Learning Heat Dynamics using Modelling and Simulation

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Abstract

In the education of energy and power plant engineers, the learning of heat transfer, its dynamics and process control plays an important role. Deeper touch in dynamic process phenomena in our vibrant times may sometimes be a challenge for students and teachers. Modelling and simulation make a continuously increasing tool as a learning method, in various kinds of application fields. In engineering, using pilot or production plants, by modelling the systems, getting results from simulations and comparing the results to real life data, the intended learning outcomes can be achieved in a varying and motivating way. This paper presents a pilot heat exchanger which was mostly constructed by a few students of energy technology and supervised by their teachers. Some basic physical and identified process models of the heat exchanger are introduced, as well as their simulation results. This heat exchanger is widely used in the basic heat transfer and control system studies of higher education. Positive learning and teaching experiences were already achieved in the design and commissioning phase. As a result, the heat exchanger system offers a multifunctional learning environment with modelling and simulation activities in practice-oriented engineer studies.

Keywords: heat transfer, modelling, simulation, process control active learning, collaborative learning

1 Introduction

Learning and teaching of engineering in our times may be rather challenging. Very often also amusing elements are expected. Collaborative learning in teams and practice-oriented experimental learning may help to overcome these challenges. The need of collaborative and practice-oriented learning elements is already referred in (Schadler and Hudson, 2004). Different kinds of active learning activities, such as analyzing, modelling, simulation, visualization, problem-solving, gaming, are emphasized in many learning and teaching instructions, such as in (Centre for teaching Excellence Canada, 2016; Carleton Science Education Center USA, 2016), for example. This paper presents an educational heat exchanger system, some modelling and simulation methods for activating and successful learning and teaching experiences.

The objective educational heat exchanger describes a plate heat exchanger and comprises two water circulations. One water circulation, the hot circulation, includes a boiler unit with an electric heating element, while another circulation, the cold circulation, uses tap water leading it to a removal pipeline. Heat is transferred from the hot circulation to the cold circulation. All pipelines are isolated in order to avoid significant heat losses.

The educational heat exchanger process can be operated using both in the downstream flow and reverse flow and, and thus this system describes many common heat exchangers and heat recovery facilities. The impacts of the circulation flows and heating power can be monitored. The characteristic curve of the pump may be defined. The controllers can be optimized. This rather simple heat transfer system offers a whole set of varying learning objectives (Figure 1).

The heat exchanger process is provided with several temperature measurement sensors with Pt-100 elements: TI-1, TI-2, TI-3, TI-4 and TI-5 being in the hot circulation, and TI-11, TI-12, TI-13, TI-14, TI-15 in the cold circulation (Figure 2). The pipelines have a square-formed cross section profile, and they have a tight contact in the length of 6 meters. The effective heat transfer area totals 0.18 square meters. The dynamics of heat transfer can be experimented and monitored in several ways.

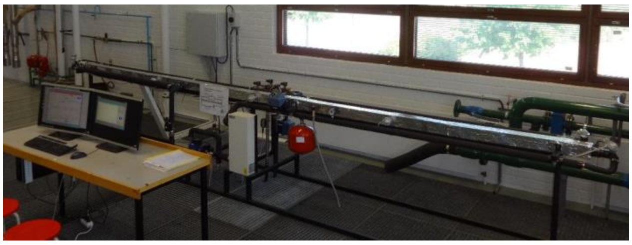

Figure 1. Educational heat exchanger system.

