

SLOVENSKÁ TECHNICKÁ UNIVERSITA V BRATISLAVE

Fakulta chemickej a potravinárskej technológie

Ústav informatizácie, automatizácie a matematiky

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Learningový modul pre termofluidný proces

Diplomová práca

Školitelia

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2007

Ústav: **Ústav informatizácie, automatizácie a matematiky**

Oddelenie: **Oddelenie informatizácie a riadenia procesov**

Číslo: **9/ÚIAM/2007**

Vec: **Zadanie diplomovej práce**

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
Názov diplomovej práce:


Learningový modul pre termofluidný proces

Termín odovzdania diplomovej práce: **19. mája 2007**


Diplomová práca sa odovzdáva v 3 exemplároch vedúcemu ústavu – oddelenia.

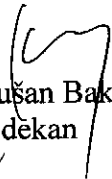
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This work would have never been written without continuous support, encouragement and help from several people.

First of all I would like to thank to Prof. Dr. Ing. Christian Schmid from Ruhr-Universität Bochum, for giving me all the guidance and support I needed. I am also grateful to Piotr Szczytowski also from Ruhr-Universität Bochum, for all his comments that helped me to improve this work.

I would like to thank to supervisor for this master thesis Ing. L'uboš Čírka, PhD., from Slovak Technical University in Bratislava. And my thanks as well belongs to Doc. Dr. Ing. Miroslav Fikar, head of the Department of Information and Process Control at Faculty of Chemical and Food Technology of the Slovak Technical University in Bratislava, for the opportunity to gain new knowledge and for his endless support during my studies.

Finally, I am grateful to my parents for all they have done for me and my studies in many ways.

Bratislava, Bochum, 2007

Eva Juhásová

Abstract

This work deals with developing a Unit of Learning (UoL) for the European Learning GRID Infrastructure (ELeGI) using the ELeGI Virtual Scientific Experiment (VSE) learning model implemented by VCLab. Grid technologies help not only to build e-Learning processes but also integrate virtual control laboratories. In Grid technologies there could be various applications implemented. As an example for the application a chemical pilot plant is taken. For this an UoL is written which includes this plant as a Learning Object (LO). Successful tests have been conducted.

Abstrakt

Táto práca sa zaoberá vytvorením learningového modulu pre European Learning GRID Infrastructure (ELeGI) použitím Virtual Scientific Experiment (VSE) learningového modulu implementovaného pomocou VCLabu. Grid technológie nielen pomáhajú budovať e-Learning, ale zároveň doň začleňujú virtuálne riadiace laboratória. Pomocou Grid technológií je možné implementovať rôzne aplikácie. Ako príklad aplikácie bolo použité chemické zariadenie. Vytvorený learningový modul zahŕňa toto chemické zariadenie VERA ako learningový objekt. Testy mali úspešné výsledky.

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List of used symbols

Physical Parameters

A	Surface
c	Concentration
c_p	Specific thermal capacitance
l	Tank level
λ	Conductivity
m	Mass
\dot{m}	Mass flow
P	Electric power
Q	Warmth
\dot{Q}	Heat flow
ρ	Density
T	Time constant
ϑ	Temperature

Components of VERA

V_{CW}	Continual control valve for cold water inflow
V_{TB}	Continual control valve for inflow to tank TS from tank TB
V_{TM}	Continual control valve for inflow to tank TS from tank TM
CW	Cold water
PR	Electrical rotary pump in circular network
PS2	Pneumatic powered pump below tank TS
TB	Tank TB
TM	Tank TM
TS	Tank TS
TW	Tank TW
Ti	Storage tank Ti

Symbols in VERA

λ_{T124}	Conductivity in storage tanks T1,T2,T4
λ_{T3}	Conductivity in storage tank T3
λ_{TB}	Conductivity in tank TB
λ_{TM}	Conductivity in tank TM
λ_{TS}	Conductivity in tank TS
$\lambda_{TS,cv}$	Controlling variable for conductivity λ_{TS} in tank TS
l_{TB}	Tank level in tank TB
l_{TM}	Tank level in tank TM
l_{TS}	Tank level in tank TS
$l_{TS,cv}$	Controlling variable for tank level l_{TS} in tank TS
ϑ_{TB}	Temperature in tank TB
ϑ_{TM}	Temperature in tank TM
ϑ_{TS}	Temperature in tank TS
$\vartheta_{TS,cv}$	Controlling variable for temperature ϑ_{TS} in tank TS
ϑ_U	Ambient temperature
\dot{m}_{T3}	Mass flow from storage tank T3 to tank TM
\dot{m}_{T124}	Mass flow from storage tanks T124 to tank TB
\dot{m}_{TM}	Mass flow from tank TM to tank TS
$\dot{m}_{0,TM,RC}$	Characteristic parameter for continual control valve V_{TM}
$c_{0,TM,RC}$	Characteristic parameter for continual control valve V_{TM}
$\dot{m}_{0,TB,RC}$	Characteristic parameter for continual control valve V_{TB}
$c_{0,TB,RC}$	Characteristic parameter for continual control valve V_{TB}
c_{PS2}	Power curve parameter for pump PS2
\dot{m}_{TB}	Mass flow from tank TB to tank TS
\dot{m}_{CW}	Cold water inflow to tank TS
\dot{m}_{TW}	Mass flow from tank TS to tank TW
$k_{A,TS,H}$	Heat convection parameter for tank TS
$\dot{Q}_{T,TS,an}$	Heat supplied by heater pins in tank TS
$\dot{Q}_{eff,TS}$	Supply of effective heat in tank TS
$\dot{Q}_{T,C,TS}$	Heat flow exchanged between tank TS and surrounding -normal cooling process
$k_{A,TB,H}$	Heat convection parameter for tank TB
$\dot{Q}_{T,TB,an}$	Heat supplied by heater pins in tank TB
$\dot{Q}_{eff,TB}$	Supply of effective heat in tank TB
k_A	Heat convection parameter

$\dot{Q}_{T,C,TB}$	Heat flow exchanged between tank TB and surrounding -normal cooling process
$T_{el,TS}$	Time constant for heating pins in tank TS
$T_{el,TB}$	Time constant for heating pins in tank TB
$T_{el,CW}$	Time constant for controll valve V_{CW}

Vectors

f	System function of dynamic systems
u	Vector of inputs of dynamic systems
$u_1 = u_{TB}$	Input for V_{TB}
$u_2 = u_{TM}$	Input for V_{TM}
$u_3 = u_{el,TB}$	Input for heating pins in tank TB
$u_4 = u_{el,TS}$	Input for heating pins in tank TS
$u_5 = u_{CW}$	Input for V_{CW}
$u_6 = u_{T3}$	Input for valve above tank TM
$u_7 = u_{T124}$	Input for valve above tank TB
$u_8 = u_{PS2}$	Input for pump PS2.
x	Vector of states of dynamic systems
$x_1 = \vartheta_{TS}$	State for temperature in tank TS
$x_2 = l_{TS}$	State for tank level in tank TS
$x_3 = c_{TS}$	State for concentration in tank TS
$x_4 = \vartheta_{TB}$	State for temperature in tank TB
$x_5 = l_{TB}$	State for tank level in tank TB
$x_6 = l_{TM}$	State for tank level in tank TM
$x_7 = x_{CW}$	State for V_{CW}
$x_8 = x_{el,TB}$	State for heating pins in tank TB
$x_9 = x_{el,TS}$	State for heating pins in tank TS
y	Vector of outputs of dynamic systems
$y_1 = \vartheta_{TS}$	Output for temperature in tank TS
$y_2 = l_{TS}$	Output for tank level in tank TS
$y_3 = \lambda_{TS}$	Output for concentration in tank TS
$y_4 = \vartheta_{TB}$	Output for temperature in tank TB
$y_5 = l_{TB}$	Output for tank level in tank TB
$y_6 = l_{TM}$	Output for tank level in tank TM
$y_7 = x_{CW}$	Output for V_{CW}
$y_8 = x_{el,TB}$	Output for heating pins in tank TB
$y_9 = x_{el,TS}$	Output for heating pins in tank TS

Chapter 1

Introduction

The learning process is very complex and never stops. It is the process of gaining the understanding that leads to the modification of attitudes and behavior through the acquisition of knowledge, skills and values, through study and experience. Learning causes a change of behavior that is persistent, measurable, and allows an individual to formulate a new mental construct or revise a prior mental construct. Learning depends on experience and leads to long-term changes.

We learn through different ways:

- informal - gaining knowledge daily by repetition of an observed process.
- formal - learning process in school system.
- nonformal - extending skills practising with people with a similar interest.

Bloom's Taxonomy [3] divides the learning process into a six-level hierarchy, where knowledge is the lowest order of cognition and evaluation the highest:

Knowledge is the memory of previously-learned materials such as facts, terms, basic concepts, and answers.

Comprehension is the understanding of facts and ideas by organization, comparison, translation, interpretation, and description.

Application is the use of new knowledge to solve problems.

Analysis is the examination and division of information into parts by identifying motives or causes. A person can analyze by making inferences and finding evidence to support generalizations.

Synthesis is the compilation of information in a new way by combining elements into patterns or proposing alternative solutions.

Evaluation is the presentation and defense of opinions by making judgments about information, validity of ideas, or quality of work based on a set of criteria.

From learning to e-learning is only a step.

E-learning is an all-encompassing term generally used to refer to computer-enhanced learning.

The advantages of e-Learning often include flexibility and convenience for the learner, greater adaptability to learner's needs, more variety in learning experience with the use of multimedia and the non-verbal presentation of teaching material.

Nowadays for e-Learning in engineering education remote or virtual laboratories with real or simulated experiments are becoming widely accepted in the control community for providing distance [5] education and for augmenting traditional laboratories to enhance learning process [10].

Using virtual laboratories, engineering students can have an active and central role in the learning process and therefore better possibilities to learn. Students can modify instruments for better understanding of principle on which the plant operates. They even can set their own conditions.

A learning grid can contribute to improve better e-Learning environment through the definition of learning services concept and their deployment through grid technologies. Each service corresponds on the learning side to a learning object (LO). The learning courses consisting of an unit of learning (UoL) can be built from LOs delivered by different grid services. The Virtual Control Laboratory (VCLab) was fully integrated into the ELeGI grid and used to implement the LO, whose application is a subsystem of the plant VERA.

Each UoL is described by an ontology, which defines the set of concepts to be taught. Each concept corresponds to a LO that constitutes the learning material. A teacher has to explain to students how a chemical plant works. The teacher makes a story board with items to be taught. To achieve a successful teaching process those items should correspond with the VSE macro phases: *Presentation, Practical Situation, Abstract Situation, Institutionalization*. The next step to build an UoL as shown in Fig. 1.1 is to apply those phases using the VCLab tools.

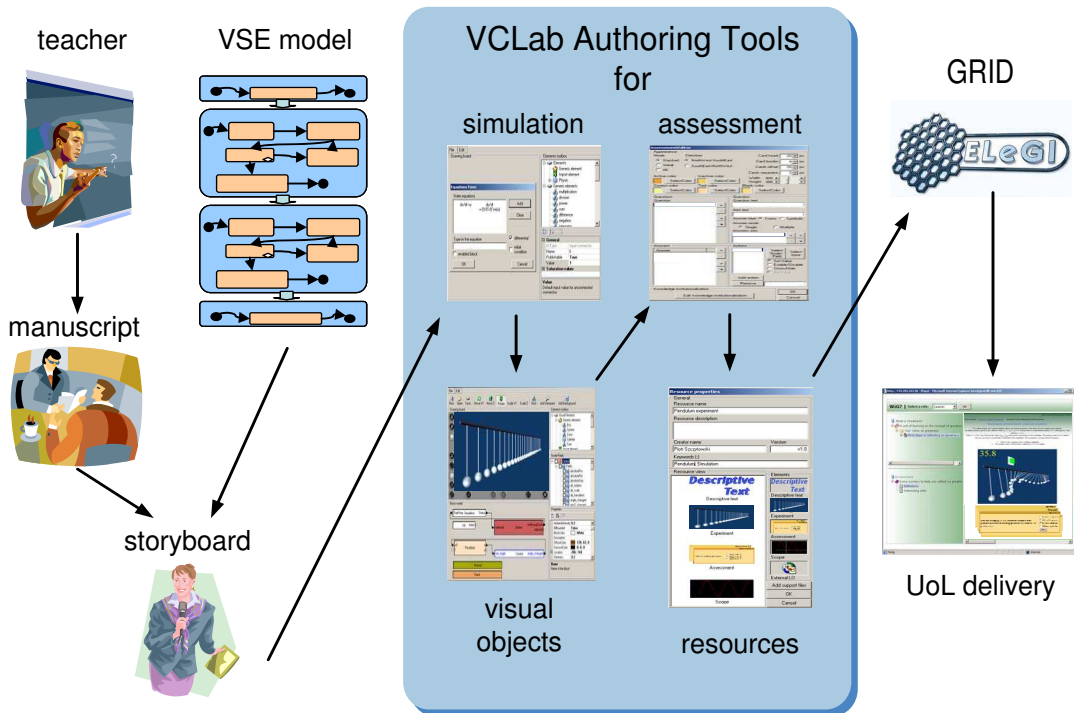


Figure 1.1: From VSE to UoL

Each plant has its *construction model* and *physical model*. The construction model defines parts of the model such as a pump or a valve. And the physical model defines how they interact with each other and their dynamical behavior by differential and algebraic equations.

In chapter 2 the functional model of the subsystem of plant VERA will be described in accordance to the construction model. The whole process model, the control and basic constraints of this subsystem are all included in simulation model, which is made by the Simulation Model Authoring Tool (SMAT).

Chapter 3 contains a description of the construction model of subsystem of the plant VERA and this is done by the Visual Object Authoring Tool (VOAT). The whole construction model is made in 3 dimensions for better approximation.

Chapter 4 presents the Unit of Learning (UoL) with application VERA as it's Learning Object (LO) including the examples published on the web page. This is the part, where user deals with experiencing the learning process itself by using his previous knowledge to gain new ones.

And chapter 5 presents conclusions for this and future work.

Chapter 2

Simulation model

The learning unit to be developed deals with a pilot plant subsystem of a chemical process, which is described by a comprehensive dynamical model given in [6]. This chapter deals with modeling of this plant. The whole process model, the control and basic constraints of the pilot plant subsystem are all included in the simulation model.

2.1 The model

The considered subsystem model is taken from the VERA plant, which exists at the Ruhr-Universität Bochum. The Simulink model has already been developed in [7].

