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Distributed Wireless Liquid Level Control of a Process Simulator Over a Network

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Abstract In a process simulator, the distributed wireless liquid level control experiments have been performed by using the generalized predictive control algorithm. The wireless local area network was established with antennas between process simulator in Unit Operations Laboratory and the computer in Process Control Laboratory. We performed the online wireless experiments with MATLAB/Simulink program. Data transfer during the wireless experiments were carried out using radio waves at a frequency of 2.4 GHz. Experiments on the same conditions were achieved by three certain values of control weighting factor in the controller algorithm, whilst the changes in valve opening and liquid level with time were monitored. In all experiments performed with the distributed control system, the control valve opening is fixed with very small oscillations after a sudden increase in the beginning. We obtained the best liquid level control response to different set point changes for the same set of controller tuning values. The Integrated Square of the Error and the Integrated Absolute of the Error values were chosen as performance criteria. The distributed wireless liquid level control was effectively realized to the process simulator and it is recommended for industrial applications.

Keywords Distributed wireless control · GPC algorithm · Liquid level control · Performance criteria

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1 Introduction

Distributed wireless control systems collect the data from various points without cable. The exchange of information takes place with electromagnetic cables radiating in the air. Since there is no cable connection, it can be moved easily. Also space and time constraints for the users are getting out of the way. The installation of the system is faster and simpler. Wireless communication with radio waves is well-suited in natural areas such as mountains, hills, rivers, etc., where wired communication is difficult [1]. Furthermore, they are improved to assure a very stable, precise and robust process to deal with complex problem domains [2].

Variables involved in an industrial process; Flow rate, liquid level, temperature, pressure, concentration, etc. Computer-aided control of industrial processes with the development of computer systems minimizes the variability in production quality and provides a real benefit in terms of system variables in real time. In addition, the large number of process variables makes it necessary to instantly and continuously control these variables with online computers. In order to obtain products in the chemical industry, operating conditions must be well defined and these operating conditions must be kept at the desired value. Reduction of the difference in production quality can be achieved by monitoring system variables in real time as well as by monitoring the effects of load on the system and by detecting the changes that may occur during production online [3].

In recent years, studies on generalized predictive control (GPC) have increased. The GPC estimates the system output taking into account the time to take a numerous samples. Recently in measurement and monitoring works, the wireless network demands has grown greatly, such as agriculture [4], environmental [5], health monitoring [6], logistics [7] and industrial [8], etc. Bluetooth, Zig-Bee [9] and Wi-Fi are well-suited technologies for data handling. Process simulator which carried out wireless temperature control was modelled with linear parametric SISO model. For the different order ARMAX models, the parameter identification is done by means of least square method [10]. Generalized Predictive Control (GPC) algorithm was applied to a process simulator which wireless temperature experiments were achieved and the results of the experiments were compared under the same conditions obtained [11].

The system model should be adequate to identify the system by taking the input and output data with the well-suited sampling interval so that the GPC control system works well for the systems that its parameters change over time. This controller is also effective for open-loop unstable, non-minimum phase and variable dead time systems. The explicit root locating self-tuning controllers may not be adequate for those with a higher model order, although they control varying dead time systems [12].

In this work we applied a fully connected GPC algorithm. While the exchange information was realized over a wireless network where environmental limitations and bandwidth constrains may restrict the distributed controller, this algorithm was carried out a reasonable trade-off between system performance and the communication information.

2 Related Work

2.1 System Model

This autoregressive integrated moving average with external input (ARIMAX) model is the most appropriate when the system disturbances consist of a random drift which can be described by integrated white noise.

In the present work, ARIMAX model [12] used is given in Eq. (1)

$$Ay(t) = Bu(t-1) + \frac{C}{\Delta}e(t) \tag{1}$$

A pseudo-random binary sequence (prbs) is introduced as a disturbance function to identify the transient behavior. The prbs applied was changed between 10 and 65% valve openness to disturb the process without control. The system model parameters were determined by using MATLAB System Identification toolbox.

2.2 Generalized Predictive Control (GPC)

It is noted that the GPC algorithm is an attractive objective function to attain stable control of processes in which the system model orders, parameters and dead-times may change with respect to time. It is implementable to a process which is simultaneously open-loop unstable and non-minimum-phase and whose model is over-parameterized [13–16]. All industrial processes are exposed to load signals which are possibly to be in form of random steps at random times in the deterministic case or of random walk in stochastic systems. To obtain offset-free closed-loop performance in the face of such loads, the controller must have inherent integral action. It is well-known that the GPC algorithm maintains an integrator. Therefore, the GPC was applicable to many processes such as distillation columns [17], reactive distillation columns [18], polymerization reactors [19], exothermic chemical reactors [20], pH neutralization of a tubular flow reactors [21], biochemical processes [22, 23], power plant [24] and flotation plant [25]. In various applications of these processes, the necessary exchange information may be obtained over a digital networked environment among subsystems [26].

The setpoints associated with the GPC control method are defined in vector form as follows;

$$[r(t+j)]; \quad j = 1,\ldots N_2 \tag{2}$$

In most cases r(t + j) is taken equal to the constant r(t). In some cases, future changes in r(t + j) are known. A linear approach to r is taken into account at the output y(t) of t. If this relationship is represented by a simple first-order model,

$$\mathrm{r}(\mathrm{t}+\mathrm{j}) = [\alpha\, \mathrm{r}(\mathrm{t}+\mathrm{j}-1) + (1-\alpha)\, \mathrm{r}(\mathrm{t}+\mathrm{j})]; \quad \mathrm{j} = 1, 2, \ldots] \tag{3}$$

For $\alpha \cong 1$, the future setpoints are equal to the actual setpoint. GPC can also be applied to future setpoint changes.