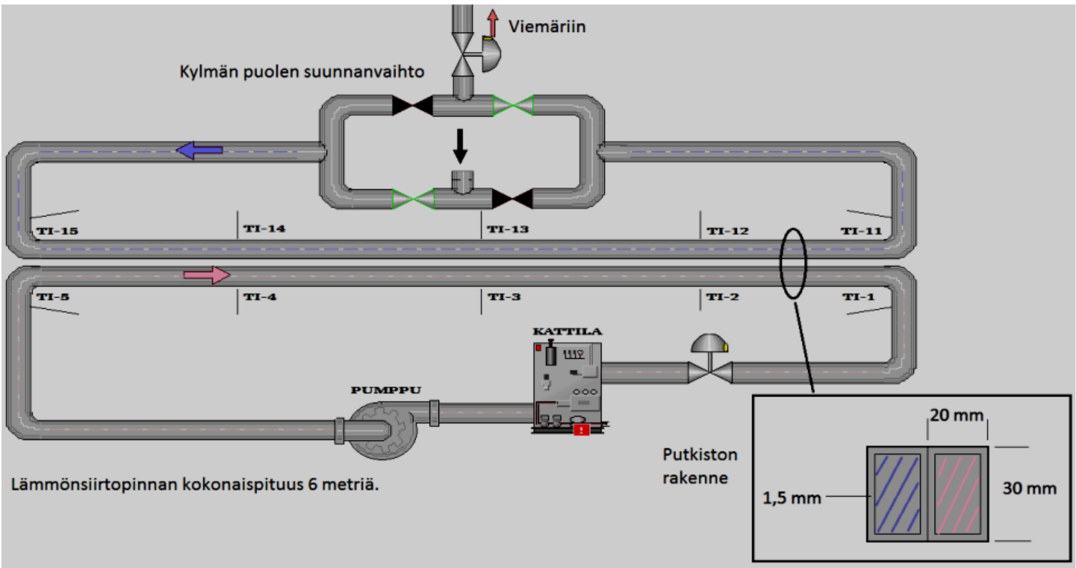

Figure 2. Structure of the educational heat exchanger system.

The temperature of the hot circulation is controlled by the power of the heating elements of the 26 kW flow type boiler (KATTILA), based on the measurement TI-1 (Figure 3). The flow of the hot circulation is controlled by the speed of a feeding pump in the control loop FIC-7. The flow of the cold circulation is controlled by the outlet valve of the control loop FIC-18. The direction of the cold circulation can be changed using a switch (SUUNTA) and related on-off valves, thus enabling the downstream and reverse flow operations.

The educational heat exchanger is provided with a programmable logic controller Siemens Simatic S7-1200 and a PC-based human machine interface (HMI) of Invensys InTouch. The HMI enables users to monitor measurement and control loops in an overview display (Figure 3) and operate them using separate loop window displays. The control system includes sampling of history data for trend curve monitoring, and for numerical tables in case of modelling and simulation.

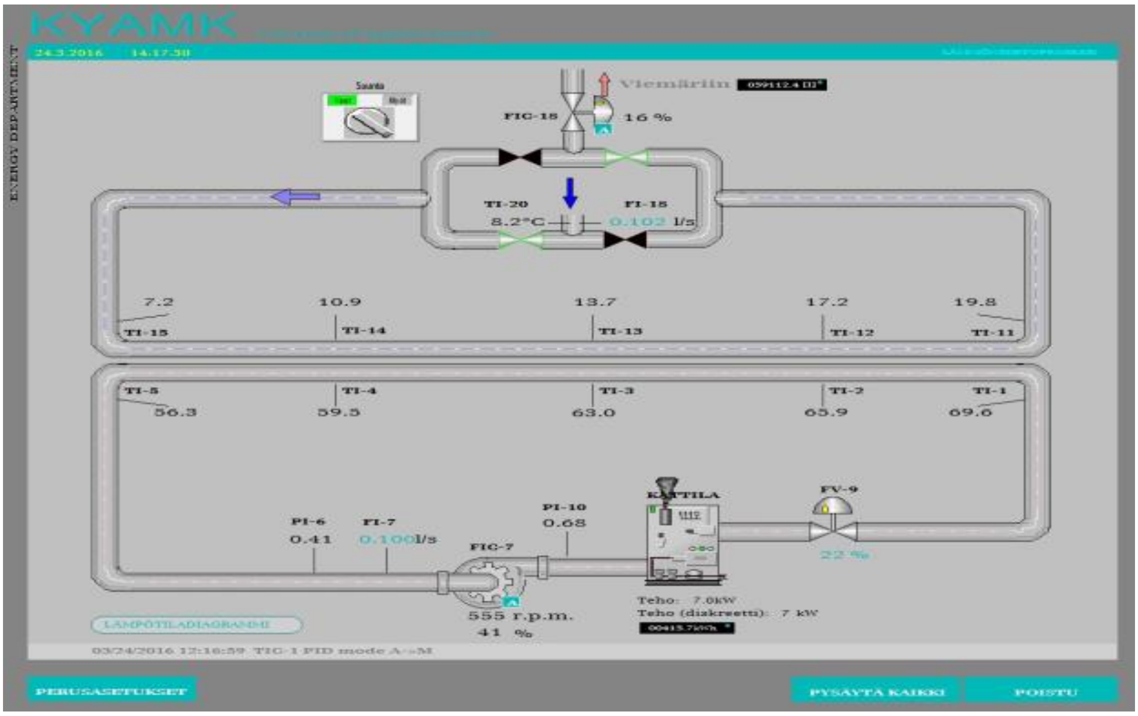

Figure 3. Overview display for monitoring.