As shown on Fig. 2.1, the subsystem consists of four storage tanks, two tanks TM and TB, one reaction tank TS, waste tank TW, heaters, two pumps and valves all together connected by pipe system. In following there are mass, energie and concentration balances of physical model for thermofluid subsystem process of the VERA plant. The main part of the process take place in the reaction tank TS.

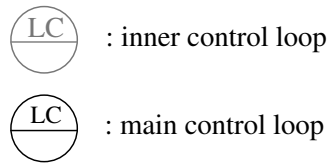


Figure 2.1: Flow chart of the considered subsystem process of VERA

2.2 Model equations

The model of pilot plant subsystem is built based on principles and laws for all the components as fluid process (Laminar flow, Torricelli flow . . .) for tanks and pipes, valves and pumps. VERA is dynamical system where $\dot{x} = \hat{f}(u, x, t)$.

Following equations describe the dynamical behavior of subsystem of pilot plant VERA.

To regulate the temperature ϑ_{TS} , there is to be consider the heat transmission based on the difference between the temperature ϑ_{TS} in tank TS and the ambient temperature ϑ_U . The same is to be done with the temperature ϑ_{TB} in tank TB to assure the temperature of inflow. Mass flows are also to be calculated. Each of the following equations is designed in VCLab through the Simulation Model Authoring Tool [9]. The explanation for those equations is in appendix (A).

2.2.1 Flows between tanks

Mass flows

Mass flow from tank TS to tank TW:

$$\dot{m}_{TW} = c_{PS2} \sqrt{l_{TS} + h_{C,TS}} u_{PS2}. \quad (2.1)$$

Mass flow from tank TB to tank TS:

$$\begin{aligned} & \text{if } u_{TB} > 0,12 \\ & \quad \dot{m}_{TB} = 0 \end{aligned} \quad (2.2a)$$

else

$$\dot{m}_{TB} = (\dot{m}_{0,TB,RC} + c_{TB,RC}(u_{TB} - 0,13)) \sqrt{l_{TB} + h_{C,TB}} \quad (2.2b)$$

end

Mass flow from tank TM to tank TS:

$$\begin{aligned} & \text{if } u_{TM} > 0,03 \\ & \quad \dot{m}_{TM} = 0 \end{aligned} \quad (2.3a)$$

else

$$\dot{m}_{TM} = (\dot{m}_{0,TM,RC} + c_{TM,RC}(u_{TM} - 0,04)) \sqrt{l_{TM} + h_{C,TM}} \quad (2.3b)$$

end

Mass flow from tanks T124 to tank TB:

$$\dot{m}_{T124} = k_{pT124} u_{T124}. \quad (2.4)$$

Mass flow from tank T3 to tank TM:

$$\dot{m}_{T3} = k_{pT3} u_{T3}. \quad (2.5)$$

Cold water inflow to tank TS:

$$\dot{m}_{CW} = k p_{CW} x_{CW}. \quad (2.6)$$

Heat flows

Heat supplied by heaters in tank TS:

$$\begin{aligned} & \text{if } \vartheta_{TS} \leq \vartheta_U \\ & \quad \dot{Q}_{T,TS,an} = 0 \end{aligned} \quad (2.7a)$$

$$\begin{aligned} & \text{else} \\ & \quad \dot{Q}_{T,TS,an} = k_{A,TS,H}(\vartheta_{TS} - \vartheta_U) \end{aligned} \quad (2.7b)$$

end

Supply of effective heat in tank TS is

$$\dot{Q}_{eff,TS} = x_{el,TS}(k_{el,TS} + \dot{Q}_{T,TS,an}). \quad (2.8)$$

Heat flow exchanged between tank TS and surrounding:

$$\begin{aligned} & \text{if } \vartheta_{TS} \leq \vartheta_U \\ & \quad \dot{Q}_{T,C,TS} = 0 \end{aligned} \quad (2.9a)$$

$$\begin{aligned} & \text{else} \\ & \quad \dot{Q}_{T,C,TS} = k_A(\vartheta_{TS} - \vartheta_U) \end{aligned} \quad (2.9b)$$

end

Heat supplied by heaters in tank TB:

$$\begin{aligned} & \text{if } \vartheta_{TB} \leq \vartheta_U \\ & \quad \dot{Q}_{T,TB,an} = 0 \end{aligned} \quad (2.10a)$$

$$\begin{aligned} & \text{else} \\ & \quad \dot{Q}_{T,TB,an} = k_{A,TB,H}(\vartheta_{TB} - \vartheta_U) \end{aligned} \quad (2.10b)$$

end

Supply of effective heat in tank TB is

$$\dot{Q}_{eff,TB} = x_{el,TB}(k_{el,TB} + \dot{Q}_{T,TB,an}). \quad (2.11)$$

Heat flow exchanged between tank TB and surrounding:

$$\begin{aligned} & \text{if } \vartheta_{TB} \leq \vartheta_U \\ & \quad \dot{Q}_{T,C,TB} = 0 \end{aligned} \quad (2.12a)$$

$$\begin{aligned} & \text{else} \\ & \quad \dot{Q}_{T,C,TB} = k_A(\vartheta_{TB} - \vartheta_U) \end{aligned} \quad (2.12b)$$

end

2.2.2 Inner tanks equations

Temperature in tank TS:

$$\begin{aligned} \frac{d\vartheta_{TS}}{dt} = & (1/(A\rho\vartheta_{TS}))((\dot{Q}_{\text{eff,TS}} + \dot{Q}_{\text{T,C,TS}})/c_p + \dot{m}_{TB}(\vartheta_{TB} - \vartheta_{TS}) \dots \\ & + \dot{m}_{TM}(\vartheta_{TM} - \vartheta_{TS}) + \dot{m}_{CW}(\vartheta_{CW} - \vartheta_{TS})) \quad \vartheta_{TS}(0) = 25^\circ\text{C} \end{aligned} \quad (2.13)$$

Liquid level in tank TS:

$$\frac{dl_{TS}}{dt} = (1/(A\rho))(\dot{m}_{TB} + \dot{m}_{TM} + \dot{m}_{CW} - \dot{m}_{TW}) \quad l_{TS}(0) = 0,335\text{m} \quad (2.14)$$

Concentration in tank TS:

$$\begin{aligned} \frac{dc_{TS}}{dt} = & ((C_{TB} - c_{TS})\dot{m}_{TB} + (C_{TM} - c_{TS})\dot{m}_{TM} + \dot{m}_{CW}) \dots \\ & / (A\rho l_{TS}) \quad c_{TS}(0) = 8,0726180598602e - 4 \end{aligned} \quad (2.15)$$

$$\lambda(c_S(t)) = 0,4469 \frac{\text{mS}}{\text{cm}} + 2047,7 \frac{\text{mS}}{\text{cm}} c_S(t) \quad (2.16)$$

Temperature in tank TB:

$$\begin{aligned} \frac{d\vartheta_{TB}}{dt} = & (1/(A\rho l_{TB}))((\dot{Q}_{\text{eff,TB}} + \dot{Q}_{\text{T,C,TB}})/c_p + \dots \\ & \dot{m}_{T124}(\vartheta_{T124} - \vartheta_{TB})) \quad \vartheta_{TB}(0) = 25^\circ\text{C} \end{aligned} \quad (2.17)$$

Liquid level in tank TB:

$$\frac{dl_{TB}}{dt} = (1/(A\rho))(\dot{m}_{T124} - \dot{m}_{TB}) \quad l_{TB}(0) = 0,41\text{m} \quad (2.18)$$

Liquid level in tank TM:

$$\frac{dl_{TM}}{dt} = (1/(A\rho))(\dot{m}_{T3} - \dot{m}_{TM}) \quad l_{TM}(0) = 0,31\text{m} \quad (2.19)$$

Adjusting actuator in dependence on cold water inflow:

$$\frac{dx_{CW}}{dt} = -(1/T_{CW})x_{CW} + (1/T_{CW})u_{CW} \quad x_{CW}(0) = 0 \quad (2.20)$$

Adjusting actuator in dependence on heating in tank TB:

$$\frac{dx_{\text{el,TB}}}{dt} = -(1/T_{\text{el,TB}})x_{\text{el,TB}} + (1/T_{\text{el,TB}})u_{\text{el,TB}} \quad x_{\text{el,TB}}(0) = 0 \quad (2.21)$$

Adjusting actuator in dependence on heating in tank TS:

$$\frac{dx_{\text{el,TS}}}{dt} = -(1/T_{\text{el,TS}})x_{\text{el,TS}} + (1/T_{\text{el,TS}})u_{\text{el,TS}} \quad x_{\text{el,TS}}(0) = 0. \quad (2.22)$$

2.3 Block diagrams

The next step to a simulation model is to create a block diagram. Block diagram is generated in the SMAT of the VCLab. As shown in Fig. 2.2, the SMAT provides a Drawing board, an Elements window and a Property window.

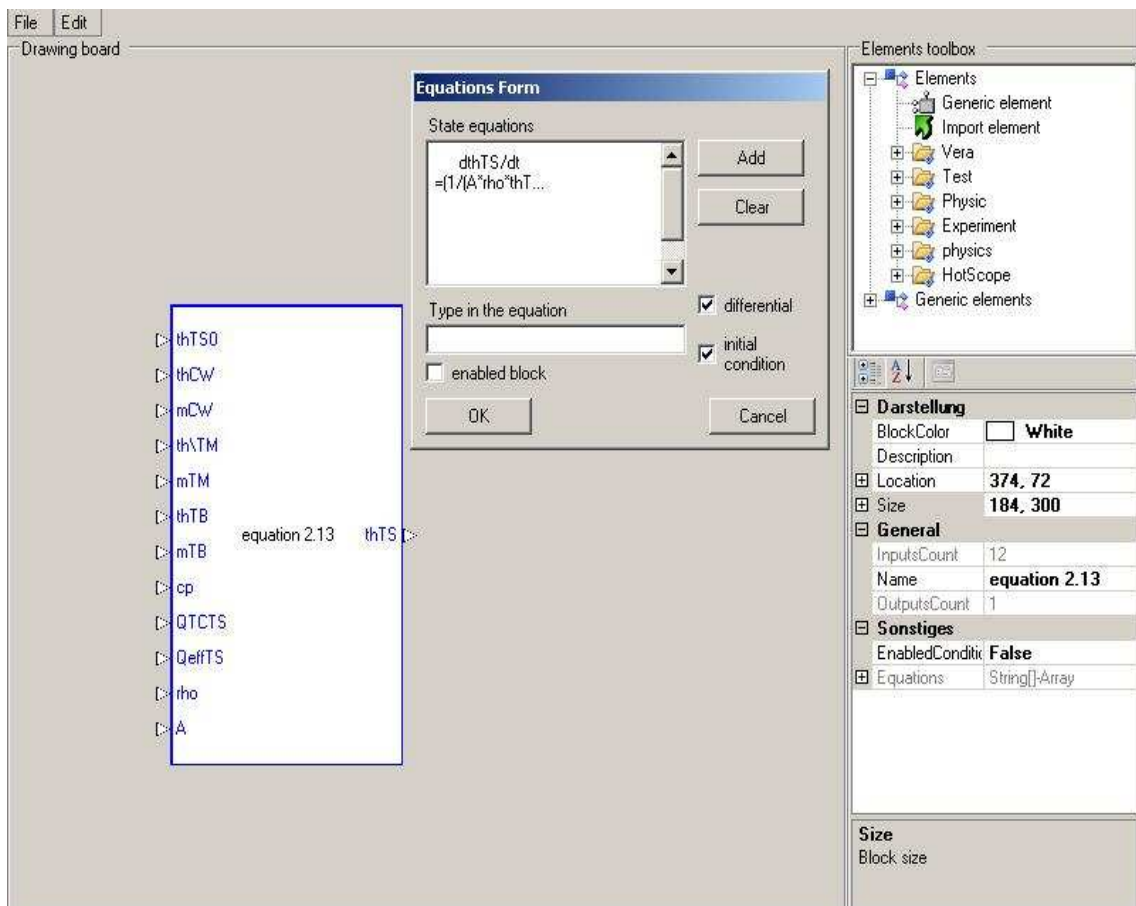


Figure 2.2: Simulation Model Authoring Tool

The Drawing board is the place, where model blocks will be placed and connected. The Property window displays properties of selected block, selected input/output of whole model being created. The Elements window delivers set of objects to build the model from. It lists already created models for use to build new, more complex ones and provides means of creating new models defined by a set of differential equations. The creation of a new element, in this case the simulation model of considered subsystem of the VERA plant, is performed by clicking on the element which is indicated through arrow labeled "Generic Element", dragging it and dropping on the drawing board. After releasing the button a form pops up for entering the equation that describe the model, see Fig. 2.2. Equations are being typed in a standard manner. Pressing "Add" button adds the equation. Accepting the form input creates the simulation block and its graphical

representation on the Drawing board. Each block presents an equation. The inputs to the block are the initial conditions that have been selected to be inputs and all literal variables on the right-hand side of the equality sign, which are not state variables. The output is the state variable and can be connected to inputs of other blocks by drawing connection lines. The created block model has several properties, which may be freely modified. Among inputs properties, there is a property called Value, which allows setting an initial or a constant value for the input. Before saving the model, it is recommended to name it and put it into a category under which it will be displayed in the Elements window. That way this model could be used as a subblock for more complex model as shown on Fig. 2.4. This block diagram consists of all equations mentioned in section 2.2. For simplicity of this block diagram, the constants are not shown. It has also initial conditions which are set as constant values. This block diagram contains special switches, which work on the principle explained in Fig. 2.3.

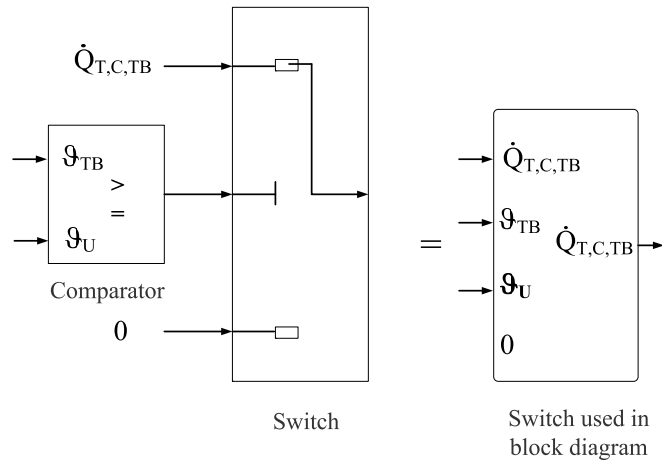


Figure 2.3: The functional model of a switch

Figure 2.4 was saved as "Equations subblock" and was put into a category named "Vera". This way it is available as a subblock in form as shown in Fig. 2.5.

