Process Control Education using a Laboratory Separation Process

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Abstract: This paper deals with description of learning objectives and activities for topics in automatic control, on a laboratory scale membrane separation unit. Students learn theoretically and practically various process loops and configurations. These are crucial in order to attain desired operation of membrane aided separation. Moreover, students need to design and implement human machine interface, local and remote operation, and to evaluate performance of basic and advanced control tasks.

Keywords: laboratory education, remote control, human machine interface, process control, membrane separation.

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1. INTRODUCTION

Methodology in control engineering education has evolved in the modern information era more than in its overall previous history. Due to the rise of various information technologies, new methods and approaches have been implemented to curricula and practical exercising was moved more towards the use of computer-aided learning.

The main goal of engineering educators is to prepare students for the real world outside academia, where they can apply their knowledge, experience, and practical skills to improve the progress in a particular field. Some of them will end up in industry, where the ability of solving practical problems is essential. This does not apply only for industrial practice, but also for other fields where young professionals can find their use. It is necessary not only to teach them what is the theory and where it came from, but also how this valuable knowledge can be applied to the real world situations.

In process control education, students need to come in contact with industrial plants to put the interconnecting pieces between theory and practice together, and to become skillful engineers. Different approaches or combination of them are used to achieve this goal. The methodology of educating students towards their practical professionalism depends on several factors. These are the number of students, availability of educational equipment, the standard of information technology of a particular institution, etc. Often, the demand is much higher than the number of actual training devices available, or the capacity of labs is the limiting factor. In these cases, educators usually opt for the use of virtual and remote laboratories. These two approaches became very popular in control education, and many educational institutions use them on a regular basis. The web-based approaches as discussed in Tzafestas (2009); Monroy et al. (2005); Sancristobal et al. (2014); Sumper et al. (2007) are being used nowadays to help students experience the practical side of process control. Some of the approaches are directly focused on industrial control systems (Golob and Bratina, 2013; Carrasco et al., 2013; Marangé et al., 2007). In recent years several remote laboratories have been deployed at our institute, improving our educational methodology (Kalúz et al., 2014, 2015). However, there are some disadvantages of virtual and remote laboratories as well. Virtual labs provide only computer simulations, and it is very unlikely that students will face the problems of real industrial world. Remote labs provide an access to real physical equipment, but they are mostly limited to small-scale and naturally safe processes. As the educational practice and research have proven, it is not suitable to focus on strictly hands-on, or remote control approach (Lindsay and Good, 2005), but rather to find some balance between them, and thus to provide students with some kind of freedom in selection of methodology.

In this paper, a fully equipped medium-scale laboratory plant is presented along with all the features that allow student to practice real world control engineering situations. The presented plant is a membrane separation process with supplementary control hardware and software that allows students to perform experimentation in the lab as well as remotely.

2. LABORATORY MEMBRANE PLANT

Membrane separation process as described in Cheryan (1998) and Zeman (1996) separates two or more different molecules from a solution, or from each other in a solution, using semi-permeable membranes. Membranes have found numerous applications in water purification (Mallevialle et al., 1996), desalination, TOC (total organic carbon) minimization, juice clarification, product separation, and purification (Crespo et al., 1994). The various driving forces for separation in membrane processes are concentration gradient, pressure, and electric potential. Pressure

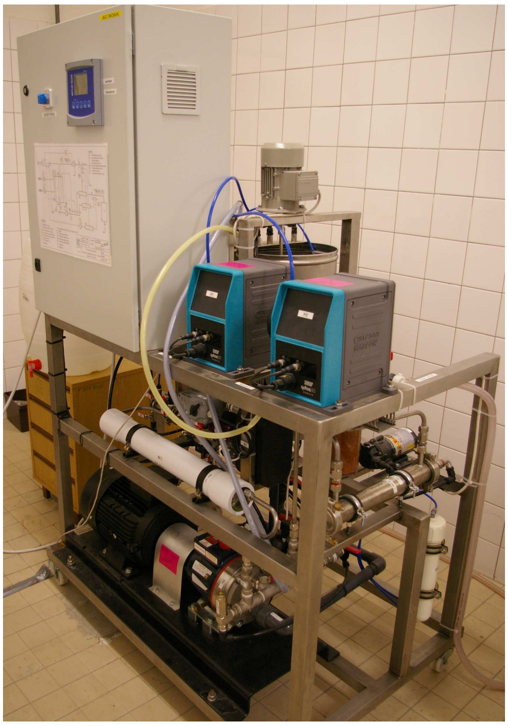


Fig. 1. Membrane separation plant.