2 Physical modelling of heat transfer

In modelling procedures we like to find relationships between interesting, interacting inputs and outputs of systems. Those systems to be modelled can be available process systems, or they may be systems to be designed. Physical models are based on well-known first principles, and they may be applied to rather simple, physically known systems. Model equations which are independent on time, describe steady state models of systems, while differential model equations, for example, present the time-dependent, dynamic behavior of systems. Steady-state models are interesting in process design, while dynamic models help to understand dynamic process phenomena from a control point of view. Modelled systems can be visualized using simulations which are needed in model validations.

We may create static or dynamic energy system models based on flow, mass and enthalpy balances, for example, as described in (Ljung and Glad, 1994). With energy systems we have different aspects. In heat transfer systems one interesting aspect comes from energy efficiency. We often like to know how much energy we do need to make a certain temperature difference in heat transfer.

2.1 First principle model of a heat exchanger

The dynamic behavior of the heat transfer in the educational heat exchanger can be described using a simplified process model of (1). Based on the dynamic heat balance, the change in the energy flow of in the releasing (or receiving) circulation can be given, based on (Ljung and Glad, 1994; Bergman et.al., 2011), as follows:

$$m * c_p * \frac{dT}{dt} = P - k * A * (T - T_n) \qquad (1)$$

m	total water mass, [kg]
c_p	specific heat capacity, [J/(kg K)]
T	water temp. of the input location, [K]
T_n	water temp. of the output loc., [K]
P	incoming heating power, [J/s]
k	average heat tr. coeff., [J/(s*K*m^2)]
A	effective heat transfer area, [m^2].

Thus, the trend of temperature in the plate heat exchanger follows an exponential relationship which is dependent on the effective heat exchange area, heat transfer coefficient, mass and enthalpy of water in the circulations. In reality, the specific heat capacity c_p and heat transfer coefficient k are not constants but dependent on the temperature range. The model (1) assumes a constant temperature T_n in the output location, although the temperature T_n also changes due to operation conditions.

2.2 Simulation results based on first principle models

The first principle model of (1) of the educational heat exchanger system was used for the simulation of the temperature T (TI-1).

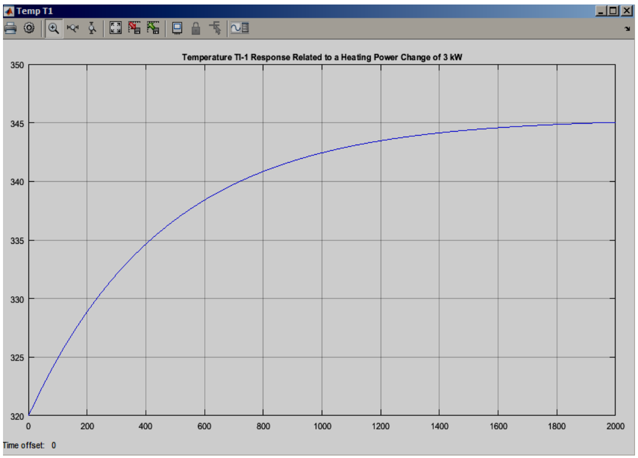

Figure 4. Simulated response of the temperature T (TI-1) related to a heating power change with time [s] in the x-axis and temperature [K] in the Y axis.

The model system was simulated using Matlab Simulink with the following heat exchanger parameters: A=0.18 m^2, T_5=312.05 K, m=10 kg, c_p=4179 J/kgK, k=500 J/sKm^2. The starting temperature T was 320 K. The response in the temperature T (TI-1) results a final increase of 25 degrees in simulations (Figure 4), and respectively in process experiments (Figure 5, red upper curve). The slowness expressed as a time constant, based on (m*cp)/(k*A), gives about 460 seconds. The time delay in the heat transfer could have been added to the simulation model but it was not known, yet.