This block diagram represents the upper level of the equations subblock of the simulation model. The inputs appearing on the upper level are the inputs coming from other blocks, as shown in Fig. 2.6, or those inputs, which are available for the user to interact with the simulation: the ambient temperature ϑ_U , the temperature of the cold water inflow ϑ_{CW} , the concentration c_{TB} in tank TB and the concentration c_{TM} in tank TM.

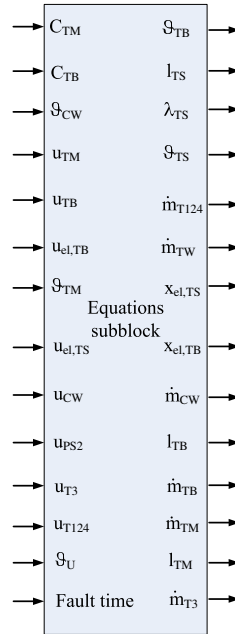


Figure 2.5: Equations subblock of simulation model

From the equations subblock, there are outputs for regulated values or those that will be connected to the visual model of the subsystem of plant VERA explained in section 3.2.

Controllers

The outputs ϑ_{TB} , ϑ_{TS} , l_{TS} and λ_{TS} are the inputs for block YmToYabs shown in the Fig. 2.6, where the feedbacks are calculated. The signals continue through the offsets and then to controllers as shown in Fig. 2.6.

In the model there are four PI controllers.

1. Controller for ϑ_{TS}
2. Controller for l_{TS}
3. Controller for λ_{TS}
4. Controller for ϑ_{TB}

Those have four output values $u_{el,TS}$, u_{PS2} , u_{TB} and $u_{el,TB}$. Additional two inputs, u_{TM} and u_{CW} are set to zero. All those signals go through the offset actuators and then continue through block UabsToUm as shown in the Fig. 2.6. Here the inputs $u_{el,TB}$, $u_{el,TS}$ and u_{PS2} are processed as PWM [1] signals. All together with the u_{T124} and u_{T3} , which are evaluated from the closed loop, are now eight inputs to the equations subblock shown on Fig. 2.5, where the outputs for the dynamical system are calculated.

There are three main regulation goals:

1. Level of liquid in tank TS: $l_{TS,cv} = 0,335 \text{ m}$
2. Temperature in tank TS: $\vartheta_{TS,cv} = 25 \text{ }^{\circ}\text{C}$
3. Electric conductivity in tank TS: $\lambda_{TS,cv} = 2,1 \frac{\text{mS}}{\text{cm}}$

For the regulation the following actuators are needed:

- Control valve V_{TB}
- Control valve V_{TM}
- Control valve V_{CW}
- Continual pump PR
- Continual pump PS2

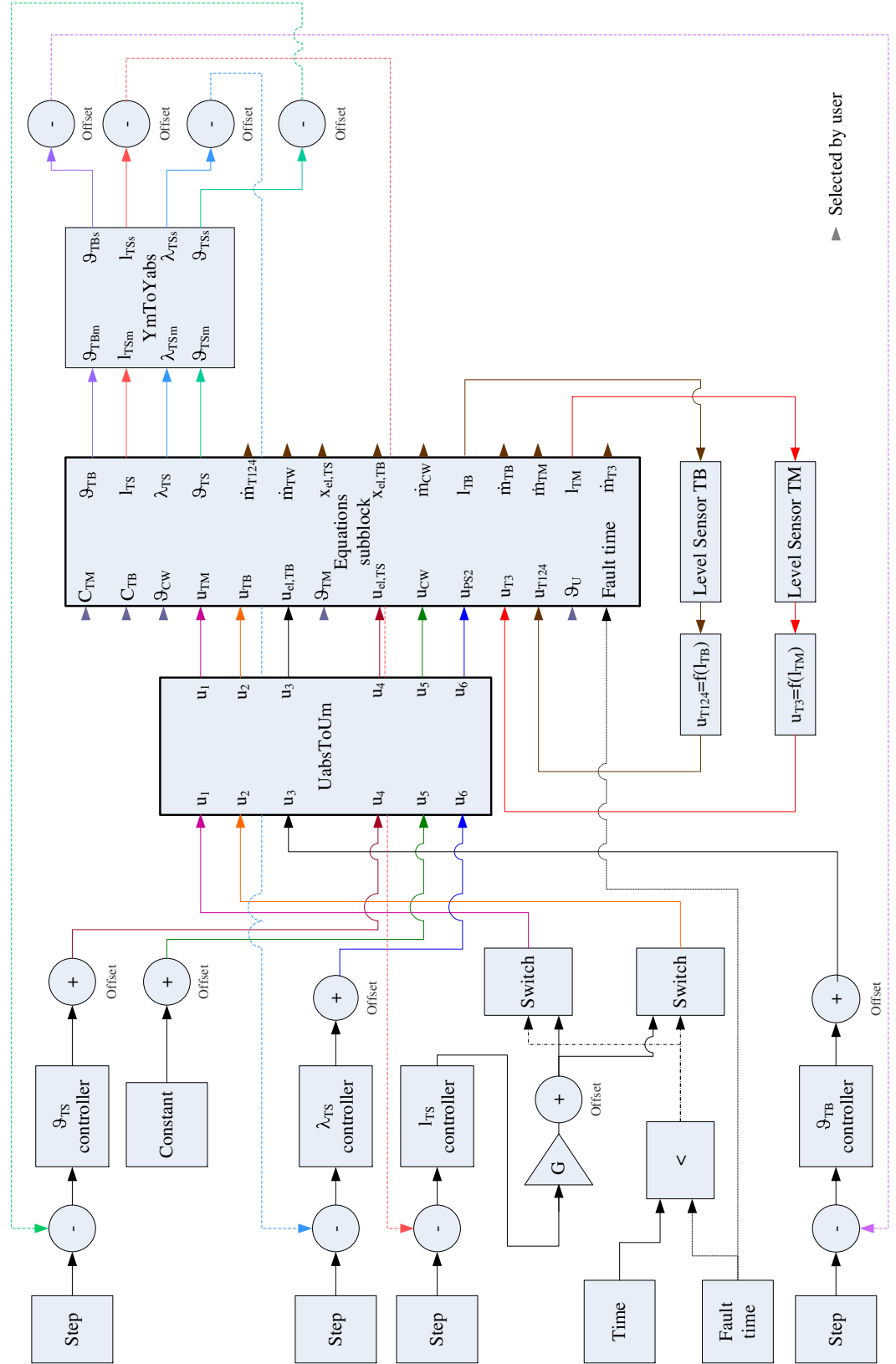


Figure 2.6: Block diagram of the complete simulation model

Constraint and redundancy control

The simulation of thermofluid subprocess of VERA as a LO is available for students not only to simulate it, but also to allow them to make changes of the temperatures and the concentrations mentioned above and that way gain the knowledge of the plant behavior.

Each plant has physical constraints. Therefore there needs to be consider marginal and additional constraints for the process.

Marginal constrains for the process:

- Cold water inflow of $40 \frac{\text{ml}}{\text{s}}$ to tank TS
- Temperature in tank TB: $\vartheta_{\text{TB}} = 25^{\circ}\text{C}$
- Level of liquid in tank TB: $l_{\text{TB}} = 0,41\text{m}$

Additional constraint for process:

- Level of liquid in tank TM: $l_{\text{TM}} = 0,31\text{m}$

The user will not only experience the plant behavior itself but he/she will also learn about the redundant control of the thermofluid subprocess of VERA. In Fig. 2.6, there is parameter "Fault time". This parameter is also available for the user to set it up. Fault time is the time, when a failure of valve V_{TB} occurs and this valve is closed. Then the valve V_{TM} takes the role.

After the simulation model is complete, just to assure that it reaches proper goals' values, this model can be rendered as a Simulink model. Then the next step is to create the visual representation of the thermofluid subprocess of VERA.

Chapter 3

Visualization

This chapter shows how the 3D visual model of the thermofluid subprocess of VERA is constructed. The 3D model will be constructed by the second tool of the VCLab called "Visual Objects Authoring Tool" and will build the visual model of this subprocess in a 3D scene. The tool offers an user interface as presented in Fig. 3.1.

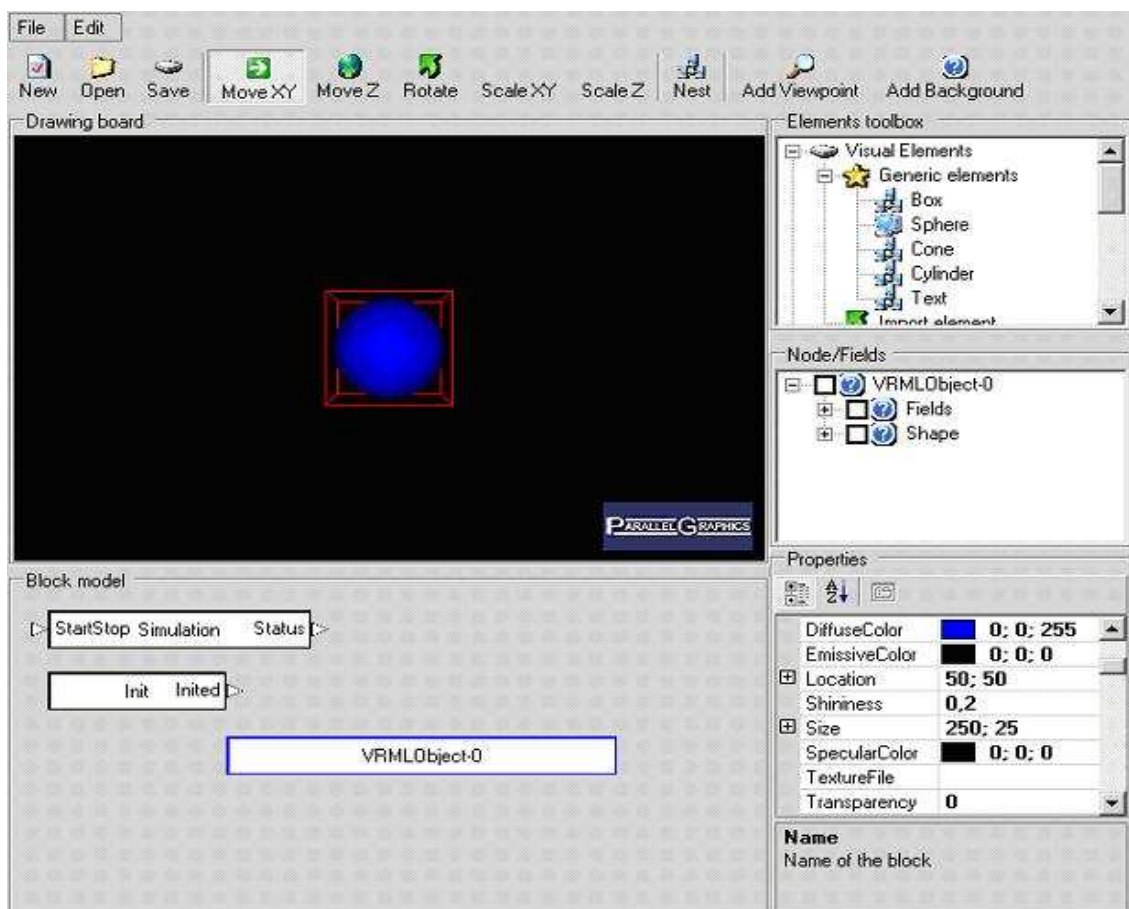


Figure 3.1: Virtual Objects Authoring Tool

The interface is split into the following elements: Actions toolbar, Drawing board, Elements window, Visual element I/Os, Property window and Block model.

The next section describes the necessary steps required for the creation of the visual model, that will resemble the actual shape of thermofluid subprocess of VERA. The construction starts from creating objects and ends with connecting their inputs with outputs from the simulation model, because there are the elements, which positions will be dynamically changed.

3.1 Elements of the visual model

3.1.1 Sliders

In accordance to the main aim of this work, there are parameters whose values can be changed by the user. As mentioned in section 2.3, there are six adjustable parameters. For each parameter, there was a slider designed with different precision. The precision for the temperatures is two decimals and for the concentrations eight decimals.

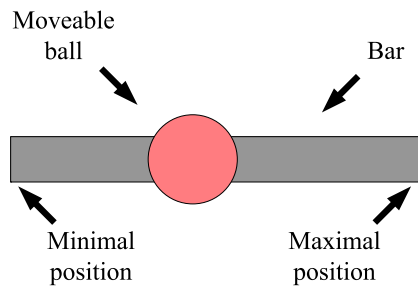


Figure 3.2: 3D view of a slider and its elements

The slider shown in Fig. 3.2 consists of a bar of certain length and a ball placed on the bar with no motion in axis z and y and a limited motion in axis x within the length of the bar. Above the slider, there is a text label, which displays the position of the ball. Figure 3.3 shows a functional model of the slider elements.

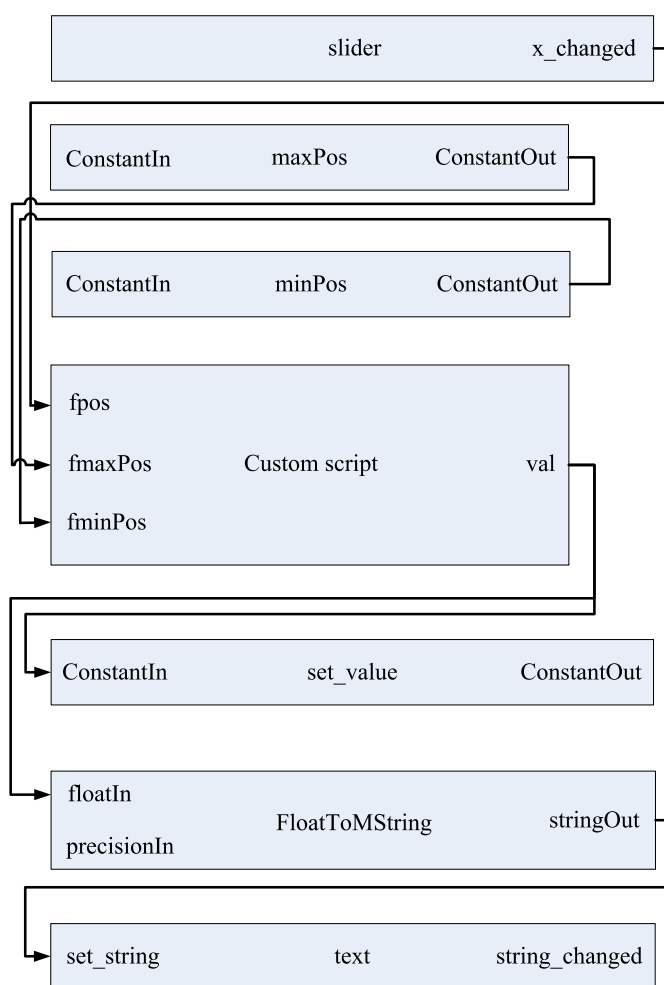


Figure 3.3: The functional model of slider

The slider elements are joined together and only the ball is allowed to move in its scope. Figure 3.4 represents the functional model of the slider, where the position of the ball is shifted to the value displayed above the slider. All of the sliders have different minimal and maximal positions in order to real values of the parameters adjustable by the user in the visual scene.

