OPERABILITY ANALYSIS AND CONTROL DESIGN OF AN IRCC CYCLE HMR UNIT WITH MEMBRANE LEAKAGE

BigCO2, Task D, WP 5 Analysis of power cycles operability

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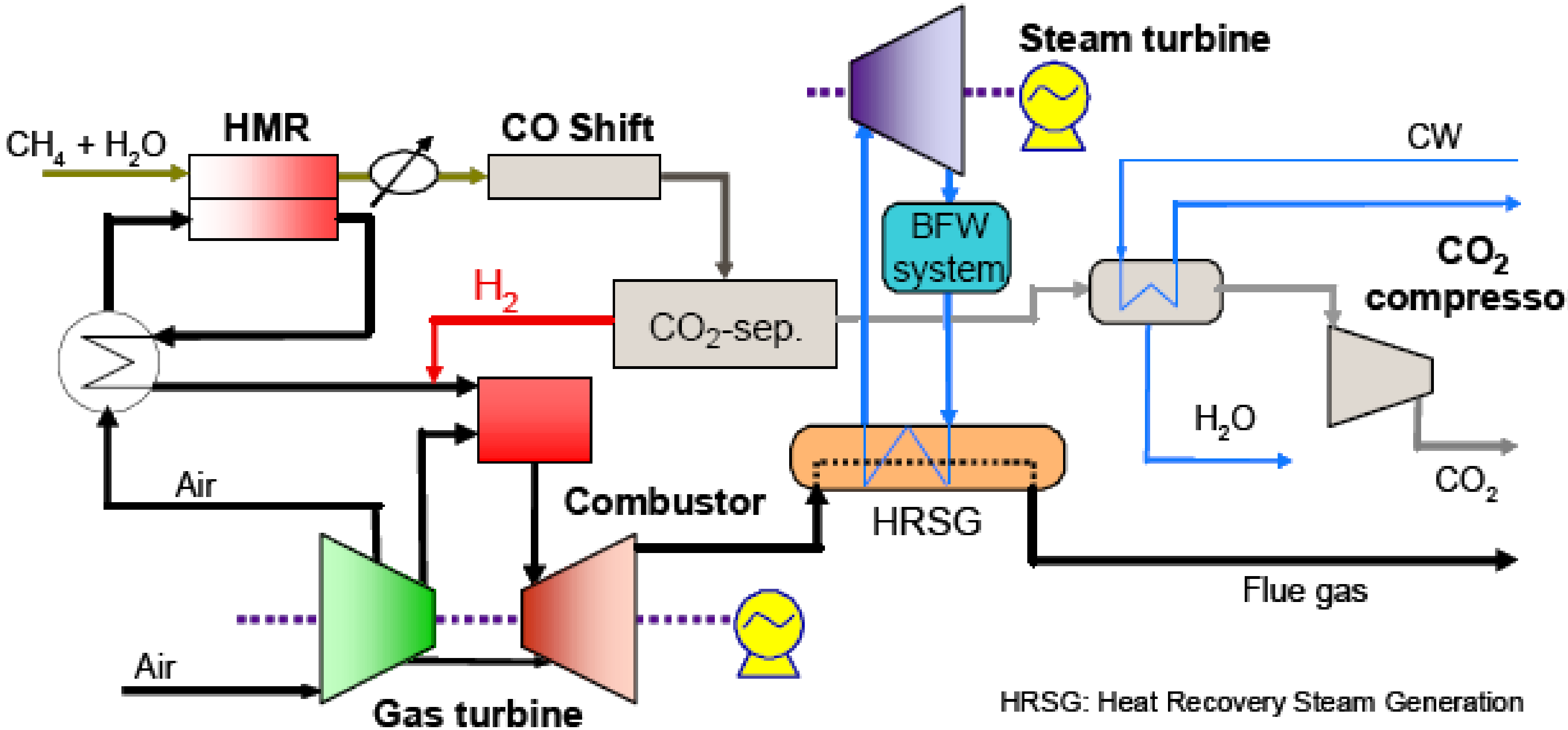
Motivation

- Membrane leakage may damage the reactor due to hot spots
- How to reject (control) the effect of leakage and what is the effect on the process efficiency and CO_2 capture?

Outline

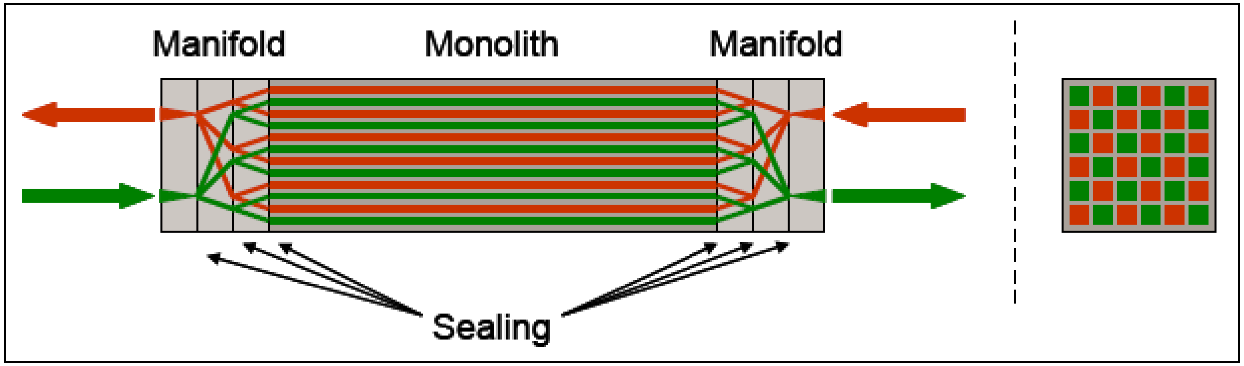
- The power cycle scheme
- Rigorous, causal, dynamic model of the HMR unit suitable for optimization calculations
- Dynamic and steady state effects of membrane leakage
- Operability analysis
  - Step response analysis (linearity?)
  - A analysis of control structure designs (self-optimizing control,…)
- Simulations of controlled HMR unit and the effect on performance measures of the power cycle

