ELSEVIER
Computers and Chemical Engineering 24 (2000) 1063–1068
Computers & Chemical Engineering
www.elsevier.com/locate/compchemeng

An RT-Linux based control system of a pilot plant for reaction kinetics and process control studies

Andrei Romanenko, José A.A.M. Castro *

Department of Chemical Engineering, University of Coimbra, Pólo II, Pinhal de Marrocos, 3030-229 Coimbra, Portugal

Abstract

The pilot plant under study is designed for determining the kinetics of the heterogeneous non-catalytic reaction of chemical pulping of wood and for teaching system dynamics and batch process control in an appropriate university course. The natural complexity of the system includes time varying dynamics and stepwise behavior and this makes it attractive for highlighting some important features of the real world of process control. Due to its specific design, the pilot plant is also very useful for kinetic studies of heterogeneous reactions involving wood, ensuring a high level of the repeatability of results. The pilot plant and its control system have been used in teaching of chemical kinetics of heterogeneous reactions and are also part of the experimental program in a process control course.

Keywords: Process control; Pulping kinetics; Real-time operating system; Experimental process control education

1. Introduction

There is no doubt that system dynamics and process control are very important subjects in chemical engineering education. These can provide students with the necessary theoretical background in fundamental and modern techniques as well as with the so widely spoken 'hands-on experience'. However, as Cleat (1994) points out, often the corresponding course becomes 'another mathematical course' and the link between theory and the real world tends to be very weak due to many reasons, particularly, to the cost of the pilot equipment on which students can carry out their experimental work, to safety concerns, and to the time necessary to complete an experiment. The use of process simulators has, therefore, increased sharply enabling students to get acquainted with a larger number of processes and to carry out 'experimental' work in a shorter period of time. Many process simulators for teaching system dynamics and process control have been developed and reported in *Chemical Engineering Education* in the last years (Cooper, 1993; Davis, 1995). A number of educators, though, have pointed out that while the use of simulators is undoubtedly beneficial, it fails to provide students with the real engineering practice. This urged the development of new experimental rigs that vary from simple systems to integrated laboratories. Lennox and Brisk (1998) and Skliar, Price and Tyler (1998) employ the distributed control system concept, an approach widely used in industry. The range of data acquisition and control software is represented by custom software (Conner Jr., 1990) and proprietary packages, such as FOXBORO PW-FB (Coughanowr, 1993), LABVIEW (Davis, 1995), GENESIS (Lira, 1992), LABTECH NOTEBOOK software (Vasudevan, 1993), MATLAB/SIMULINK (Badmus, Grant & Shah, 1996), and others.

In her work, Carvalho (1999) describes a typical experimental rig for the Kraft pulping of wood that consists of a vessel where the temperature is controlled by a conventional PID controller. Only temperature profiles are available at the end of a batch, leaving out other important information, such as density and conductivity profiles that can be very useful for studying the kinetics of the process. Moreover, it is difficult to ensure that from batch to batch the wood is exposed to the same pulping conditions. Each complete experiment takes between three and four hours and since one needs to have several data points to determine the kinetics, it calls for a significant time investment, which makes it difficult to use in a university course.

* Corresponding author. Tel.: +351-239-798700; fax: +351-239-7698703.
E-mail address: eq1jmc@eq.uc.pt (J.A.A.M. Castro)

0098-1354/00/$ - see front matter
PII: S0098-1354(00)00527-5

In this work we describe an experimental set-up that can be used in two university courses: first, system dynamics and control — its complexity can introduce students to the real world of batch process control of a time-variant system; second, Kraft pulping of wood — it significantly reduces the time needed for acquiring a reasonable number of experimental points for determining the kinetics of such liquid solid reaction.