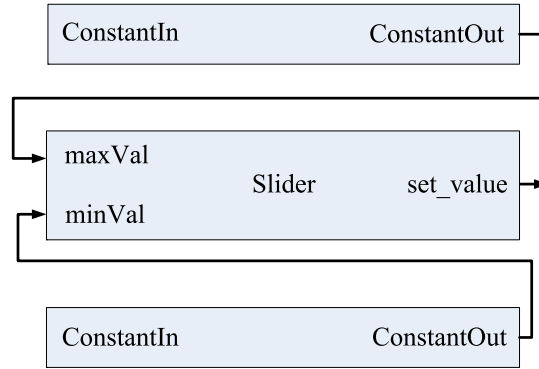


Figure 3.4: The functional model of the slider after joining the elements

3.1.2 Tanks

The thermofluid process takes place in eight tanks, see Fig. 2.1. T3 is the storage tank for tank TM. T1, T2 and T4 all together named as T124 are the storage tanks for tank TB. Tank TB can be heated. Then there is a reaction tank TS and below the reaction tank TS there is a waste tank TW. All of those tanks have the same visual implementation as shown in Fig. 3.5.

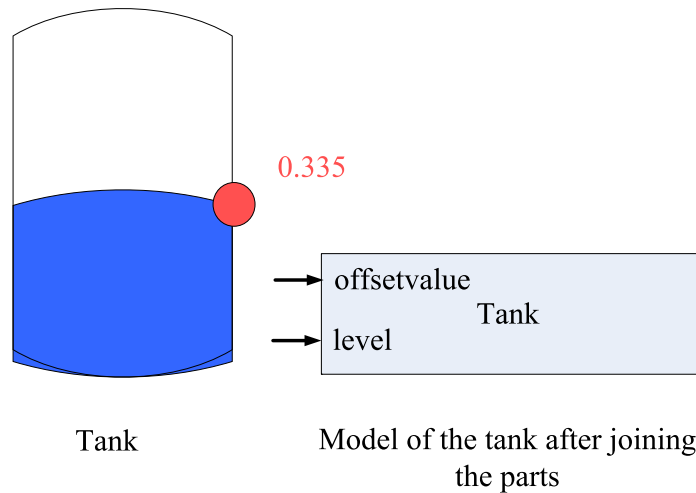


Figure 3.5: 3D view of the tank and functional model of the tank after joining the elements

The tank consists of 2 cylinders, one for the container-steady scale and one to illustrate the liquid changeable scale in vertical axis. There is a ball, which works as a slider, attached to the cylinder. The position of the ball is shifted to a value of the liquid level of the tank displayed by the text label on the right-hand side of the tank.

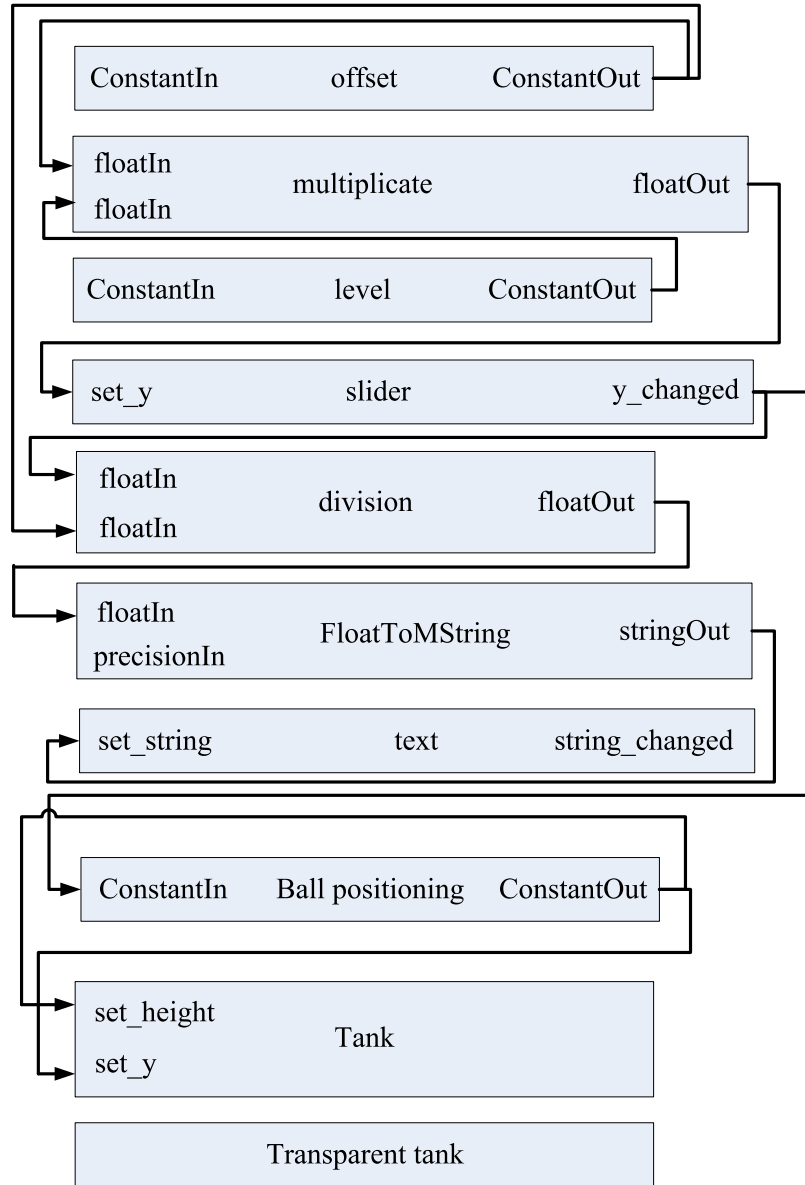


Figure 3.6: The functional model of tank

Those elements are joined together in one model as shown in Fig. 3.5 and only the ball is allowed to move in its scope.

Figure 3.6 shows functional model of the tank. There is one signal input for the tank representing the liquid level of the tank calculated in simulation model see section 2.2.2.

In the tank TS there is a mixing process also to be considered. For visual effect of reaching the goal value of λ_{TS} there is a change of color included. Default state is visualized by a blue liquid color and it occurs when the value of λ_{TS} is lower than $2,1 \frac{mS}{cm}$. Otherwise the state will be switched to selected state, see the Tab. 4.1.

3.1.3 Control valves and pumps

As shown in Fig. 2.1, there are two control valves V_{TB} and V_{TM} in the master control loop and five valves V_{T3} , V_{T124} and V_{CW} in slave control loop. All of them have the same visual representation as shown in Fig. 3.7.

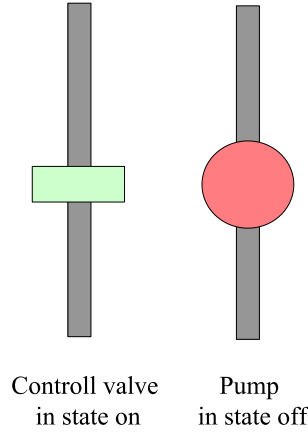


Figure 3.7: 3D view of valve and pump

They are composed of a box attached to a pipe and are only allowed to rotate around the vertical axis. Except the valve V_{CW} , which is allowed to rotate around the horizontal axis. A valve has two states. Open or closed. Changing the state is according to a boolean variable from a comparator for the correspondent mass flow. The boolean variable 1-True means that the proper mass flow is greater than zero and valve is open and 0-False means, that the proper mass flow is equal to zero and valve is closed. Different states are here displayed by changing the color. For chosen color see the Tab. 4.1. This option is set in the selected part of each element and then allowed to be changed by the state `set_selected` and `selected_changed` as shown in Fig. 3.8.

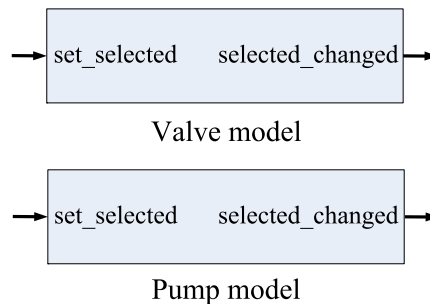


Figure 3.8: The functional model of ventil and pump

The model of pumps PR and PS2 is based on the same principle as the model of the control valves except, that pumps have a shape of a sphere as shown in Fig. 3.7. The change of the state is performed in the same way as for the valves. For the pump PS2, there is only one mass flow \dot{m}_{TW}

to be considered. When \dot{m}_{TW} is greater than zero, then the output of the comparator is equal 1 and the color of pump PS2 will change to selected state.

For the pump PR, there are two mass flows \dot{m}_{TB} and \dot{m}_{TM} . The state, when both mass flows are equal to zero is considered as a default state. If any of those two mass flows is greater than zero, then the output of the comparator is 1-True and the change of the color is applied.

3.1.4 Mass flows

Mass flows are not only used to change the selected state of the control valves and the pumps, but also for designing the liquid flow. There are four liquid flows which depend only on their own mass flows. Those are \dot{m}_{T3} , \dot{m}_{T124} , \dot{m}_{CW} and \dot{m}_{TW} . They are designed as a blue cylinder of certain height and radius. The change of the state is visualized by the option "transparency".

When mass flow is greater than zero, the output of comparator is then a boolean value of 1-True and the state of the blue cylinder will switch to the selected state. When the mass flow is equal to zero the state will be switched to default state.

The inflow to tank TS depends on two mass flows. \dot{m}_{TB} coming from tank TB and \dot{m}_{TM} coming from tank TM. If any of those two mass flows is greater than zero then the output of comparator is 1-True and the state of blue cylinder will change to the selected state. The moment at which both mass flows are equal to zero, the state of blue cylinder will change to the default state according to Fig. 3.9.

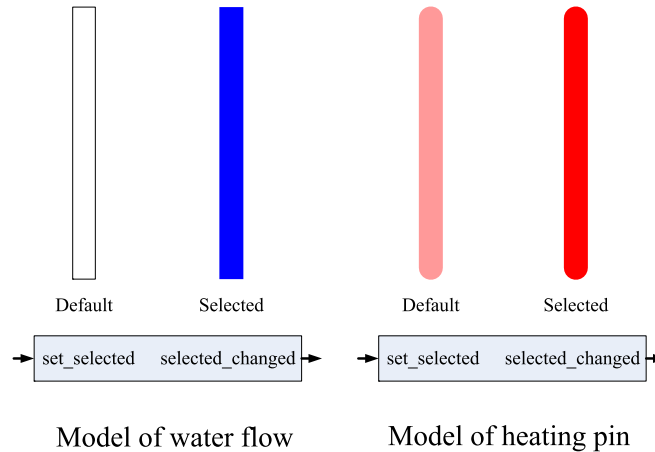


Figure 3.9: 3D view of heater rod and water flow and their functional models

3.1.5 Heating rods

The model of heating rods is based on the same principle as liquid flows. As shown in Fig. 3.9, the shapes are similar. The only difference is the selected state. For a heating rod it is not the transparency that is changed, but a color. The state when $x_{el,TB}$ is lower than a certain value is considered as the default state, which means that the heating system is switched off. When the output from the comparator is 0-False, the state will be shifted to the selected one, which means that the heating system is on.

The same is to be considered with the heating rods in tank TS. There the selected state varies by $x_{el,TS}$. For chosen colors see the Tab. 4.1.

3.1.6 Alarm

For the redundancy control there is a text label "Alarm" designed. The state of the text label, when the time of the simulation is lower than the fault time, is set to invisible. The state, when the time of the simulation is larger, is considered to be a `selected_state`.

	Option	Default state	Selected state
Electric conductivity	color	blue	light-lilac
Control valve	color	light-salmon	light-green
Pump	color	light-salmon	light-green
Mass flow	transparency	transparent	non-transparent
Alarm	transparency	invisible	visible

Table 3.1: States of elements

3.2 The binding process

The final step in creating the Experiment element is to bind the simulation model and the visual model. This is also done using the Visual Objects Authoring Tool by importing the simulation model of the thermofluid process shown in Fig. 3.10.

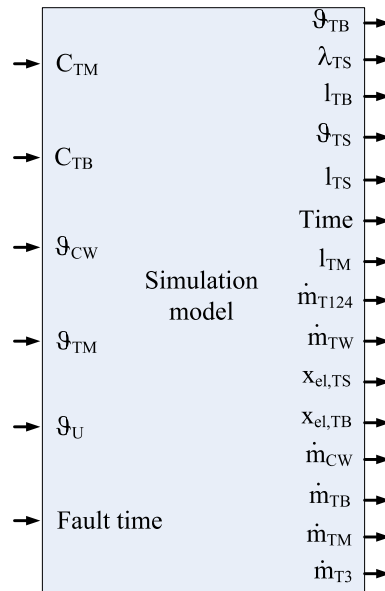


Figure 3.10: Masked model of the thermofluid process

The inputs of the simulation model are connected with sliders outputs and the outputs of the VERA model are connected to the appropriate comparators for mass flows, $x_{el,TS}$, $x_{el,TB}$ and λ_{TS} or constants as to display the temperatures, the tank levels and the electrical conductivity. There is also a start button designed to start or stop the simulation. The whole learning object is shown in Fig. 3.11.

