Multi-Stage-Flash Desalination

Hybrid Modelling and Control of a Brine Heater

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Goal of the work

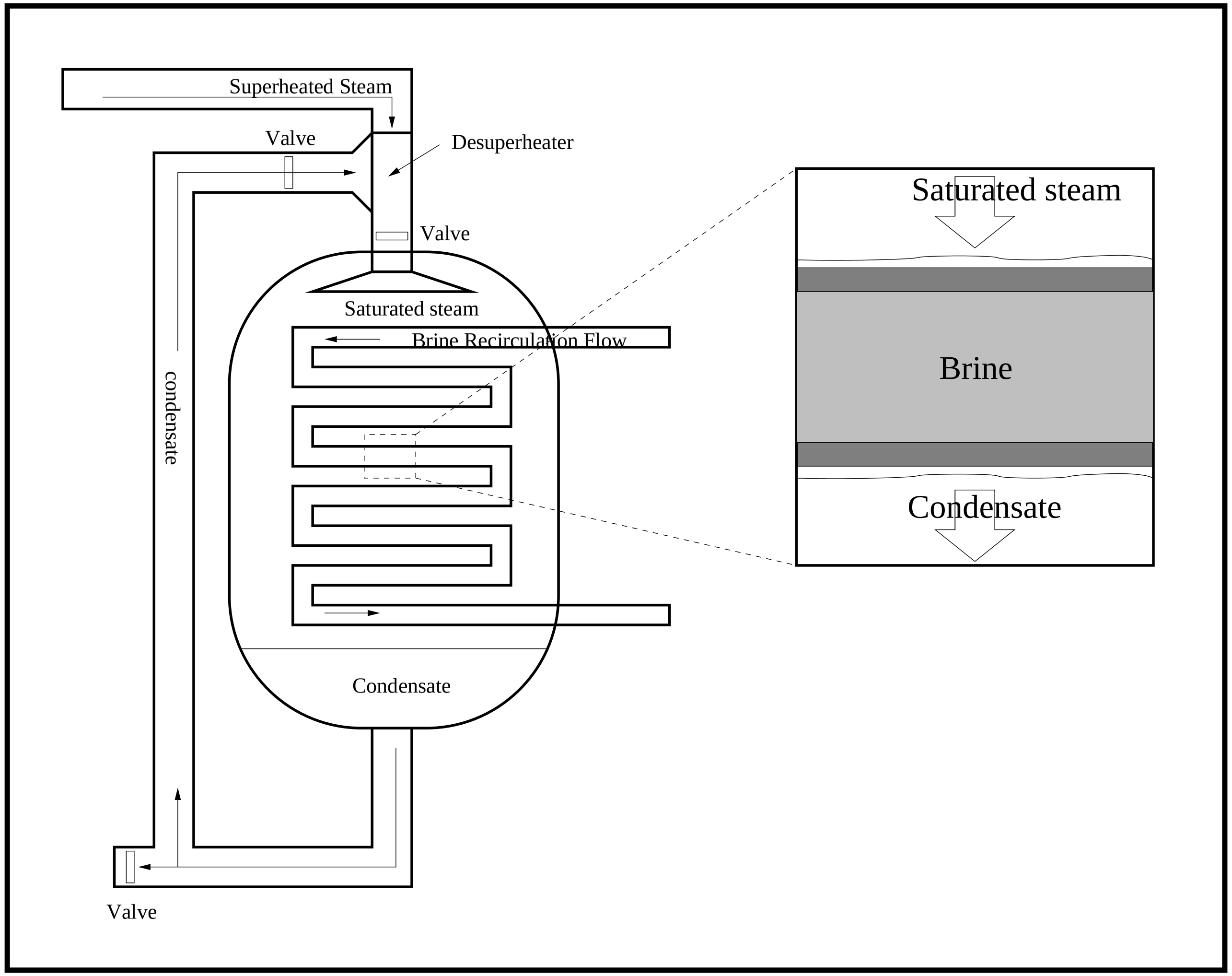
- Development of a dynamic model for a brine heater subsystem of a multi-stage-flash desalination plant
- Control the brine-heater in different setpoints

Structure of the work

- Hybrid modell with respect to thermodynamic laws and models presented in literature
- Optimized PID-Control in 4 setpoints - Ziegler-Nichols
- Setpoint-detection, setpoint-change and bumpless transfer with a hybrid automaton - two different approaches
- Scenario-generation
- The graphical user interface (GUI)

The dynamic model

The Brine-Heater



The dynamic model

The models purpose

- Research and Developement of innovative Control concepts

  → Interaction of incoming heat and resulting heat change of TBT

  → Time constants and dynamic behaviour

  → Steady states

- Show the andvantages of modern control concepts

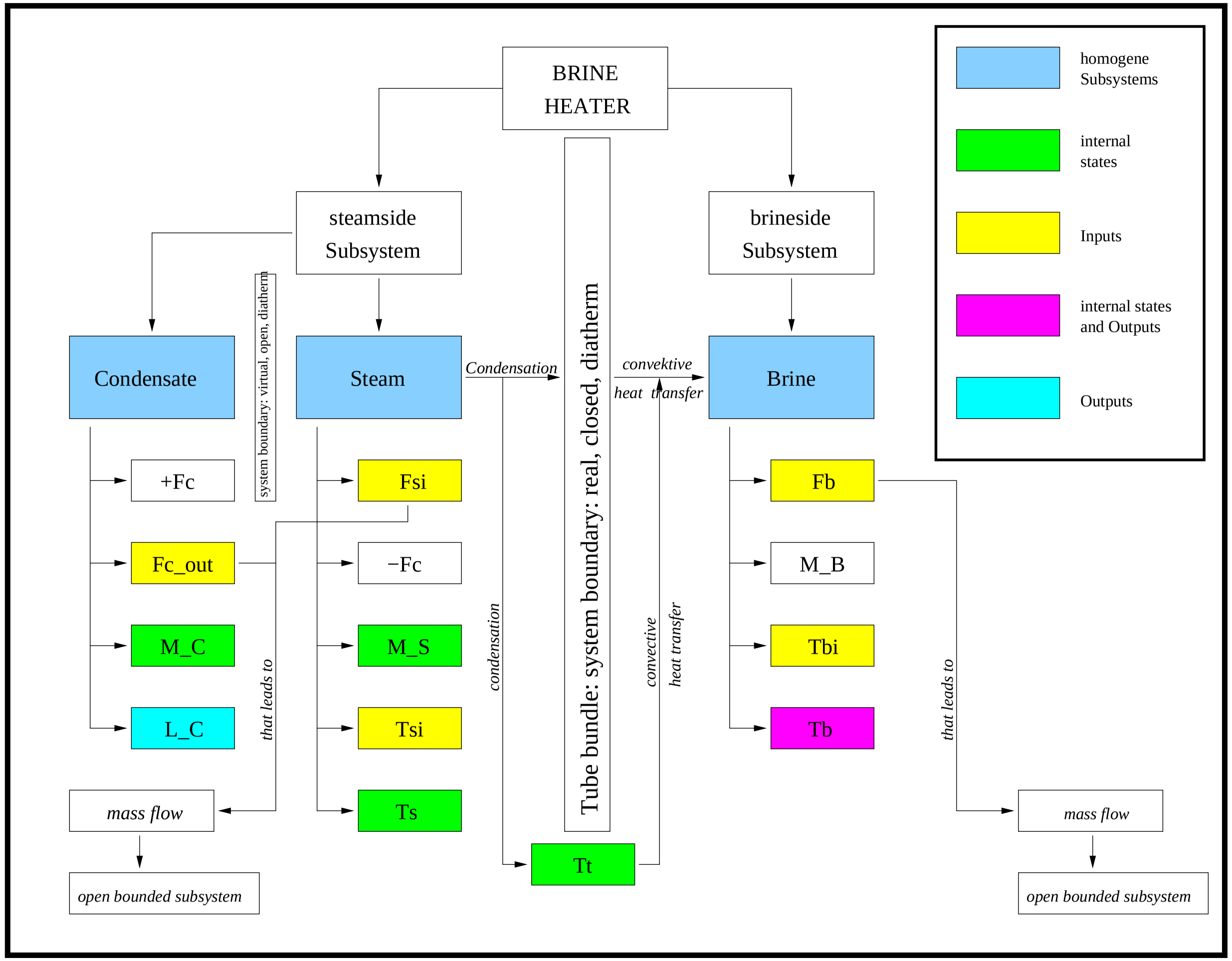
The dynamic model

Decomposition and Coordination

1. Decomposition (→ divide system into subsystems)
2. Simplifications (→ adapt model to its purpose)
3. Identification (→ inputs, internal states, outputs)
4. Energy balance equations (→ heat exchange)
5. Differential equations (→ concrete description)
6. Degree of freedom (DOF) (→ solubility)
7. Simulation and Validation (→ is the model well suited?)
8. Coordination (→ build up entire model)