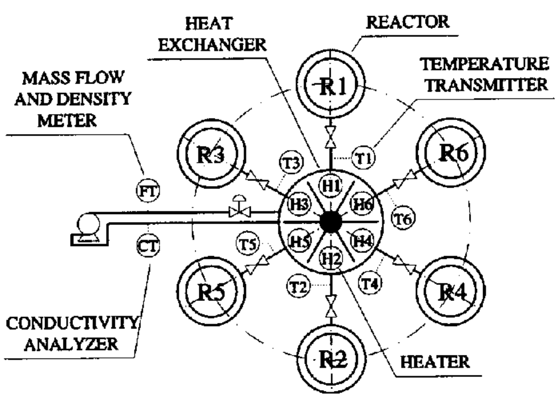

Fig. 1. Reaction unit. Top view.

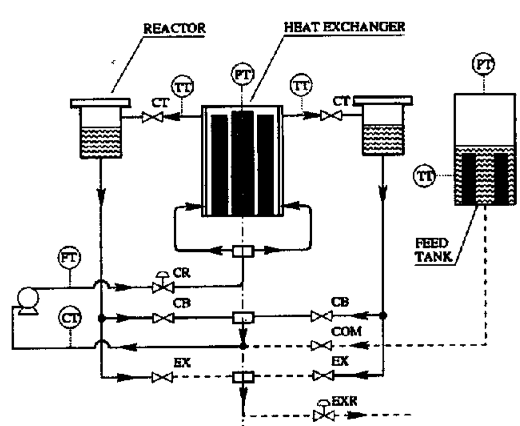

Fig. 2. Simplified scheme of the reaction unit.

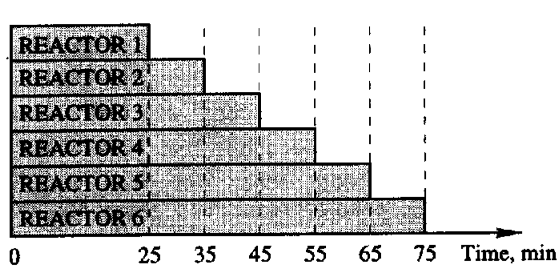

Fig. 3. An example of pulping experiment schedule.

2. Pilot plant

2.1. Description and operation

The reaction unit consists of a set of six equivalent flow through reactors in which wood chips are exposed to a circulating liquid flow containing the Kraft pulping chemicals (see Fig. 1). The reaction is highly dependent both on the temperature and on the concentration of liquid reactants. During an experiment the reactors are sequentially shut off in order to stop the reaction and to sample the wood and liquid at different cooking times. The energy required for the chemical reaction is supplied by a 15 kW heat exchanger equipped with six electrical resistances that provide independent heating of the liquid streams circulating through each reactor. As shown in Fig. 1, each heater is dedicated to the control of temperature in the corresponding reactor, although it is not fully isolated from the other heaters allowing for temperature compensation at high energy levels. At the bottom of the system (Fig. 2) the flows leaving all the pressure vessels are mixed to ensure the same concentration history. Each reaction unit branch is equipped with a PT100 temperature sensor (Fig. 1). At the top of the heat exchanger a pressure transmitter measures the total pressure in the system and the unit is also equipped with a mass flow meter providing online flow rate and density measurements, and a conductivity analyzer. The pilot plant's actuators include nineteen on-off valves, a pneumatic control valve, and a circulating pump. A typical pulping experiment is carried out as follows — at the beginning, the cooking liquor is preheated in the feed tank up to a specified temperature (Fig. 2). Afterwards, wood chips, fully impregnated with water, are loaded into the preheated reactors and the hot cooking liquor is transferred into the reaction unit through the valve COM and the system is pressurized with nitrogen. The pump and the temperature control system are turned on to maintain continuous circulation of the liquid reactants and to provide a pre-specified time history of temperature similar to that often used in the pulp and paper industry. As the experiment proceeds, according to a given sampling strategy (Fig. 3) the reactors are sequentially shut off and depressurized. Samples of cooking liquor are collected during this depressurization step and the wood chips are taken for chemical analysis. Therefore, with this equipment and the above operating strategy it is possible to obtain six experimental points of the Kraft pulping of wood at different times in a single experiment.