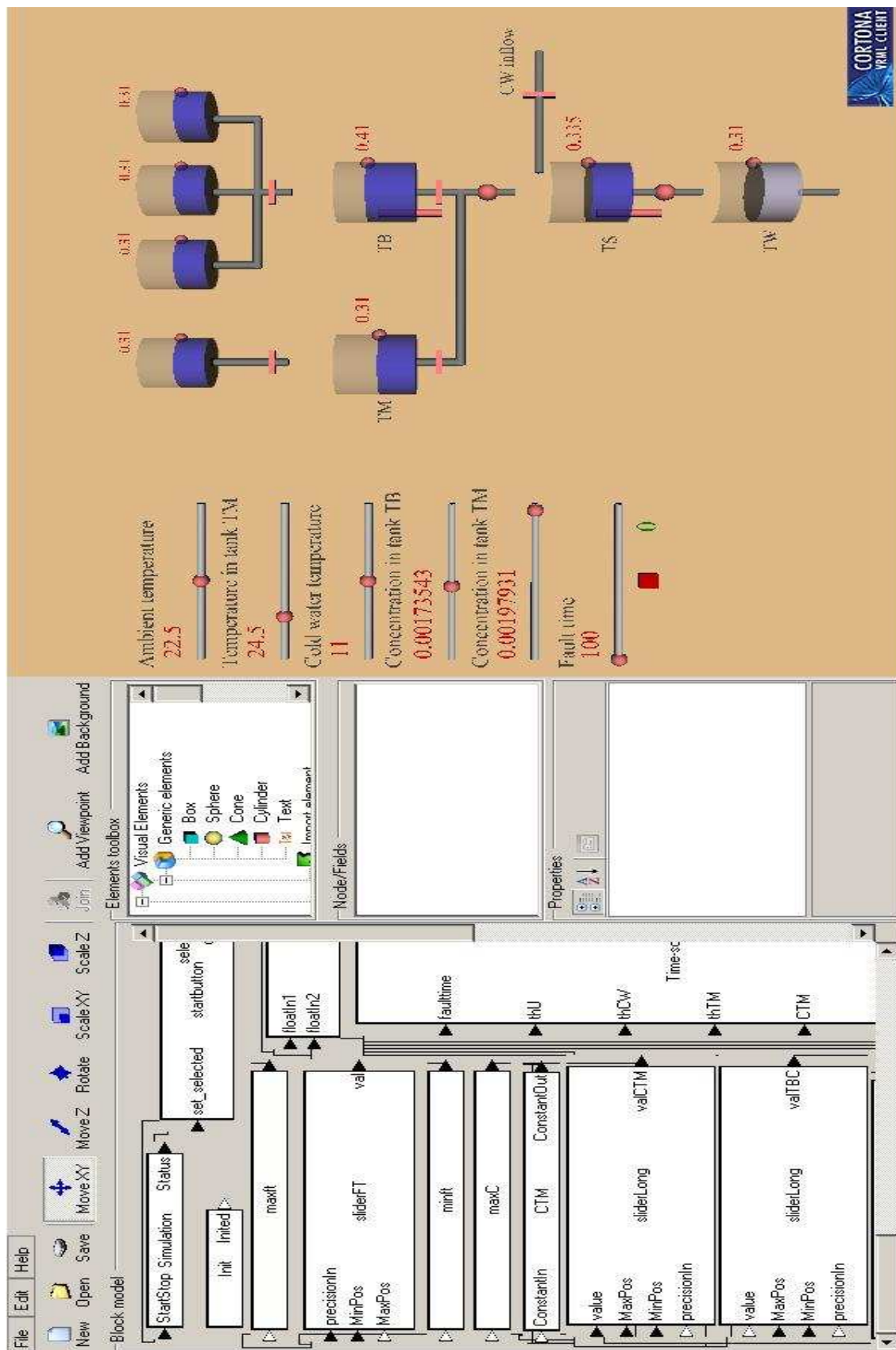


Figure 3.11: View of the binding process

Chapter 4

A learning unit for a thermofluid process

This chapter presents the Unit of Learning (UoL) using the thermofluid subprocess of the VERA plant as its Learning Object (LO). This is the part, where the user deals with experiencing the learning process itself by using his previous knowledge to gain new ones.

4.1 The VSE learning model

The VCLab supports learning using Virtual Scientific Experiments (VSE). Each UoL designed for the VSE is described by an ontology, which defines the set of concepts to be taught. Each concept corresponds to a LO that constitutes the learning material. The VSE learning model includes four macrophases:

- Presentation
- Practical Situation
- Abstract Situation
- Institutionalization

During the *Presentation* phase the learner is introduced into the problem and the theory regarding the studied phenomenon together with the background information.

The *Practical Situation* phase is split into several microphases:

- Active Situation
- Collaborative Learning
- Assessment

- Addressed Situation
- Knowledge Institutionalization

The *Active Situation* phase concentrates on delivering the main experience by means of animation and interaction using a 3D virtual user environment. The *Collaborative Learning* phase provides the way for learners to communicate with each other and exchange their observation. The further progress with the learning material requires some form of verification of the learning progress. This task is realized within the *Assessment* phase. The learner is confronted with a test. On success the ***Practical Situation*** macro-phase is left through the *Knowledge Institutionalization* phase. Otherwise the learner will be redirected to the *Addressed Situation* phase, which is the modified version of the *Active Situation* phase, in which the emphasis is put on a particular aspect of the experiment activity. Entering the *Knowledge Institutionalization* phase on success of the assessment, the validity of own knowledge will be shown to the learner, indicating both what has been acquired from the analysis of the practical situation and what would have to be acquired for to catch up a satisfactory knowledge.

The ***Abstract Situation*** macro-phase consists of the same set of micro-phases as in ***Practical Situation***. They differ in the form and therefore they may be realized by different type of LOs. The movements of objects shown in the 3D visualization of the ***Practical Situation*** are now presented as signal graphs using a scope.

The final ***Institutionalization*** macro-phase presents the formalized knowledge, which learner should have obtained when successfully completing the learning activity [8].

All mentioned above is included in a VCLab resource. A VCLab resource has five elements:

Descriptive text element is used to deliver information describing the elements that are placed above or below of it or may be used to present additional information. This part corresponds with the *Presentation* macro-phase of the VSE.

Experiment element realizes the 3D virtual user environment. It animates the behavior of the experimental plant in the 3D scene and provides the means of altering the experiment parameters through a set of buttons or sliders rendered as 3D objects. This part is the micro-phase of the *Practical Situation* macro-phase of the VSE.

Scope element provides the possibility to display signal history plots. This part corresponds with the *Abstract Situation* macro-phase of the VSE.

Assessment element defines a set of multiple/single choice questions that needs to be answered. Answers may be associated to events defining modifications of the experiment parameters. Assessment is a micro-phase of the *Practical situation* macro phase.

Embedded LO element may be used e.g. a chat component for communication with other learners.

4.2 The goals of the learning unit for the thermofluid process

This UoL integrates the virtual control laboratory for the thermofluid process of the VERA plant. There are three main regulation goals to observe to be reached. They are mentioned in section 2.3. The fact is, that no matter what are the values of the parameters available for the learner to interact with them, the regulation goals will be reached. Alongside there are more matters to notice. First of them is how the ambient temperature affects the function of the heating systems used in the plant and the progress of the parameters. Another matter to observe is how the temperature of the inflows to the reaction tank TS influences the temperature of the mixture in the tank TS. The next concern is what the concentrations of the liquid in the tanks TB and TM are affecting. Last but not least, there is the redundancy control to be observed.

4.3 Elements of the VCLab resource

The UoL of the thermofluid process starts in the presentation section with a short textual description of the experiment and the goals. It introduces the learner into the handling of the experiment and gives instructions how to run it and gives guidelines what to be observed.

Descriptive text

The user should have a basic knowledge about flux control, laminar flux, turbulent flux and Torricelli flux. There is also desired a basic knowledge of how the shape of pipes, valves or pumps influence the flow. The learner should gain knowledge about how temperatures and concentrations influence the nominal electric conductivity by manipulating with mentioned parameters. The learner will be also experienced with redundancy control of the chemical subprocess of the VERA plant.

How to run the simulation

Set the desire values of the temperatures and the concentrations by using sliders on the left-hand side of the plant shown on Fig. 4.1. Under the sliders, there is the power button to start or stop the simulation.

What to observe

First of all there is the liquid level of the tank TS. Then there are heating systems in the tank TB and in the tank TS. For better view of progress of the temperature ϑ_{TB} and the temperature ϑ_{TS} look at scopes below. There is also important to observe the change of the electric conductivity. After a certain time, there will be a problem with valve V_{TB} simulated, so tank TM would play role in the process. Notice, that tank TM has no heating system and that there is a constant temperature

the learner can set by the slider. Another fact to notice is that the liquid in tank TM has different concentration than the liquid in tank TB. Try to find out how it will influence the process.

Experiment

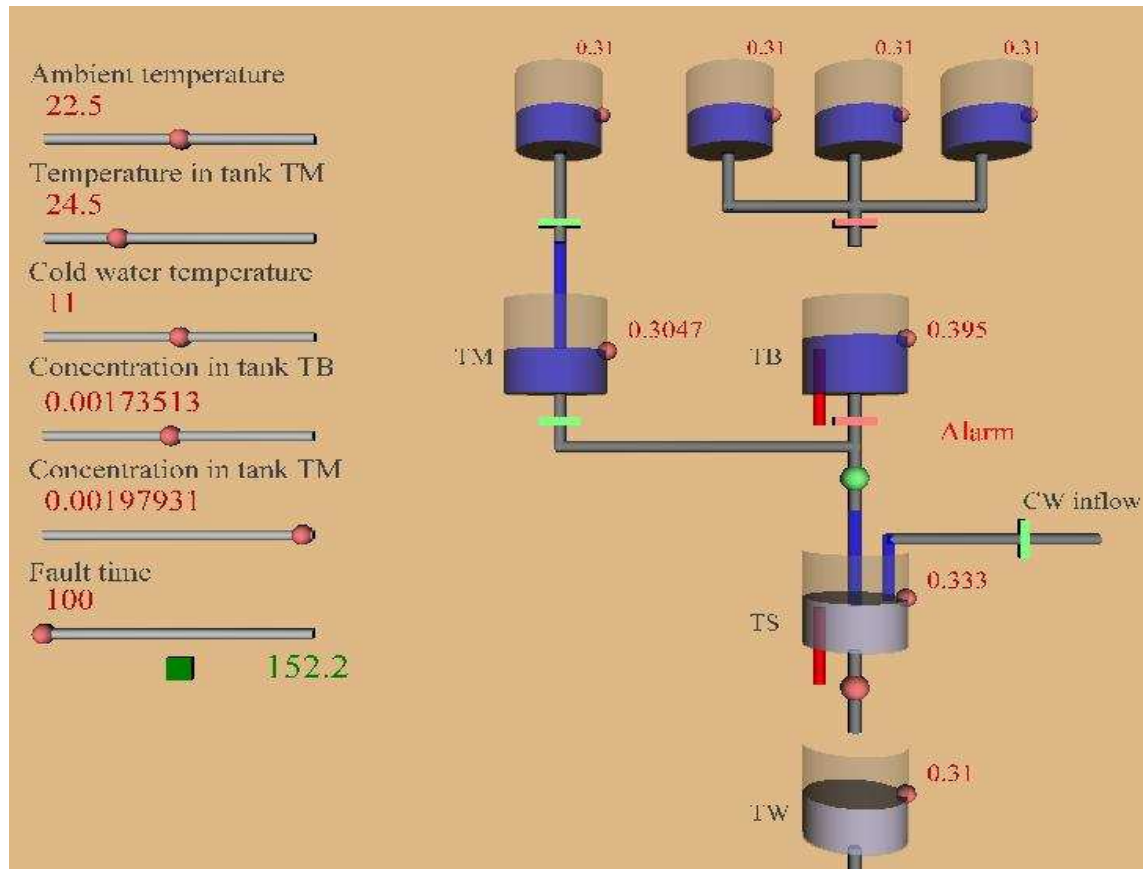


Figure 4.1: The experiment

The chosen values of the parameters in this scene are following:

Variable	Value
ϑ_U	22,5°C
ϑ_{CW}	11°C
ϑ_{TM}	24,5°C
c_{TB}	0.00173513209943
c_{TM}	0.00197930849245
Fault time	100 s

Table 4.1: Chosen values of parameters

With those values of the parameters the simulation in the 3D view shown in Fig. 4.1 was started.

The simulation in this figure is at time 152.2s and as shown, the "Alarm" sign is on. The control valves V_{T3} and V_{TM} play the role in adjusting the inflow to tank TS. Also the pump PR is open. The user can see the level of each tank. The control valve V_{CW} for the cold water inflow is open. The electric conductivity of the mixture in tank TS is higher than $2.1 \frac{mS}{cm}$. Pump PS2 is off and there is now outflow of the mixture from tank TS to the waste tank TW. At that time, the heating systems are on.

From the scene shown in Fig. 4.1, the user cannot see the actual value of the temperatures or the electric conductivity of the mixture in tank TS. For that reason there are scopes available.

Scopes

Regulation goals of the simulation were reached as shown in following figures.

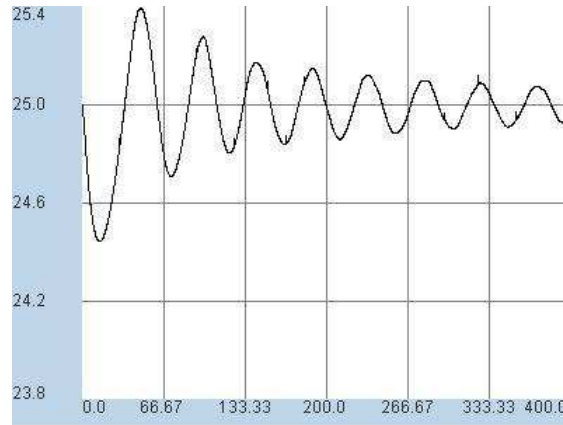


Figure 4.2: Temperature in tank TS

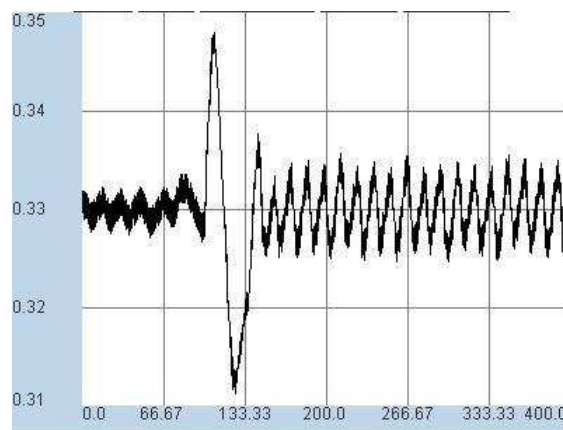


Figure 4.3: Liquid level of the tank TS

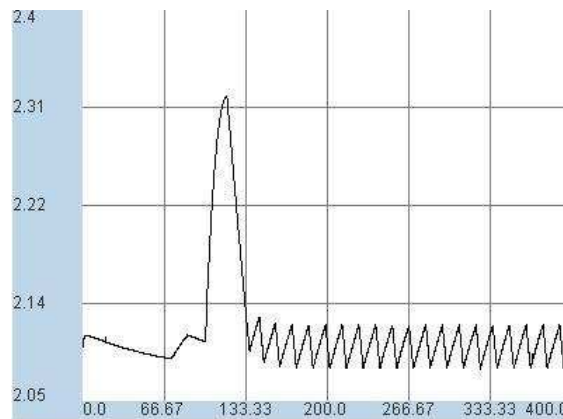


Figure 4.4: Electric conductivity in tank TS

Assessment

By answering the following questions you will test your knowledge.