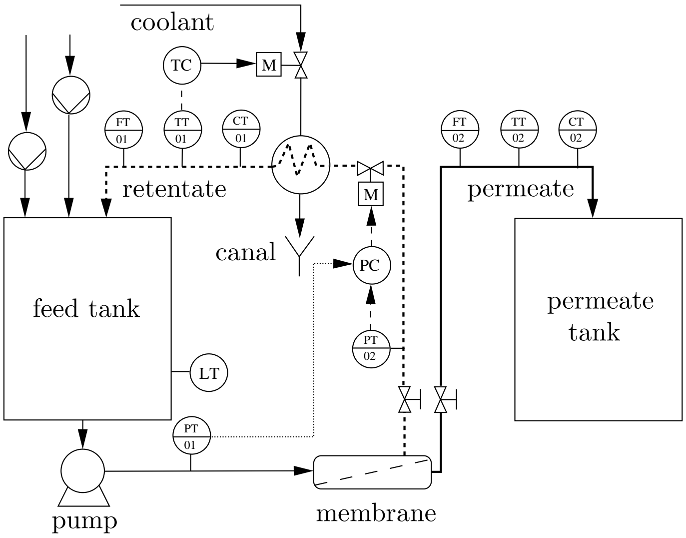


Fig. 2. Schematic diagram of membrane separation plant.

based membrane processes can be divided into micro-, ultra-, nano-filtration, and reverse osmosis. Every process has a range of pressure that can be defined by transmembrane pressure (TMP). The violation of these limits may damage the membrane and the plant, and hence negatively effect the process performance and product quality. Physical parameters i.e. temperature (Mänttäri et al., 2002) and pressure (Ahmad et al., 2013) play a big role in these membrane separation processes, and hence students must know to control them theoretically and practically.

The membrane separation plant (Fig. 1) installed at the Institute of Information Engineering, Automation and Mathematics (IAM), is represented in P&ID diagram in Fig. 2. The membrane separates the feed in two streams: retentate stream (dashed line in figure), i.e. the concentrated stream, and permeate stream (bold black in figure). In this plant, the possible membranes that can be used are ultrafilter (UF), nanofilter (NF), and reverse osmosis (RO).

As mentioned, these processes are highly influenced by operating parameters, such as temperature and pressure. The high pressure pump on the membrane inlet generates heat and increases the temperature. The other reason for heat generation is due to the fluid dynamics resulting in molecular frictional heat, and viscous heat. Therefore, the temperature needs to be controlled and maintained in a safe zone. As shown in Fig. 2, the process is equipped with a heat exchanger in order to cool the retentate returning to the feed tank. The plant has temperature sensors on both retentate and permeate sides.

Along with temperature, pressure too must be maintained between specific ranges, and hence the identification and control of the pressure is a necessity. The pressure of the process can be influenced by two inputs, i.e. by the pump located upstream to the membrane, or by the retentate side valve downstream to the membrane. The retentate side valve is motorized, and hence with the aid of pressure sensors located upstream and downstream to the membrane, students can study the effect of each input, and control the processing pressure.

The objective of applying membranes is to separate solutes (for e.g. lactose and NaCl) from a solution, till the desired concentrations of these solutes are achieved. Concentrations can be inferred from conductivity sensors installed on both permeate and retentate sides. The concentrations during the membrane processing can be altered with the help of a diluent (diafiltration), or the feed solution itself. This possibility of external input is accomplished by two extra pumps installed at inlets to the feed tank (Fig. 2). Depending on the diluent or a solution being added to the system during the run, the following modes can be defined on the process:

- no addition of diluent, i.e. concentration mode (C);
- diluent flow rate equals the flow rate of permeate leaving the system, i.e. constant volume diafiltration mode (CVD);
- diluent flow rate is not equal to the flow rate of permeate leaving the system, i.e. variable volume diafiltration mode (VVD).

The switching between these modes can result in saving costs and time to achieve certain concentration of product and impurities as explained in Paulen et al. (2013).

3. LEARNING OBJECTIVES

In the education process at IAM, students enroll for several courses focused on system identification, control design, plant optimization, and overall automation of industrial systems. These courses are supplemented by laboratory exercises where students can test the theory in practice. To provide them with even higher freedom in practical experimentation, students enroll courses focused on individual or group practical projects that are held at our laboratories or even in the facilities of our industrial partners.