2.2. Data acquisition and control system

Many old control systems comprise of several digital computers that work under different operating systems

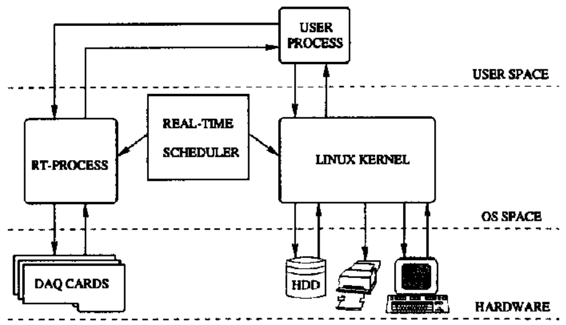

Fig. 4. Data flowchart.

according to the function each of them is expected to perform — the trend that was caused by the need for a distributed control system (DCS) environment, or by the fact that it was impossible to perform all operations on a single computer due to its resource limitations. Usually, in such configuration the computer that carries out data acquisition and actuation works in a single task mode under a light-weight operating system, e.g. MS-DOS in order not to hinder its performance, while the controller and graphical user interface run on a different computer that is specifically designated for this task (Afonso, 1998). The slave computer communicates with the host graphical workstation over a local area network. In recent years, the computational power of personal computers has vastly increased, making it possible to create control systems using a single computer system only, provided that the application is reasonably small and does not require a DCS. One of the drawbacks of this architecture is that if one tries to use a general purpose operating system, a resource bottle-neck can arise, deteriorating the performance of the data acquisition task when the system is under significant load. This can be overcome by the use of real-time operating systems and by dividing tasks into two groups — real-time tasks and nonreal-time tasks. A large number of industrial applications use proprietary real-time operating systems, such as QNX, WxWorks, Windows NT with RTOS extensions. The first two are inherently capable of controlling a hard real-time system (i.e., a system, whose response to an external event is guaranteed to meet a certain deadline) and have technical and customer support, but they are considerably expensive. In their articles, Timmerman and Monfret (1997a,b) showed that Windows NT can be used for developing a soft real-time system (i.e., a system, whose response to an external event is statistically defined) as it is, but there is a need to take special measures in order to enable Windows NT to perform hard real-time computing. In any case, the cost of Windows NT with all required extensions is a factor, as well.

Linux is a UNIX-like operating system that has grown from a project of the original author, Linus Torvalds, into a modern open source free operating system. Many programmers worldwide have contributed to its development, and according to http://www.linux.org/info/index.html there are dozens of ongoing projects for porting Linux to various hardware configurations and purposes. An important extension of Linux, developed at the New Mexico Institute of Mining and Technology and enabling it to work as a real-time system is RT-Linux (Barabanov, 1997) where a small real-time kernel coexists with the POSIX-like Linux kernel. Real-time tasks may have higher priorities compared to the Linux kernel, and may preempt it in order to meet deadline requirements. Success has been reported in using RT-Linux in such areas as meteorology (Wright & Walsh, 1999) and medicine (Cristini, Stein, Markowitz & Lerman, 1999), but there have been no reports on using this operating system in the area of chemical engineering. In this application, the data acquisition and control system runs under RT-Linux Beta10, Linux kernel 2.2.10, RedHat Linux 6.0 operating system on an APPRO 5U industrial PC. The rack mount chassis contains a 14 slot passive backplane, a CP-MA51 single board computer with a Pentium MMX 200 MHz and 32 MB RAM onboard. Six data acquisition and control boards from Computer Boards Inc. provide 24 4–20 mA analog input channels, 16 0–10 V analog output channels, two 4–20 mA analog output channels, as well as 48 isolated digital input channels and 48 digital output channels.