The aim of the GPC control method is to approximate the future system outputs y(t + j) to r(t + j), as shown below. Control activity requires realization. In order to make GPC control design, the cost function is firstly minimized.

$$J(u,t) = E\left\{\sum_{j=N_1}^{N_2} (y(t+j) - r(t+j))^2 + \lambda \sum_{j=1}^{Nu} (\Delta u(t+j-1))^2\right\} \tag{4}$$

N_1: Minimum cost horizon, N_2: Maximum cost horizon, r(t): setpoint. The setpoint is chosen as the path that should be followed by the system output. A positive constant variable λ (control weighting factor) acts as a weight to reduce the error in the control. It makes the necessary control adjustment.

In the optimization process, the cost function takes into account future system output and Nu as well as the future setting variable. One of the important assumptions of this algorithm is that the actual system delay takes a value between N_1 and N_2. The GPC setting parameters are selected according to the conditions shown below.

2.2.1 Minimum Output Horizon N_1

If the dead time of the process is known exactly, N_1 should be taken equal to k. If N_1 is smaller than k, unnecessary calculations are done. If k is unknown or variant $N_1 = 1$ is taken and B polynomial in Eq. (1) is generalized to include all k values. For this reason, the N_1 value is not generally used as a design parameter. *Maximum Output horizon N_2*: Generally large values of N_2 are used in practice and a value close to the process rise time is selected. *Controlling Horizon Nu:* Generally, setting Nu = 1 provides an acceptable control. Increasing the control cost horizon causes the control to be more active. This activity is up to a point. Increasing the subsequent Nu value is suitable for complex systems. *Control Weighting Factor λ*: If $\lambda = \delta$ (a small value), It is considered a good control setting.

The GPC criterion is chosen to optimize J(u, t). This practice includes Diophantine equations.

ARIMAX model represents the system. For the estimation of the output variables for the j step forward, the Diophantine equation needs to be solved.

2.3 Wireless Process Control

The wireless control applications have several advantages such as reduced operational costs, scalability and easy-upgrading.

We compared the GPC strategy applicability of the present work with the previous studies in Table 1. The wired GPC control applicability to a waste heat recovery system and to a pH, neutralization process was shown respectively in [21, 24]. In [27] the wired cascade GPC control application to a boiler drum level was achieved. It was noted that its performance was better than the well-tuned cascade PID controller performance. For use in control systems, wired communications has been conventionally utilized. The access capability limitations of this communications make wireless communication become popular in plants. The wireless GPC strategy was applied to a heating process operating on a simulator and its applicability was demonstrated in [11]. We implemented the GPC strategy to the liquid level process of a simulator with wireless communication in the present work.

3 Equipment and Procedure

3.1 Process Simulator

We carried out Experimental studies in the Cussons P3005 model Process Control Simulator and the distributed wireless communication system was established to provide data transfer between the system and the computer. A number of modifications were applied to the process control simulator for addition of the distributed wireless control system. For this purpose, two antennas are installed to provide data transmission between the system and the control room in order to provide communication between the computer and the system. The liquid level control, the heater, the pressure control valves are calibrated and

Table 1 Comparison of the present work with the previously published studies

Control strategy	Communication type	System	Applicability	Ref. no.
GPC	Wireless	A liquid level process simulator	Successful	The present work
GPC	Wireless	A heating process simulator	Successful	[11]
GPC	Wired	A pH neutralization process	Successful	[21]
GPC	Wired	A waste heat recovery system	Applicable	[24]
Cascade GPC	Wired	A boiler drum level process	Performed better than the well-tuned cascade PID controller	[27]

their outputs are connected to the modules. These modules contain the transmitted data between the two antennas. The other part of the process control simulator is the panel where the electronic circuits are located. This pan can control and measure temperature, liquid level and flow rate. New equipment was added for distributed wireless control and measurement. Figure 1 shows a modified process control simulator with distributed wireless controller.

There are a liquid storage tank for feeding to the system with a pump, a jacket cooler in which network water flows, two glass tanks that contain water in the system, an electricity level control valve (CV1), a control valve (CV2), an orifice meter for measuring the flow velocity, a transmitter for converting the differential pressure to liquid level, a fuse that automatically closes the pump to prevent overflow of the liquid, a pneumatic pressure controller indicator, a pneumatic pressure transmitter, a pneumatic pressure control valve. There are also two regulators in the system that delivers air from the compressor to the air at the desired pressure. In addition, there are manually adjusted valves in the system to create four different test setups [28].

3.2 Wireless Control Procedure

One of the antennas in Process Control Laboratory is connected to the computer where MATLAB/Simulink program was utilized and the other is mounted on the control panel of the process simulator in Unit Operations Laboratory. The radio waves [11] at a frequency of 2.4 GHz were used for data transfer in the present work.

Distributed wireless liquid level control experiments were performed using GPC algorithm. Once the required parameter values are determined for each controller, the liquid level is controlled with the algorithm used. In the close loop experiments, the liquid level control valve opening was changed for 100 min at 10% opening percentage value, and the system response was observed for disturbance rejection. Then, the control algorithms were activated and the system was controlled. Figure 2 shows the CV2 tank in the liquid level system and manually adjustable flow rate valves.