The membrane separation process has found its versatile use in several courses such as the *Diploma project*, *Semestral project*, *Project of process control*, *Industrial control systems* and *Technical means of automation*. These courses/projects are available in the master's degree study programme at IAM. Since the projects are individual, students often choose to work on challenging topics such as the membrane separation process. This laboratory plant provides wide spectrum of problems that students can solve. These are for example:

- *Sensor/actuator calibration and signal processing* – Here students learn basic principles of sensors and signals. Moreover they find out fundamental relations between real physical quantities and their representation as electrical quantities used by a control equipment, and thus the necessity of sensor/actuator calibration and translation of measured signals to form comprehensible for both human, and the control system.
- *Identification of basic subsystems* – Most of the automated plants use several hierarchical levels of control. The most basic control loops are operating at the lowest level and are used to directly control the behavior of physical quantities influenced by actuators (pumps, valves, heaters, etc.) based on sensor readings (flow sensors, temperature sensors, conductivity, etc.). Students learn crucial relations between these inputs and outputs of physical system, and will be able to mathematically express their dynamics in order to design basic control loops.
- *Upper-level control design* At this level, students are encouraged to design more advanced control schemes, where more likely the overall operation of the whole plant is controlled, rather than basic subsystems. They apply knowledge of process optimization, observer design or predictive control.
- *Work with industrial network systems* Here students can test their knowledge in two different areas. Firstly, the information technologies for control system design that cover the composition of industrial network infrastructure, communications, technology interconnection, and overall human machine interface (HMI) design. The second area is the theory of stochastic control over network, where some interesting problems such as varying transport delays occur.

3.1 Communication and Operation

We consider various techniques for efficient communication between the sensors and the computer. The detailed description of techniques for signal transfer between various sensors and operator (PC) is described. All these technologies are used to read the necessary data via visualization.

Fig. 3 shows the overall communication setup of the laboratory membrane process. It is based on programmable logic controller (PLC) and industrial network router (INR). The PLC ensures the basic data acquisition and control tasks, and it is directly interconnected with the sensors and actuators of the membrane plant. The PLC is connected in the industrial Ethernet network which is used as the main communication network within the laboratory, where the plant and all supplementary control devices are located. The second industrial device that extends the network usage of membrane plat is the INR. The industrial router used in the setup is the eWON Flexy 203 (eWON, 2014), that can be described as a coupler for industrial controllers. The main features of this INR are:

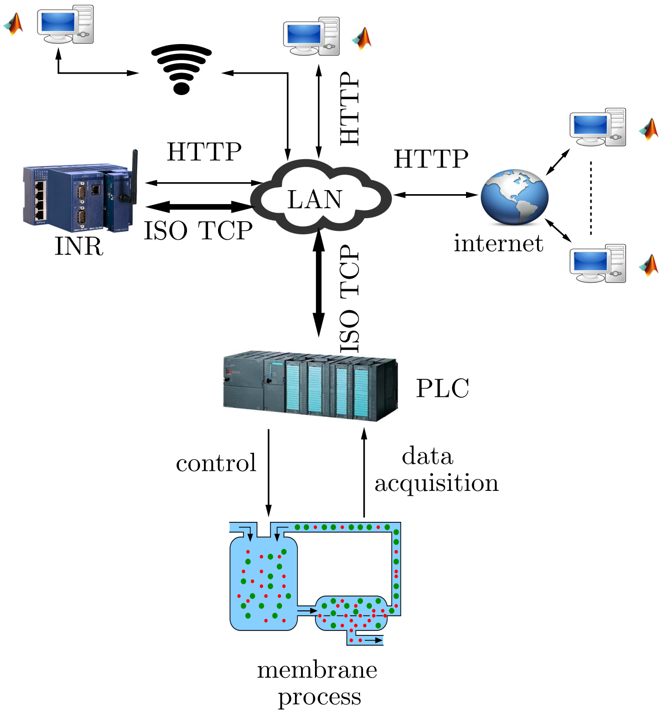


Fig. 3. Industrial communication and control devices connected to membrane plant.

- industrial protocol translation;
- direct access to PLC program variables (read/update);
- data acquisition from PLC;
- server-side script runtime environment;
- data and event logging;
- process security and alarms;
- FTP and Web server.