Question1: How does the ambient temperature influence the temperature in tank TB?

Answer1: Does not influence it at all.

Answer2: It has an influence on it.

In following graphs, there are results from three different simulations. In Fig. 4.8, there is the result from the simulation, where the value of ϑ_U was set to 22,5°C. For the simulation result shown in Fig. 4.6, the value of ϑ_U was set to 20°C.

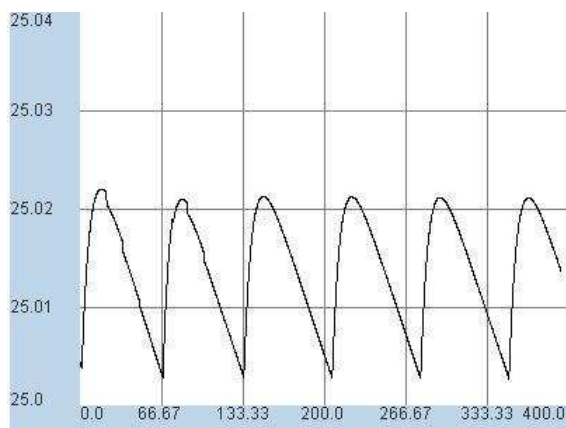


Figure 4.5: Temperature in tank TB, a

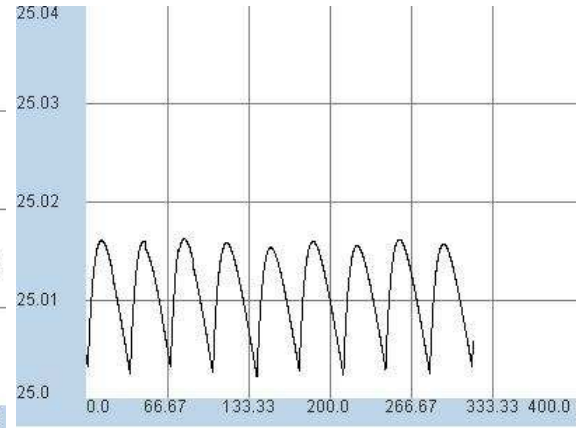


Figure 4.6: Temperature in tank TB, b

Correct answer: It has an influence on it.

If the user's answer is incorrect, the user will be navigated back to the simulation, where the value of the ϑ_U was set to 28°C. The result of that simulation is shown in Fig. 4.7.



Figure 4.7: Temperature in tank TB, c

Question2: How does the temperature of cold water influence the temperature in tank TB?

Answer1: Does not influence it at all.

Answer2: It has an influence on it.

In following graphs, there are results from three simulations. In Fig. 4.8, there is the result from the simulation, where the value of ϑ_{CW} was set to 11°C. For the simulation result shown in Fig. 4.9, the value of ϑ_{CW} was set to 18°C.

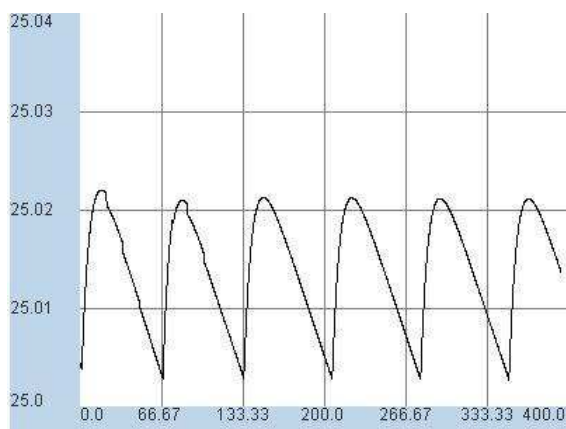


Figure 4.8: Temperature in tank TB, d

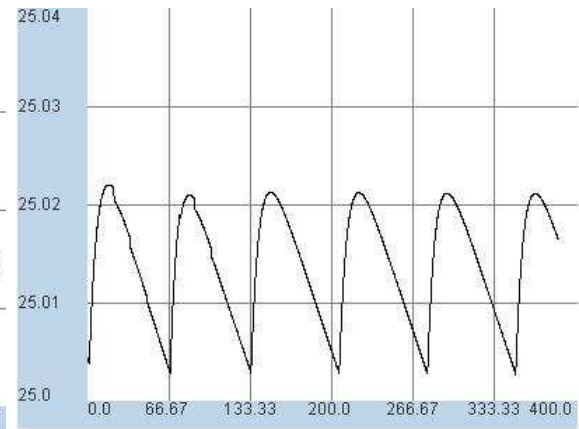


Figure 4.9: Temperature in tank TB, e

Correct answer: Does not influence it at all.

If the user's answer is incorrect, the user will be navigated back to the simulation, where the value of the ϑ_{CW} was set to 5°C. The result of that simulation is shown in Fig. 4.10.

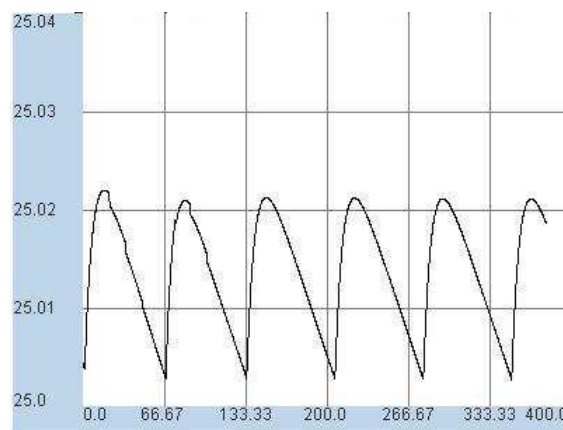


Figure 4.10: Temperature in tank TB, f

Question3: How does the temperature of cold water influence the temperature in tank TS?

Answer1: Does not influence it at all.

Answer2: It has an influence on it.

In following graphs, there are results from three simulations. In Fig. 4.11, there is the result from the simulation, where the value of ϑ_{CW} was set to 11°C. For the simulation result shown in Fig. 4.12, the value of ϑ_{CW} was set to 5°C.

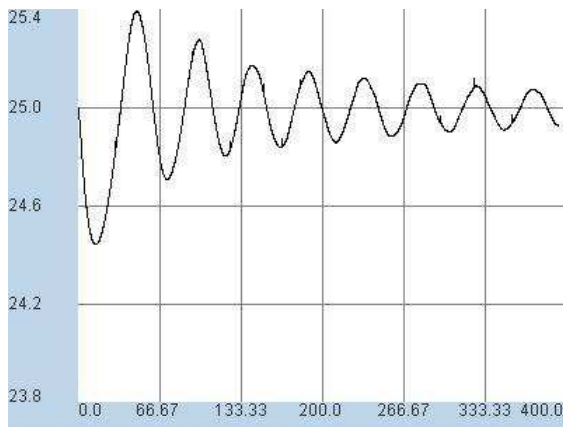


Figure 4.11: Temperature in tank TS, a

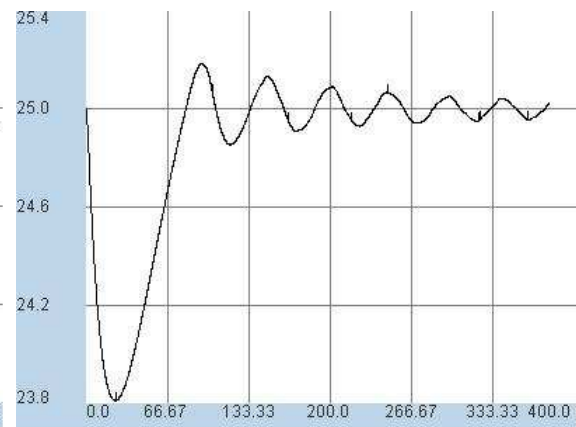


Figure 4.12: Temperature in tank TS, c

Correct answer: It has an influence on it.

If the user's answer is incorrect, the user will be navigated back to the simulation, where the value of the ϑ_{CW} was set to 18°C. The result of that simulation is shown in Fig. 4.13.

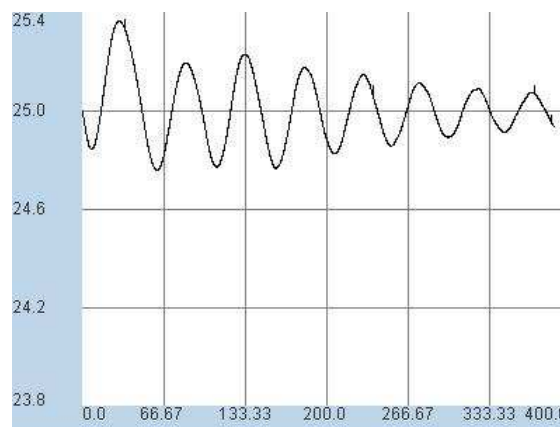


Figure 4.13: Temperature in tank TS, b

Question4: How does the temperature of the cold water inflow influence the final value of electric conductivity in tank TS?

Answer1: Does not influence it at all.

Answer2: It has an influence on it.

In following graphs, there are results from three simulations. In Fig. 4.21, there is the result from the simulation, where the value of ϑ_{CW} was set to 11°C. For the simulation result shown in Fig. 4.15, the value of ϑ_{CW} was set to 18°C.

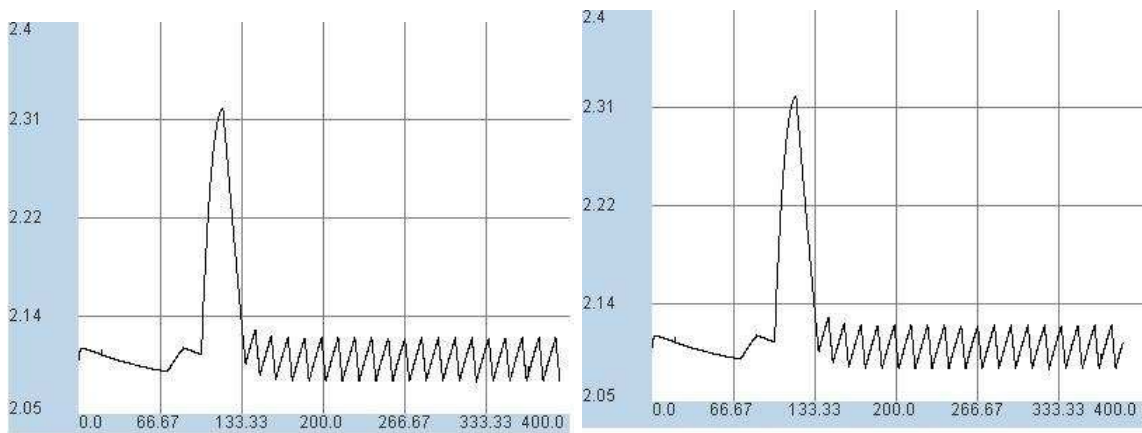


Figure 4.14: Electric conductivity in tank TS, a Figure 4.15: Electric conductivity in tank TS, b

Correct answer: Does not influence it at all.

If the user's answer is incorrect, the user will be navigated back to the simulation, where the value of the ϑ_{CW} was set to 5°C. The result of that simulation is shown in Fig. 4.12.

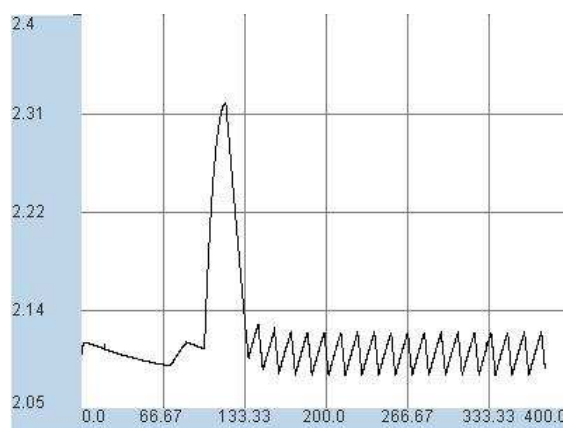


Figure 4.16: Electric conductivity in tank TS, c

Question5: In tank TM, there is higher concentration of salt than in tank TB. Consider the difficulties with valve V_{TB} so it will be shut down and the tank TM will play role. To get the same results of regulation what would happen?

Answer1: Inflow from tank TM is lower than inflow from tank TB.

Answer2: Nothing, it has no influence on it at all.

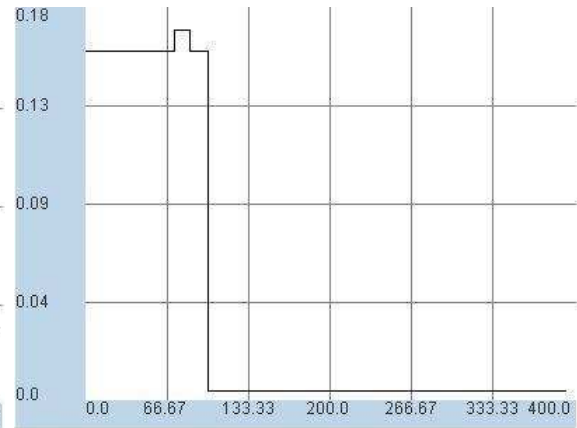


Figure 4.17: Adjustment for control valve V_{TM} Figure 4.18: Adjustment for control valve V_{TB}

Correct answer: Inflow from tank TM is lower than inflow from tank TB.