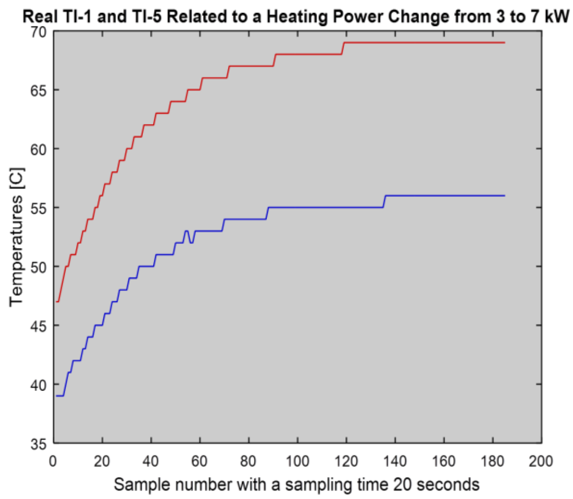

Figure 5. Temperature responses TI-1 (red upper curve), TI-5 (blue lower curve) related to heating power change in a real process experiment.

3 Identification models of heat transfer

Identified models can be achieved based on practical process experiments. Principally, it is a question of fitting sampled data to some ready-made models. These models are often mathematical, or they may even be linguistic such as fuzzy logic models (Yager, 1996; Åström and Hägglund, 1995). On one hand, the data based on simple step response tests can be fitted in time-continuous Laplace models. The most popular Laplace models, due to their physics-related parameters, are the settling first order model and the integrating model. On the other hand, the data sets based on pseudo random binary signal (PRBS) response tests can be fitted in time-discrete AutoRegressive with an eXogenous input (ARX), models, for example, according to (Ljung and Glad, 1994).

3.1 Identified Laplace model with simulation results

The first order Laplace transfer function model between the resulting output Y and excitation input U, for settling dynamics, can be given in the Laplace domain in (2), like presented in (Åström and Hägglund, 1995; Bolton, 2004; Dorf and Bishop, 2004):

$$\frac{Y}{U} = \frac{K}{T*s+1} * e^{-L*s} \tag{2}$$

Y resulting output
U excitation input
K process gain
T time constant
L time delay
s Laplace operator.

In the first identification modelling case we liked to find out the relationship between the hot circulation temperature TI-1 and the heating power. Using the heating power of 7 kW, the heating process was taken to a steady state. Exact trend curves could be monitored (Figure 6). The heating power was changed to 11 kW, and the temperature T-1 started to increase gradually from 45.4 ºC to 63.4 ºC, after a time delay of 41 seconds. The temperature TI-1 reaches its final temperature 63.4 ºC after about 21 minutes. In the process experiment, the step response of the temperature TI-1 related to the heating power change settles down to a new level and the trend resembles a first order Laplace model response given in (2). The time constant, representing the slowness of the change can be defined to be 570 seconds. Thus, based on the step response curves, and by applying the first order Laplace model of (2), the process model between the temperature TI-1 and heating power can be stated as follows in (3):

$$\frac{Temp}{Heat\ power} = \frac{18/4}{570*s+1} * e^{-41*s}. \tag{3}$$

The Laplace model of (3) was also constructed in the Matlab Simulink. In a simulation with a heating power change from 7 to 11 kW, the step response in the temperature TI-1 (Figure 6) gives matching results compared to the original process experiment data (Figure 7).

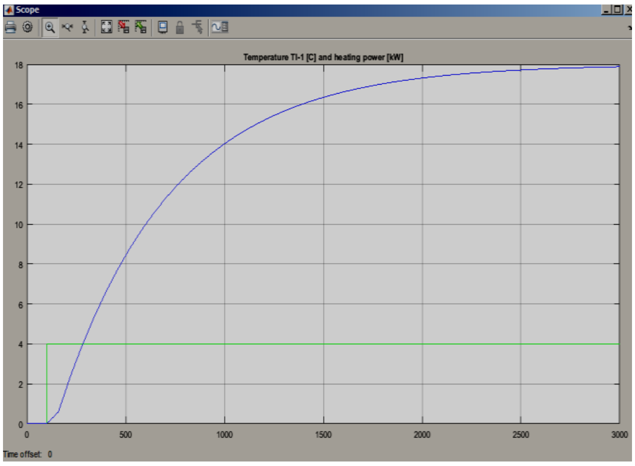

Figure 6. Simulated step response of the temperature TI-1 (blue upper curve) related to the heating power change from 7 to 11 kW (green lower curve).