The main advantage of an industrial router is that it does not depend on the used protocols. This means that it allows universal communication with most of the industrially used equipments. The other important feature of INR is that it allows to access the internal program variables of PLC, through common HTTP, and hence allows to extend the plant's control system by various control environments that are capable of HTTP communication. These are e.g. Web-based applications and visualizations, MATLAB, Python programs, etc. Since the used industrial network is connected to wide area network, this allows the users to connect to INR from different locations, either to use direct connection through (local PC or WiFi), or indirectly from a remote location through the Internet.

This aids the users or students to directly work on the process, even if they are located outside the laboratory. Moreover, the user-friendly communication with the laboratory process through PLC and INR allows the students to develop visualization environment in MATLAB/Simulink or WinCC. The visualization schemes can be also used for remote control of the process where the students do not need to install the appropriate software (MATLAB/Simulink,

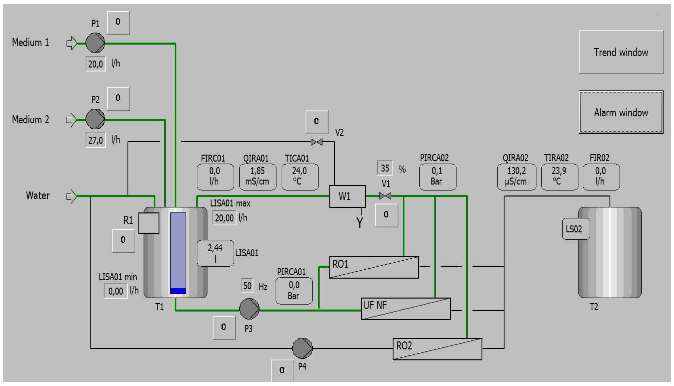


Fig. 4. Human Machine Interface (HMI) designed using WinCC flexible environment, to run and control the membrane plant.

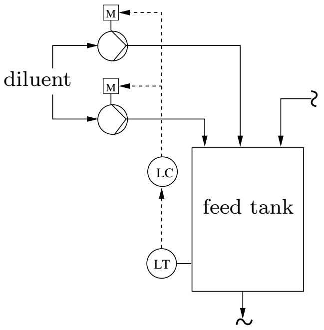
WinCC) on their computers and will communicate with the process through the Internet, where the visualization scheme is a part of a Web page. In such a visualization, the student or user will only set the desired values of parameters, e.g. of pressure and temperature. The corresponding signals for these desired values will be sent to INR, and finally through PLC these signals will be actuated on to the hardware.

The visualization is one of the most indispensable part in controlling the process. An example of visualization solution is shown in Fig. 4. The visualization is not only for effective reading of data from the sensors, but it also allows the students to control the individual parts of the process (e.g. pumps, valves, agitator). Moreover, in visualization the students can directly implement the process constraints for the pump, valve, feed level etc. Trends and alarms can be created for displaying and analyzing the values during long-term experiments. It is also worth mentioning that even though this visualization was done in WinCC, it is also possible to create it in MATLAB GUI, therefore enlarging the pool of possible projects for the students.

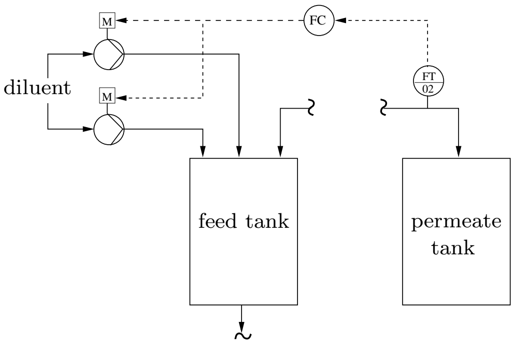
3.2 Process Control

The control loops provide challenges for the students in the implementation of standard (PID based) and advanced (optimal) controllers. Moreover, the challenges are not only in the tuning of the controllers, but also in their safe implementation. This means, that students have to account for all the possible safety issues encountered during the process operation. These are mainly the physical constraints like maximum/minimum flow rate, level, temperature, and pressure.