The dynamic model

Decomposition



The dynamic model

Simplifications (1)

- Desuperheater is neglected

  [no direct effect on brine]

- System is thermodynamical insulated

  [no external effects]

- Change in brine-density is neglected

  [$F_{Bi} = F_B$]

- Brine fills up tubes ideal

  [air $\rightarrow$ efficiency]

The dynamic model

Simplifications (2)

- Condensate droplets delivers no additional heat

  [pressure nearly constant]

- Oxidation and scaling effects are neclected

  [no parameters, validation, plant-specific properties]

- No local temperature-variation ($\frac{\partial T}{\partial x} = \frac{\partial T}{\partial y} = \frac{\partial T}{\partial z} = 0$)

  $\rightarrow$ models with distributed parameters

  $\rightarrow$ partial differential equations

The dynamic model

Identification (1) - Parameters

Steam-side:

- Volume of vessel -
  $Vol = M_S Vol + M_C Vol = 4000m^3$
- Outer tube surface - A_e - $[m^2]$
- Number of Tubes - $N = 5000$
- Outer tube diameter - d_e - $[m]$
- Tube thickness - $w = 0.0012m$
- Tube length - $l = 70m$

The dynamic model

Identification (2) - Parameters

Tube-Bundle:

- Tube mass (s) - $M_T = 15.000kg$
- specific heat capacity - $c_{pT} = 4.184 \cdot 0.12 \cdot 10^3 \frac{J}{kg \cdot K}$

Brine-side:

- Inner tube surface - A_i - $[m^2]$
- Brine salinity (s) - $C = 0.057 \frac{kg}{kg}$
- Brine mass (s) - $M_B = 35.000kg$

The dynamic model

Identification (3) - Internal states

Internal states:

- Steam temperature - T_S - $[^\circ C]$
- Tube temperature - T_T - $[^\circ C]$
- Brine temperature - T_B - $[^\circ C]$
- Steam mass - M_S - $[kg]$
- Condensate mass - M_C - $[kg]$

The dynamic model

Identification (4) - Inputs

Inputs:

- Brine input temperature - T_{Bi} - $[°C]$
- Steam input temperature - T_{Si} - $[°C]$
- Brine flowrate - F_{Bi} - $[\frac{kg}{s}]$
- **Steam flowrate -** F_{Si} **-** $[\frac{kg}{s}]$
- **Outgoing condensate flowrate -** F_cOut **-** $\frac{kg}{s}$

The dynamic model

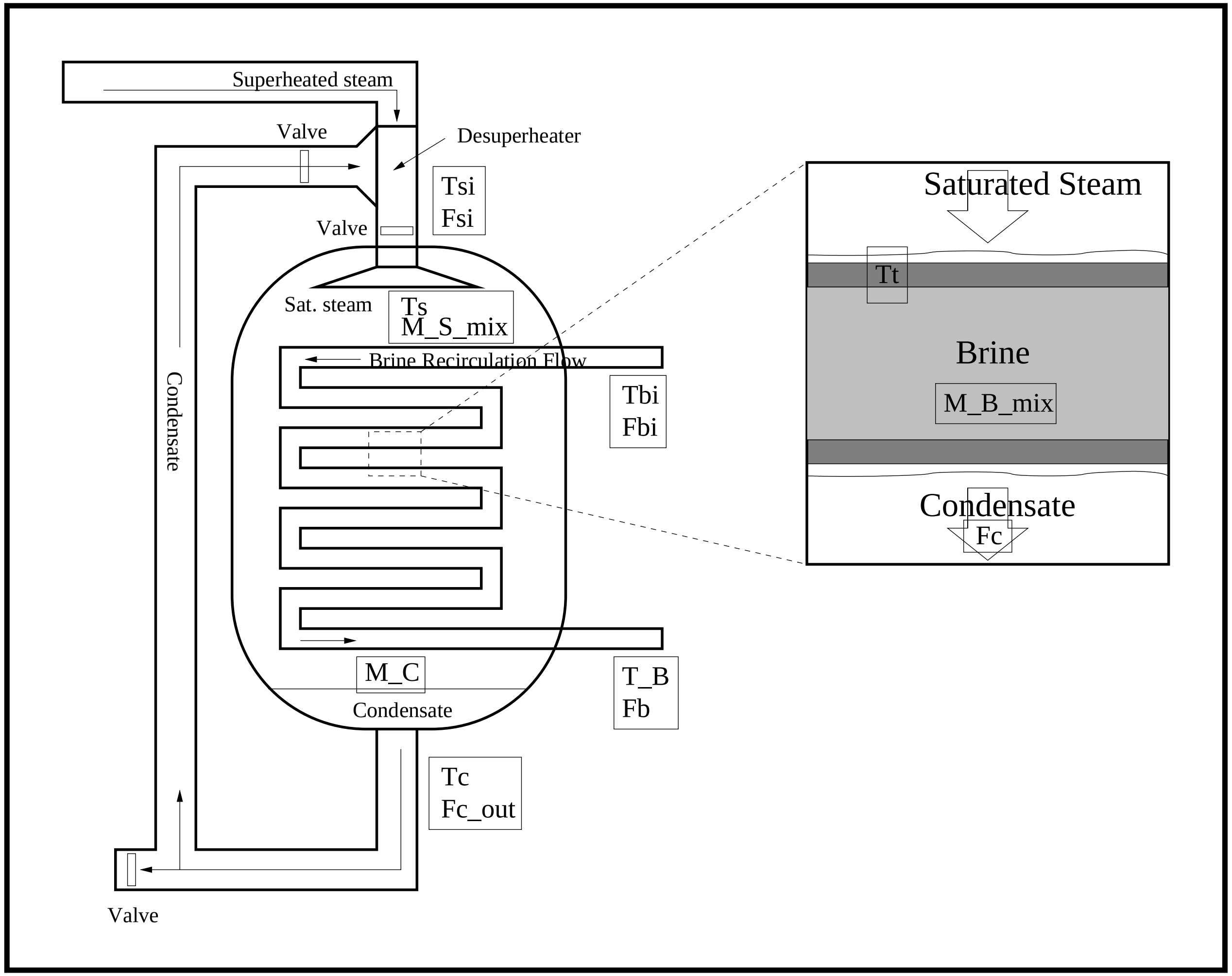
Identification (5) - Outputs

Outputs:

- Brine temperature - T_B - $[^\circ C]$
- Condensate level - L_C - $[m]$

The dynamic model

Identification (6) - Schematic



The dynamic model

Energy- and mass-balance equations

$$\frac{dQ_S}{dt} = \frac{dQ_{Si}}{dt} - \frac{dQ_C}{dt} - \frac{dQ_{Env}}{dt}$$

$$\frac{dQ_T}{dt} = Q_C - Q_{Cv}$$

$$\frac{dQ_B}{dt} = \frac{dQ_{Cv}}{dt} - \frac{dQ_{Bi}}{dt}$$

$$\frac{dM_S}{dt} = F_{Si} - F_C$$

$$\frac{dM_C}{dt} = F_C - F_C Out$$

The dynamic model

Differential and algebraic equations (1)

$$
\begin{aligned}
M_S \cdot c_{pS} \cdot \frac{dT_S}{dt} &= F_{Si} \cdot \left[h''_{Si}\left(T_{Si}, P\right) - h''_S\left(T_S, P\right)\right] \\
&\quad -\alpha_C \cdot A_e \cdot \left[T_S - T_T\right] \\
M_T \cdot c_{pT} \cdot \frac{dT_T}{dt} &= \alpha_C \cdot A_e \cdot \left[T_S - T_T\right] \\
&\quad -\alpha_{Cv} \cdot A_i \cdot \left[T_T - T_B\right] \\
M_B \cdot c_{pB} \cdot \frac{dT_B}{dt} &= \alpha_{Cv} \cdot A_i \cdot \left[T_T - T_B\right] \\
&\quad -F_B \cdot \left[h'_{Bi}\left(T_{Bi}, C\right) - h'_B\left(T_B, C\right)\right] \\
\frac{dM_S}{dt} &= \left[F_{Si} - F_C\right] \\
\frac{dM_C}{dt} &= \left[F_C - F_{COut}\right]
\end{aligned}
$$

The dynamic model

Differential and **algebraic** equations (2)

Algebraic Equations:

$$M_S Vol = Vol - \nu(T_S, P) \cdot M_S$$

$$F_C = \frac{\dot{Q}}{\triangle h}$$

The dynamic model

Properties of **water, steam** and sea water (1)

Water and steam (IAPWS-IF97):

Property	Symbol	Dependency
specific enthalpy of steam	h''_S	$h''_S = f(T_S, P)$
specific heat capacity of steam at constant pressure	c_{pS}	$c_p = f(T_S, P)$
specific volume of steam	ν_S	$\nu_S = f(T_S, P)$
specific volume of condensate	ν_C	$\nu_C = f(T_C, P)$
saturation temperature	t_s	$t_s = f(P)$