Hydrogen membrane reformer (HMR) in a pre-combustion carbon capture gas power cycle



Statoil, Smith et al. GHGT-9 (2008)

Distributed dynamic model of the HMR unit

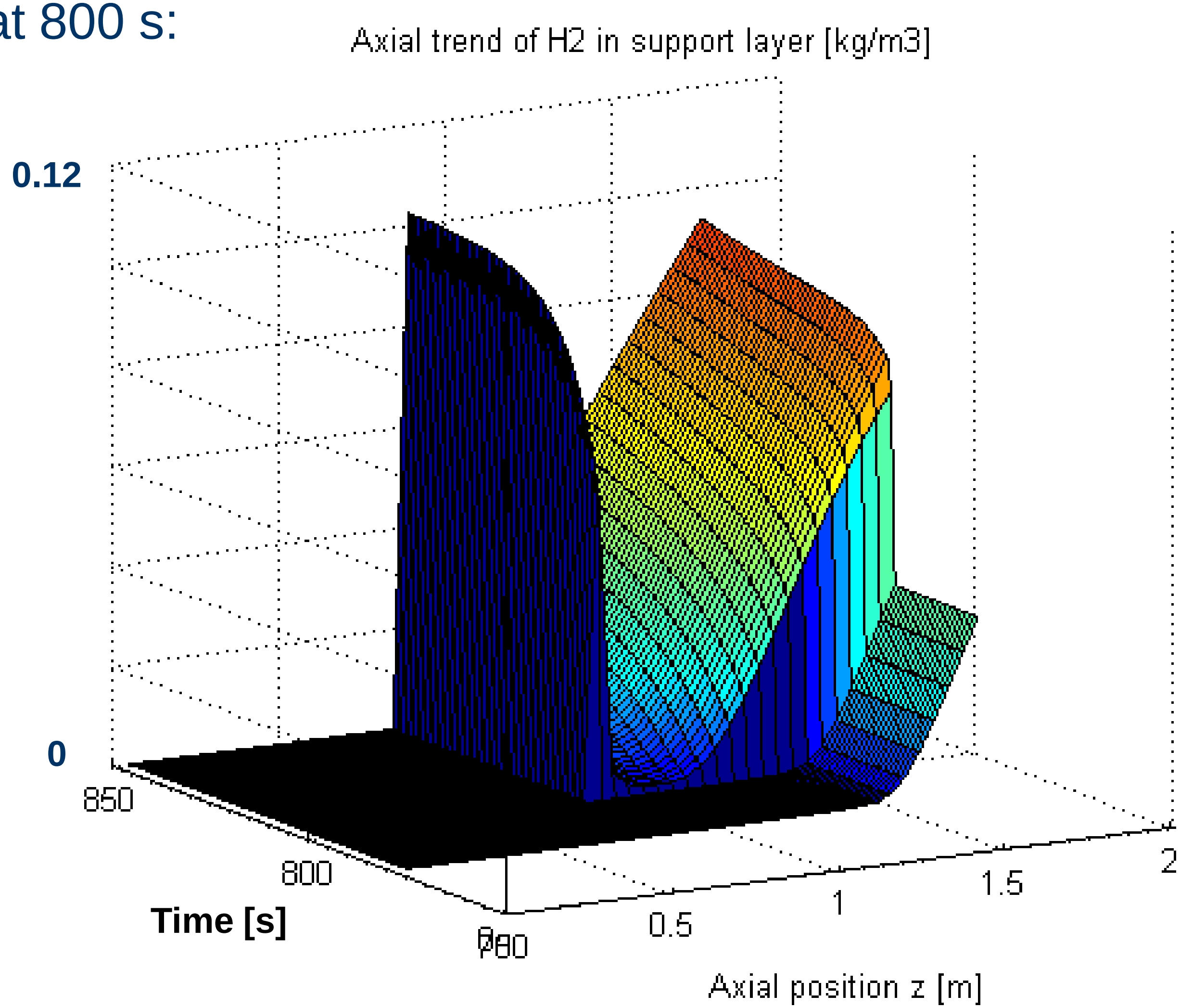


$15 \cdot 15 \cdot 70\ cm^3$

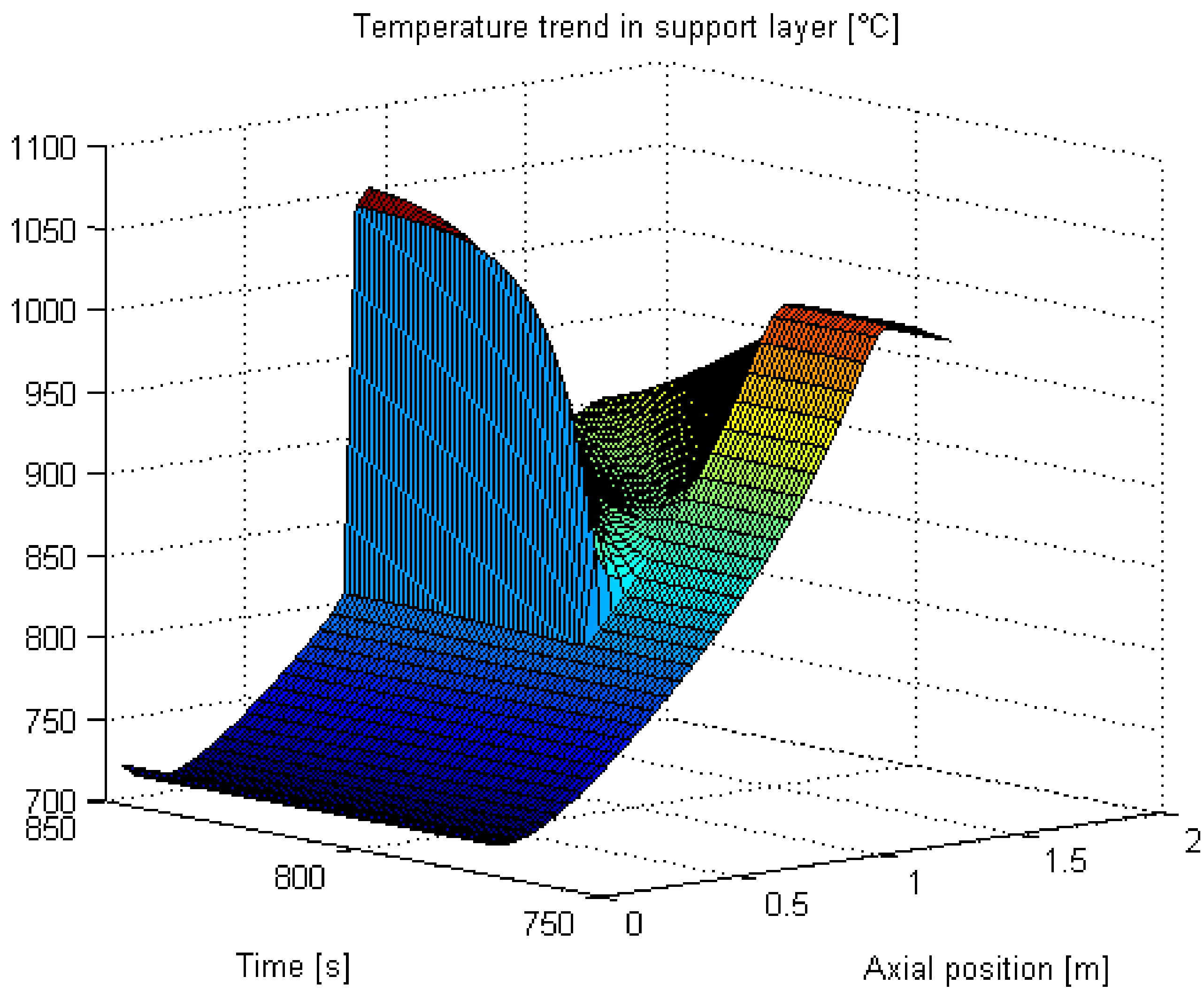
- Purposes:
  - Process understanding
  - Describing the essential steady state and dynamic features of the process as a basis for operability analysis
