

## Chapter 2

# Case Study and Application Examples

In this chapter, three application examples are introduced, which will be applied to illustrate the major process monitoring, diagnosis and control schemes presented and studied in this book. The first two are real laboratory control systems, which are widely used both in the model-based and data-driven fault diagnosis research. The third one is a benchmark process that is mainly applied for the test and demonstration of data-driven control and monitoring schemes. The objective of introducing these application examples in the first part of this book, immediately after *Introduction*, is to provide the reader with the useful application background and understandings of some basic technical concepts in the process monitoring and fault diagnosis field.

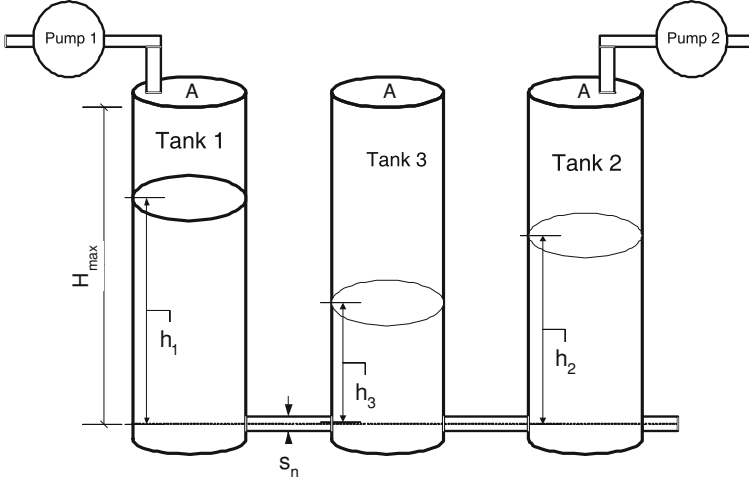
### 2.1 Three-Tank System

A three-tank systems, as sketched in Fig. 2.1, has typical characteristics of tanks, pipelines and pumps used in chemical industry and thus often serves as a benchmark process in laboratories for process control. The model and the parameters of the three-tank system introduced here are from the laboratory setup DTS200.

#### 2.1.1 Process Dynamics and Its Description

Applying the incoming and outgoing mass flows under consideration of Torricelli's law, the dynamics of DTS200 is modeled by

$$\begin{aligned}A\dot{h}_1 &= Q_1 - Q_{13}, A\dot{h}_2 = Q_2 + Q_{32} - Q_{20}, A\dot{h}_3 = Q_{13} - Q_{32} \\ Q_{13} &= a_1 s_{13} \operatorname{sgn}(h_1 - h_3) \sqrt{2g|h_1 - h_3|} \\ Q_{32} &= a_3 s_{23} \operatorname{sgn}(h_3 - h_2) \sqrt{2g|h_3 - h_2|}, Q_{20} = a_2 s_0 \sqrt{2gh_2}\end{aligned}$$



**Fig. 2.1** DTS200 setup

where

- $Q_1, Q_2$  are incoming mass flow ( $\text{cm}^3/\text{s}$ )
- $Q_{ij}$  is the mass flow ( $\text{cm}^3/\text{s}$ ) from the  $i$ th tank to the  $j$ th tank
- $h_i(t), i = 1, 2, 3$ , are the water level (cm) in each tank and measurement variables
- $s_{13} = s_{23} = s_0 = s_n$ .

The parameters are given in Table 2.1.

In most of our studies, we deal with linear systems. The linear form of the above model can be achieved by a linearization at an operating point as follows:

$$\begin{aligned} \dot{x} &= Ax + Bu, y = Cx \\ x &= \begin{bmatrix} h_1 - h_{1,o} \\ h_2 - h_{2,o} \\ h_3 - h_{3,o} \end{bmatrix}, u = \begin{bmatrix} Q_1 - Q_{1,o} \\ Q_2 - Q_{2,o} \end{bmatrix}, Q_o = \begin{bmatrix} Q_{1,o} \\ Q_{2,o} \end{bmatrix} \\ A &= \frac{\partial f}{\partial h} \Big|_{h=h_o}, B = \begin{bmatrix} \frac{1}{A} & 0 \\ 0 & \frac{1}{A} \\ 0 & 0 \end{bmatrix}, C = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \end{aligned} \quad (2.1)$$

where  $h_{i,o}, i = 1, 2, 3$ ,  $Q_{1,o}, Q_{2,o}$  denote the operating point under consideration and