The dynamic model

Properties of water, steam and **sea water** (2)

Sea water (Fichtner Handbook 1978):

Property	Symbol	Dependency
specific enthalpy	h'_B	$h'_B = f(T_B, C)$
specific heat capacity at constant pressure	c_{pB}	$c_{pB} = f(T_B, C)$
density	ρ_B	$\rho_B = f(T_B, C)$
dynamic viscosity	η_C	$\eta_C = f(T_B, C)$
heat consuctivity	λ_B	$\lambda_B = f(T_B, C)$

The dynamic model

Degree of freedom (DOF)

$$
\begin{aligned}
N_F &= N_V - N_E \\
N_V &= N_{In} + N_{State} + N_{Out} \\
N_E &= N_{Algebraic} + N_{Diffferential} \\
N_V &= 2 + 5 + 2 \\
N_E &= 5 + 2 \\
N_F &= 2
\end{aligned}
$$

PROBLEM: UNDERSPECIFIED MODEL

SOLUTION: REDUCE DOF WITH 2 CONTROL LAWS

RESULT: EXACTLY SPECIFIED MODEL

The dynamic model

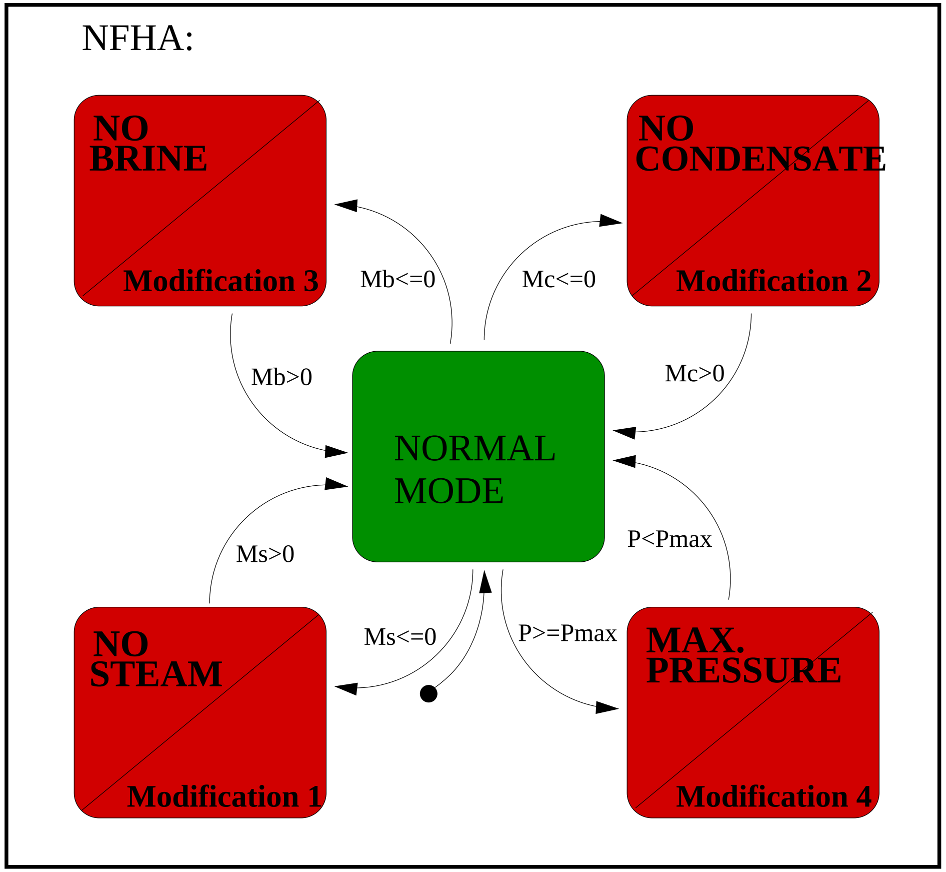
Discrete events and singularities

Discrete event	Property
no steam in vessel	$M_S = 0$
no condensate in vessel	$M_C = 0$
no brine in tubes	$M_B = 0$
max pressure	$P = P_{max}$

The dynamic model

The hybrid automaton

Nondeterministic hybrid automaton:



The dynamic model

Modification of differential equations (1)

Modification 1: No steam ($M_S = 0$)

$$\frac{dT_{\mathrm{S}}}{dt} = 0$$

$$\frac{dM_S}{dt} = F_{\mathrm{Si}}$$

Modification 2: No condensate ($M_C = 0$)

$$\frac{dM_C}{dt} = F_{\mathrm{C}}$$

The dynamic model

Modification of differential equations (2)

Modification 3: No brine ($M_B = 0$)

$$\frac{dT_\mathrm{B}}{dt} = 0$$

Modification 4: Max. pressure ($P \geq P_{max}$)

$$\frac{dT_\mathrm{S}}{dt} = -\frac{Q_C}{M_S \cdot c_\mathrm{pS}}$$

$$\frac{dM_\mathrm{S}}{dt} = -F_\mathrm{C}$$

The dynamic model
The 4 setpoints

(source: Desalination, no.73, pp.173-190, 1999)

	Setpoint 1 Summer / Night		Setpoint 2 Winter / Night	
Var	MSF-plant	Simulation	MSF-plant	Simulation
T_{Sea}	$32.22^\circ C$	$30^\circ C$	$14.4^\circ C$	$12^\circ C$
T_{Bi}	$84.89^\circ C$	$85^\circ C$	$82.13^\circ C$	$83^\circ C$
T_B at TBT	$90.56^\circ C$	$90^\circ C$	$88.08^\circ C$	$88^\circ C$
T_{Si}	$100^\circ C$	$100^\circ C$	$97.59^\circ C$	$98^\circ C$
F_B	$3986.4 \frac{kg}{s}$	$3900 \frac{kg}{s}$	$3795.3 \frac{kg}{s}$	$3700 \frac{kg}{s}$
F_{Si}	$39.16 \frac{kg}{s}$	$74.5 \frac{kg}{s}$	$39.16 \frac{kg}{s}$	$56.38 \frac{kg}{s}$

The dynamic model
The 4 setpoints

(source: Desalination, no.73, pp.173-190, 1999)

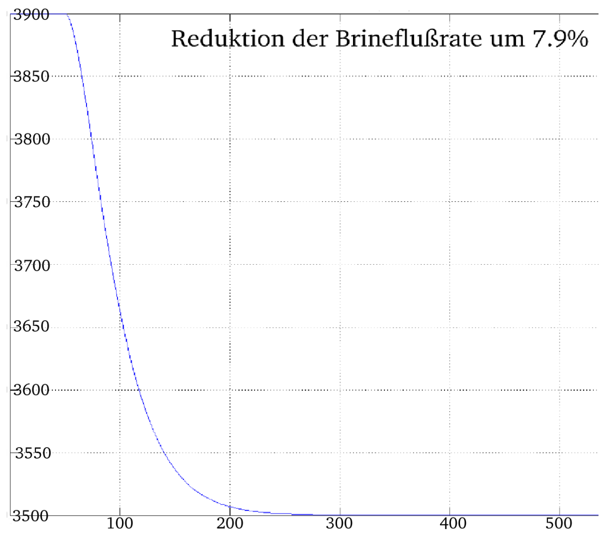
	Setpoint 3 Summer / Day		Setpoint 4 Winter / Day	
Var	MSF-plant	Simulation	MSF-plant	Simulation
T_{Sea}	$32.22^{\circ} C$	$34^{\circ} C$	$14.4^{\circ} C$	$16^{\circ} C$
T_{Bi}	$103.02^{\circ} C$	$106^{\circ} C$	$100.59^{\circ} C$	$103^{\circ} C$
T_B at TBT	$110^{\circ} C$	$110^{\circ} C$	$107.94^{\circ} C$	$108^{\circ} C$
T_{Si}	$119.85^{\circ} C$	$120^{\circ} C$	$117.78^{\circ} C$	$117^{\circ} C$
F_B	$3476.4 \frac{kg}{s}$	$2700 \frac{kg}{s}$	$3314.2 \frac{kg}{s}$	$3000 \frac{kg}{s}$
F_{Si}	$43.46 \frac{kg}{s}$ *	$152.23 \frac{kg}{s}$	$43.46 \frac{kg}{s}$ *	$220.16 \frac{kg}{s}$