The first feed-back control loop deals with the control of the feed tank level by using peristaltic pumps as shown in Fig. 5. There are two possible ways to control the level in the feed tank. The first one directly manipulates inlet flows to the tank as shown in Fig. 5(a) using the level transmitter as sensor. The level in the tank can also be changed indirectly by manipulating the ratio between the diluent inflow and permeate flow (Fig.5(b)). In this case, the permeate flow sensor is used to indirectly account the decrease in system volume, and accordingly the pumps adjust the flow rate of diluent. For example, if constant level is desired; then diluant inflow rate rate from pumps is equal to permeate flow rate reading coming from the sensor. As mentioned earlier, the constraints that need to be identified by student are the maximum/minimum flow of the peristaltic pumps, and the maximum/minimum level in the feed tank.



(a) Direct feed tank level control with the aid of level transmitter.



(b) Indirect level control in the feed tank using ratio of diluent and permeate flows (permeate flow transmitter)

Fig. 5. Level control in the feed tank, for e.g. by using a diluent.

The other vital operating parameter is the pressure. Due to the external or internal rheological factors, the pressure during operation can vary. Therefore, the design of a controller to monitor and control pressure is a necessity. One of the possibilities to regulate the pressure during the separation of solutes is shown in Fig. 2. Two pressure transmitters are placed to account for the change of inlet and outlet membrane pressure. Based on the information provided by the transmitters, the controller (PC) opens or closes the retentate valve to increase or decrease the pressure in the system. Moreover, as mentioned above, by using different membranes, students need to account for different maximum/minimum operating pressures.

The last feedback loop is the control of temperature. In most of the food and chemical processes, it is vital to maintain constant and safe temperature during the operation because:

- It can adversely influence the physical and chemical properties of the solutes or molecules (for e.g. protein denaturation).
- It affects the properties and sensitivity of measuring sensors.
- It can damage the physical structure and can alter the chemical characteristics of the membrane.

In the membrane plant, the temperature is controlled by a heat exchanger as shown in Fig. 2, where the solution is cooled down by water from external source. Based on the information from the temperature transmitter (TT) the controller computes the appropriate control action. The valve for the coolant is only on/off type. The temperature has to be maintained in some reasonable interval where the properties of the solutes are not altered.

Higher level control strategies that can be investigated by the students include implementation and switching between different operational modes (e.g. C, CVD). These involve various lower level controllers described above. The switchings are dependent on concentration of solutes, and can be performed by obtaining the concentration indirectly from the conductivity transmitter (CT) installed on the retentate or permeate site, and by adding diluent through the peristaltic pumps at some controlled flow rate (Paulen et al., 2013). Therefore, all these control loops present a learning and interesting benchmark for the students, as during lectures they learn many techniques and methods for identification and process control. Moreover, as this plant is installed and ready with all the up to date industrial control and communication devices, the students can implement their process control knowledge, and use this experience in future for industry.

4. CASE STUDY

Different case studies are implemented here to study the general individual control loops, described in subsection 3.2. The membrane considered is of nanofiltration type. A solution containing salt and lactose is used for studying the control of pressure and temperature. In case of level control, distilled water is used, since the level is not influenced by solutes.

4.1 Control of Transmembrane Pressure (TMP)

TMP is calculated based on the inlet and outlet pressure of the membrane according to the following equation

$$\mathrm{TMP} = \frac{P_{01} + P_{02}}{2} - P_{\mathrm{atm}}, \qquad (1)$$

where P_{01} is the inlet membrane pressure (absolute feed pressure), P_{02} is the outlet membrane pressure (absolute retentate pressure) and P_{atm} is the atmospheric pressure (permeate pressure). This information is computed in the controller part and the controller actuates the corresponding opening of the valve. A proportional controller was implemented, but in future the students have an opportunity to design and implement a better performing advanced controller.

Fig. 6 shows the desired TMP, i.e. 25 bar (dashed red line) and the measured TMP (blue line). The designed controller was sufficiently good to maintain TMP at desired value, with an acceptable error margin of 0-5 % from set point, and despite of changing concentration (increase in lactose from 80 to 450[g/L]).

4.2 Control of Temperature

The second case considers the control of the retentate temperature. Fig. 7 shows the control of temperature to a desired value (red dashed line) of 25 °C (± 0.5 °C). It is again worth mentioning that the laboratory membrane plant is installed with an on/off type valve for the coolant input. This too presents as an interesting task for students, to get insights into the hardware of the process, and design better solutions for temperature control.

