger freeboard \( \rightarrow \) less entrainment and more mixing of CO₂ and N₂
  - Desired entrainment rate = desired oxygen carrier replenishment rate
  - CO₂ and N₂ mixing can also be reduced via a short purging stage

Middle of fuel stage (92.5 s)
- Reduction and reforming reactions taking place simultaneously
- NiO still present and is continuously reduced by CH₄, H₂ and CO
- Reduction and reforming reactions taking place simultaneously
- Desired entrainment rate = desired oxygen carrier replenishment rate
- CO₂ and N₂ mixing can also be reduced via a short purging stage
- Large axial H₂ gradient due to membrane extraction

Hydrogen recovery
Greater degree of reduction \( \rightarrow \) Faster reforming & slower reduction \( \rightarrow \) More H₂ formation:
- Increased H₂ potential
- Increased H₂ membrane extraction
- Increased H₂ at reactor exit

More H₂ formation \( \rightarrow \) Higher H₂ concentration
- Less CO & CH₄ converted to H₂ in overall steam methane reforming
- Reduced overall H₂ recovery

Recommended Future Work
- Achieving steady performance during the fuel stage
- Gradual variation in H₂ recovery over the fuel stage is not desired
- Steady performance could be achieved by varying the CH₄/H₂O feed ratio across the fuel stage
- Future research into increased membrane permeability
- Literature shows a very large variation in membrane performance
- CSR performance limited by membranes and not by oxygen carrier
- Increased permeability would therefore lead to greater throughput
- Membrane size and positioning should be optimized
- Minimize membrane investment and maximize H₂ extraction
- Improved reaction kinetic and equilibrium data
- Kinetic data is still uncertain
- Low temperature data is especially important

A Visual Representation
Three snapshots over the cycle are presented via instantaneous contour plots. Ranges of the blue-to-red colourmap are shown in brackets on each contour plot.

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