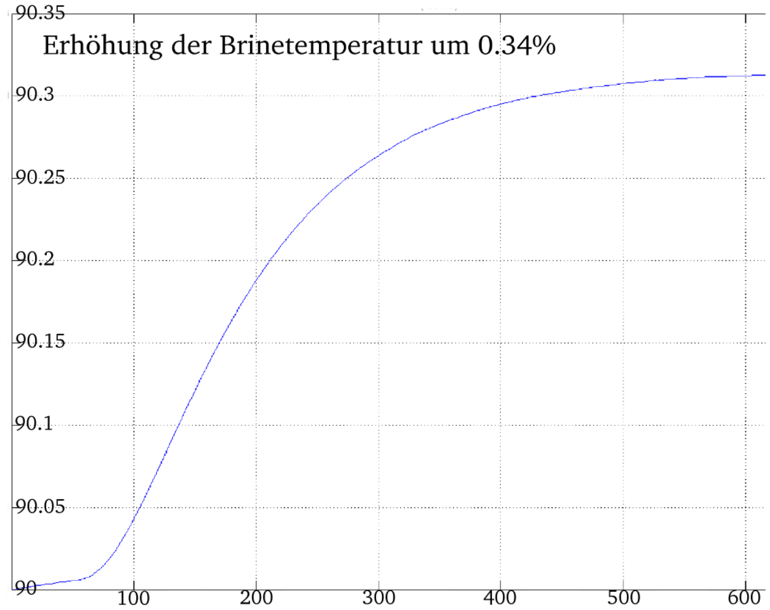
* no pressure variation considered, chain of heat transfer: $Q_{Si} \rightarrow Q_S \rightarrow Q_B$,

most complete setpoint and parameter data

The dynamic model

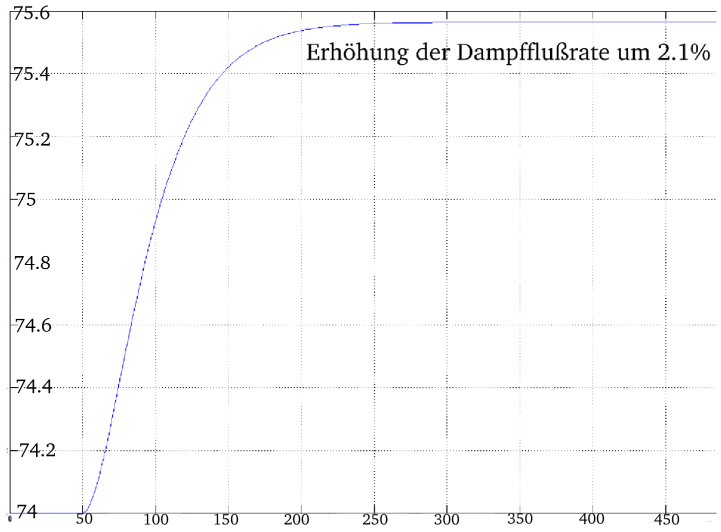
Simulation - change in brine flowrate F_{Bi}

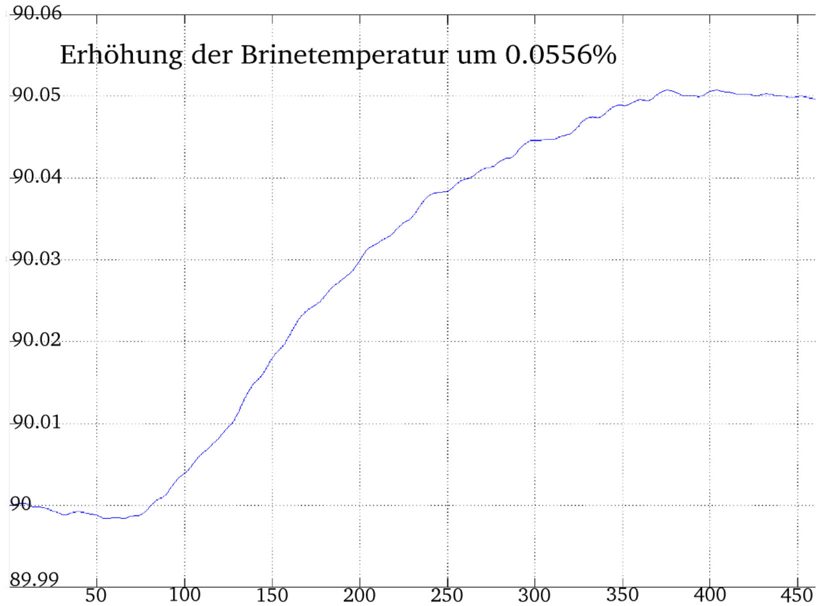




The dynamic model

Simulation - change in steam flow rate F_{Si}

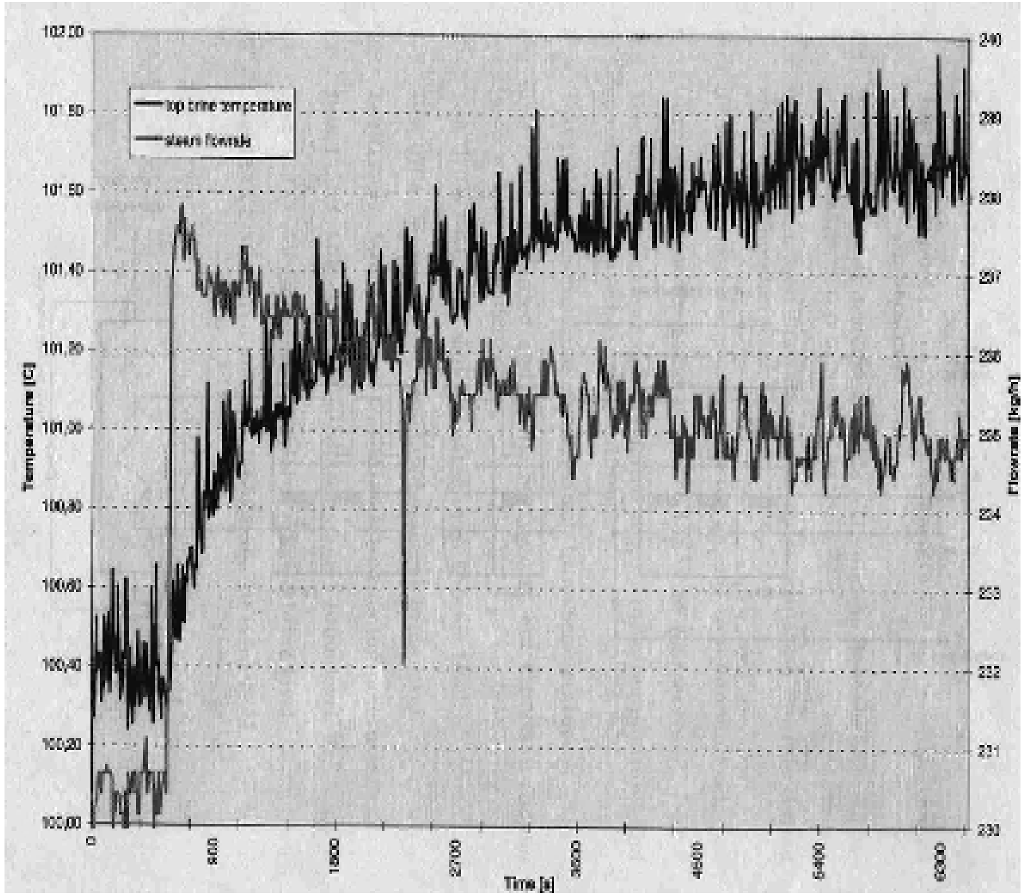




The dynamic model

Verification - change in steam flow rate

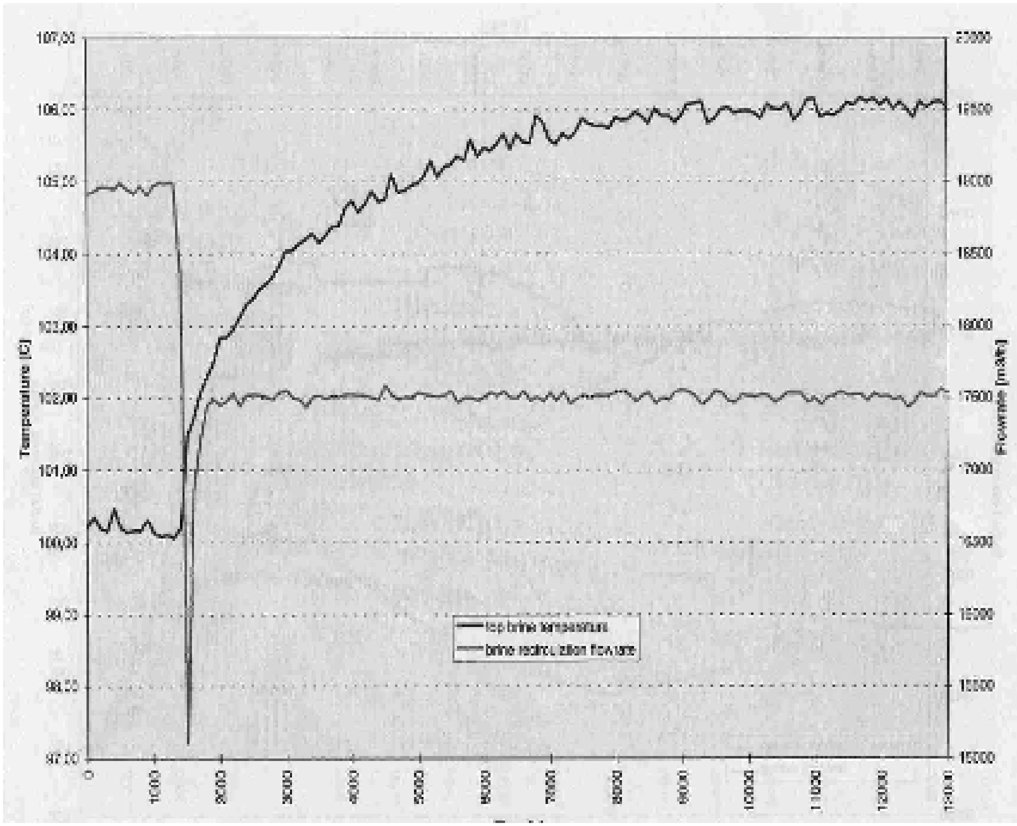
Source: LPT-1999-29, Lehrstuhl für Prozetechnik, RWTH Aachen, techreport