$$f(h) = \begin{bmatrix} \frac{-a_1 s_{13} \text{sgn}(h_1 - h_3) \sqrt{2g|h_1 - h_3|}}{A} \\ \frac{a_3 s_{23} \text{sgn}(h_3 - h_2) \sqrt{2g|h_3 - h_2|} - a_2 s_0 \sqrt{2gh_2}}{A} \\ \frac{a_1 s_{13} \text{sgn}(h_1 - h_3) \sqrt{2g|h_1 - h_3|} - a_3 s_{23} \text{sgn}(h_3 - h_2) \sqrt{2g|h_3 - h_2|}}{A} \end{bmatrix}, h = \begin{bmatrix} h_1 \\ h_2 \\ h_3 \end{bmatrix}.$$

**Table 2.1** Parameters of DTS200

Parameters	Symbol	Value	Unit
Cross section area of tanks	$\mathcal{A}$	154	cm <sup>2</sup>
Cross section area of pipes	$s_n$	0.5	cm <sup>2</sup>
Max. height of tanks	$H_{max}$	62	cm
Max. flow rate of pump 1	$Q_{1max}$	100	cm <sup>3</sup> /s
Max. flow rate of pump 2	$Q_{2max}$	100	cm <sup>3</sup> /s
Coeff. of flow for pipe 1	$a_1$	0.46	
Coeff. of flow for pipe 2	$a_2$	0.60	
Coeff. of flow for pipe 3	$a_3$	0.45	

In the steady state at the operating point, it holds

$$A \begin{bmatrix} h_{1,o} \\ h_{2,o} \\ h_{3,o} \end{bmatrix} + B \begin{bmatrix} Q_{1,o} \\ Q_{2,o} \end{bmatrix} = 0 \iff [A \ B] \begin{bmatrix} h_o \\ Q_o \end{bmatrix} = 0. \quad (2.2)$$

It is remarkable that in practice fault diagnosis is often realized as the process runs in the steady state. For this reason, multivariate analysis technique is widely applied to detect faults in the process under consideration.

In our study on the data-driven design of fault diagnosis and fault-tolerant control systems, data will be typically collected at or around an operating point, both in the steady and dynamic operating modes. Serving for the study on adaptive technique, we also consider the case with changes in operating points. It is evident that a linearization at different operating points will result in linear models with different system parameters. System adaptive techniques are powerful tools to deal with such situations.

### 2.1.2 Description of Typical Faults

Three types of faults are often considered in a benchmark study:

- component faults: leaks in the three tanks, which can be described as additional mass flows out of the tanks,

$$\theta_{A_1}\sqrt{2gh_1}, \theta_{A_2}\sqrt{2gh_2}, \theta_{A_3}\sqrt{2gh_3}$$

where  $\theta_{A_1}$ ,  $\theta_{A_2}$  and  $\theta_{A_3}$  are unknown and depend on the size of the leaks

- component faults: pluggings between two tanks and in the letout pipe by tank 2, which cause changes in  $Q_{13}$ ,  $Q_{32}$  and  $Q_{20}$  and thus can be modeled by

$$\theta_{A_4} a_{13} s_{13} \operatorname{sgn}(h_1 - h_3) \sqrt{2g|h_1 - h_3|}, \theta_{A_6} a_{32} s_{23} \operatorname{sgn}(h_3 - h_2) \sqrt{2g|h_3 - h_2|}, \\ \theta_{A_5} a_{20} \sqrt{2gh_2}$$

where  $\theta_{A_4}, \theta_{A_5}, \theta_{A_6} \in [-1, 0]$  and are unknown

- sensor faults: three additive faults in the three sensors, denoted by  $f_1, f_2$  and  $f_3$
- actuator faults: faults in pumps, denoted by  $f_4$  and  $f_5$ .

The influences of these faults can be integrated into the models introduced above. The linear form is given as follows

$$\dot{x} = (A + \Delta A_F) x + Bu + E_f f, y = Cx + F_f f \quad (2.3)$$

$$\Delta A_F = \sum_{i=1}^6 A_i \theta_{A_i}, f = \begin{bmatrix} f_1 \\ \vdots \\ f_5 \end{bmatrix}, E_f = \begin{bmatrix} 0 & B \end{bmatrix} \in \mathcal{R}^{3 \times 5}$$

$$F_f = \begin{bmatrix} I_{3 \times 3} & 0 \end{bmatrix} \in \mathcal{R}^{3 \times 5}.$$

Those faults modeled by an additive term in the state space representation, e.g.  $E_f f$ , are called additive faults, while the ones like  $\theta_{A_i}$  are called multiplicative faults, which may cause changes in the system eigen-dynamics.