- Features:
  - Dynamic mass and energy balances (first principles)
  - Axial distribution
  - Validation against an in-house steady state Aspen Plus model from Statoil.
  - Implemented in Matlab/Simulink

Responses to mebrane leakage

A crack at 800 s:

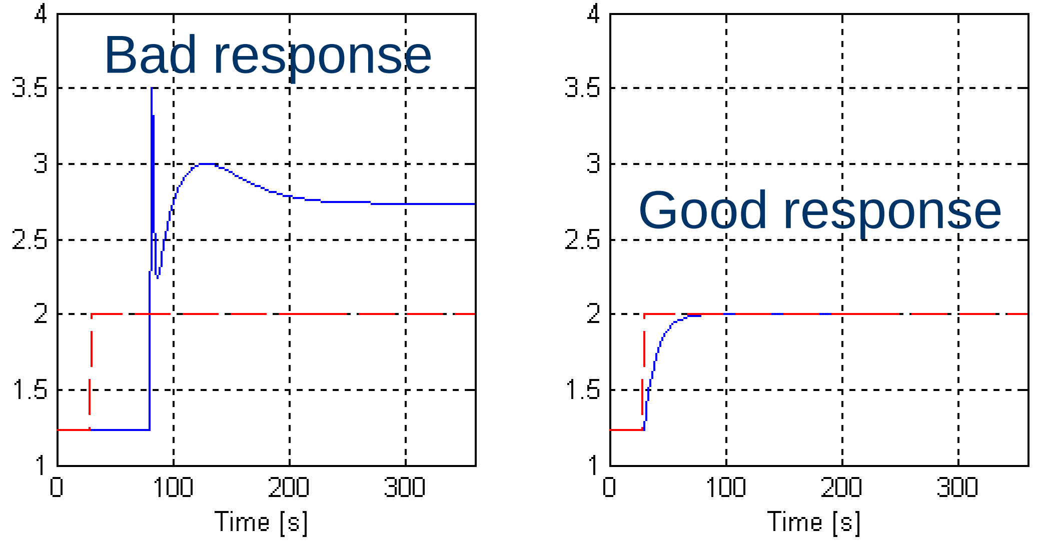


…leads to a ”hot spot”