If the user's answer is incorrect, the user will be navigated to the simulation, where the value of the concentration in tank TM will be set to the same value as the value of the concentration in tank TB.

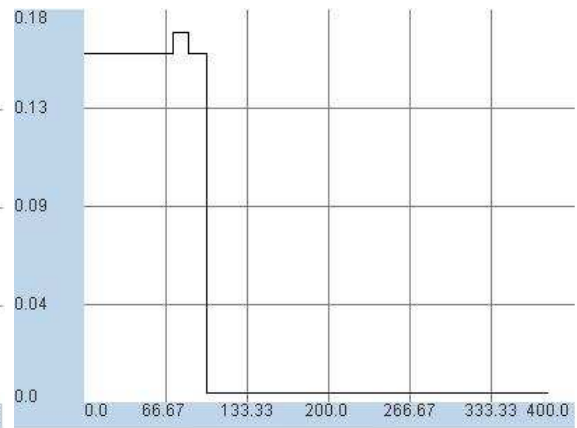
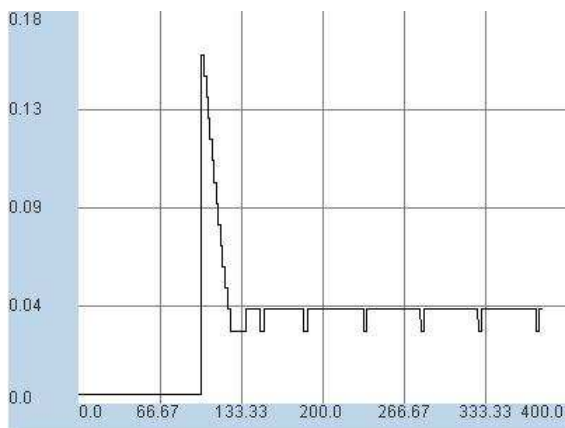


Figure 4.19: Adjustment for control valve V_{TM} Figure 4.20: Adjustment for control valve V_{TB}

Question6: How does the concentration in tank TM influence the final value of electric conductivity in tank TS?

Answer1: Does not influence the final value.

Answer2: It has an influence the final value.

In following graphs, there are results from three simulations. In Fig. 4.21, there is the result from the simulation, where the value of c_{TM} was set to 0.00197930849245. For the simulation result shown in Fig. 4.22, the value of c_{TM} was set to 0.00173513209943.

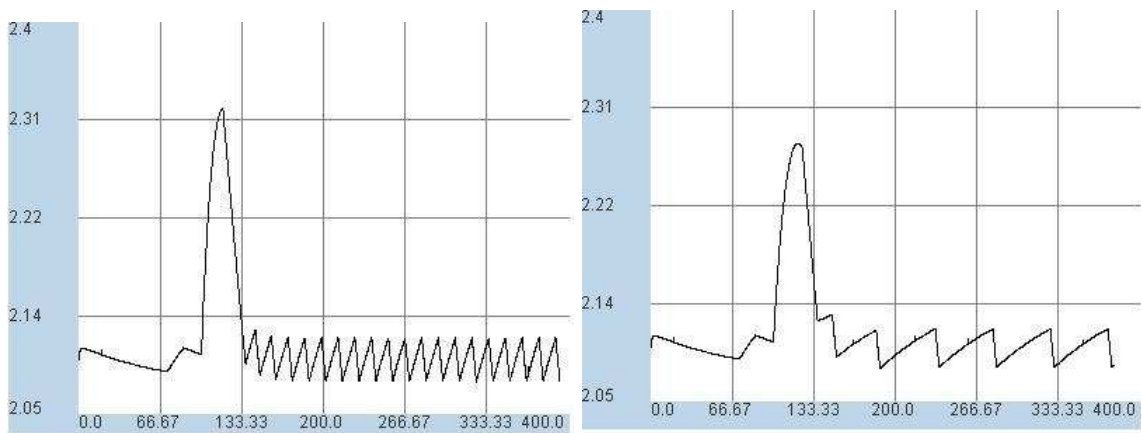


Figure 4.21: Electric conductivity in tank TS, d Figure 4.22: Electric conductivity in tank TS, f

Correct answer: Does not influence the final value.

If the user's answer is incorrect, the user will be navigated to the simulation, where the value of c_{TM} will be set to the value 0.0016.

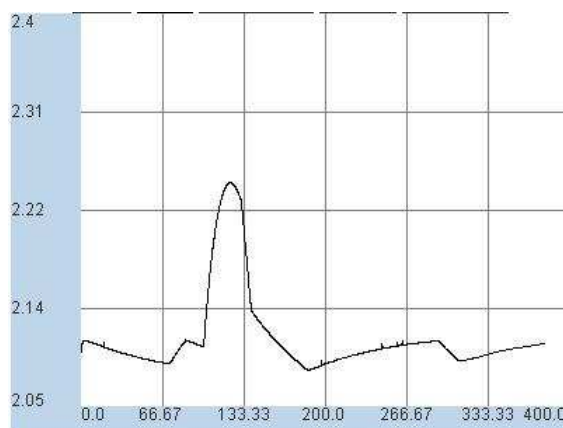


Figure 4.23: Electric conductivity in tank TS, e

As shown in figures above, there is an influence on the curve of the electric conductivity, but at the end of the simulation the final value is same.

Institutionalization

From this simulation the user should learn about plant behavior. The learner should find out, that the temperature of cold water inflow has no influence on the temperature in tank TB, because from Fig. 2.1 it is obvious, that they are not connected in any way.

The case, where cold water is mixing with inflow to tank TS, is a simple case of mixing two liquids with different temperatures. If one of liquids will become colder, the temperature of mixture will become lower and vice versa. But in tank TS, there is a heating system, which plays role in sustaining the regulation goal $\vartheta_{TS,cv} = 25\text{ }^{\circ}\text{C}$.

Another phenomenon is playing role in case, where the ambient temperature has an influence on the temperature in tank TB. If the ambient temperature is lower than the temperature in tank TB, there is a simple cooling process to be considered. Like in tank TS, there is the heating system in tank TB to maintain the temperature.

For the concentration, it is the fact, that for the same result with more concentrate liquid, less amount of this liquid is needed.

Assessment

Try to answer the questions below.
Click on the title head to popup question.

How does the concentration in tank TM influence the final value of electric conductivity in tank TS?

☒ Does not influence the final value.
☐ It has an influence on the final value.

Question 6

1 5

tion 4

estion 3

Question 2

Question 1

What is now my knowledge?

The case, where cold water is mixing with inflow to tank TS, is a simple case of mixing two liquids with different temperatures. If one of the liquids will become colder, the temperature of mixture will become lower and vice versa. In tank TS, there is a heating system, which plays role in sustaining the regulation goal 25 degree Celsius .

The temperature of cold water inflow has no influence on the temperature in tank TB, because they are not connected in any way.

Another phenomenom is playing role in case, where the ambient temperature has an influence on the temperature in tank TB. If the ambient temperature is lower than the temperature in tank TB, there is a simple cooling process to be considered. As in the tank TS, there is also a heating system in tank TB to maintain the temperature around 25 degree Celsius.

For the concentration, it is the fact, that for the same result with more concentrate liquid, less amount of this liquid is needed.

Figure 4.24: The Assessment and Knowlegde institutionalization phase

After observing the plant behavior the learner is directed to the assessment section. He/she should answer questions about the plant behavior. If the answer is wrong, he/she will be redirected to the *Addressed Situation* phase. This is a modified version of the *Active Situation* micro phase in which the emphasis is put on a particular aspect of the experiment activity. Passing through *Assessment* phase is a sign, that the user's knowledge is valid, see Fig. 4.24.

This is acknowledged by statements shown to the learner containing the correct solution and a list of concepts which should be known after completing this activity, see Fig. 4.24.

Chapter 5

Conclusions

The main aim of this work was to implement an UoL with the aid of VCLab. The pilot plant subsystem of a thermofluid process is the application for a LO.

For this work, this is one of many ways, how to design such a UoL. There could be some improvements to be done as to time scaling the LO or to the visual presentation. Learning in such an environment by experimenting is certainly not a full equivalent substitute of having experiments in a real laboratory. But it is capable enough to demonstrate underlying principles. It also allows having experiments that are in reality not easily accessible or even hardly performed in laboratory because of various reason. The grid approach allows to use profession simulators and large simulation models that are closer to reality than academic ones. This way learning will become more open to learners. From the 3D visual presentation the learner can get the information more effective than from 2D scopes or only a text presentation. And commonly knowledge gained this way last longer.

Continuing this work will bring an outstanding way of learning. Imagine that this way would be applied all the experience in chemical laboratories. This would bring not only cost saving speaking about the chemicals and equipment, but also the environment will be taken care of. Time here also takes an important role. The thermofluid process is time-demanding. In real time it takes more than 10 minutes to reach previously discussed results. This simulation is time scaled and gives the same results 4 times faster than in real time.

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Appendix A

Thermofluid Plant Specifications

A.1 Physical Model

A.1.1 Level of liquid in tank TS

Through the inflow of cold water, salty water provided by tanks TB, TM and the outflow provided by pump to tank TW, the level of liquid in tank TS can be calculate.

$$\begin{aligned}\dot{m}_{TS}(t) &= \sum_i \dot{m}_{in,i}(t) - \sum_j \dot{m}_{out,j}(t) \\ &= \dot{m}_{TB}(t) + \dot{m}_{TM}(t) + \dot{m}_{CW}(t) - \dot{m}_{TW}(t).\end{aligned}\tag{A.1}$$

The level l_{TS} is in relation to salty water mass.

$$m_{TS}(t) = A_{TS}\rho l_{TS}(t).\tag{A.2}$$

The density of all salty water inflow could be consider as the density of water

$$\rho = \rho_{W,20^\circ C} = 0,998 \frac{\text{kg}}{\text{dm}^3}.$$
¹

From the Eq. (A.2) the level of liquid in tank TS is calculated

$$l_{TS}(t) = \frac{m_{TS}(t)}{A_{TS}\rho}.$$

The time relation of level of liquid is then

$$\dot{l}_{TS}(t) = \frac{\dot{m}_{TB}(t) + \dot{m}_{TM}(t) + \dot{m}_{CW}(t) - \dot{m}_{TW}(t)}{A_{TS}\rho}.\tag{A.3}$$

A.1.2 Temperature

The energy balance

$$\frac{dQ_{TS}(t)}{dt} = P_{el,TS}(t) + \dot{Q}_{WS,in,TS}(t) - \dot{Q}_{WS,out,TS}(t) - \dot{Q}_{T,out,TS}(t)\tag{A.4}$$

¹ Natriumchlorid has density $\rho_{NaCl} \approx 2,165 \frac{\text{kg}}{\text{dm}^3}$, which is approximately two times more than the density of water. Amount of used salt concentration is in 10^{-3} could be the density of salt water consider as the density of water.

is the basic for physical description of temperature.

Heat Q is in dependance of heat inflows \dot{m}_{TB} , \dot{m}_{TM} , \dot{m}_{CW} and heat outflow \dot{m}_{TW} . Each of heat flows is describe as

$$\dot{Q}_{WS}(t) = \dot{m}(t)c_p\vartheta(t)$$

The sum of heat inflows to tank TS

$$\begin{aligned}\dot{Q}_{WS,in,TS}(t) &= \sum_i \dot{Q}_{WS,i}(t) \\ &= \dot{Q}_{TB}(t) + \dot{Q}_{TM}(t) + \dot{Q}_{CW}(t) \\ &= c_p(\dot{m}_{TB}(t)\vartheta_{TB}(t) + \dot{m}_{TM}(t)\vartheta_{TM}(t) + \dot{m}_{CW}(t)\vartheta_{CW}(t))\end{aligned}\quad (A.5)$$

consists of heat flows from tank TB and TM and inflow of cold water. Heat outflow

$$\begin{aligned}\dot{Q}_{WS,out,TS}(t) &= \dot{Q}_{TW}(t) \\ &= \dot{m}_{TW}(t)c_p\vartheta_{TW}(t)\end{aligned}\quad (A.6)$$

is given by pumping the salty water to tank TW. Other possibility to change the heat is heating system which include electrical heating pins in tank TS. Each of those four heating pins has electrical power about 1 kW [6]. It gives

$$P_{el,TS} = 4\text{kW}$$

for all heating pins. In tank TB there will be six heating pins in the heating system to control the temperature ϑ_{TB} , each with electrical power 3 kW.

There must be also consider the heat transmission to surrounding. The heat loss by heat transfer through the surface A_{TS} of the tank TS [2] are

$$\begin{aligned}\dot{Q}_{T,TS}(t) &= k_{TS}A_{TS}(\vartheta_{TS}(t) - \vartheta_U) \\ &= k_{TS}A_{TS}\Delta\vartheta_{TS}(t)\end{aligned}\quad (A.7)$$

With constant heat-transfer coefficient k_{TS} the heat transfer is then proportional to difference between the temperature of salty water ϑ_{TS} and the temperature of surrounding ϑ_U .

The accumulated heat in tank TS is

$$Q_{TS}(t) = m_{TS}(t)c_p\vartheta_{TS}(t).\quad (A.8)$$

The c_p constant is the specific heat capacity of the salty water solution.² The accumulated heat Q_{TS} is constant mass proportional to temperature ϑ_{TS} . The time relation of the heat flow \dot{Q}_{TS} consider

²The 5% solution has almost no influence on the heat capacity so it was considered that the salty water solution has the same specific heat capacity $c_p = 4187 \frac{\text{J}}{\text{kgK}}$ as water.

the Eq. (A.8) is following:

$$\begin{aligned}\frac{dQ_{TS}(t)}{dt} &= \frac{d}{dt}(\dot{m}_{TS}(t)c_p\vartheta_{TS}(t)) \\ &= c_p(\dot{m}_{TS}(t)\vartheta_{TS}(t) + m_{TS}(t)\dot{\vartheta}_{TS}(t))\end{aligned}\quad (A.9)$$

From energy balance Eq. (A.4) and also the Eq. (A.5), Eq. (A.6) and (A.9) the differential equation for temperature in tank TS is following:

$$\dot{\vartheta}_{TS} = \frac{P_{el,TS} - \dot{Q}_{T,TS}}{m_{TS}c_p} + \frac{\dot{m}_{TB}\vartheta_{TS} + \dot{m}_{TM}\vartheta_{TM} + \dot{m}_{CW}\vartheta_{CW} - \dot{m}_{TW}\vartheta_{TS} - \dot{m}_{TS}\vartheta_{TS}}{m_{TS}}.$$

From Eq. (A.1) and (A.2) the differential equation

$$\begin{aligned}\dot{\vartheta}_{TS} = \frac{1}{A_{TS}\rho l_{TS}} \left\{ \frac{P_{el,TS} - \dot{Q}_{T,TS}}{c_p} + \dot{m}_{TB}(\vartheta_{TB} - \vartheta_{TS}) \right. \\ \left. + \dot{m}_{TM}(\vartheta_{TM} - \vartheta_{TS}) + \dot{m}_{KW}(\vartheta_{KW} - \vartheta_{TS}) \right\}\end{aligned}\quad (A.10)$$

is calculated. The temperature in tank TS does not depend on outflow \dot{m}_{TW} , it has the same temperature as ϑ_{TS} , so also the same heat flow.