### 2.1.3 Closed-Loop Dynamics

In DTS200, a nonlinear controller is implemented which leads to a full decoupling of the three tank system into

- two linear sub-systems of the first order and
- a nonlinear sub-system of the first order.

This controller can be schematically described as follows:

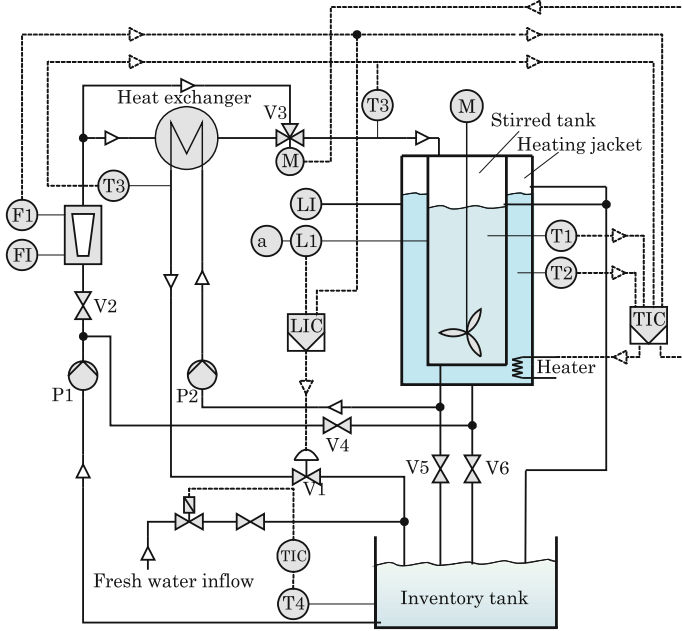
$$u_1 = Q_1 = Q_{13} + A(a_{11}h_1 + v_1(w_1 - h_1)) \quad (2.4)$$

$$u_2 = Q_2 = Q_{20} - Q_{32} + A(a_{22}h_2 + v_2(w_2 - h_2)) \quad (2.5)$$

where  $a_{11}, a_{22} < 0$ ,  $v_1, v_2$  represent two prefilters and  $w_1, w_2$  are reference signals. The nominal (fault-free) closed-loop dynamics is described by

$$\begin{bmatrix} \dot{h}_1 \\ \dot{h}_2 \\ \dot{h}_3 \end{bmatrix} = \begin{bmatrix} (a_{11} - v_1)h_1 \\ (a_{22} - v_2)h_2 \\ \frac{a_{13}s_{13}\operatorname{sgn}(h_1-h_3)\sqrt{2g|h_1-h_3|} - a_{32}s_{23}\operatorname{sgn}(h_3-h_2)\sqrt{2g|h_3-h_2|}}{A} \end{bmatrix} \quad (2.6)$$

$$+ \begin{bmatrix} v_1 & 0 \\ 0 & v_2 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \end{bmatrix}.$$



**Fig. 2.2** Laboratory setup CSH

In the steady state, we have

$$\begin{bmatrix} (a_{11} - v_1) h_1 \\ (a_{22} - v_2) h_2 \\ \frac{a_1 s_{13} \operatorname{sgn}(h_1 - h_3) \sqrt{2g|h_1 - h_3|} - a_3 s_{23} \operatorname{sgn}(h_3 - h_2) \sqrt{2g|h_3 - h_2|}}{A} \end{bmatrix} + \begin{bmatrix} v_1 & 0 \\ 0 & v_2 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \end{bmatrix} = 0. \quad (2.7)$$

It should be mentioned that detecting a fault in the closed-loop configuration is a challenging topic, in particular in the data-driven framework.

## 2.2 Continuous Stirred Tank Heater

In this section, we briefly introduce a linear model of the laboratory setup continuous stirred tank heater (CSH), which is a typical control system often met in process industry.