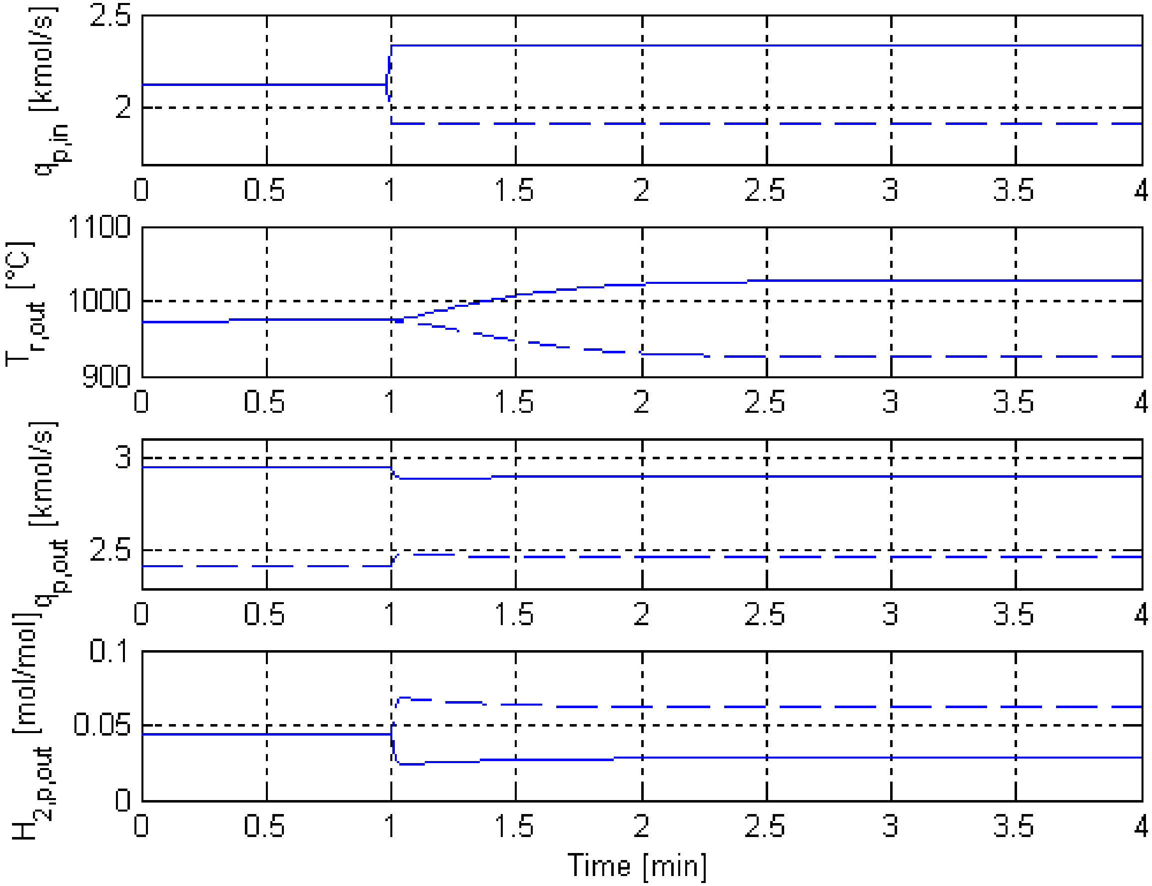
Operability analysis

- Operability is the ability (goodness) of a system to be operated as required under disturbances and set point changes.
- In process operation, this means e.g. whether it is possible to bring the process to different steady state conditions (steady state requirements), by a smooth and fast transition in order to minimize deviations (dynamic requirements) to obtain minimum costs.



Step response analysis

+-10% step change in air flow rate:



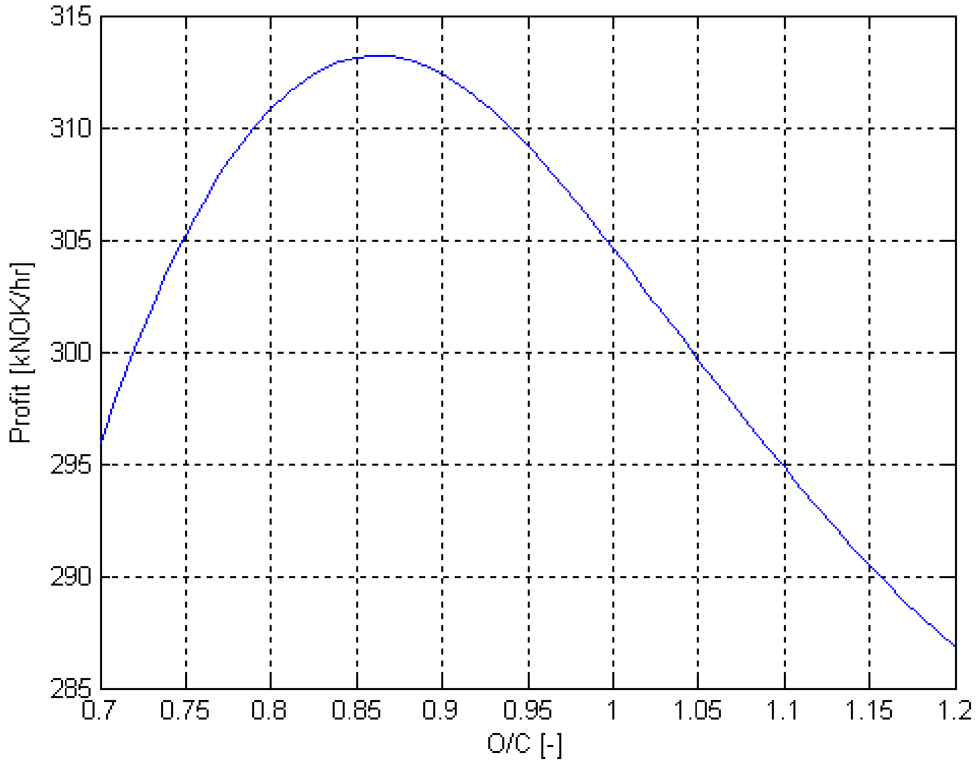
The steady state responses to changes in air flow rate are approximately linear. Hence, *linear analysis is relevant!*