The dynamic model

Verification - change in brine flow rate

Source: LPT-1999-29, Lehrstuhl für Prozetechnik, RWTH Aachen, techreport



The dynamic model

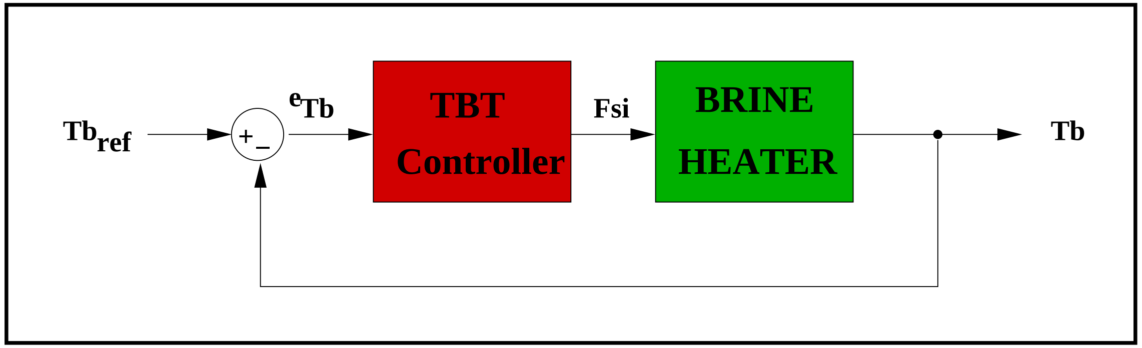
Innovations

- Consideration of convective heat transfer (Nußelt theory - ”Ähnlichkeitstheorie”)
- Chain of heat effect: $Q_{Si} \rightarrow Q_S \rightarrow Q_T \rightarrow Q_B$
- Tube as subsystem with its own energy balance equation
- Model handles discrete events
- Variation of saturation temperature with respect to the pressure variation in the brine-heater shell (steam and condensate masses)

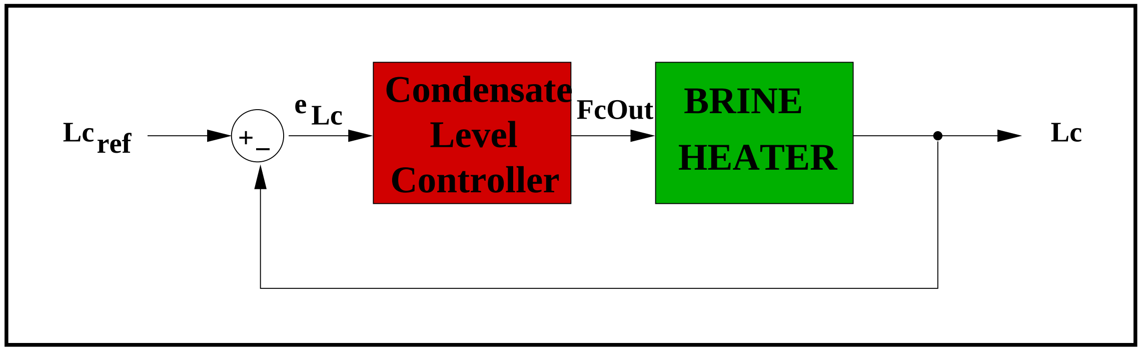
Linearization and Control

The control loops

Top Brine Temperature control loop:



Condensate level control loop:



Linearization and Control

The control strategy

PID-Controller:

$$u(t) = K_p \cdot \left[e(t) + T_d \cdot \frac{d}{dt} \cdot e(t) + \frac{1}{T_i} \cdot \int_{t_0}^{t} e(t)dt \right]$$

Modified PID-Controller:

$$u(t) = K_p \cdot \left[K_b \cdot r(t) - y(t) + T_d \cdot \frac{d}{dt} \cdot e(t) + \frac{1}{T_i} \cdot \int_{t_0}^{t} e(t)dt \right]$$

Ziegler-Nichols parameters:

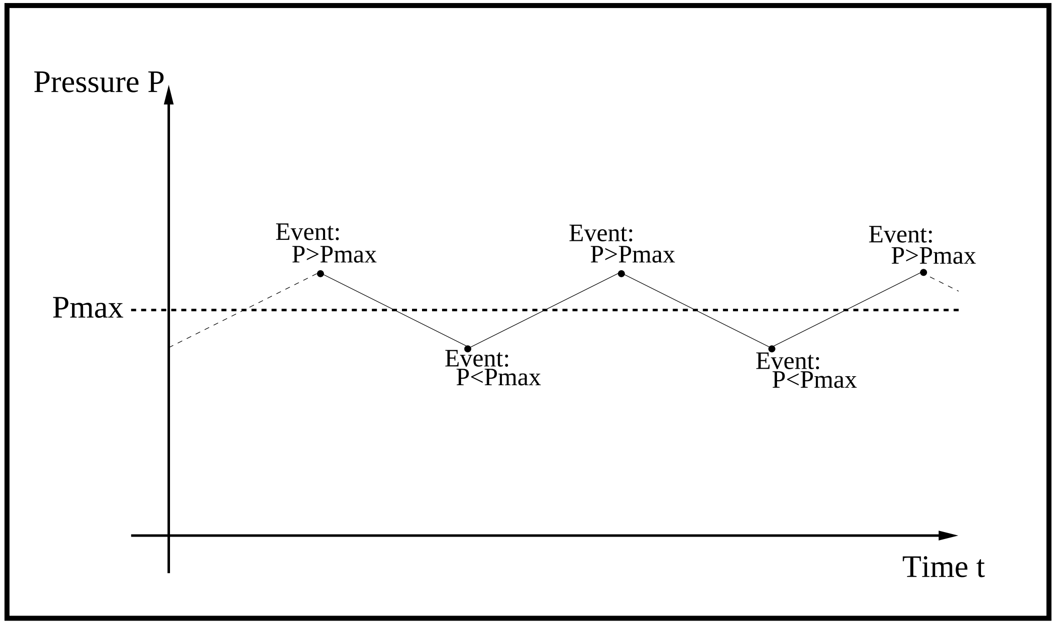
$$\begin{aligned} K_p &= \frac{T_a}{1.2 \cdot K_s \cdot T_u} \\ T_d &= 0.5 \cdot T_a \\ T_i &= 2 \cdot T_u \end{aligned}$$

+ Anti-Windup Strategies (I-Stop, I-Reset and I-Subtraction)

Linearization and Control

Linearization in 4 setpoints

The pressure oscillation problem



Remarks: amplitude depends on valve sensitivity or calculation exactness respectively, oscillation has effect on steam and condensate masses

Linearization and Control

Pressure oscillation problem

PROBLEM:

- Oscillation makes linearization inexact
- Convergence of linearization algorithm not sure
- Linear model should map temperature variation and not pressure or mass oscillation

PROPERTIES:

- Steam and condensate masses are oscillating about average values
- Effect of mass oscillation on temperature variation is low
- Exclude condensate control from linearization ($FcOut \stackrel{!}{=} Fc$)

SOLUTION:

- Set steam and condensate mass constant to average values
- modifiy differential equations that no mass variation occurs
- Set pressure constant (Pmax)