The control code consists of two processes — a time-critical task, containing hardware drivers and necessary scheduling code, and a non-time critical task processing the data and running a graphical user interface. The first task is designed as a real-time module that can be dynamically loaded into the memory. It directly interacts with the hardware and does not need operating system resources, such as access to file systems and networking. The second task is a general user-space UNIX process. The two processes communicate over two first-in-first-out (FIFO) channels (Fig. 4). For a large amount of data, shared memory regions can be used for interprocess communication. Both the Linux kernel and the RT-process are supervised by the real-time scheduler. The former is treated as a low priority real-time task and runs only if other RT-processes are idle. The resulting system has features both of a modern UNIX system with all appropriate services at hand and of a hard real-time system able to meet timing requirements typical for processes under control. Besides, its modular architecture simplifies further development, which is an important issue for an educational tool.

The graphical user interface, based on the XForms library version 0.88, allows the user to monitor data from all the installed sensors and transmitters and to closely follow the current operating modes of each reactor. Using GUI controls, one can also operate the actuators. The interface has two graphic plot windows in which temperatures, conductivity, density, mass flow rate, and pressure are continuously displayed.

3. Discussion of results

The reaction unit can be considered as a set of six piecewise time-variant SISO systems and is controlled by six independent feedback PID controllers. A number of step response runs were carried out in the normal operating temperature region in order to determine initial estimates for the PID constants. These parameters were determined using the Cohen and Coon design relations and further refined in experimental runs; the resulting values for this set of experiments are as follows: $K_c = 3.0$, $\tau_1 = 7.0$ min and $\tau_2 = 0.2$ min.

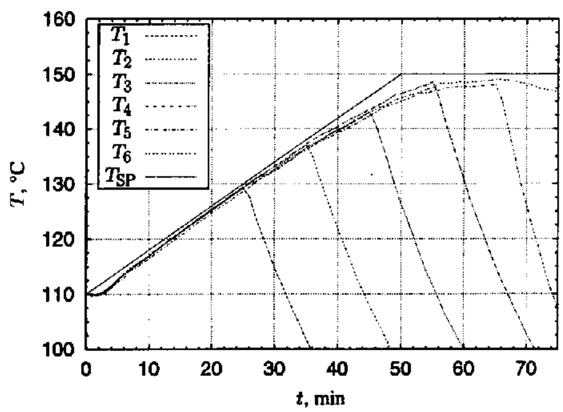

Fig. 5. The heaters of disconnected branches are turned off.

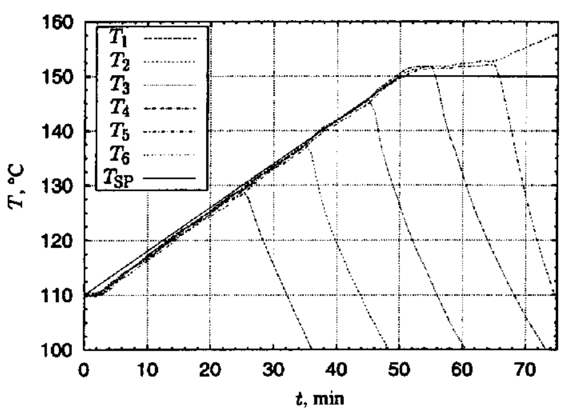

Fig. 6. The heaters of disconnected branches are set to 50% of maximum power.

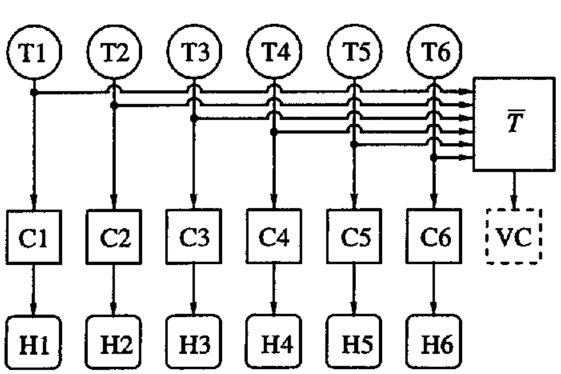

Fig. 7. Control scheme: Reactors 1–6 are on.