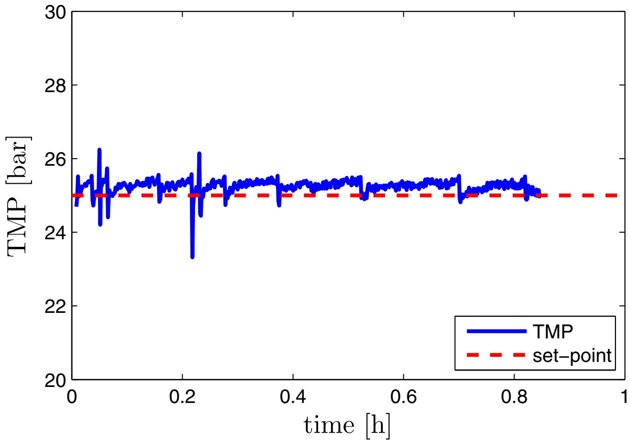


Fig. 6. Control of transmembrane pressure.

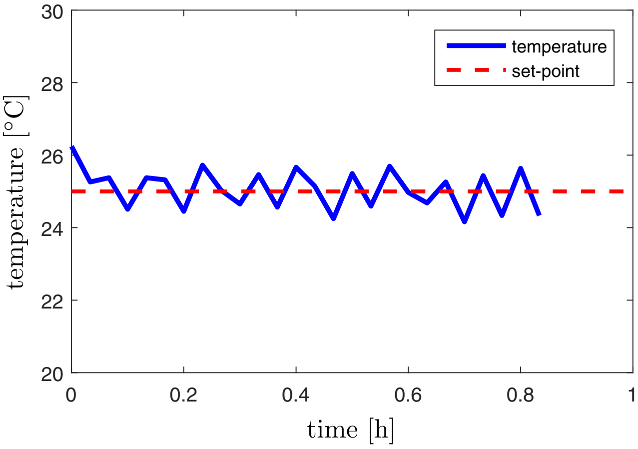


Fig. 7. Control of retentate temperature.

4.3 Control of Level in Feed Tank

The next case presents an example of maintaining steady level inside the feed tank, as explained in Fig. 5(a). A proportional controller was implemented to achieve this constant volume separation. The results could be studied from Fig. 8. Distilled water volume was first reduced from 4.25 L to 3.8 L and then controlled at this value (± 0.1 L). As we can notice in the figure, the volume or level monitored by the sensor suddenly jumps to a lower value and then returns back. On detailed study, it was identified that this trend was a result of temperature regulation. As the temperature crosses the set point, the coolant valve opens and suddenly the process temperature falls below the set point due to a high temperature difference between coolant and process fluid. That alters the sensor reading of the feed tank volume or level. The level sensor on this plant is based on pressure forced by the liquid/solution in feed tank, and these pressure based sensors are prone to changes in temperature. The students can research on solving such a problem by checking the wires, changing

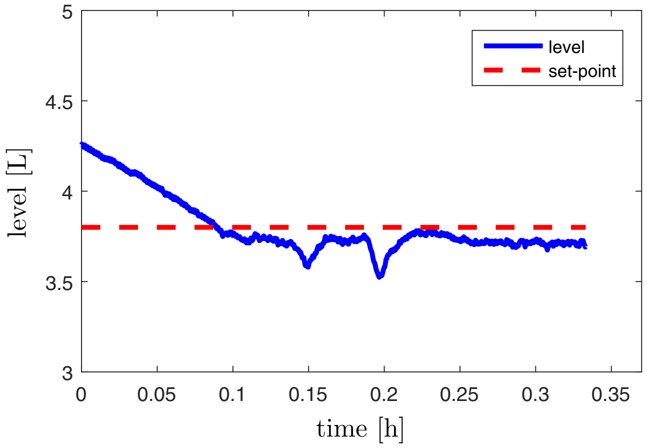


Fig. 8. Level control in feed tank.

the controller, modifying the coolant source, and by using a pre-heater, etc.

The closed-loop control cases studied above represent the common issues in the process control field and industry. Therefore, this laboratory plant provides a suitable working device for the students to learn and perform diverse experiments with general or advanced control loops on a single unit.

5. CONCLUSIONS

This paper illustrates the advances in learning process control, with the aid of a laboratory scale – membrane separation unit. The paper discusses the importance of informatics and automation in the field of process control for up to date education of students. The aims of education included design of the human machine interface and process visualization, local and remote control of process using modern industrial communication devices. The basic control loops can be examined and tuned. On the higher level, advanced control strategies can be proposed to optimize the plant operation. The understanding of separation using membranes was introduced in order to identify and control the critical parameters influencing the process.

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