Linearization and Control

Modified dynamic model for linearization

$$
\begin{aligned}
M_S \cdot c_{pS} \cdot \frac{dT_S}{dt} &= F_{Si} \cdot \left[h''_{Si}\left(T_{Si}, P\right) - h''_S\left(T_S, P\right)\right] \\
&\quad -\alpha_C \cdot A_e \cdot \left[T_S - T_T\right] \\
M_T \cdot c_{pT} \cdot \frac{dT_T}{dt} &= \alpha_C \cdot A_e \cdot \left[T_S - T_T\right] \\
&\quad -\alpha_{Cv} \cdot A_i \cdot \left[T_T - T_B\right] \\
M_B \cdot c_{pB} \cdot \frac{dT_B}{dt} &= \alpha_{Cv} \cdot A_i \cdot \left[T_T - T_B\right] \\
&\quad -F_B \cdot \left[h'_{Bi}\left(T_{Bi}, C\right) - h'_B\left(T_B, C\right)\right] \\
\frac{dM_S}{dt} &= 0 \\
\frac{dM_C}{dt} &= 0
\end{aligned}
$$

$$M_S = 0.5 \cdot \left(M_S^{Pmax+\triangle} + M_S^{Pmax-\triangle}\right)$$

$$M_C = 0.5 \cdot \left(M_C^{Pmax+\triangle} + M_C^{Pmax-\triangle}\right)$$

Linearization and Control

Integrated errors - 4 setpoints

	P_1	P_2	P_3	P_4
SP_1	**34.1335**	45.7013	39.062	38.3583
SP_2	38.9341	**32.4166**	38.1411	43.4094
SP_3	72.8779	74.9681	**72.5999**	79.7223
SP_4	109.9233	111.7416	110.0951	**108.9884**

REMARK: Coincident sets produces best results, motivation for parameter change at setpoint change

Linearization and Control

Innovations

- Modified PID-Controller
- Linearization approach (pressure oscillation problem)
-
-
-

Hybrid automaton, parameter change and bumpless transfer

General introduction

Motivation:

- Corresponding parameters and setpoints have better control quality

Goal:

- Use corresponding set of parameter and setpoint

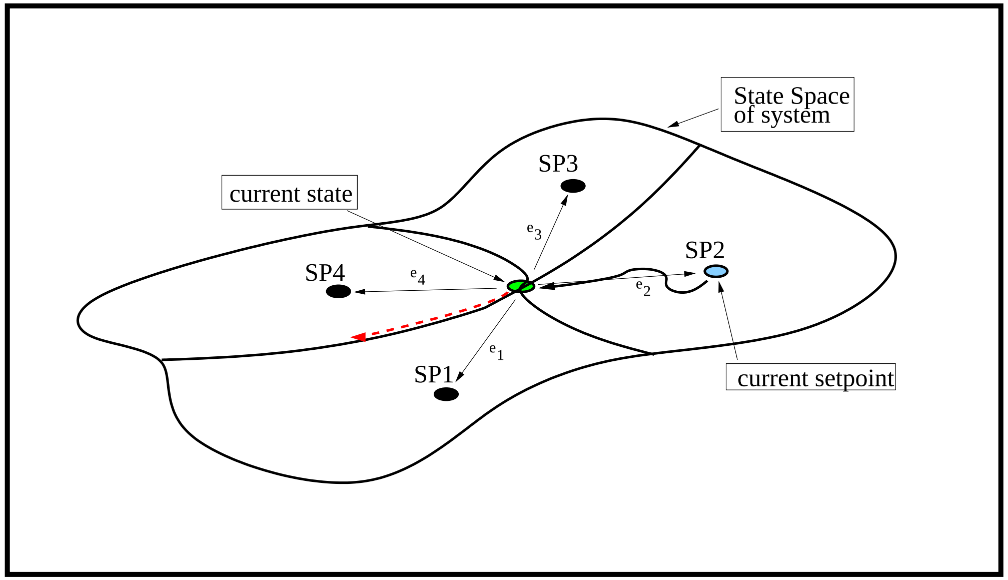
Questions:

- When does a setpoint change takes place?
- How to detect a setpoint change?
- Which moment of parameter change is advantageous?
- How to accomplish a bumpless transfer with a hybrid structure?

Hybrid automaton, parameter change and bumpless transfer

General idea and the equal error problem

PROBLEM: Equal deviation



SOLUTION: Dynamic priority distribution in rulebase leads to robust classifier

Hybrid automaton, parameter change and bumpless transfer

Setpoint detection with fuzzy classifier

PURPOSE:

- Detect if a setpoint change takes place

INPUT:

- normalized Lyapunov-functions (weighted square errors), $V_i^{norm}, i = 1...4$

OUTPUT:

- Setpoint number $N = 1...4$

FUZZY-CLASSIFIER:

- Rule and database to provide a setpoint detection

Hybrid automaton, parameter change and bumpless transfer

Fuzzy-Classifier - rule- and database

DATABASE: Membershipfunctions for input and output

Input i - linguistic value $Error_i$ describing the linguistic variable V_i^{norm}

Output - 4 singletons describing the linguistic variable *Setpoint*

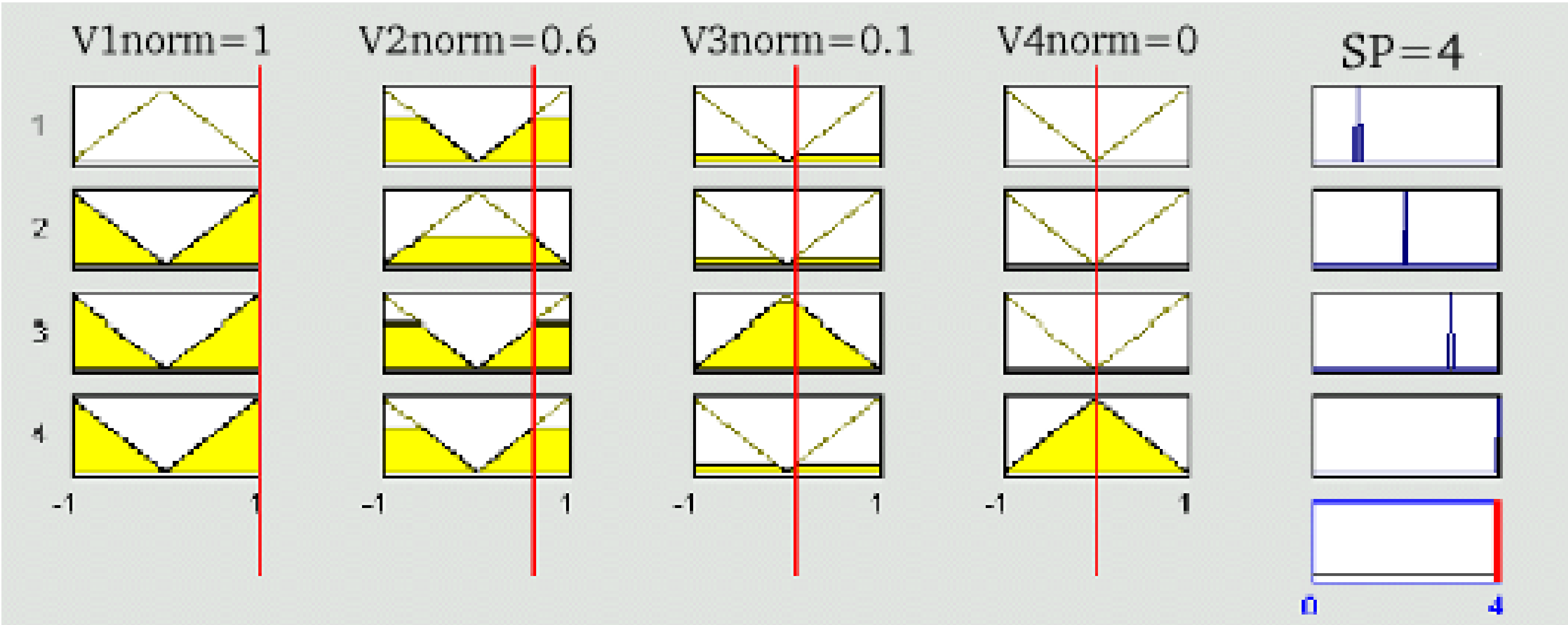
RULEBASE:

IF $(V_i^{norm} == Error_i)$ & $(V_i^{norm} \neq Error_j)(\forall j \neq i)$
THEN $(SP = SP_i)$