4 Results and Discussion

Experiments were carried out with the GPC algorithm by selecting different liquid level setpoints and the control weighting values $\lambda = 0.5, 0.05, 0.005$, and the other control tuning values $Nu = 1$, $N_2 = 2$. After the liquid level control valve is operated at 10%

Fig. 1 Process control simulator modified for distributed wireless control purpose

openness, the block which includes the GPC control algorithm is activated with the help of the key block in the MATLAB/Simulink block diagram and the control experiments are carried out. The ARIMAX model used in this algorithm is given in Eq. (1), in which its parameters were identified using responses to the pseudo disturbance effect. The MATLAB/Simulink block diagram used in the wireless fluid level GPC control experiment is shown in Fig. 3.

In Fig. 3, There are four modules, the wireless on/off block for turn on/off the wireless communications, the numerical or graphical display blocks of process parameters, the block for given numerical opening percentage values between 0 and 100% to the valve, the S-function block for previously prepared and saved the GPC algorithm as MATLAB m.file and the blocks of stored errors for the MATLAB/Simulink diagram.

In the experiments using the GPC algorithm, it is observed that the level control valve operates at 100% openness (saturation value) except for values of $Nu = 1$ $N_2 = 2$. The liquid level sensor is activated to prevent flooding in the system due to sudden increases in the liquid level and experiments on these saturated values are not carried out.

Liquid level control experiments were performed at different setpoints (i.e. 3, 4, 5, 6 dm) by means of the GPC algorithm using the different values of λ parameter with the wireless network (see Figs. 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27).The best control results were obtained at $\lambda = 0.05$ by selecting different liquid level setpoints.

As seen in Tables 2 and 3, ISE and IAE values were obtained from the change of the liquid level with time, as opposed to the setpoint values, respectively. According to these experiments and the calculated ISE and IAE values, the best control is provided for $\lambda = 0.05$.

Fig. 2 V2 tank in the liquid level system and manually adjustable flow rate valves

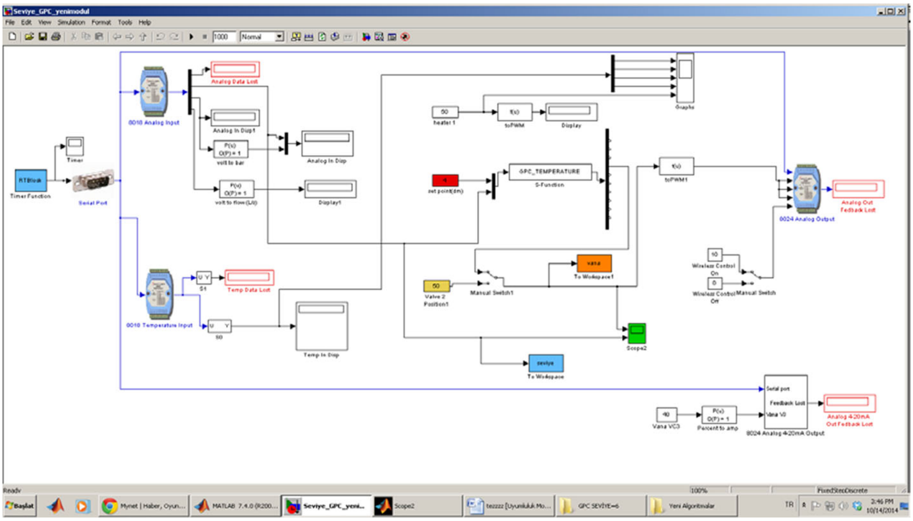

Fig. 3 MATLAB/Simulink block diagram of liquid level control experiments using GPC algorithm

5 Conclusions

We have successfully applied a distributed wireless liquid level control using the GPC algorithm to a simulator. The control works were performed by choosing different values of λ, N_2, Nu coefficients which are the tuning parameters of the GPC algorithm. It was noted that the level control valve was operating at 100% (saturation) in all values of

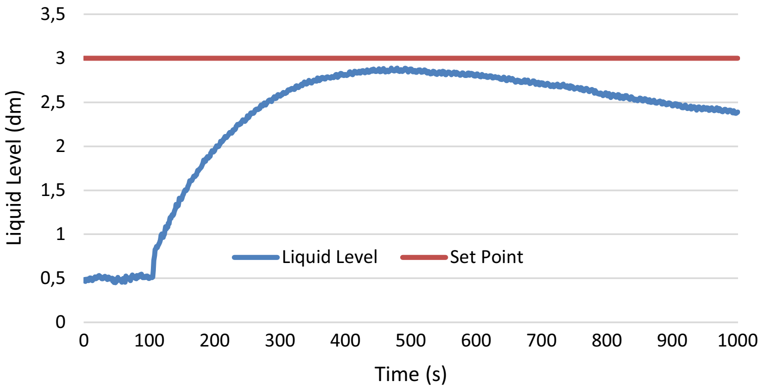

Fig. 4 Controlled liquid level changes for set point 3 dm, Nu = 1, N_2 = 2 and λ = 0.5

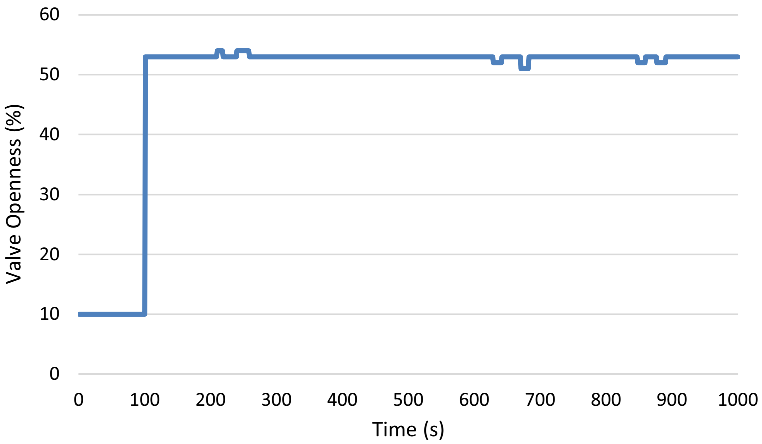

Fig. 5 Liquid level valve position changes for set point 3 dm, Nu = 1, N_2 = 2 and λ = 0.5