There is analogy in controlling the temperature ϑ_{TS} and ϑ_{TB} . The time relation for ϑ_{TB} is then analogue to Eq. (A.10)

$$\dot{\vartheta}_{TB}(t) = \frac{1}{A_{TB}\rho l_{TB}} \left\{ \frac{P_{el,TB}(t) - \dot{Q}_{T,TB}(t)}{c_p} + \dot{m}_{T124}(t)(\vartheta_{T124} - \vartheta_{TB}(t)) \right\}. \quad (A.11)$$

The heating system provide electric power $P_{el,TB} = 18\text{kW}$. [6]

The heat loss by heat transfer through the surface A_{TB} of the tank TB is analogue to Eq. (A.7)

$$\begin{aligned}\dot{Q}_{T,TB}(t) &= k_{TB}A_{TB}(\vartheta_{TB}(t) - \vartheta_U) \\ &= k_{TB}A_{TB}\Delta\vartheta_{TB}(t).\end{aligned}\quad (A.12)$$

Temperature in the tank TM will be set up by user and will be constant during whole simulation.

A.1.3 Electric conductivity

Third of regulation goal is electric conductivity λ_{TS} of salty water solution in tank TS. This conductivity

$$\lambda_{TS}(t) = f(c_{TS}(t), \vartheta_{TS}(t)) \quad (A.13)$$

depends not only on salt concentration but also on the temperature of solution. The concentration

$$c_{TS}(t) = \frac{m_{S,TS}(t)}{m_{TS}(t)} \quad (A.14)$$

is given by weight ration. From the Eq. (A.14) the time relation of salt concentration

$$\dot{c}_{TS}(t) = \frac{\dot{m}_{S,TS}(t)m_{TS}(t) - m_{S,TS}(t)\dot{m}_{TS}(t)}{m_{TS}^2(t)} \quad (A.15)$$

is implied. The time relation of salt flow in tank TS

$$\dot{m}_{S,TS}(t) = \dot{m}_{TB}(t)c_{TB}(t) + \dot{m}_{TM}(t)c_{TM}(t) - \dot{m}_{TW}(t)c_{TS}(t) \quad (A.16)$$

is given by inflows of salty water solution from tanks TB, TM and also of outflow to tank TM provided by pump PS2. By using Eq. (A.1), (A.2) in Eq. (A.15) the time relation of concentration of salt

$$\dot{c}_{TS}(t) = \frac{\dot{m}_{TB}(t)(c_{TB} - c_{TS}(t)) + \dot{m}_{TM}(t)(c_{TM} - c_{TS}(t)) - \dot{m}_{CW}(t)c_{TM}}{A_{TS}\rho l_{TS}(t)} \quad (A.17)$$

is calculated. The electrical conductivity of salty water solution λ is in direct dependency with concentration of salt and temperature. By [7] the Eq. (A.13) the electrical conductivity

$$\lambda(c_S(t)) = 0,4469 \frac{\text{mS}}{\text{cm}} + 2047,7 \frac{\text{mS}}{\text{cm}} c_S(t) \quad (A.18)$$

is approximated around constant temperature 25°C which is equivalent to ϑ_{TS} . The conductivity $\lambda(0) = \lambda_{\text{water}} = 0,4469 \frac{\text{mS}}{\text{cm}}$ is for naturally mineralize water.

A.2 Parameters

For the nominal process there were parameters for process quantities in dependance on setting units estimated.[6]

A.2.1 Cold water inflow setting

The inflow of cold water to tank TS is secure through the continual control valve V_{CW} . To control inflow of cold water \dot{m}_{CW} PI-controller [4], which output is u_{CW} . This internal control of cold water inflow is model as a operative control valve by which cold water inflow is directly adjusted.

$$\dot{x}_{CW}(t) = -\frac{1}{T_{CW}}x_{CW}(t) + \frac{1}{T_{CW}}u_{CW}(t) \quad (A.19a)$$

$$\dot{m}_{CW}(t) = x_{CW}(t) \quad (A.19b)$$

The time constant of this control valve could not be neglected and its value is $T_{CW} = 3,7\text{s}$ [7]

A.2.2 Pump PS2

Pump used in this model is adjustable from 0-100% by 1%. Pump PS2 will start to pump the water from tank TS to tank TW after dead zone 10%, so the pump is by the pulse width modulation with period $T_{PWM} = 6\text{s}$ setup as pseudocontinual. The regulation goal l_{TS} depends on switching rate

$$u_{PS2}(t) = \frac{T_{Ein}(t)}{T_{PWM}}.$$

During the period of pulse wave modulation there is also time period T_{Ein} involved. Based on the approximation the performance of pump PS2 is:

$$\dot{m}_{PS2}(t) = \dot{m}_{TW}(t) = 0,1679 \frac{\text{kg}}{\text{s} \sqrt{\text{m}}} u_{PS}(t) \sqrt{l_{TS}(t) + 0,36\text{m}} \quad (\text{A.20})$$

In consequence of various levels of liquid the performance of pump differs according to Eq. (A.20). In Eq. (A.20) there is underflow discharge of tank TS set to 0,36 m above the feed pipe, so this height must be added to the level of liquid l_{TS} . [7]

A.2.3 Control valve

The continual adjustable valve V_{TB} controll the inflow of salty water solution from tank TB to tank TS. The valve could be open in range 0-100% in 1%. Water pumping is realizing with the help of discrete pump PR. The pump is used when the levels of both tanks have the same level of liquid. Based on the performance of pump PR the pumping of salty water solution starts when the control valve is at 13% open. The flow through the V_{TB} with dead zone is approximated as:

$$\dot{m}_{TB}(t) = \begin{cases} \left(0,019 \frac{\text{kg}}{\text{s} \sqrt{\text{m}}} + 0,727 \frac{\text{kg}}{\text{s} \sqrt{\text{m}}} (u_{TB}(t) - 0,13)\right) \sqrt{l_{TB} + 0,3\text{m}}, & \text{when } u_{TB} \geq 0,13 \\ 0 \frac{\text{kg}}{\text{s}}, & \text{when } u_{TB} < 0,13 \end{cases} \quad (\text{A.21})$$

The Eq. (A.21) presenting the mass flow shows, that to l_{TB} there is constant value 0,3m added which represent the height of the tank TB above the feed-pipe of pump PR.

The salty water solution flows from tank TM to tank TS through the continual adjustable control valve V_{TM} . Even though V_{TM} is structurally the same as control valve V_{TB} pumping starts when control valve is at 4% open. The approximate [6] mass flow \dot{m}_{TM} is following:

$$\dot{m}_{TM}(t) = \begin{cases} \left(0,047 \frac{\text{kg}}{\text{s} \sqrt{\text{m}}} + 0,605 \frac{\text{kg}}{\text{s} \sqrt{\text{m}}} (u_{TM}(t) - 0,04)\right) \sqrt{l_{TM} + 0,3\text{m}}, & \text{when } u_{TM} \geq 0,04 \\ 0 \frac{\text{kg}}{\text{s}}, & \text{when } u_{TM} < 0,04 \end{cases} \quad (\text{A.22})$$

Tank TM is 0,3m above the feed-pipe of pump PR.

A.2.4 Heating tank TS

The heating system as mention in (A.1.2) consist of four heating pins. Those could be on or off all together in once. Those discrete heating pins were set as pseudocontinual by pulse width modulation with period $T_{PWM} = 6\text{s}$.

The heating transmission depends on heating system state. With the state off, the heating transmission is consider as normal cooling process with rising heating transmission $\dot{Q}_{T,C,TS}$. When the

state of heating system is on, then there is additional heating transmission $\dot{Q}_{T,TS,an}$ to be consider. The heating system is then as

$$\dot{Q}_{T,TS}(\vartheta_{TS}(t)) = \begin{cases} \dot{Q}_{T,TS,an}(\vartheta_{TS}(t)), & \text{when heating system is on} \\ \dot{Q}_{T,C,TS}(\vartheta_{TS}(t)), & \text{when heating system is off} \end{cases} \quad (A.23)$$

with

$$\dot{Q}_{T,TS,an}(\vartheta_{TS}(t)) = \dot{Q}_{T,H,TS}(\vartheta_{TS}(t)) + \dot{Q}_{T,C,TS}(\vartheta_{TS}(t)). \quad (A.24)$$

The effective heat inflow

$$\dot{Q}_{eff,TS}(\vartheta_{TS}(t)) = P_{el,TS}(t) - \dot{Q}_{T,TS,an}(\vartheta_{TS}(t)) \quad (A.25)$$

is difference between electric power and heat transmission during heating process. Since the heating pins grow warm slowly they do not have their full power from the beginning of the heating process. It is necessary to model them as PT₁ actuator with input $u_{el,TS}$ and output $P_{el,TS}$.

$$\dot{x}_{el,TS}(t) = -\frac{1}{T_{el,TS}}x_{el,TS}(t) + \frac{1}{T_{el,TS}}u_{el,TS}(t) \quad (A.26a)$$

$$P_{el,TS}(t) = k_{el,TS}x_{el,TS}(t) \quad (A.26b)$$

Time constant is $T_{el,TS} = 65s$ and $x_{el,TS} = 4kW$ [6]. The heat transmission during heating process is through modified Eq. (A.25)

$$\dot{Q}_{T,TS,an}(\vartheta_{TS}(t)) = P_{el,TS}(t) - \dot{Q}_{eff,TS}(\vartheta_{TS}(t))$$

calculated. The heat transmission during the on state of heating system is calculated as:

$$\dot{Q}_{T,TS,an}(\vartheta_{TS}(t)) = \begin{cases} 42,0435 \frac{W}{^\circ C}(\vartheta_{TS}(t) - \vartheta_U), & \text{when } \vartheta_{TS} \geq \vartheta_U \\ 0W, & \text{when } \vartheta_{TS} < \vartheta_U \end{cases} \quad (A.27)$$

The normal cooling process brings heat transmission as follow

$$\dot{Q}_{T,C,TS}(\vartheta_{TS}(t)) = \begin{cases} 4,8968 \frac{W}{^\circ C}(\vartheta_{TS}(t) - \vartheta_U), & \text{when } \vartheta_{TS} \geq \vartheta_U \\ 0W, & \text{when } \vartheta_{TS} < \vartheta_U \end{cases} \quad (A.28)$$

A.2.5 Heating tank TB

Model of heating system in tank TB which is analog to heating system in tank TS consists of six heating pins. They could be on or off all together in once. Discrete heating pins were set as pseudocontinual by pulse width modulation with period $T_{PWM} = 6s$. Those were also model as PT₁ actuator with input $u_{el,TB}$ and output $P_{el,TB}$

$$\dot{x}_{el,TB}(t) = -\frac{1}{T_{el,TB}}x_{el,TB}(t) + \frac{1}{T_{el,TB}}u_{el,TB}(t) \quad (A.29a)$$

$$P_{el,TB}(t) = k_{el,TB}x_{el,TB}(t) \quad (A.29b)$$

with $T_{el,TB} = 27s$ and $k_{el,TB} = 18kW$ [6]. The heating transmission depends on heating system state. With the state off, the heating transmission is consider as normal cooling process with rising heating transmission $\dot{Q}_{T,C,TB}$. When the state of heating system is on, then there is additional heating transmission $\dot{Q}_{T,TB,an}$ to be consider. The heating system is then

$$\dot{Q}_{T,TB}(\vartheta_{TB}(t)) = \begin{cases} \dot{Q}_{T,TB,an}(\vartheta_{TB}(t)), & \text{when heating system is on} \\ \dot{Q}_{T,C,TB}(\vartheta_{TB}(t)), & \text{when heating system is off} \end{cases} \quad (A.30)$$

with

$$\dot{Q}_{T,TB,an}(\vartheta_{TB}(t)) = \dot{Q}_{T,H,TB}(\vartheta_{TB}(t)) + \dot{Q}_{T,C,TB}(\vartheta_{TB}(t)). \quad (A.31)$$

The effective heat inflow

$$\dot{Q}_{eff,TB}(\vartheta_{TB}(t)) = P_{el,TB}(t) - \dot{Q}_{T,TB,an}(\vartheta_{TB}(t)) \quad (A.32)$$

is difference between electric power and heat transmission during heating process. The heat transmission during heating process is through modified Eq. (A.32)

$$\dot{Q}_{T,TB,an}(\vartheta_{TB}(t)) = P_{el,TB}(t) - \dot{Q}_{eff,TB}(\vartheta_{TB}(t))$$

calculated. The heat transmission during the on state of heating system is calculated as:

$$\dot{Q}_{T,TB,an}(\vartheta_{TB}(t)) = \begin{cases} 130,5712 \frac{W}{^{\circ}C}(\vartheta_{TB}(t) - \vartheta_U), & \text{when } \vartheta_{TB} \geq \vartheta_U \\ 0W, & \text{when } \vartheta_{TB} < \vartheta_U \end{cases} \quad (A.33)$$

The normal cooling process brings heat transmission as follow

$$\dot{Q}_{T,C,TB}(\vartheta_{TB}(t)) = \begin{cases} 4,8968 \frac{W}{^{\circ}C}(\vartheta_{TB}(t) - \vartheta_U), & \text{when } \vartheta_{TB} \geq \vartheta_U \\ 0W, & \text{when } \vartheta_{TB} < \vartheta_U \end{cases} \quad (A.34)$$

Glossary

LO	Learning Object, 13
PWM	Pulse width modulation, 23
SMAT	Simulation Model Authoring Tool, 13
UoL	Unit of Learning, 13
VCLab	Virtual Control Laboratory, 13
VOAT	Visual Object Authoring Tool, 13
VSE	Virtual Scientific Experiments, 36