The control problem is complicated by the fact that when one of the reactors is switched off, the global thermal dynamics of the system changes. Thus, manipulating all the six heaters with one controller is not appropriate because when one of the reactors is shut off, the liquid flow rate through the corresponding heat exchanger's compartment dramatically decreases. This may give rise to overheating of the equipment and cause mechanical damage to the structure. To avoid this, each heater is then controlled independently by a distinctive PID controller. Numerous experiments have shown that it is not acceptable to fully disable the heater associated with a given reactor when its operation is interrupted because the remaining power of the heat exchanger may become insufficient to compensate the heat losses to the environment. As can be seen in Fig. 5, this effect is especially pronounced at the end of the experiment. Another possible control policy is to set up the heaters of disconnected branches at a fraction of the corresponding available power. This setting depends on the working temperature of the system, ambient temperature, and the mass of wood and liquid in the system. As illustrated in Fig. 6, when such setting is made equal to 50% of the full power provided by each heater, the system's behavior during the heating up period is better than that shown in Fig. 5; nevertheless, overheating can be observed at the end of the experiment. In a heuristic approach we use a seventh *virtual controller* (VC) whose purpose is to manipulate the power that becomes available as the branches are being disconnected. Its parameters ($K_c = 2.5$, $\tau_1 = 60$ min and $\tau_2 = 0.04$ min) were tuned to ensure satisfactory system responsiveness while eliminating inappropriate overshoot and oscillations. The input of this VC is calculated as the average temperature in the working branches. The structure of the control system at the beginning of the experiment is illustrated in Fig. 7.

In this situation, controllers C1–C6 receive feedback from the corresponding sensors T1–T6 and actuate heaters H1–H6. Although the VC makes use of the average value of such temperature readings, its actual output is not used. As the experiment proceeds, the reactors are sequentially stopped and the structure of the control system changes accordingly, as highlighted in Fig. 8 for a situation where Reactors 1, 2, and 3 have been stopped. In this case, the individual control loops of Reactors 4, 5, and 6 remain fully active and sensors T4–T6 also provide feedback to the virtual controller

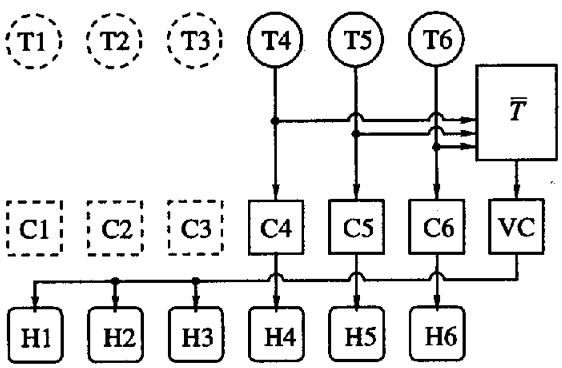

Fig. 8. Control scheme: Reactors 4–6 are on.

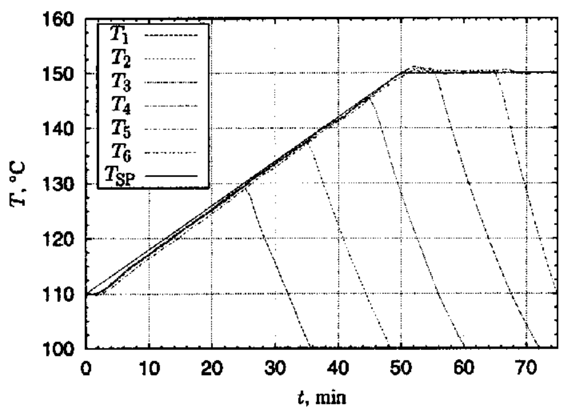

Fig. 9. The heaters of disconnected branches are operated by the virtual controller.

that is actuating heaters H1–H3. As can be seen, even in the absence of feedback from the sensors in the disconnected branches all the heaters are used throughout the experiment providing bumpless time history of temperature despite the abrupt online reconfiguration of the system (Fig. 9). This is critical because chemical reactions that take place in the process of Kraft pulping are very sensitive to temperature. Furthermore, such controller performance contributes to the reproducibility of results of the kinetics studies, which is of paramount importance in heterogeneous reaction systems involving natural products, such as wood.