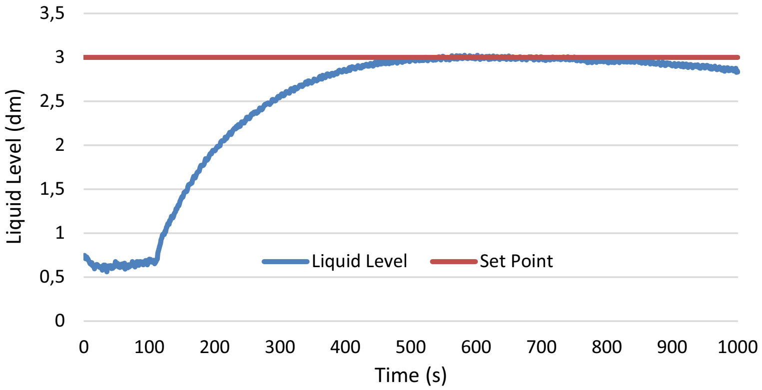

Fig. 6 Controlled liquid level changes for set point 3 dm, Nu = 1, N_2 = 2 and λ = 0.05

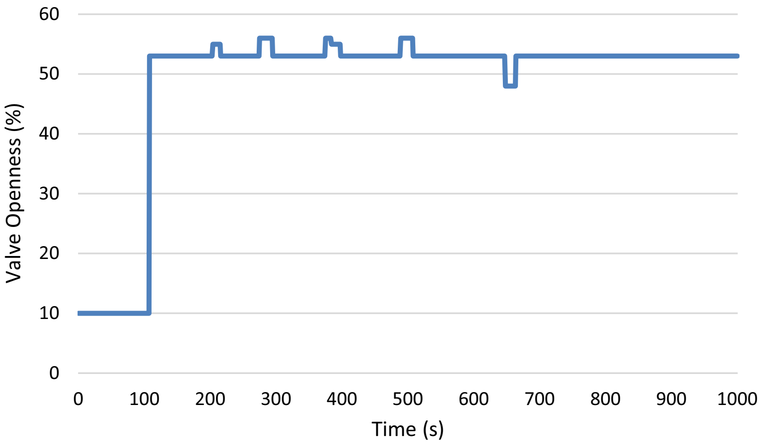

Fig. 7 Liquid level valve position changes for set point 3 dm, Nu = 1, N_2 = 2 and λ = 0.05

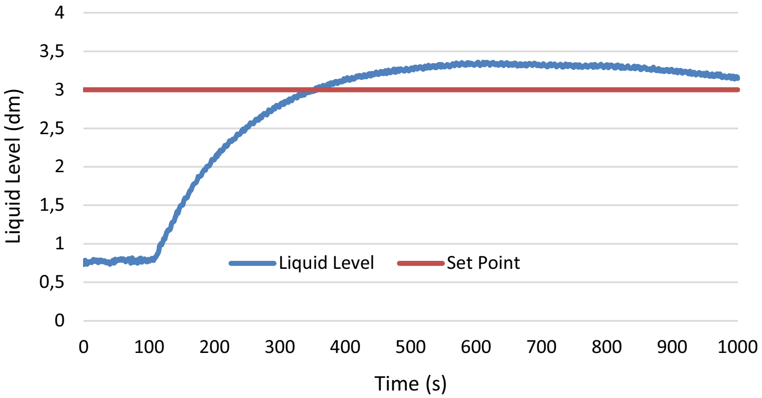

Fig. 8 Controlled liquid level changes for set point 3 dm, Nu = 1, N_2 = 2 and λ = 0.005

Nu > 1 and $N_2 > 2$ except Nu = 1, $N_2 = 2$ during the wireless level control experiments using the GPC algorithm. To prevent flooding, the liquid level sensor has been activated in the system and the experiments limitations and constrains were taking into account. In the distributed wireless level control experiments using the GPC algorithm, changes in valve opening and liquid level were monitored under the same conditions for three certain weighting factor values at λ = 0.5, 0.05, 0.005 in the algorithm. In all cases studied, it was observed that the control valve opening percentages come to the ultimate value with very small oscillations after a sudden increase at the beginning. The best control response among all controlled variable changes for different setpoints in the same conditions was found for a certain weighting factor value, λ = 0.05.

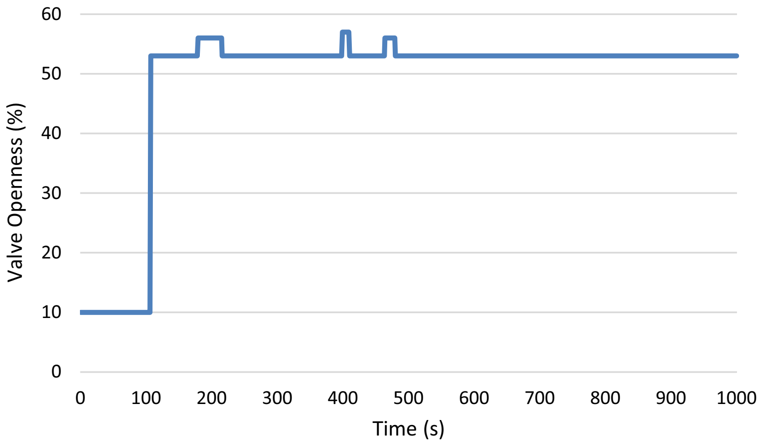

Fig. 9 Liquid level valve position changes for set point 3 dm, Nu = 1, N_2 = 2 and λ = 0.005