Hybrid automaton, parameter change and bumpless transfer

Fuzzy Classifier

The Rulebase



Hybrid automaton, parameter change and bumpless transfer

Fuzzy Classifier - theoretical background

The Min-Switch Strategy

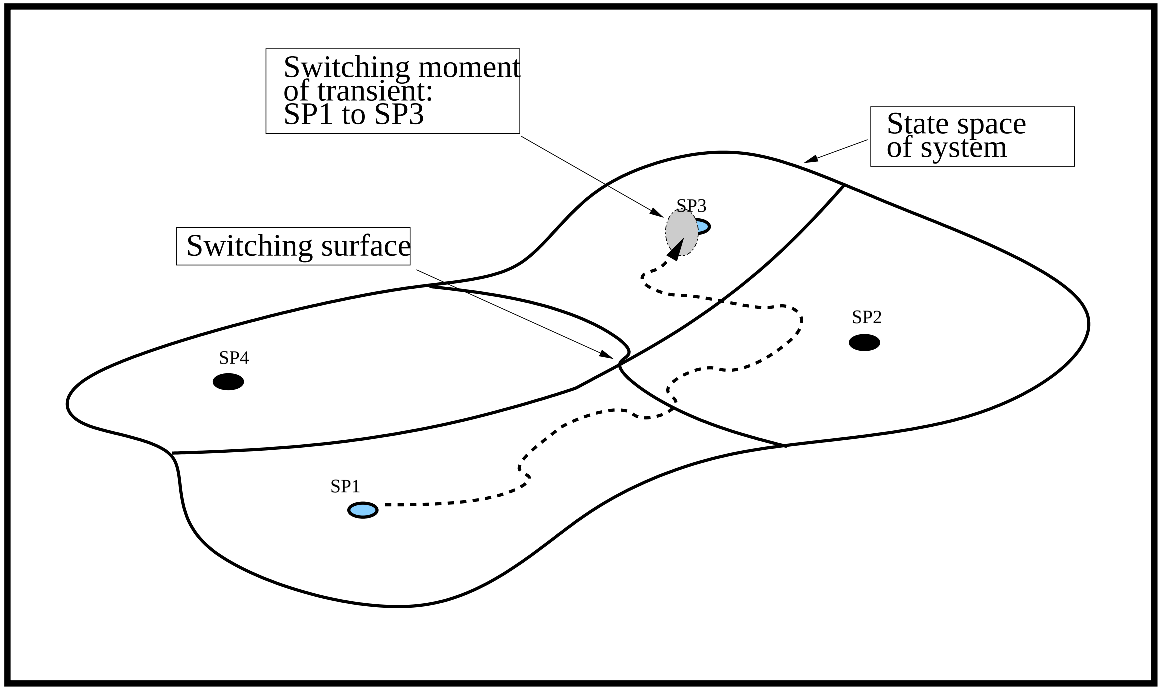
MIN-SWITCH STRATEGY

- Lyapunov-theory based approach
- Parameter change according to minimum Lyapunov-candidate
- Proof of stability given

Hybrid automaton, parameter change and bumpless transfer

Moment of setpoint change - 2 methods

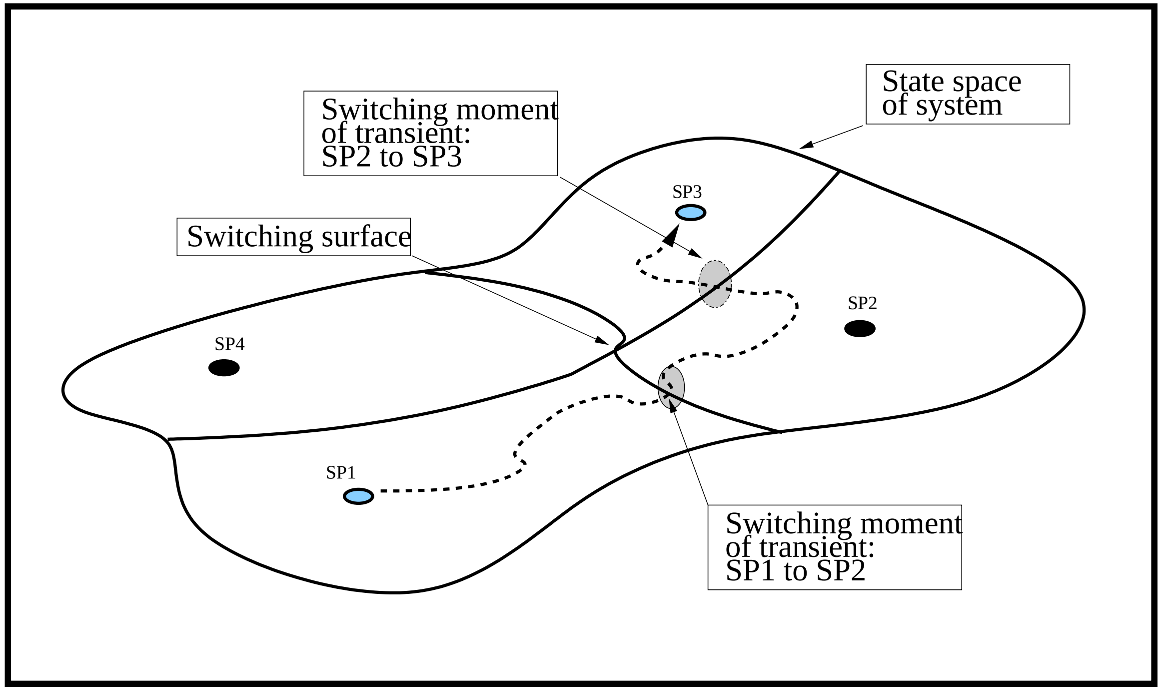
METHOD 1: Switch in setpoint



Hybrid automaton, parameter change and bumpless transfer

Moment of setpoint change - 2 methods

METHOD 2: Switch in transient phase



Hybrid automaton, parameter change and bumpless transfer

The bumpless transfer

BASIC IDEA: Eliminate control error!

METHOD 1:

$T_B^{Ref} \leftarrow T_B$ once (conventional approach)

Drawback: parameter change not until setpoint is reached

METHOD 1:

$T_B^{Ref} \leftarrow T_B$ permanent (innovative approach)

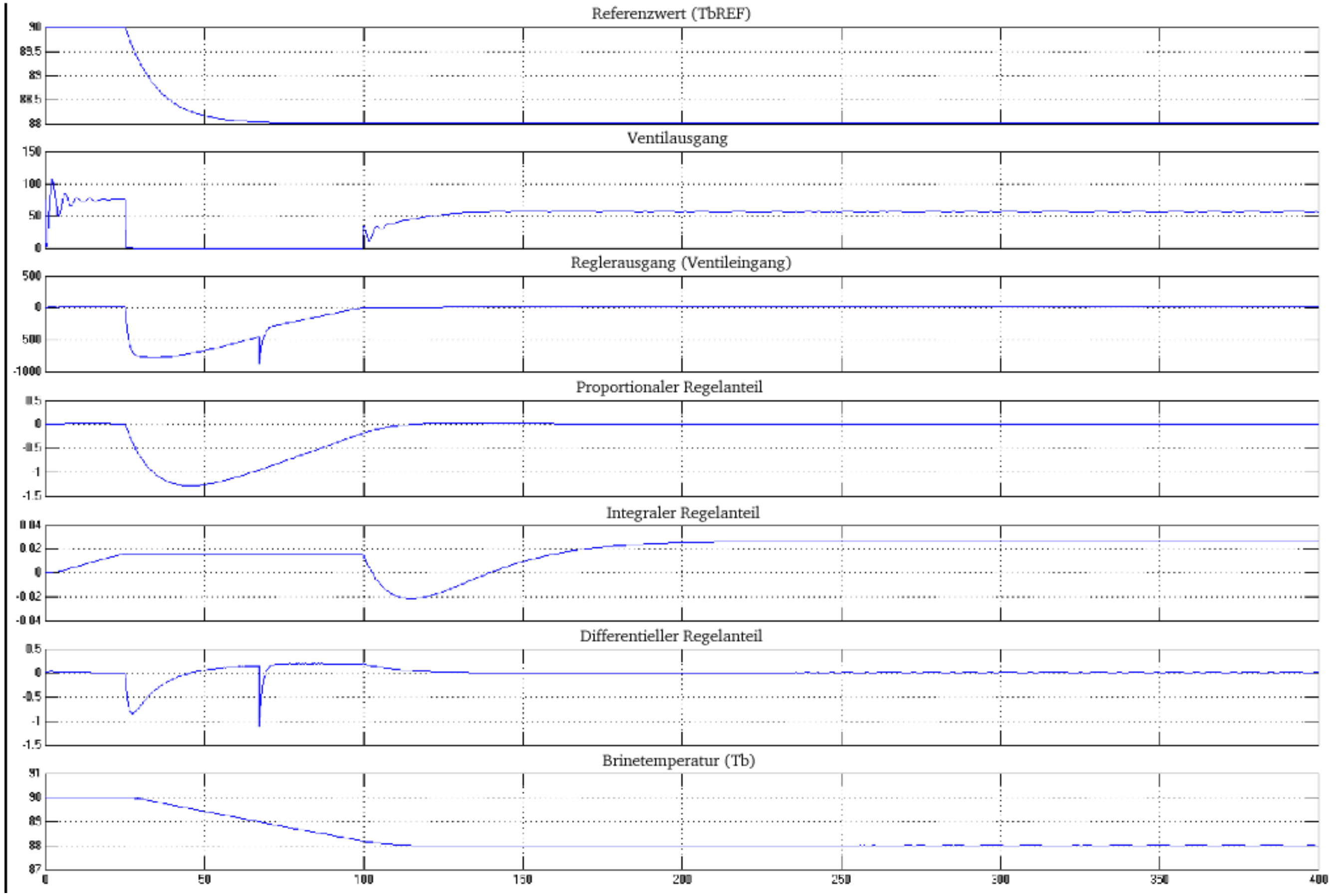
Advantage: immediate parameter change

REMARKS:

- If setpoint change is detected, the setpoint-relevant parameters are still changing
- Controller doesn't have enough bandwidth to eliminate error on transient

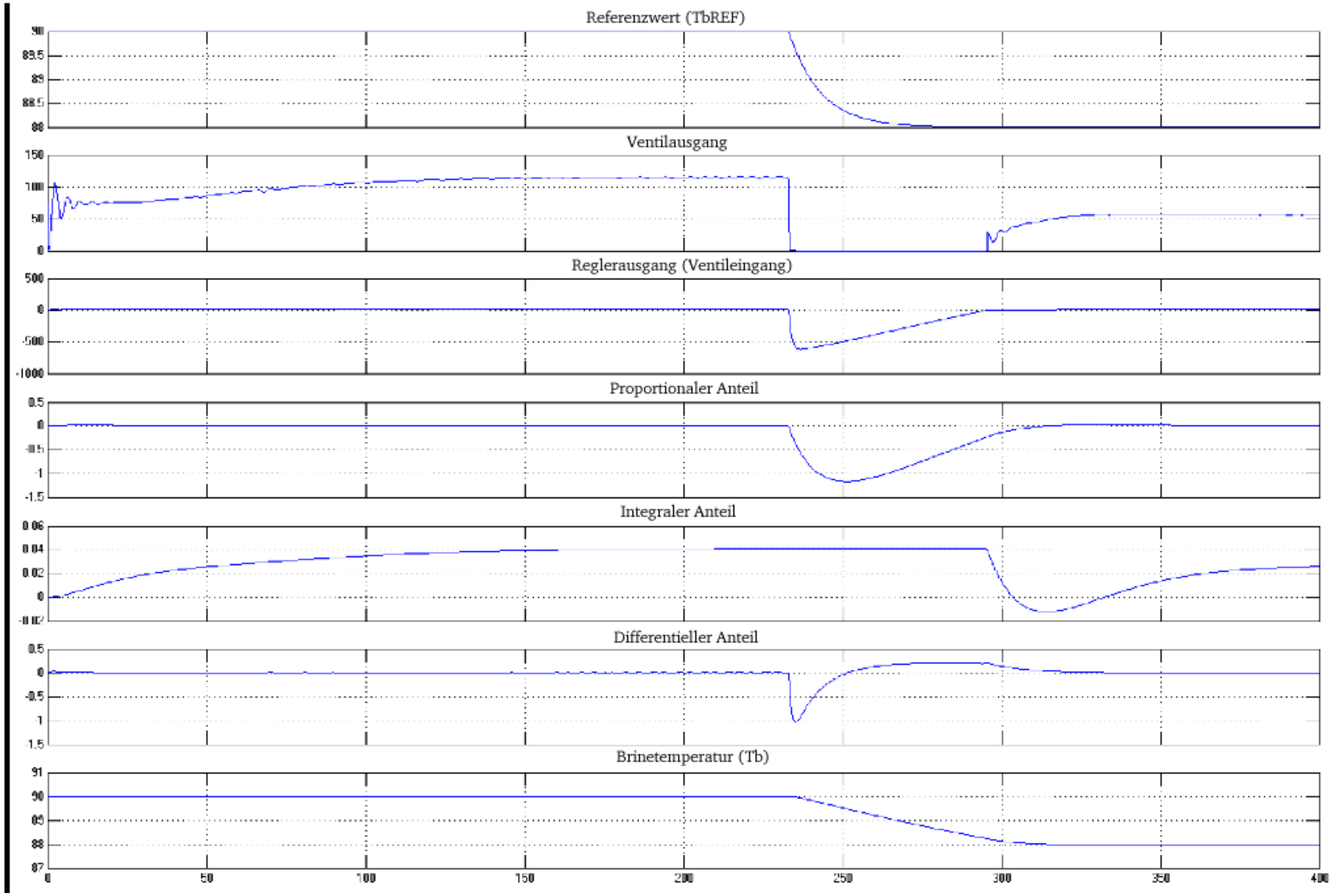
Hybrid automaton, parameter change and bumpless transfer

Simulation results - No Method



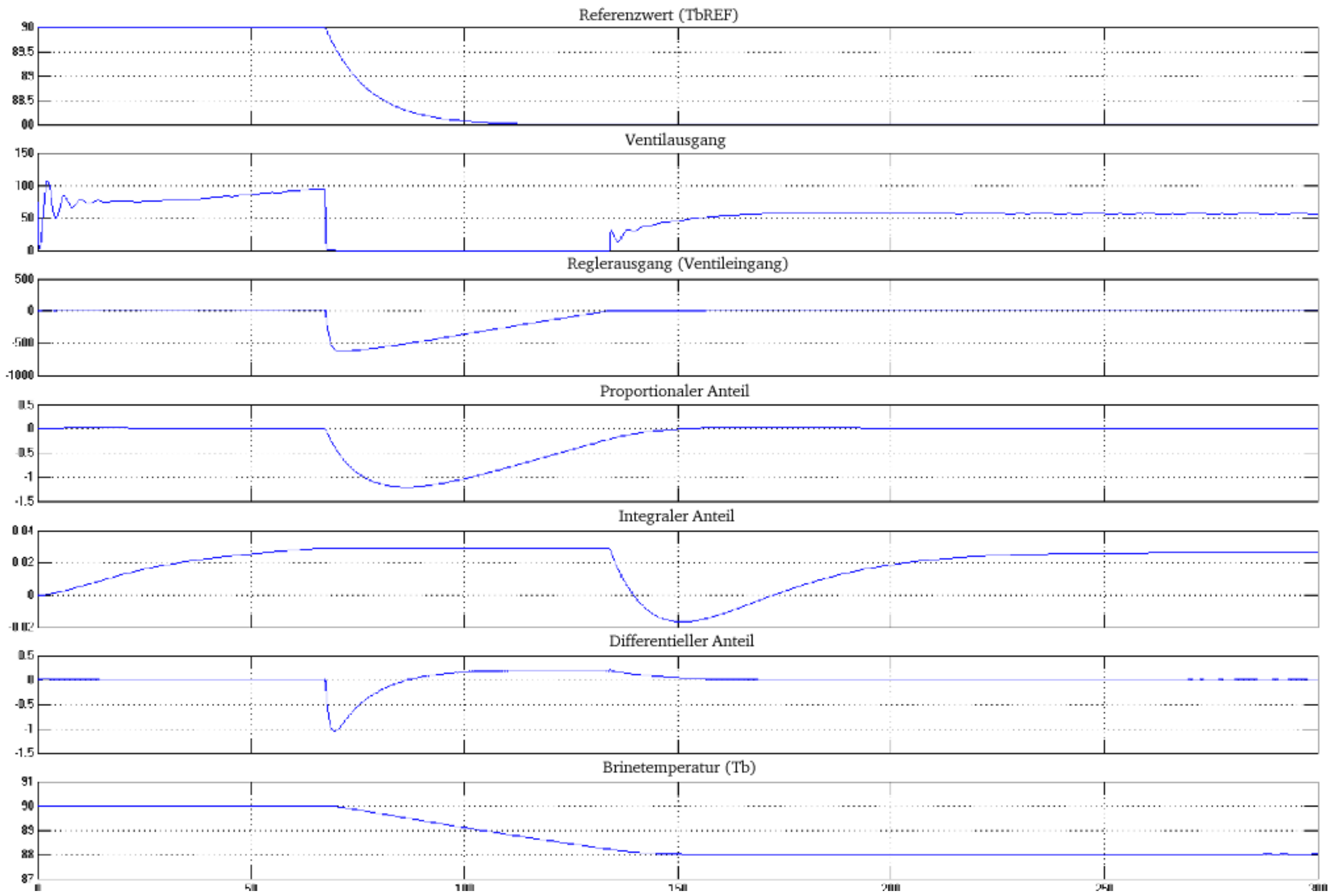
Hybrid automaton, parameter change and bumpless transfer

Simulation results - Method 1



Hybrid automaton, parameter change and bumpless transfer

Simulation results - Method 2



Hybrid automaton, parameter change and bumpless transfer

Innovations

- Parameter change on transient phase
- Fuzzy classifier for setpoint detection
-
-
-

Scenario Generation

A Fuzzy approach

MOTIVATION:

Automatic setpoint choice with respect to seasonal temperature variations of the sea water

INPUT:

Sea water temperature

OUTPUT:

Reference values for the entire plant, as well as for the brine heater

REMARKS:

T_{Sea} is only one criterion - for further optimization, economic criterions can be taken into consideration

Scenario Generation

The rule and database