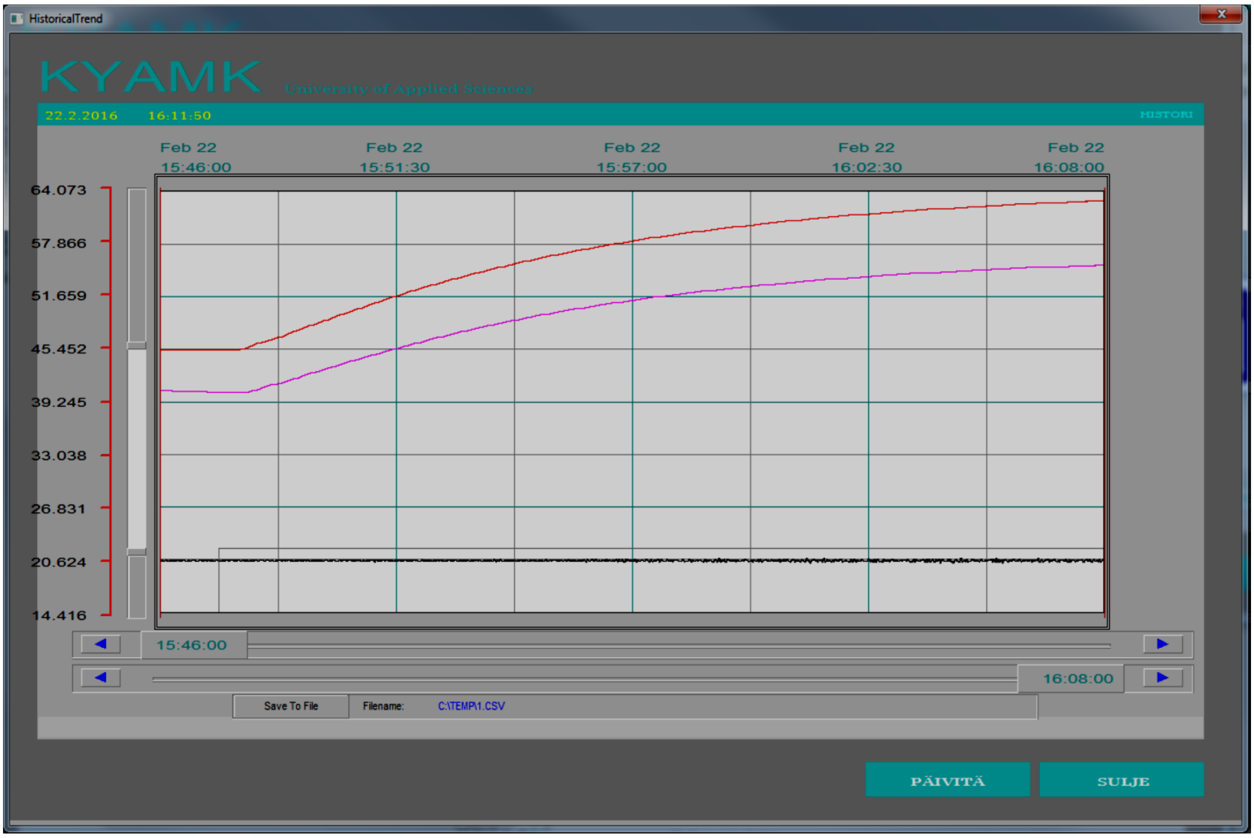

Figure 7. Real step response of the temperature TI-1 (upper red curve), TI-5 (next magenta curve) with the heating power change from 7 to 11 kW (lower stepwise gray curve) in the HMI monitoring.

3.2 ARX model with simulation results

Likewise presented in (Ljung and Glad, 1994; Åström and Wittenmark, 1997) a ready-made ARX model can be applied to practical modelling cases when data sets from process experiments with responses to pseudo random binary signal (PBRS) inputs are available. The ARX model can be given as a Z transfer function, as follows in (4):

$$\frac{Y(z)}{U(z)} = \frac{b_1 z^{-1} + b_2 z^{-2} + \cdots}{1 + a_1 z^{-1} + a_2 + \cdots} \tag{4}$$

$a_1, a_2, \ldots$ estimated model parameters
$b_1, b_2, \ldots$ estimated model parameters
z Z domain operator.

According to (Ljung and Glad, 1994; Åström and Wittenmark) the parameter estimation of vectors' a and b in (4) can be computed using the least squares method. A process data set, comprising input-output data is fitted to the model structure, and the parameter estimation computing gives the parameters $a_1, a_2, \ldots, a_n$ and $b_1, b_2, \ldots, b_n$.