### 2.2.1 Plant Dynamics and Its Description

Figure 2.2 gives a schematic description of the laboratory setup CSH, where water is used as the product and reactant. Without considering the dynamic behaviors of

**Table 2.2** Technical data of CSTH

Symbol	Description	Unit
$V_T$	Water volume in the tank	L
$H_T$	Enthalpy in the tank	J
$T_{hj}$	Temperature in the heating jacket	°C
$\dot{V}_{in}, \dot{V}_{out}$	Water flows in and out of the tank	l/s
$\dot{H}_{hjT}$	Enthalpy flow from the jacket to the tank	J/s
$\dot{H}_{in}, \dot{H}_{out}$	Enthalpy flows from in- and out-flowing water	J/s
$m_{hj}$	Water mass in the heating jacket	kg
$P_h$	Electrical heater power	W = J/s
$h_T$	Water level in the tank	m
$T_T$	Water temperature in the tank	°C
$m_T$	Water mass in the tank	kg
$\dot{m}_{in}, \dot{m}_{out}$	Mass flows in and out of the tank	kg/s
$T_{in}, T_{out}$	Temperature of the in- and out-flowing water	°C
$A_{eff}$	The base area of the tank	m <sup>2</sup>
$c_p$	Heat capacity of water	J/kg °C

the heat exchanger, the system dynamics can be represented by the tank volume  $V_T$ , the enthalpy in the tank  $H_T$  and the water temperature in the heating jacket  $T_{hj}$  and modeled by

$$\begin{bmatrix} \dot{V}_T \\ \dot{H}_T \\ \dot{T}_{hj} \end{bmatrix} = \begin{bmatrix} \dot{V}_{in} - \dot{V}_{out} \\ \dot{H}_{hjT} + \dot{H}_{in} - \dot{H}_{out} \\ \frac{1}{m_{hj} \cdot c_p} (P_h - \dot{H}_{hjT}) \end{bmatrix}. \quad (2.8)$$

The physical meanings of the process variables and parameters used above and in the sequel are listed in Table 2.2. Let

$$\dot{V}_{in} - \dot{V}_{out} := u_1, P_h := u_2$$

be the input variables. Considering that

$$\dot{H}_{hjT} = f(T_{hj} - T_T), \dot{H}_{in} = \dot{m}_{in} c_p T_{in}, \dot{H}_{out} = \dot{m}_{out} c_p T_{out} = H_T \frac{\dot{V}_{out}}{V_T}$$

we have

$$\begin{bmatrix} \dot{V}_T \\ \dot{H}_T \\ \dot{T}_{hj} \end{bmatrix} = \begin{bmatrix} 0 \\ f\left(T_{hj} - \frac{H_T}{m_T \cdot c_p}\right) + \dot{m}_{in} c_p T_{in} - H_T \frac{\dot{V}_{out}}{V_T} \\ \frac{-f\left(T_{hj} - \frac{H_T}{m_T \cdot c_p}\right)}{m_{hj} \cdot c_p} \end{bmatrix} + \begin{bmatrix} 1 & 0 \\ 0 & 0 \\ 0 & \frac{1}{m_{hj} \cdot c_p} \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \quad (2.9)$$

with  $f$  denoting some nonlinear function. In CSTH, the water level  $h_T$ , the temperature of the water in the tank  $T_T$  as well as  $T_{hj}$  are measurement variables which satisfy

$$\begin{bmatrix} h_T \\ T_T \\ T_{hj} \end{bmatrix} = \begin{bmatrix} \frac{V_T}{A_{eff}} \\ \frac{H_T}{m_T \cdot c_p} \\ T_{hj} \end{bmatrix}.$$

### 2.2.2 Faults Under Consideration

Different kinds of faults can be considered in the benchmark study, for instance

- leakage in the tank A leakage will cause a change in the first equation in (2.9) as follows

$$\dot{V}_T = \dot{V}_{in} - \dot{V}_{out} - \theta_{leak} \sqrt{2gh_T} = u_1 - \theta_A \sqrt{\frac{2gV_T}{A_{eff}}} \quad (2.10)$$

where  $\theta_A$  is a coefficient proportional to the size of the leakage. It is evident that  $\theta_A$  is a multiplicative component fault.