Optimization of a profit function J:

J = Income from production of H_2
- costs for natural gas, production of steam and high pressure air

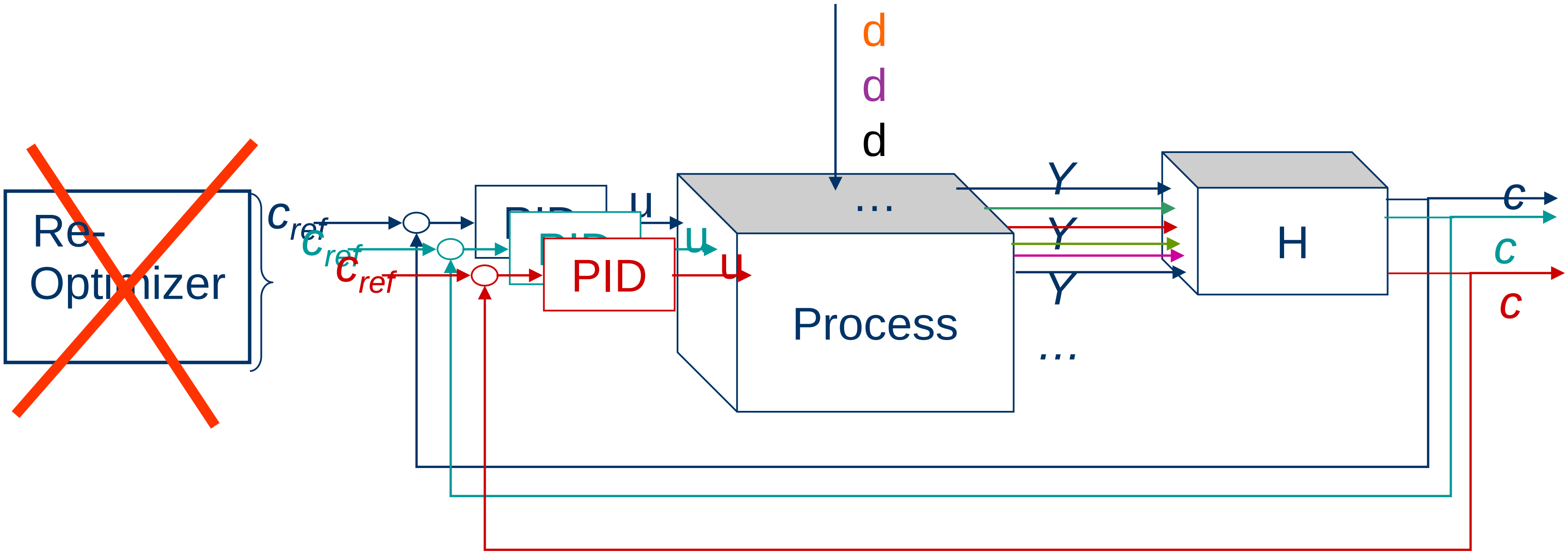
J as function of the S/C and O/C ratios:

S/C=2.3:



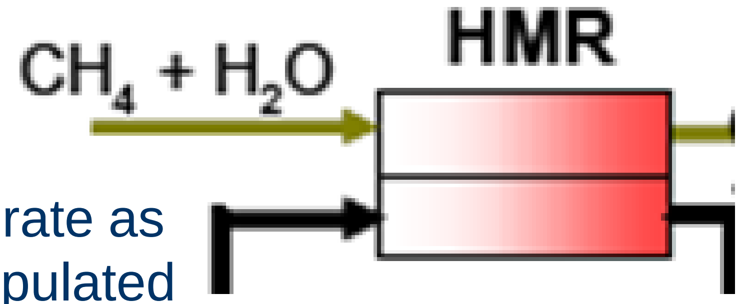
The nominal optimum for S/C=2.3 is located at O/C=0.86

Operability analysis by self-optimizing control



Self optimizing control involves methods for selection of controlled variables in order to make the *optimal* plant operation robust to disturbances and model uncertainties at constant setpoints.

Resulting optimal measurement combinations



Air flow rate as manipulated variable for control

Candidate measurements:

Process gas:
CH_4, H_2O, H_2, CO_2, CO, q_r, T_r

Exhaust gas: H_2O, O_2, H_2, q_p, T_p

Without measurement noise:

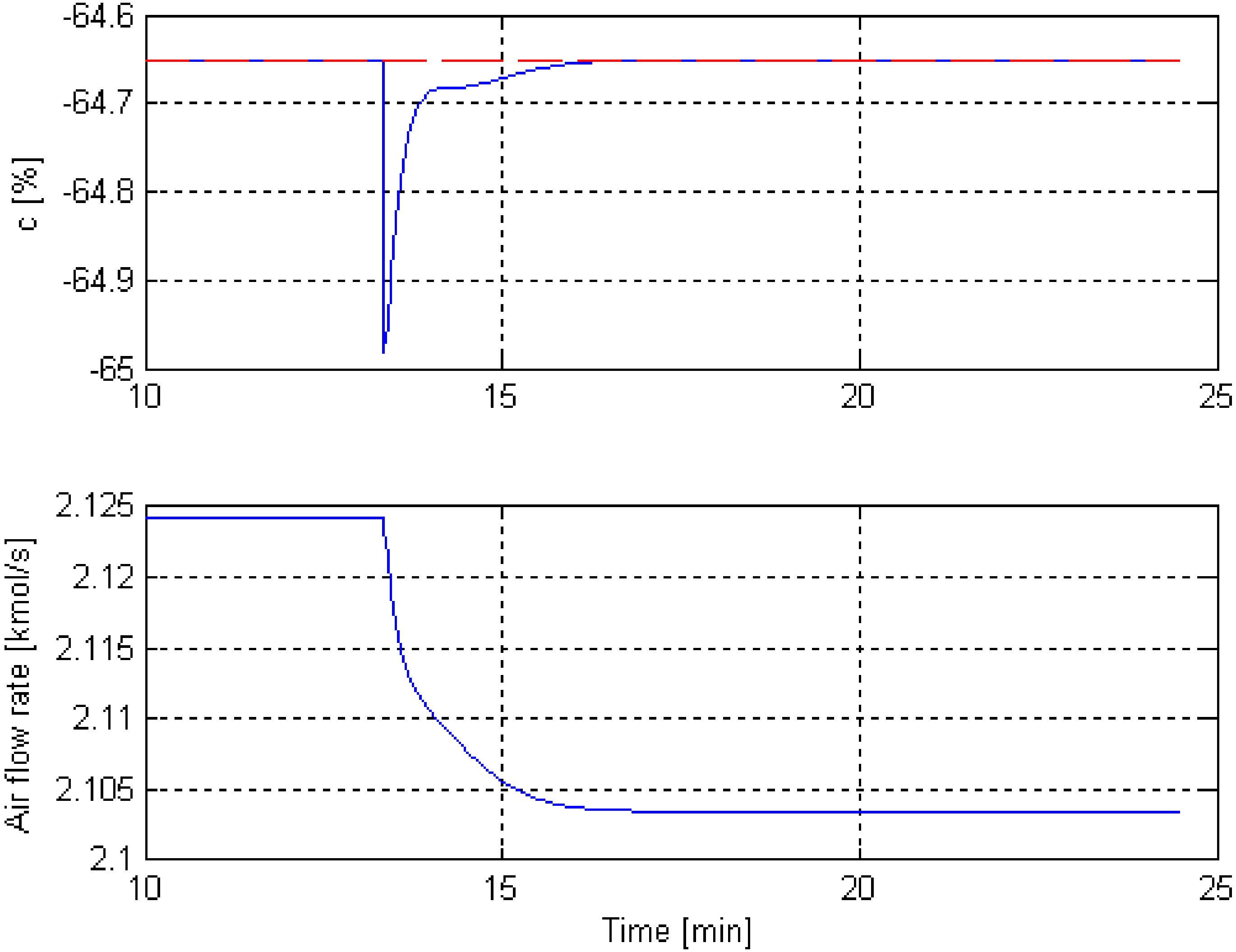
$$c = -0.70\, q_p + 0.71 H_{2,p}$$

Including moderate measurement noise:

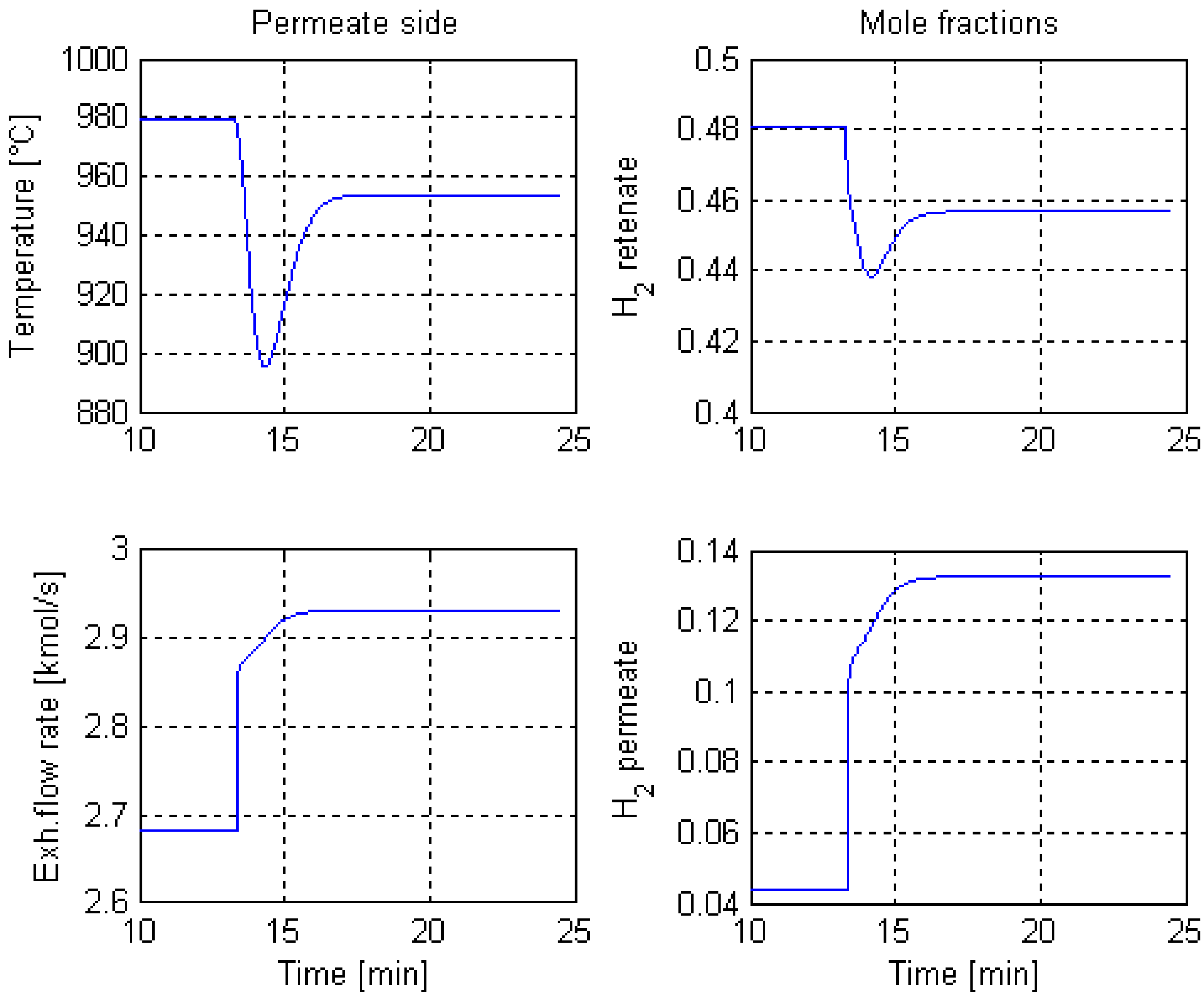
$$c = -0.56\, q_p - 0.58\, T_r - 0.59\, T_p$$