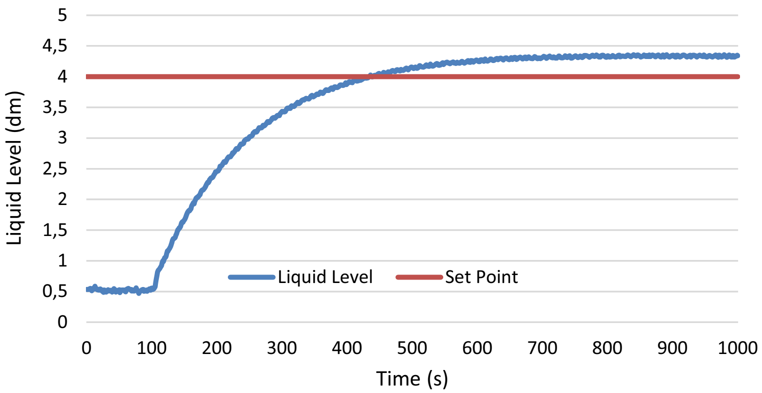

Fig. 10 Controlled liquid level changes for set point 4 dm, Nu = 1, N_2 = 2 and λ = 0.5

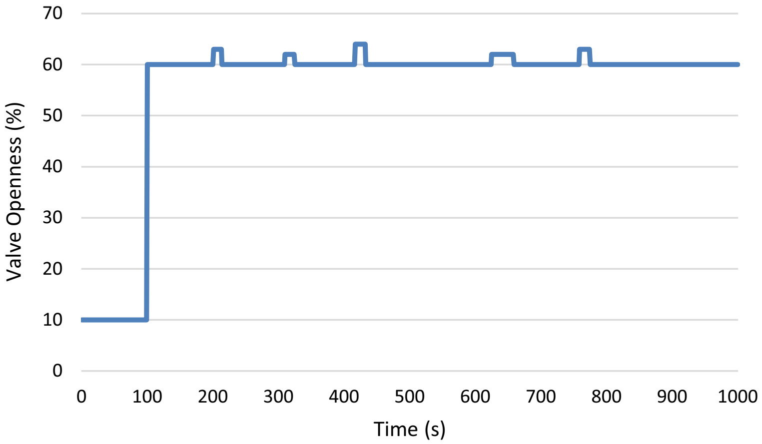

Fig. 11 Liquid level valve position changes for set point 4 dm, Nu = 1, N_2 = 2 and λ = 0.5

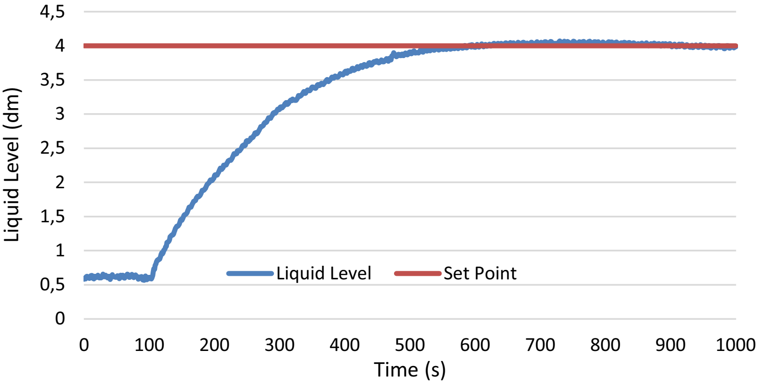

Fig. 12 Controlled liquid level changes for set point 4 dm, Nu = 1, N_2 = 2 and λ = 0.05

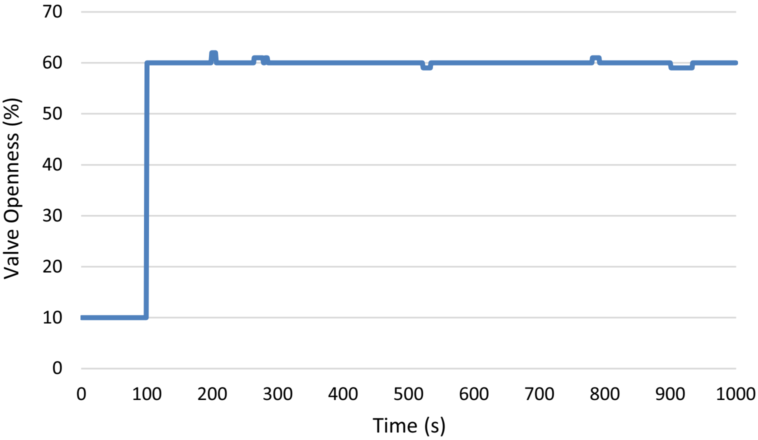

Fig. 13 Liquid level valve position changes for set point 4 dm, Nu = 1, N_2 = 2 and λ = 0.05