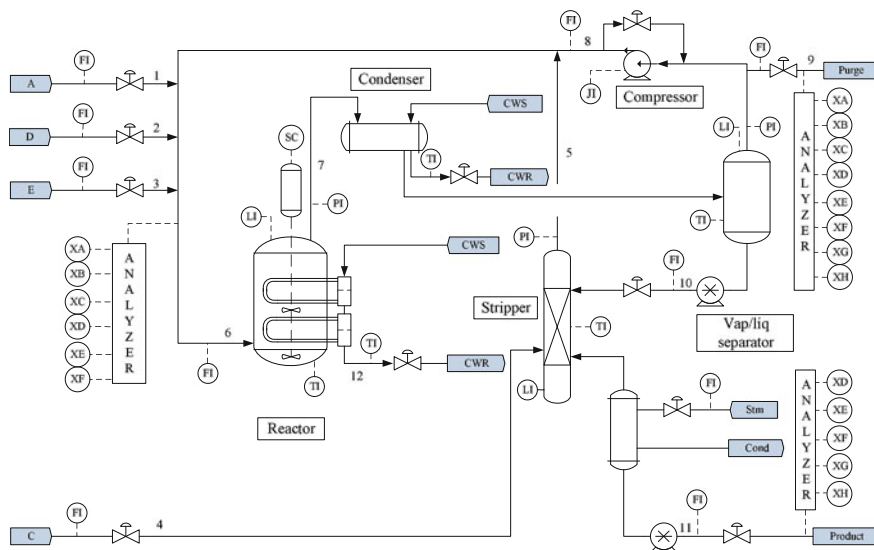
- an additive actuator fault in  $u_1$
- additive faults in the temperature measurements.

## 2.3 An Industrial Benchmark: Tennessee Eastman Process

Tennessee Eastman process (TEP) is a realistic simulation of a chemical process that was created by Eastman chemical company in open loop operation. Since its publication by Downs and Fogel in 1993, TEP is widely accepted as a benchmark for control and monitoring studies and used by the control and fault diagnosis communities as a source of data for comparison studies of various control, monitoring and fault diagnosis schemes and methods. In this book, TEP mainly serves for illustrating and demonstrating the data-driven process monitoring and fault diagnosis schemes.

### 2.3.1 Process Description and Simulation

Figure 2.3 shows the flow diagram of the process with five major units, namely, reactor, condenser, compressor, separator and stripper. The process has two products from four reactants. Additionally, an inert and a by-product are also produced making



**Fig. 2.3** The Tennessee Eastman process

**Table 2.3** Process manipulated variables

Variable name	Number	Base value (%)	Units
D feed flow	XMV(1)	63.053	$\text{kg h}^{-1}$
E feed flow	XMV(2)	53.980	$\text{kg h}^{-1}$
A feed flow	XMV(3)	24.644	$\text{kscmh}$
A and C feed flow	XMV(4)	61.302	$\text{kscmh}$
Compressor recycle valve	XMV(5)	22.210	%
Purge valve	XMV(6)	40.064	%
Separator pot liquid flow	XMV(7)	38.100	$\text{m}^3 \text{h}^{-1}$
Stripper liquid product flow	XMV(8)	46.534	$\text{m}^3 \text{h}^{-1}$
Stripper steam valve	XMV(9)	47.446	%
Reactor cooling water flow	XMV(10)	41.106	$\text{m}^3 \text{h}^{-1}$
Condenser cooling water flow	XMV(11)	18.114	$\text{m}^3 \text{h}^{-1}$

a total of 8 components denoted as A, B, C, D, E, F, G and H. TEP allows total 52 measurements, out of which 11 are manipulated variables and 41 are process variables, as listed respectively in Tables 2.3 and 2.4.

The first TEP simulation was programmed in the FORTRAN code. In the past two decades, different program versions have been developed. For our study in this book, the Simulink code provided by Ricker is used, which is available at the website <http://depts.washington.edu/control/LARRY/TE/download.html> and can be downloaded. This Simulink simulator allows an easy setting and generation of the operation modes, measurement noises, sampling time and magnitudes of