The amount of measurement noise affects which measurements that are included in c !

Simulation of control variables for a PI controller with the non-linear model:

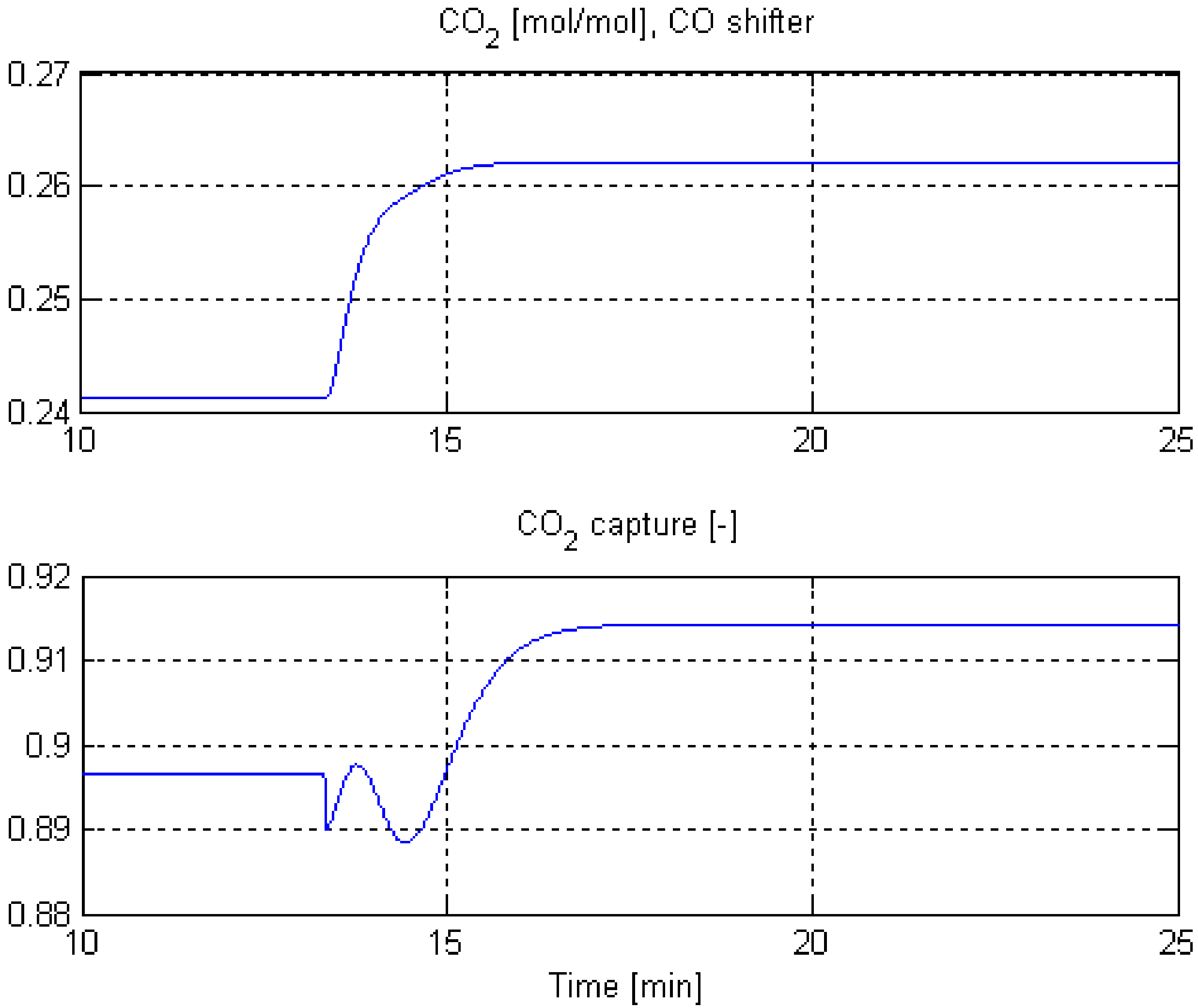


Same case:

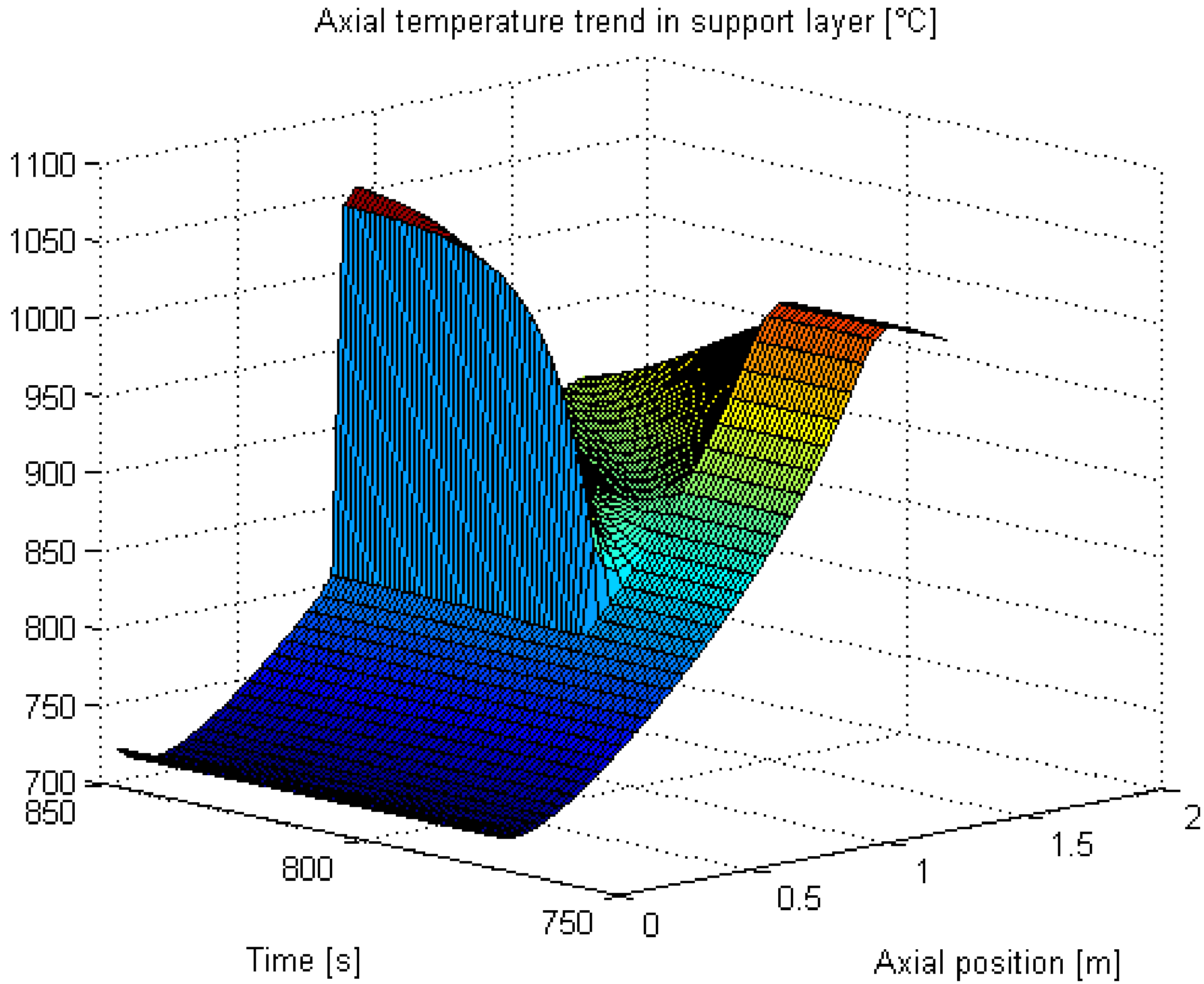


This means reduced plant efficiency, …

… more production and capture of CO_2 (the ratio between the captured CO_2 and the carbon content in the natural gas) …



… and marginal rejection of the ”hot spot”:



The reason for bad performance is that ***c is designed to minimize the loss of production profit J. Further, c contains outlet variables.***

Alternative control structures:

- Control of the temperature at the leakage location rejects the hot spot by reduction of the air flow rate. This leads to reduced outlet temperature and conversion of methane, and thereby ***reduced efficiency and <u>reduced CO_2 production.</u>*** NB: Requires advanced measurement or estimation.
- Control of outlet temperature ***does not reject the hot spot*** and also leads to ***reduced efficiency and increased CO_2 production.***

Conclusions

- Rigorous distributed dynamic model of an HMR gives physical insight and a good basis for operability analysis and control design studies.
- A limitation is averaging radially across the reactor.
- Process disturbances, manipulated variables for control, candidate measurements, noise, constraints and control objective all affect the control performance (operability) by:
  - Deciding what to control (controlled variables)
  - Affecting the ease of control (operability)
- Control of hot spots due to membrane leakage is not easy without loosing efficiency.
- Control of hot spots requires embedded sensors. Then, reduced CO_2 production can be achieved.
- Handling membrane leakage by fault detection and interv.?

Final comments

- The higher CO_2 concentration from the HMR system will allow a more efficient CO_2 separation as compared to conventional reformer designs (e.g. ATR). A master student is making such a comparison this summer.
- A systematic procedure for integrated process and control design can improve both design and operation. This area should be further explored.
- Publication in Energy Procedia