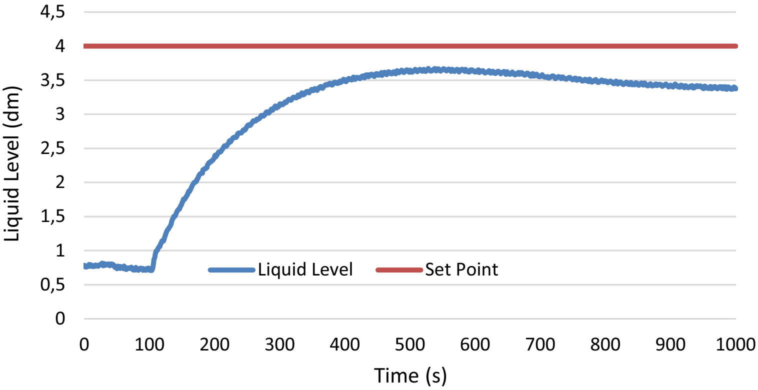

Fig. 14 Controlled liquid level changes for set point 4 dm, Nu = 1, N_2 = 2 and λ = 0.005

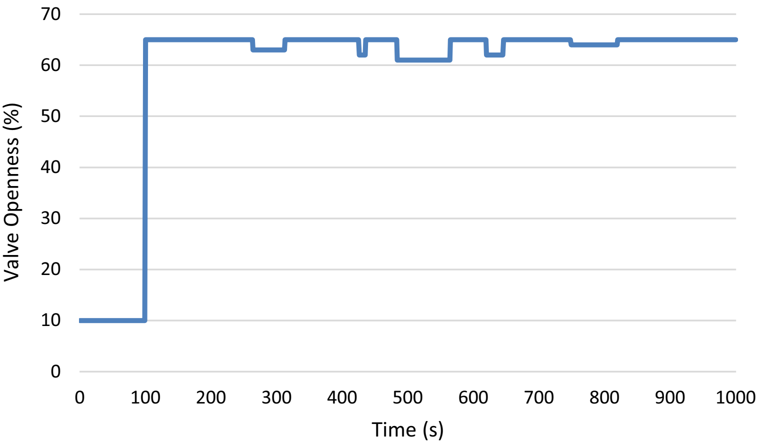

Fig. 15 Liquid level valve position changes for set point 4 dm, Nu = 1, N_2 = 2 and λ = 0.005

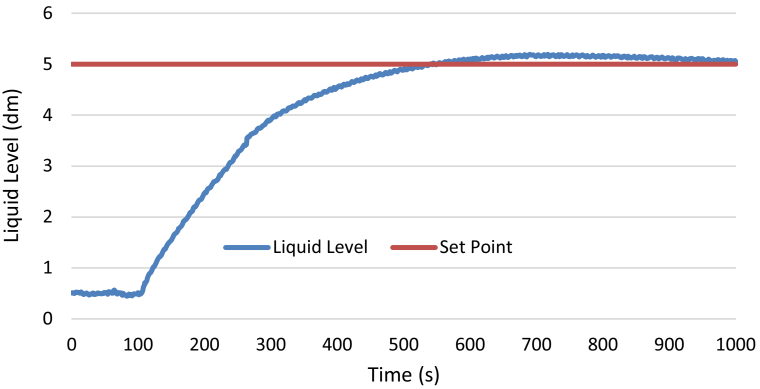

Fig. 16 Liquid level changes for set point 5 dm, Nu = 1, N_2 = 2 and λ = 0.5

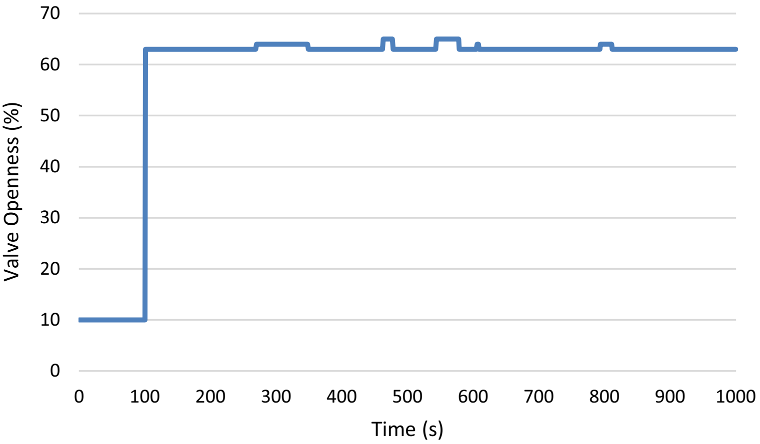

Fig. 17 Liquid level valve position changes for set point 5 dm, Nu = 1, N_2 = 2 and λ = 0.5

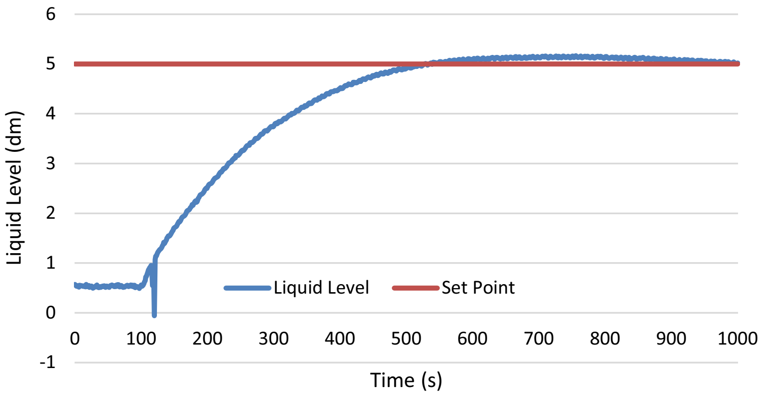

Fig. 18 Controlled liquid level changes for set point 5 dm, Nu = 1, N_2 = 2 and λ = 0.05