4. Conclusions

A temperature control system for a complex pilot plant to study the kinetics of a heterogeneous non-catalytic liquid solid reaction was developed. Since the controllers are all software based, it is also possible for the students to investigate different control structures, including model predictive strategies, and to evaluate the corresponding performances. The advantages of the chosen system structure were outlined, emphasizing the pertinence of its use in appropriate university courses. A heuristic approach to ensure bumpless state transition and adequate set-point tracking showed clearly favorable results. The use of a freely distributed operating system with a real-time extension was justified. This experimental set-up is currently in use to teach batch process control and Kraft pulping of wood to students engaged in a Masters course at the University of Coimbra.

Acknowledgements

The authors are grateful to the Ministry of Science and Technology for financial support under project PRAXIS 3/3.2/PAPEL/2327/95. Andrei Romanenko is thankful to the program PRAXIS for his scholarship PRAXIS XXI/BD/19609/99. The efforts of the authors who have contributed to the development of Linux OS and RT-Linux are acknowledged.

References

Afonso, P. A. F. N. A. (1998). *Produção assistida por computador na indústria dos processos químicos*. Ph.D. thesis. University of Coimbra.

Badmus, O., Grant, F. D., & Shah, S. L. (1996). Real-time, sensor-based computing in the laboratory. *Chemical Engineering Education, 30*(4), 280–289.

Barabanov, M. (1997). *A Linux-based real-time operating system*. M.Sc. thesis. New Mexico Institute of Mining & Technology.

Carvalho, M. G. V. S. (1999). *Efeito das variáveis de cozimento nas características químicas de pastas Kraft*. Ph.D. thesis. University of Coimbra.

Cleat, W. R. (1994). Process control education: an academic perspective. *Pulp Pap. Can., 95*(1), 57–60.

Conner, W. C. Jr. (1990). Incorporation of process control computers in the undergraduate laboratory. *Chemical Engineering Education, 24*(2), 106–116.

Cooper, D. J. (1993). Picles — a simulator for teaching the real world of process control. *Chemical Engineering Education, 27*(4), 176–181.

Coughanowr, D. R. (1993). Microprocessor-based controllers at Drexel University. *Chemical Engineering Education, 27*(4), 188–192.

Cristini, D. J., Stein, K. M., Markowitz, S. M., & Lerman, B. B. (1999). Practical real-time computing system for biomedical experiment interface. *Annals of Biomedical Engineering, 27*, 180–186.

Davis, R. A. (1995). Create virtual unit operations with your data acquisition software. *Chemical Engineering Education, 29*(4), 270–274.

Lennox, B., & Brisk, M. (1998). Network process control laboratory. *Chemical Engineering Education, 32*(4), 314–317.

Lira, C. T. (1992). Computer control of a distillation experiment. *Chemical Engineering Education, 26*(1), 38–43.

Skliar, M., Price, J. W., & Tyler, C. A. (1998). Experimental projects in teaching process control. *Chemical Engineering Education, 32*(4), 254–259.

Timmerman, M., & Monfret, J. C. (1997a). Evaluating Windows NT real-time extensions. *Real-Time Magazine*, *2*. http://www.realtime-info.be/encyc/magazine/97q2/winntext.htm.

Timmerman, M., & Monfret, J. C. (1997b). Windows NT as real-time OS? *Real-Time Magazine*, *2*. http://www.realtime-info.be/encyc/magazine/97q2/winntasrtos.htm.

Vasudevan, P. T. (1993). A comprehensive process control laboratory course. *Chemical Engineering Education*, *27*(3), 184–193.

Wright, C. W. & Walsh, E. J. (1999). Hunting hurricanes. *Linux Journal*, *58*. http://lidar.wff.nasa.gov/sra/lj98.