**Table 2.4** Process variables

Block name	Variable name	Number
Input feed	A feed (stream 1)	XMEAS(1)
	D feed (stream 2)	XMEAS(2)
	E feed (stream 3)	XMEAS(3)
	A and C feed	XMEAS(4)
Reactor	Reactor feed rate	XMEAS(6)
	Reactor pressure	XMEAS(7)
	Reactor level	XMEAS(8)
	Reactor temperature	XMEAS(9)
Separator	Separator temperature	XMEAS(11)
	Separator level	XMEAS(12)
	Separator pressure	XMEAS(13)
	Separator underflow	XMEAS(14)
Stripper	Stripper level	XMEAS(15)
	Stripper pressure	XMEAS(16)
	Stripper underflow	XMEAS(17)
	Stripper temperature	XMEAS(18)
Miscellaneous	Stripper steam flow	XMEAS(19)
	Recycle flow	XMEAS(5)
	Purge rate	XMEAS(10)
	Compressor work	XMEAS(20)
Reactor feed analysis	Reactor water temperature	XMEAS(21)
	Separator water temperature	XMEAS(22)
	Component A	XMEAS(23)
	Component B	XMEAS(24)
Purge gas analysis	Component C	XMEAS(25)
	Component D	XMEAS(26)
	Component E	XMEAS(27)
	Component F	XMEAS(28)
Product analysis	Component A	XMEAS(29)
	Component B	XMEAS(30)
	Component C	XMEAS(31)
	Component D	XMEAS(32)
	Component E	XMEAS(33)
	Component F	XMEAS(34)
	Component G	XMEAS(35)
	Component H	XMEAS(36)
	Component D	XMEAS(37)
	Component E	XMEAS(38)
	Component F	XMEAS(39)
	Component G	XMEAS(40)
	Component H	XMEAS(41)

**Table 2.5** Descriptions of process faults in TE process

Fault number	Process variable	Type
IDV(1)	A/C feed ratio, B composition constant	Step
IDV(2)	B composition, A/C ration constant	Step
IDV(3)	D feed temperature	Step
IDV(4)	Reactor cooling water inlet temperature	Step
IDV(5)	Condenser cooling water inlet temperature	Step
IDV(6)	A feed loss	Step
IDV(7)	C header pressure loss-reduced availability	Step
IDV(8)	A, B, C feed composition	Random variation
IDV(9)	D feed temperature	Random variation
IDV(10)	C feed temperature	Random variation
IDV(11)	Reactor cooling water inlet temperature	Random variation
IDV(12)	Condenser cooling water inlet temperature	Random variation
IDV(13)	Reaction kinetics	Slow Drift
IDV(14)	Reactor cooling water valve	Sticking
IDV(15)	Condenser cooling water valve	Sticking
IDV(16)	Unknown	Unknown
IDV(17)	Unknown	Unknown
IDV(18)	Unknown	Unknown
IDV(19)	Unknown	Unknown
IDV(20)	Unknown	Unknown
IDV(21)	The valve fixed at steady state position	Constant position

the faults. It is thus very helpful for the data-driven study. It is worth to remark that the data sets once generated by Chiang et al. are widely accepted for process monitoring and fault diagnosis research, in which 22 training sets, including 21 faulty and normal operating conditions, were collected to record the process measurements for 24 operation hours. In order to ensure a comparable investigation, in our study the simulator is parameterized in the base operating mode which is comparable with the case considered by Chiang et al.

Note that there are numerous control schemes and structures applied to the TEP simulation. The simulator provided by Ricker simulates the closed loop behavior of the TEP with a decentralized control strategy, which is different from the one adopted by Chiang et al. for the generation of their simulation data.

### 2.3.2 Simulated Faults in TEP

In the process monitoring and fault diagnosis study, the 21 faults listed in Table 2.5 are considered. These faults mainly affect process variables, reaction kinetics, feed concentration and actuators such as pump valves. Correspondingly, 22 (on-line) test data sets including 48 h plant operation time have been generated in the work

by Chiang et al., where the faults were introduced after 8 simulation hours. By considering the time constants of the process in closed loop, the sampling time was selected as 3 min.

## 2.4 Notes and references

In this chapter, we have introduced three case and application examples. The first two systems, three-tank system DTS200 and continuous stirred tank heater, a product of the company G.U.N.T. Gerätebau GmbH, are laboratory test beds. For the technical details, the reader is referred to the practical instructions, [1] for DTS200 and [2] for CSTH. It is worth mentioning that a similar CSTH setup has been introduced in [3] for the purpose of benchmark study.

The TEP simulation has first been published by Downs and Fogel in 1993 [4]. In their book on fault detection and diagnosis in industrial systems [5], Chiang et al. have systematically studied process monitoring and fault diagnosis problems on the TEP simulator. For this purpose, 22 training data sets have been generated, which include 21 faulty and the normal operating conditions. These data sets have been available from the Internet and widely adopted by the control and fault diagnosis communities, in particular as a benchmark process for the comparison studied, for instance the work reported in [6]. Ricker has developed a Simulink TEP simulator and presented a control scheme applied to the TEP in [7]. The simulator can be downloaded at his website.

As mentioned previously, a further motivation for introducing these three application cases is that they will serve as application examples for illustrating and demonstrating the results of our study in the forthcoming chapters.

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