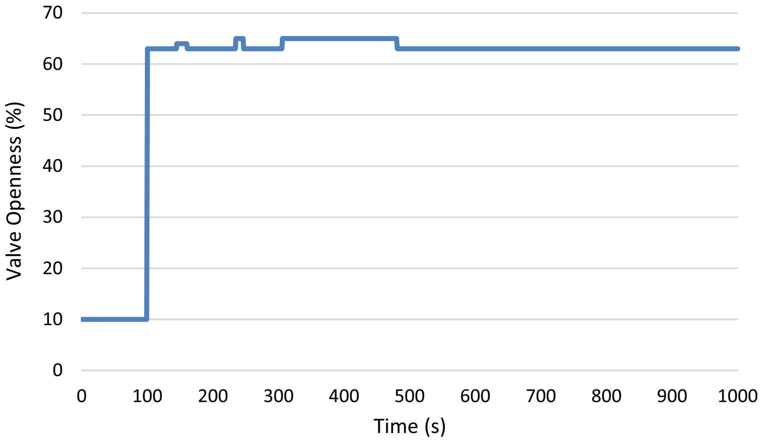

Fig. 19 Liquid level valve position changes for set point 5 dm, Nu = 1, N_2 = 2 and λ = 0.05

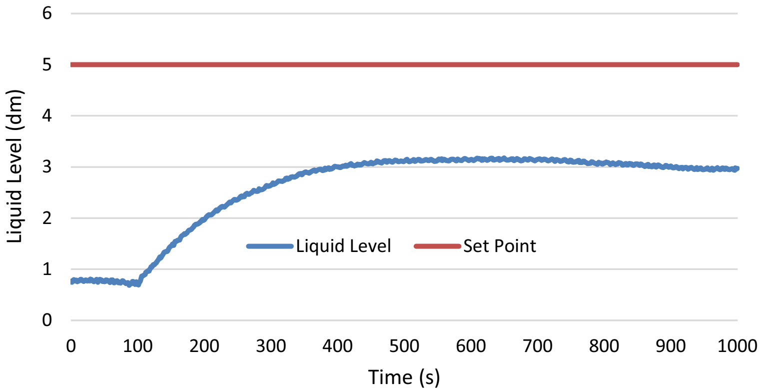

Fig. 20 Liquid level changes for set point 5 dm, Nu = 1, N_2 = 2 and λ = 0.005

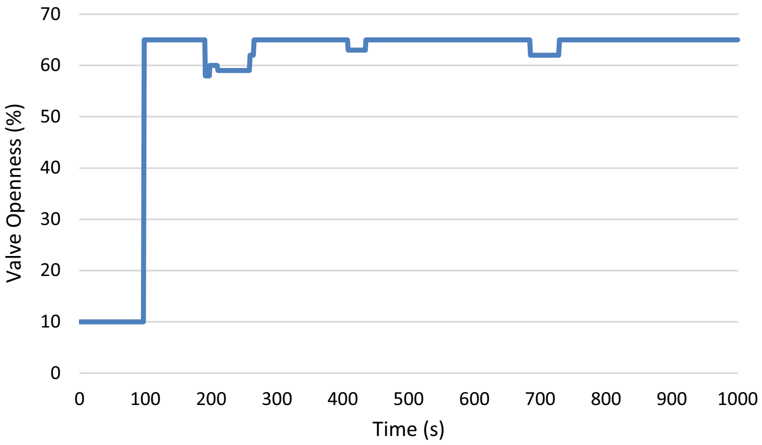

Fig. 21 Liquid level valve position changes for set point 5 dm, Nu = 1, N_2 = 2 and λ = 0.005

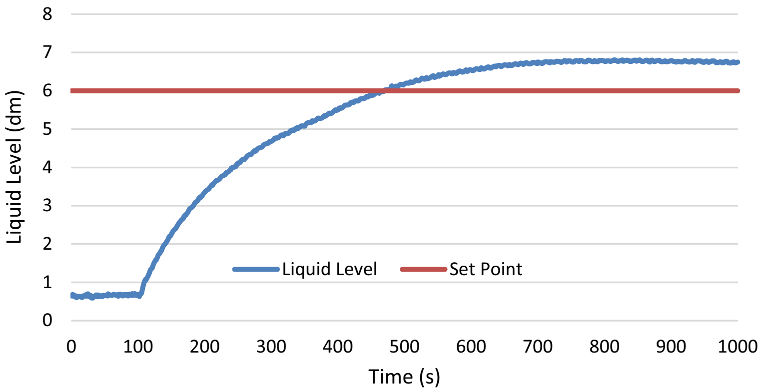

Fig. 22 Controlled liquid level changes for set point 6 dm, Nu = 1, N_2 = 2 and λ = 0.5

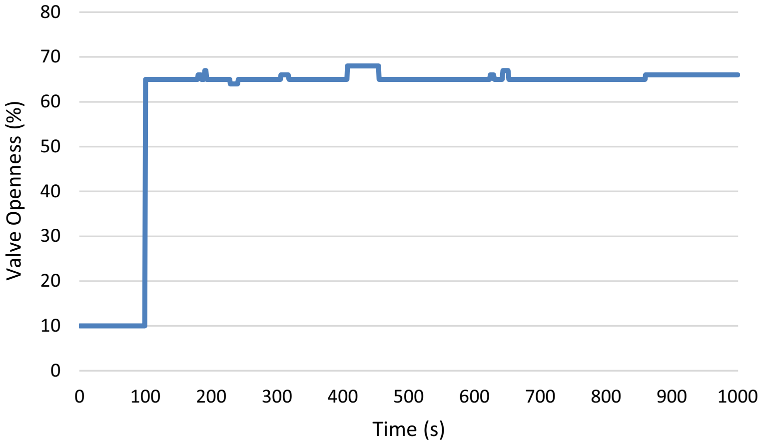

Fig. 23 Liquid level valve position changes for set point 6 dm, Nu = 1, N_2 = 2 and λ = 0.5