The ARX identification model was applied to a data set comprising the temperature TI-1 and heating power. The heating power was set randomly stepwise in 7 and 11 kW giving the response presented (Figure 7). Using the Matlab IDENT for the parameter estimation of an ARX model, the model parameters $a_1, a_2, \ldots, a_n$ and $b_1, b_2, \ldots, b_n$ could be estimated. The parameter estimation was based on a sampled data set with a sample time of 20 seconds. The heating power was switched to 7 and 11 kW, while the temperature TI-1 varied between 63 and 45 Celcius degrees. The first parameter estimation procedure using four a and four b parameters gave rather matching results (Figure 8), but the fitting procedure could be improved.

With eleven a, and ten b parameters the fit could be improved to be about 98 %. The modelling procedure should have been validated using another data set of the process experiment but the validation data was not available. Based on the PRBS process experiment of the pilot heat exchanger, the dynamic ARX model between the temperature TI-1 and heating power can be given using the model (4) where the estimated vectors a and b are:

a = [1.0000 -0.7586 -0.3667 -0.0649 -0.0215 -0.0870 0.1961 0.0999 -0.0810 0.1643 -0.0821]
b = [0 0.2742 0.0806 -0.0142 -0.0552 -0.0790 -0.1086 -0.0569 0.0160 -0.0528 0.0193].

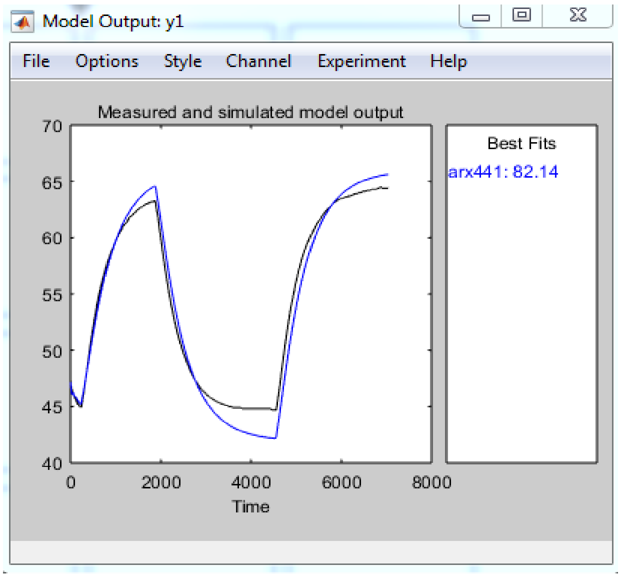

Figure 8. Simulated and ARX model responses, related to PRBS input data.

4 Conclusions

Positive - even attractive and entertaining - learning experiences are expected today also in the education of energy and power plant engineers in many countries. However, hard and some more difficult phenomena should be adapted, as well. Modelling and simulation of practical processes offer interesting learning experiences with many different aspects.

The experiences in learning the dynamics of heat transfer using an educational heat exchanger have been very positive. Combining the theory with practice has helped students to understand and analyze systems with some complexity. Firstly, first principle models based on nature laws could be modelled, constructed and simulated, and finally verified using experimental data. Secondly, based on step response tests, ready-made Laplace models could be parametrized, simulated and compared to the real data. Thirdly, based on PRBS response tests, discrete time series models could be parametrized and simulated.

Cooperative process experiments using the self-made heat exchanger system, modern control system tools, video recordings, photos and shared Moodle course materials with smartphones have been successful elements in the first learning phase. A further interactive analyzing, modelling and simulation phase using Matlab Simulink and Identification Toolbox tools deepened the learning and collaboration. It has been also encouraging to see that students don't have to manage "everything" in Matlab to be able to try basic analyzing, modelling and simulation methods. However, patience is needed in this kind of working. Several practical problems have to be overcome. This kind of a learning process offers a collaborative development environment both to students and teachers and from different disciplines, such as machinery, process technology and system engineering.

In the future, the educational heat exchanger will be provided with remote monitoring and operation in order to support flexible process experiments and data sampling. An interactive learning package based on the Moodle platform with touch-on instructions in plain language will be completed. A special attention will be paid to motivating tools and varying working procedures. Modelling and simulation aspects will be extended step by step. The dependence of specific heat capacity on temperature could be examined and included. Partial models will be collected to make an extended multivariable system model of the educational heat exchanger. The controllers could be provided by additional smart properties. Some parts and activities of this learning package could even be included in a web-based Massive Open Online Course (MOOC).

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