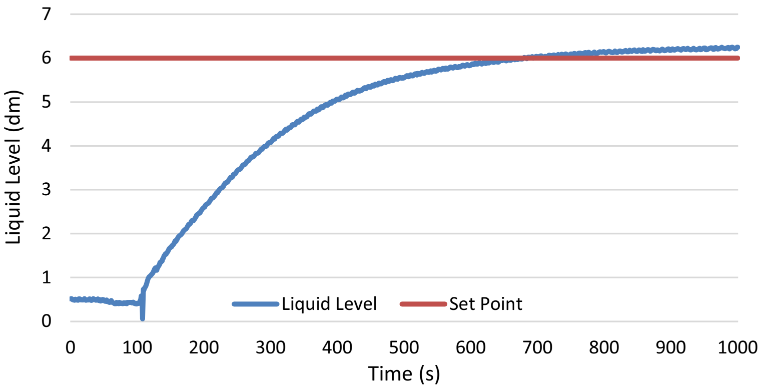

Fig. 24 Controlled liquid level changes for set point 6 dm, Nu = 1, N_2 = 2 and λ = 0.05

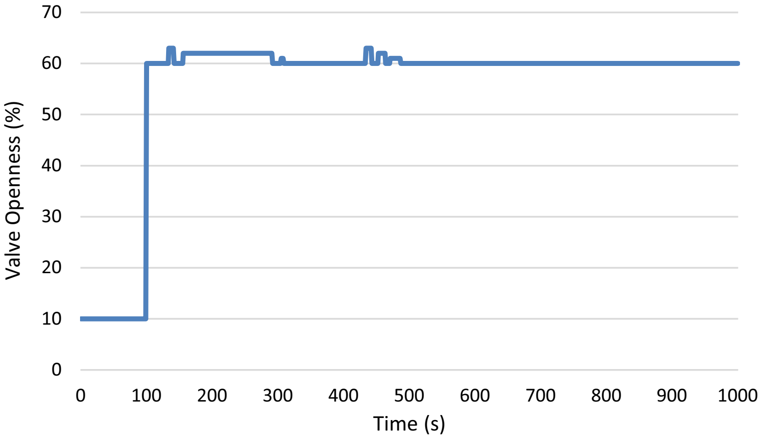

Fig. 25 Liquid level valve position changes for set point 6 dm, Nu = 1, N_2 = 2 and λ = 0.05

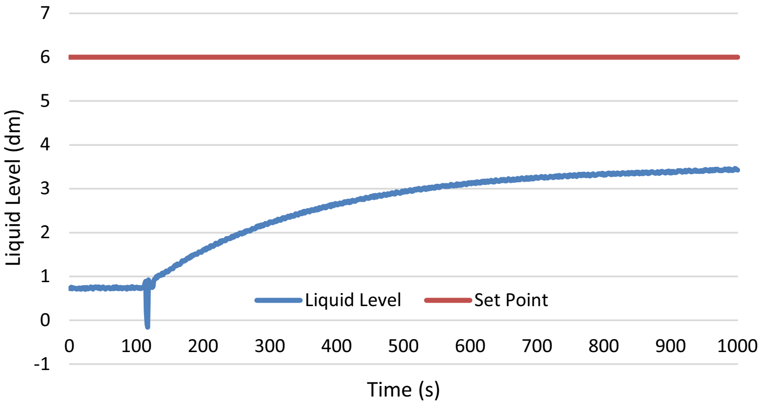

Fig. 26 Controlled liquid level changes for set point 6 dm, Nu = 1, N_2 = 2 and λ = 0.005

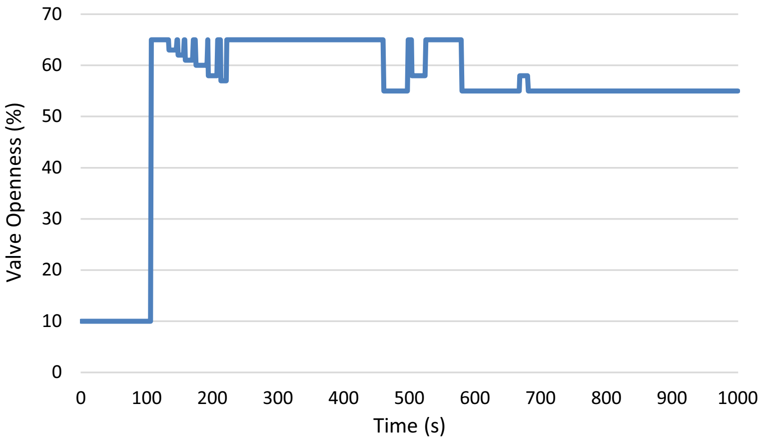

Fig. 27 Liquid level valve position changes for set point 6 dm, Nu = 1, N_2 = 2 and λ = 0.005

Table 2 ISE values of GPC results for different set points (3, 4, 5, 6 dm)

λ	3 dm	4 dm	5 dm	6 dm
0.5	1046.222	1983.824	3683.182	5994.471
0.05	825.962	1963.749	3615.333	5117.357
0.005	909.73	2094.802	6486.967	12,903.93

Table 3 IAE values of GPC results for different set points (3, 4, 5, 6 dm)

λ	3 dm	4 dm	5 dm	6 dm
0.5	704.292	877.561	1133.984	1555.465
0.05	529.624	842.369	1124.977	1539.133
0.005	599.105	1028.845	2417.218	3472.46

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Publisher's Note

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